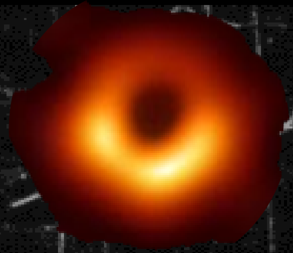
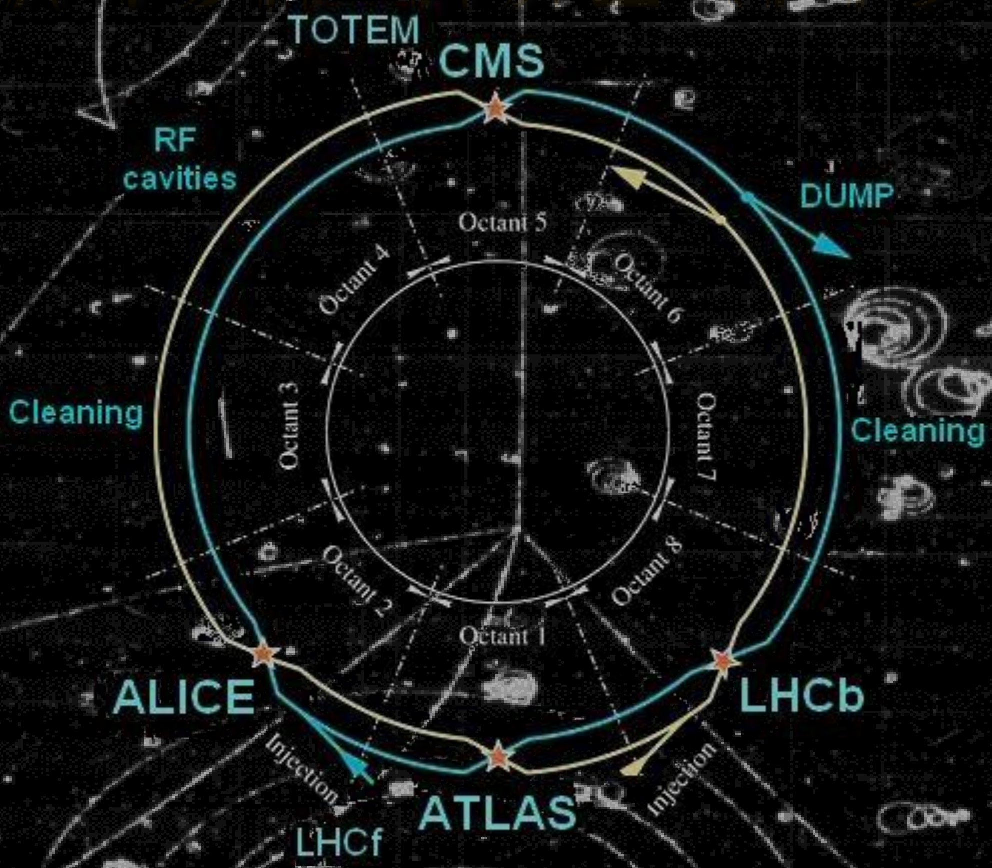
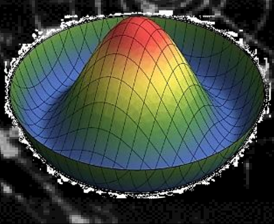


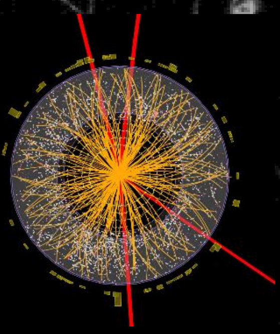
MEGA SCIENCE VISION-2035



High Energy Physics

A Roadmap prepared by the
Indian High Energy Physics Community





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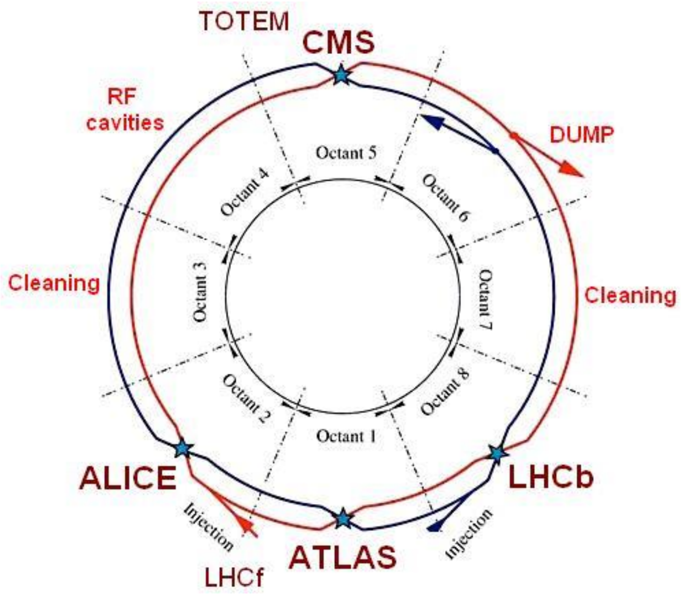


High Energy Physics

A roadmap prepared by the Indian High Energy Physics community with TIFR, Mumbai as the Nodal Scientific Institution

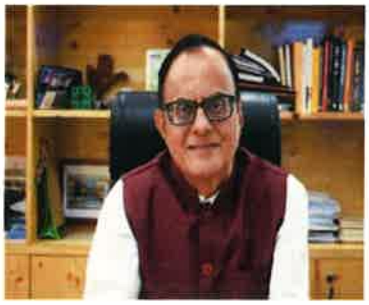
and submitted to

The Office of the Principal Scientific Advisor to the Government of India

अजय के. सूद
भारत सरकार के प्रमुख वैज्ञानिक सलाहकार
Ajay K. Sood
Principal Scientific Adviser to the Govt. of India

सत्यमेव जयते

विज्ञान भवन एनेक्सी
मौलाना आजाद मार्ग, नई दिल्ली–110011
Vigyan Bhawan Annexe
Maulana Azad Road, New Delhi - 110011
Tel. : +91-11-23022112
Fax: +91-11-23022113
E-mail : sood.ajay@gov.in
office-psa@nic.in
Website : www.psa.gov.in



MESSAGE

It is with great pleasure that I receive the Mega Science Vision-2035-High Energy Physics (MSV-2035-HEP) Report. HEP, or Particle Physics, may be aptly called the most fundamental of all fundamental sciences, aiming to discover the most elementary constituents of matter and the nature of interactions between them. It has a natural overlap with cosmology as HEP insights help us understand the very early Universe; and also with a wide range of astrophysical processes and cosmic rays. HEP, especially over the past 75 years or so, has made spectacular strides resulting in the development of the Standard Model of Particle Physics (SM) and its stunning experimental vindication so far. As Indians, it is matter of pride that our scientists have been a part of this journey right from the early days of this field, with some notable achievements in cosmic ray and theoretical research and also well-recognized contributions to international collaborations leading to momentous discoveries such as those of the top quark, Higgs boson and Quark Gluon Plasma.

Given the nature of physical systems that this discipline tries to study, access to Mega Science Projects (MSPs) is a necessity for making progress in this field of research. In the accelerator domain, these are in the form of very high energy and/or very high intensity facilities. The Large Hadron Collider at CERN is the highest energy accelerator today and manifestly demonstrates what MSPs are and what they are all about. And in the non-accelerator domain, these are in the form of sensitive (often very large) detector systems for studies with cosmic rays etc. HEP and MSPs are natural partners and it is not surprising that HEP was included in the MSV-2035 Exercise as a prominent discipline by the Office of the Principal Scientific Adviser to the Government of India (O/o PSA).

This Report makes a well-considered case, and presents a well thought-out and prioritized plan, for India to pursue MSPs in HEP to remain internationally competitive in this field by experimental exploration along three axes of enquiry, viz. the energy frontier, the intensity frontier and the cosmic frontier. It highlights the importance of pushing the theory frontiers of the field as well. Theoretical developments have quite often preceded

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their experimental confirmations in this field. The path shown by the fundamental symmetries of Nature and the principles of relativistic quantum field theory have served the scientific community well while advancing the knowledge in this field. The Report establishes the need to participate in both international projects and to build national facilities, based on sound physics arguments and honest assessment of national capabilities. It also makes suggestions for strengthening the national eco-system for MSPs. Coming as it does after intense and extensive nation-wide consultations (as well as interaction with national and international experts), the Report carries the wisdom of the entire HEP community of the country. I am sure it will be valuable for planning our future mega science activities in HEP. And given its comprehensive coverage, I am confident that it will be read with interest by the international HEP community as well.

I must thank the Tata Institute of Fundamental Research, Mumbai, for leading this exercise, and our colleagues on the Drafting and Working Groups for the enormous effort put in by them. Having formulated such a nice plan, I am sure the high energy physics community in the country will join hands and take steps to turn them into reality. My best wishes to them!

I thank Dr. Praver Asthana from my office for his invaluable help in coordinating & bringing out this report.

(Ajay K. Sood)

Dated: 24th July, 2025

सत्यमेव जयते

डॉ. (श्रीमती) परविन्दर मैनी
वैज्ञानिक सचिव

Dr. (Mrs) Parvinder Maini
Scientific Secretary

भारत सरकार के
प्रमुख वैज्ञानिक सलाहकार के कार्यालय
विज्ञान भवन एनेक्सी
मौलाना आजाद मार्ग, नई दिल्ली - 110011

Office of the Principal Scientific Adviser
to the Government of India
Vigyan Bhawan Annexe
Maulana Azad Road, New Delhi-110011

New Delhi dated 22nd July, 2025

FOREWORD

High Energy Physics (HEP), or Particle Physics, is the area of fundamental research where Mega Science Projects (MSPs) are the most required. Its goal is to discover the most elementary constituents of matter and the nature of interactions between them. This requires access to very high energy particle accelerators, as well as non-accelerator-based experiments, both employing sophisticated (and usually very large) detector systems. The Large Hadron Collider is the leading global facility for HEP research today, and is a supreme example of what MSPs are all about. Not surprisingly, HEP was a major discipline included in the Mega Science Vision-2035 Exercise facilitated by the Office of the Principal Scientific Adviser to the Government of India (O/o PSA). I am glad that the MSV-2035-HEP Report is now being released after extensive national consultations within the HEP community, and also after consultations with leading national and international experts.

This lucidly-written Report starts with giving the current status of the field including a brief account of the development of the Standard Model of Particle Physics (SM), contributions made by Indian scientists in this development, the successes of the SM and the current scientific challenges in the field. It then summarizes the Indian involvement in the current projects, both accelerator-based as well as non-accelerator-based, giving in each case the scientific and technological (hardware) contributions, HRD efforts, contributions by the Indian industry, expected funding requirements, and an overall appraisal. Building on this assessment of the experience and expertise gained so far, the Report proposes a bouquet of future experimental activities, international as well as national including a prioritized list of projects and two budgetary scenarios. To arrive at a community-wide consensus to prioritize the experimental plan and moderate the budgetary requirements is no mean achievement and the community needs special thanks for this. The Report also presents an honest SWOT analysis of the Indian potential for MSPs in HEP and puts forward concrete suggestions to strengthen the national eco-system for such experimental activities. HEP has natural connections with Nuclear Physics, Accelerator Physics and Astronomy & Astrophysics. The Report also outlines possible synergies with these areas.

This Report would not have been possible without the enormous and sustained efforts made by the Drafting and Working Groups (DG and WG) set up by the O/o PSA. Three successive Directors of the Tata Institute of Fundamental Research (TIFR), Mumbai, closely guided these efforts (Prof. Sandip Trivedi, Prof. S. Ramakrishnan and Prof. Jayaram Chengalur) with their immense experience, knowledge and wisdom as the Chair of the WG. Prof. Amol Dighe of TIFR, the Member-Secretary of the WG, proved to be the strong pivot around which this entire Exercise revolved. We deeply acknowledge their contributions and express our heartfelt thanks.

Special thanks are due to Dr. Praveer Asthana, PSA Fellow, who supported this activity and provided valuable inputs.

I have every reason to believe that this Report will be greatly valuable for researchers and funding agencies while planning and supporting HEP-MSP activities in the country.

(Parvinder Maini)

Tel: +91-11-23022090 Fax : +91-11-23022116 E-mail: parvinder.maini@gov.in Web: http://www.psa.gov.in

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ABOUT THE MEGA SCIENCE VISION-2035 EXERCISE

Mega Science Projects (MSPs) are scientifically and technologically complex projects, requiring collaboration among scientists, engineers, technicians, project managers, funding organizations, industry, etc. on a large scale – occasionally from institutions and organizations in different nations across the world. MSPs, quite often, are also large in physical size and require large monetary, capital, human and intellectual resources. MSPs are also very long-term engagements – typically taking ten years for planning, another ten years for construction and, finally, remaining in operation anywhere from 20-50 years. It follows as a corollary that, at any given time, only a few such projects can be taken up nationally, or even globally.[1]

It is natural that the decision regarding which projects to launch nationally, or which projects to participate in internationally, is always taken through wide national consultations among the concerned scientific communities. This is the way it is done the world over. And, this is the way it has been done in India, at least over the past three decades. Such structured and periodic national consultations in India have been known by several names in the past. From some point of time, they have come to be known as "Vision Exercises". Since the disciplines of nuclear physics, high energy physics and accelerator science and technology and applications were the first to experience the need for MSPs, the Vision Exercises in India in the past were facilitated by the Department of Atomic Energy (DAE) and the Department of Science and Technology (DST). In the case of Astronomy & Astrophysics, the Astronomical Society of India has been periodically organizing such exercises.

In the Indian context, by 2020, a number of MSPs that had been identified in the earlier Vision Exercises had moved further towards funding and implementation. It was, therefore, felt that a time had come to carry out the next Mega Science Vision (MSV) Exercise. It was also realized that the country had travelled a long-way from the days of India-CERN Collaboration, which could aptly be called the turning point for India's engagement with MSPs. There were a number of national as well as international projects which India had nationally launched, or in which India was participating internationally. The concerned scientific communities in India had also grown more confident and ambitious about getting involved in more such projects. Also, large collaborations had become necessary in a number of other science disciplines too. It was, therefore, decided to make the MSV Exercise more structured, inclusive and comprehensive.

In consultation with DAE and DST, which had been facilitating such exercises earlier in a few disciplines, it was decided that it would be better if the Office of the Principal Scientific Adviser to the Government of India (O/o PSA to GoI) facilitated the Exercise this time — given its pre-eminent S&T policy-making and coordination role in the GoI. The centre of activities thus got shifted to the O/o PSA to GoI. The O/o PSA to GoI decided that the Exercise this time would be carried out not only in Nuclear Physics, High Energy Physics, Astronomy & Astrophysics and Accelerator Science & Technology and Applications, but also in two additional areas, viz. Climate Research and Ecology & Environmental Science. Both these areas also require large-scale experimentation, data-gathering and analyses, and in many ways have been involved in MSPs without calling it by that name or realizing the same. The outcome of the MSV Exercise was expected to be comprehensive Roadmap Reports, one in each of the six areas. Given the typical time frame of MSPs, 2020-35 was decided as the period of focus for this MSV Exercise. Hence was born the Mega Science Vision-2035 (MSV-2035) Exercise in the six areas mentioned above.

For carrying out the MSV-2035 Exercise in High Energy Physics (HEP), the O/o PSA to GoI requested the Tata Institute of Fundamental Research (TIFR), Mumbai, to act as the Nodal Institution, to which it readily agreed. TIFR also nominated Prof. Amol Dighe as the Nodal Scientist. In consultation with TIFR, a Working Group (WG) was constituted with Director-

TIFR as the Chair, and Prof. Amol Dighe as the Member-Secretary. A smaller sub-group of the WG acted as the Drafting Group (DG). The O/o PSA to GoI also laid down the goals of the Exercise and the methodology for national as well as international consultations during the Exercise.

The DG made exemplary effort in putting together several drafts of the document by reaching out to a large number of leading researchers in HEP in the country, and after consulting similar roadmap documents from elsewhere in the world. The WG also met several times to look at the evolving drafts and offered valuable suggestions. A discussion was also organized among all the six WGs to exchange ideas about several issues that were common to all the six disciplines — for example, management structures for MSPs, aspects of fund flow, human resource development, outreach efforts, etc. Finally, a draft of the MSV-2035-HEP Report got evolved which was approved by the WG for wider national consultations. Comments on the Draft Report were electronically invited from about 750 researchers working in HEP and other proximate areas in the country. Comments from about 30 individual researchers, India-CMS Collaboration and India-Belle Collaboration were received and the draft was further modified in view of those comments. This draft was sent to 24 eminent national and international experts for their comments, and 10 of them sent their written comments. 14 of these 24 experts were also invited for an on-line discussion. 12 participated and provided their comments orally. The draft was again revised in view of these written as well as oral comments from the experts. The draft so developed was presented before the PSA to GoI, prior to its submission. Comments and suggestions received during this meeting were also incorporated to the maximum possible extent. After all these steps, this final MSV-2035-HEP Report has emerged.

This MSV-2035-HEP Report is a "Roadmap" prepared by the national HEP community outlining their hopes and aspirations for mega science activities till 2035, as best as they can foresee today. Needless to say, if there are some momentous changes in the field in this period, it might change some of the projections contained in this Report. And, a similar Exercise will again take place after another 5-6 years where this Report will get updated.

It must be emphasized that this is a 'HEP community document', the preparation of which has been facilitated by the O/o PSA to GoI. Apart from putting the Report on the PSA Office website, it is planned to circulate the Report to various Ministries/Departments and Funding Agencies. It is sincerely hoped that the Report will be found useful by everyone associated with MSPs in the country in any manner. It is also hoped that the Report will be found useful by the international HEP community as well.

(PRAVEER ASTHANA)
PSA Fellow, O/o PSA to GoI

1. Asthana, P., Mega Science Programme in India – evolution and prospects, *Current Science*, 2022, **123**, 26.

Preface

Scientists are the bearers of the torch of discovery in our quest for knowledge
— Stephen Hawking

High Energy Physics is the study of elementary particles and their interactions at the most fundamental level. Emerging out of nuclear physics in the 1930s, this discipline forms the cutting edge of our knowledge of the smallest known objects and of the earliest times after the origin of the Universe. It is a matter of pride that Indian scientists have been involved in this exciting field right from the beginning, and that many have left their mark on the way the subject has progressed. In a sense, therefore, it is imperative that we keep the flag of discovery flying in this area. The highway to this is through large experiments which investigate the ultra-small; it is such experiments that collectively go by the name Mega Science.

The Office of the Principal Scientific Advisor (PSA) to the Government of India has taken up the challenging task of preparing a blueprint for the participation in and development of Mega Science enterprises by Indian scientists, with a target period up to 2035. This programme, aptly named the Mega Science Vision-2035 (MSV-2035), is being carried out in six different areas, of which High Energy Physics is one. For each area, a Working Group and a Drafting Group were created, in order to come up with a report on the best way in which India could develop Mega Science projects in the area. The mandate given to these groups was, in brief, (a) to report the state-of-the-art in the field and make a strengths, weaknesses, opportunities and threats (SWOT) analysis for India in the time window 2020–2035, (b) to enunciate the need for continuing and undertaking new Mega Science projects, (c) to examine the relevance of such Mega Science programmes for India's scientific and technological goals and (d) to suggest appropriate evaluation, funding and management structures for such programs. The present report represents the culmination of these efforts, which have included a community-wide consultation exercise where a large and significant fraction of the High Energy Physics community in India have provided useful inputs. This report, therefore, may be regarded as the collective view of the entire High Energy Physics community in India.

It may be worthwhile, at the very outset, to take a brief look at the earlier developments in High Energy Physics research in India, for that would be the solid foundation on which any future programmes can be built. We may note that the cloud chamber, the vehicle for so many early discoveries in particle physics, was perfected by C. T. R. Wilson in 1911, at Cambridge, the same year that Ernest Rutherford, H. Geiger and E. Marsden discovered the atomic nucleus. A young Indian student, D.M. Bose, was trained by Wilson to build a cloud chamber and he brought back this skill when he returned to India in 1913. Cosmic rays had just been discovered in 1912 and their particulate nature was not yet understood. Bose moved to Berlin for the period 1914 – 1919, where he pioneered the use of a cloud chamber to study these mysterious cosmic rays. His discovery of nuclear recoil following cosmic ray interactions had a deep influence on their eventual identification as high energy particles of extraterrestrial origin. Returning to India in 1919, Bose and his student S.K. Ghosh soon constructed a cloud chamber indigenously. Theirs were the first subatomic particle tracks to be recorded in India.

Cosmic ray and particle physics really took off in the 1930s, with Wolfgang Pauli's hypothesis of the neutrino and C.D. Anderson's discovery of the positron. It was in this period that Indian scientists began to contribute to the theoretical side of the subject. M. N. Saha and D. S. Kothari, at Allahabad University, constructed an elegant theory of beta decay which does not need a neutrino. Saha went on to construct a theory of magnetic monopoles, and discussed a monopole-anti-monopole bound state *à la* positronium. At Bangalore, N.S. Nagendranath, working with Max Born (on a one-year visit to India) developed a theory of the photon as a neutrino-antineutrino bound state. None of these speculations survived long, but the same ideas have been re-used in the case of other particle systems. More impactful was the work of Homi J. Bhabha, whose calculation of electron-positron scattering is now described in all the textbooks as 'Bhabha scattering'. Bhabha, with W. H. Heitler, went on to develop the theory of cosmic ray showers, which is still the standard description of what happens when a cosmic ray particle hits the upper atmosphere.

In the late 1930s and 1940s, there was a proliferation of Indian cosmic ray experiments, based on the photographic emulsion technique pioneered by M. Blau and H. Wambacher at Vienna. D.M. Bose and Biva Chowdhury (1939 – 45) were the first to employ this technique to look for the 'mesotron' proposed by H. Yukawa in 1935, which they carried out in parallel with worldwide efforts by, among others, C.F. Powell at Bristol, L. Leprince-Ringuet at Paris and L.F. Curtiss and A.V. Astin at Washington D.C. Others using the emulsion technique in India around the same time were H.J. Taylor and V.D. Dabholkar at Bombay, P.S. Gill at Lahore (then in undivided India) and Homi Bhabha at Bangalore. During the War years 1940 – 45, Vikram Sarabhai was also present at Bangalore, carrying out several cosmic ray studies focussing on the latitude effect and geomagnetism.

All of the above were essentially individual efforts. Systematic and institutional research began with the founding of the Tata Institute of Fundamental Research (TIFR) at Bombay by Bhabha in the run-up to Independence, and the founding of the Physical Research Laboratory (PRL) at Ahmedabad by Sarabhai immediately after Independence. Bhabha created a strong research group by inviting contemporary stars like Bernard Peters, M.G.K. Menon, Sukumar Biswas and Biva Chowdhury to come to TIFR, and his group produced brilliant students like B.V. Sreekantan, Devendra Lal and Yash Pal. Bhabha and Alladi Ramakrishnan were the first to employ stochastic methods to cosmic ray shower formation. Another bright spark to join this group was E.C.G. Sudarshan, but he soon moved to the USA, where, with Robert Marshak, he went on to propose the V-A theory of weak interactions. Sarabhai, on the other hand, created a group single-handedly with his own students, of whom U.R. Rao is probably the best known. Bhabha had already started launching atmospheric balloons with scientific payloads during his Bangalore days, and in the 1950s and 1960s both TIFR and PRL were launching balloons and making studies of cosmic rays and their effect on the upper atmosphere. It was also during this period that Bhabha initiated studies of the cosmic ray flux in the depths of the Kolar gold mines, near Bangalore. It was then discovered by Sreekantan and others that at depths of about 2.2 km, the flux of cosmic ray muons produced in the upper atmosphere dies down completely. Bhabha and his group were quick to realise that such an environment was an ideal example of the background-free zone proposed by M.A. Markov (1957) as a place to search for the so-called atmospheric neutrinos, by detecting muons produced by rare inverse Compton scattering events among the neighbouring rocks. This led to India's first Mega Science experiment (by the standards of the time), where a set of seven iron calorimeter detectors were set up at a depth of 2.3 km in two of the deepest gold mine shafts by a joint TIFR-Osaka-Durham collaboration. Success followed when this group narrowly beat a rival American group to become the discoverer of atmospheric neutrinos (1965). In the 1970s, a new Mega Science experiment was set up in the gold mines to look for proton decay as well as magnetic monopoles. However, no events were detected till the experiment had to be shut down in 1992 following closure of the mines.

During this entire period, Indian scientists, especially from TIFR, were also participating in emulsion experiments at CERN, which was gradually becoming the particle physics hub of the world. In the 1960s, TIFR formed a bubble chamber group, and participated in experiments using the recently-invented bubble chamber. In fact, as the 1970s merged into the 1980s, cosmic ray studies began to take a back seat in High Energy Physics and accelerator-based studies came to the fore. By the 1990s, the discovery of particles like the gluon, the W and Z bosons, the τ lepton, the b quark and the t quark, served to consolidate the predominance of collider-based studies over cosmic ray experiments. Indian scientists from TIFR worked in an emulsion experiment at the Intersecting Storage Rings (ISR) accelerator, the first prototype of what has now become the standard collider design. Indian scientists made significant contributions in bubble chamber experiments at CERN, e.g. the measurement strategies proposed by them helped to achieve the best precision on the anti-proton lifetime. In the mid-1980s, the TIFR group joined the L3 Collaboration at the upcoming Large Electron Positron (LEP) Collider, which ran at CERN from 1989 – 2001. The group contributed to the R&D of endcap muon detectors and scintillator detectors for the L3 experiment and made key contributions to software development and physics analysis. Another group joined the DØ Collaboration at the Tevatron collider at Fermilab, and were mostly involved in hardware and physics analysis.

By the early 1990s, Indian contributions to Mega Science experiments had moved mostly overseas. Cosmic ray experiments at Udhagamandalam (Ooty), commenced in 1953, and were upgraded to become the GRAPES-1 experiment. Balloon launches had moved to Hyderabad by 1959, and a permanent facility was set up in 1970. This became the National Balloon Facility in 1980. However, the main focus of the time was on the CERN mega-experiments LEP and its successor, the Large Hadron Collider (LHC). India, through the Department of Atomic Energy (DAE), signed a five-year Cooperation Agreement with CERN in 1991. This was augmented by a DAE-CERN protocol in 1996, which has been the basis of India-CERN collaboration ever since. India had been one of the earliest non-member states to support the LHC proposal in 1994. The initiation of the LHC project led to the formation of the India-CMS Collaboration, as a part of the larger Compact Muon Solenoid (CMS) Collaboration [LlewellynS 2015]. Initially, this consisted of groups from TIFR, BARC, the University of Delhi and Panjab University, but later many other institutions have joined in. In 2002, India was granted Observer status in this predominantly European facility and became an Associate Member in 2016. While the initial contributions to the construction of the LHC accelerator were funded by the DAE, the remaining activities under the India-CERN Collaboration in HEP have been funded jointly by the DAE and the DST. Indian scientists have contributed to the development of accelerator magnets and detector components, and the participation continues today via hardware, software, operation, computing, data collection scrutiny, analysis, collaboration management, etc. India has also become a Tier-II centre for the grid computing programme, by which LHC is marshalling worldwide resources to satisfy their massive computing needs. Members of the India-CMS collaboration are now actively working on the High Luminosity upgrade (HL-LHC) currently scheduled to start in 2029.

As the above account makes clear, India has a long and sustained record of participation in High Energy Physics research at the cutting edge. Over the years, as the knowledge frontier has gone deeper and deeper, experiments in this area have become larger, more expensive and intergenerational in terms of the time scale. As a result, it has become increasingly difficult for all but the largest economies to build such facilities; in fact, the present model is for international collaborations with some share in the funding contributed by all members. Clearly, then, any progress envisaged for Indian science at the cutting edge can be pursued only on two fronts, viz. (*a*) participation in international collaborations as far as possible, with a view to learning and bringing back new technologies to India, and (*b*) development of smaller-scale experimental facilities within India, for which we must look for interesting niche-style physics problems, which are nevertheless of significance at the frontier of knowledge. Any such programme must aim, therefore, to fully exploit the results from the past investments in High Energy Physics programmes, tap international links to further boost the technology capacity building in niche high-tech areas (in collaboration with industry, as far as possible), start complementary national initiatives and also attempt to translate some components of basic science research to applications. The current report has been prepared with such goals in mind. To achieve these, an appropriate increase in research funding would be required in the coming decade, but it should pay handsome dividends by allowing the large pool of existing young scientists in the country to take up worldwide leadership roles in High Energy Physics research, address some of the deepest questions in science and create a conducive environment for the long-term development of science and technology in the country.

MEGA SCIENCE VISION - 2035

High Energy Physics

The Report

Working Group

Dr. Jayaram Chengalur (Dr. S. Ramakrishnan) (Dr. Sandip P. Trivedi)	Director, TIFR, Mumbai	Chairperson
Drafting Group		
Dr. Amol Dighe	TIFR, Mumbai	Member
Dr. Sreerup Raychaudhuri	TIFR, Mumbai	Member
Dr. Sudhir Vempati	IISc, Bengaluru	Member
Dr. Seema Sharma	IISER Pune	Member
Dr. Anirban Kundu	University of Calcutta, Kolkata	Member
Dr. Pratik Majumdar	SINP, Kolkata	Member
Other Expert Members		
Dr. Kajari Mazumdar	TIFR, Mumbai	Member
Dr. Pravata K. Mohanty	TIFR, Mumbai	Member
Dr. Jim Libby	IIT Madras, Chennai	Member
Dr. Bipul Bhuyan	IIT Guwahati	Member
Dr. Brajesh Chaudhary	University of Delhi	Member
Dr. Manas Maity	Visva Bharati, Santiniketan	Member
Dr. Bhawna Gomber	University of Hyderabad	Member
Dr. Sanjay Swain (India-CMS Spokesperson)	NISER, Bhubaneswar	Member
Agency Representatives		
Mr. Sanjay Malhotra (Nominee of Secretary DAE)	BARC, Mumbai	Member
Shri Gaurav Aggarwal (Nominee of Secretary DST)	DST, New Delhi	Member
Representatives of the O/o PSA		
Dr. Praveer Asthana	PSA Fellow and National Coordinator	Member
Dr. Arun Bhardwaj	Scientist-F	Member
Nodal Scientist		
Dr. Amol Dighe	TIFR, Mumbai	Member-Secretary

Executive Summary

It is my ambition to say in ten sentences what others say in a whole book
— Friedrich Nietzsche

High Energy Physics (HEP) is concerned with the most fundamental constituents of the Universe, and in that sense, is the deepest layer to which humans can probe into the secrets of Nature. It is a matter of pride for Indian scientists and researchers to be an integral part of this worldwide endeavour. This report aims to examine the current portfolio of projects in which India has substantial involvement, and plan for the future in which our unique strengths provide a path to international leadership. Efforts to achieve this would be carried out on the following four fronts.

1. **The Energy Frontier:** This direction comprises investigations in the next energy regime of particle collisions. This includes the precision measurements of the mass and couplings of the Higgs boson, as well as searches for physics beyond the Standard Model (BSM) at high-energy colliders, where new fundamental particles may be directly produced and observed.

2. **The Intensity Frontier:** In this direction the emphasis is more on probing the quantum structure of the interactions and impact of radiative corrections in the observables. To observe these generally small effects, one requires high-precision measurements, which may be achieved with experiments having high intensity beams, even when the energies involved are not very high. Another aspect of this frontier lies in the neutrino experiments, where high-intensity beams are essential since only a tiny fraction of the neutrinos passing through the detector are expected to have interactions with it.

3. **The Cosmic Frontier:** This direction is concerned with astrophysical and cosmological observations which include cosmic rays, gamma rays and neutrinos and their implications for understanding the acceleration of high energy cosmic particles, nature of dark matter, inflation, baryogenesis, matter-antimatter asymmetry etc. In addition to studying the astrophysical origins of these signals, one also looks for possible signatures of dark matter particles passing through and interacting inside the detectors.

4. **The Theory Frontier:** This aspect tries to assimilate the information obtained from all the above directions with the aim of coming up with a consistent theoretical model of fundamental particles and their interactions. It also covers new mathematical and computational techniques which can be applied to estimate various processes at high precision and test the limits of existing theories.

   Note that these four frontiers cover the three science themes, 'Deciphering the Quantum Realm', 'Illuminating the Invisible Universe' and 'Exploring New Paradigms in Physics', which are outlined in the US Particle Physics Project Prioritization Panel (P5) report [P5 2023].

   Progress in any or all of the four frontiers mentioned above is crucially dependent on Mega Science Projects (MSPs) that combine the expertise and resources from all over the world. Given the material as well as human resources which have to be invested, each project is one-of-a-kind, and has its own specific advantages. This report focuses on the MSPs that Indian HEP researchers are currently involved in, are planning to be involved in, or should be involved in, given the expertise that has been gained from the experience of participating in MSPs over the last many decades.

Current involvement: At the Energy Frontier, India is currently strongly invested[1] in the CMS experiment at the Large Hadron Collider (LHC) in CERN, Switzerland. At the Intensity Frontier, the major involvement is in the flavour-physics experiment Belle II at KEK, Japan, which produces a copious number of B mesons and studies their decays. In addition, Indian scientists have been involved in the neutrino experiment NOνA that makes precision measurements of neutrino oscillations and the Minerva experiment that measures neutrino-nucleus cross sections. At the Cosmic Frontier, there is involvement in the dark matter search experiments PICO/PICASSO in the Sudbury Neutrino Observatory, Canada, and in the high-energy gamma ray experiment MAGIC, located at La Palma in the Canary Islands, Spain.

The above MSPs are all located outside India. Indian scientists have been contributing to them via (*i*) the R&D and hardware for detector components, (*ii*) operation and maintenance of the experiments, and (*iii*) analysis of the data obtained from the experiments. On the other hand, there are a few projects located in India that have been planned and executed indigenously. GRAPES-3, an advanced version of the gamma ray astrophysics GRAPES project going on for the last few decades, is carrying out observations of GeV-energy muons, with possible implications for understanding space weather. The gamma ray experiment HAGAR is entering into its second phase, in the form of a 21-metre imaging telescope MACE. The prototype mini-ICAL detector built for the proposed India-based Neutrino Observatory (INO) has been taking cosmic ray data at Madurai; however, the INO project itself is stalled indefinitely due to lack of a suitable site.

Future prospects (International): In the coming decades, the present generation of collider experiments will naturally lead to successors with higher luminosities and energies. However, the exact timeline and nature of these new colliders will depend on several factors, including the consensus among the international HEP community. Since this cannot be decided by the Indian HEP community in isolation, we have to be ready for multiple scenarios, and to participate in the detector development efforts taking place on several fronts. The LHC, including its high-luminosity phase HL-LHC, will continue operations at least till 2040's, after which it may be replaced by a Future Circular Collider (FCC). The Belle II e^+e^- experiment is scheduled to wind down its operations by 2035. Some of the possible next-generation e^+e^- colliders are (*i*) the International Linear Collider (ILC) in Japan, (*ii*) the Compact Linear Collider (CLIC) at CERN, (*iii*) the Circular Electron Positron Collider (CEPC) in China and (*iv*) the Future Circular e^+e^- Collider (FCC-ee), also at CERN. A muon-antimuon ($\mu^+\mu^-$) collider is also an option currently under very serious consideration. On a longer time scale the FCC-ee may be replaced by an FCC-pp hadron collider. The R&D for the detectors to be deployed at these colliders will have to start now, if we want to play an important role in whichever facility comes up. In particular, the Indian community has the expertise to work on silicon detectors, scintillators, gas-based detectors, resistive plate chambers (RPC), etc. which can be marshalled towards this goal.

In the near future, one of the more promising directions where a relatively modest investment would be adequate is the study of long-lived particles, and the construction of customised detectors, which are to be located near the current LHC experiments. Some Indian institutions have already expressed an interest in participating in experiments with the MATHUSLA detector, which is proposed to be constructed near the CMS site. This could be a good opportunity to be involved right from the early stages of the project. Given that India is an Associate Member of CERN, there may be further opportunities for initiating novel experiments utilising the expertise and facilities available at CERN, which should be explored.

[1] India is also involved in the ALICE experiment at CERN, which is discussed in detail in the MSV-2035 Report in Nuclear Physics [MSV-2035-NP] and in the LIGO-India Experiment, which is discussed in detail in the MSV-2035 Report in Astronomy and Astrophysics [MSV-2035-A&A].

On the neutrino front, Indian physicists are likely to get involved in two international MSPs that will study neutrino oscillation physics, the Deep Underground Neutrino Experiment (DUNE) in the USA and the Hyper-Kamiokande (HK) experiment in Japan, both of which are expected to start within the next decade. The DUNE participation of Indian scientists would be a continuation of that in the NOνA and MINERνA projects, with the prospect of contributing to the construction of the near detector. Possible areas where Indian scientists could contribute to HK are being explored. In addition, the IceCube detector at the South Pole, which detects ultrahigh-energy neutrinos, will soon be upgraded to IceCube-Gen2, for which some contributions from Indian scientists in the form of detector assembly, integration and testing are being envisaged.

The Cherenkov Telescope Array (CTA) would be the most sensitive gamma ray astrophysics experiment in the world. Some Indian institutions have already been participating in CTA, but a formally-coordinated participation of Indian scientists (on the lines of the India-CMS or LIGO-India collaborations) would be highly desirable. There may also be some interest in becoming a part of the proposed Southern Wide-field Gamma-ray Observatory (SWGO). For dark matter detection, in addition to the PICO/PICASSO projects, participation in the SuperCDMS project that looks for weakly interacting massive particles (WIMPs) as dark matter and in GNOME/ADMX experiments that look for light axions as dark matter are envisaged.

Possibilities for India-based MSPs: Participation in leading experiments around the world gives India the opportunity to play a role in new scientific discoveries and provides exposure to cutting-edge technology. There is an absolute need for India to engage strategically and meaningfully in such projects to boost her scientific capabilities, drive technological innovation, and enhance her global scientific standing. However, the long-term aim should be to be one of the leading countries in knowledge creation in general and in the domain of MSPs in particular. This means that there should be experiments that are conceived, planned, executed and led by Indian scientists, preferably on Indian soil. This also has the advantage that our young generation of students will get the experience of working on MSPs from an early stage. Moreover, this would attract more students to science, and lead to a major growth in their numbers and expertise. Furthermore, this would lead to an overall improvement in innovation, conception and development of various technologies in India.

Cosmic ray experiments such as GRAPES-3 and MACE, as well as the ICAL prototype developed for INO, already represent some positive steps in the above direction. However, the number of such projects needs to grow. In this regard, it may be prudent to focus our efforts on niche experiments where the investment and expertise needed is commensurate with our scientific and technological strengths. Some such projects in their preliminary stages are (*i*) the dark matter search using superheated-liquid detector technology at the Jaduguda Underground Science Laboratory (JUSL), (*ii*) the neutrinoless double beta decay detection in Sn (the TinTin experiment) using a cryogenic bolometer, (*iii*) India-based Coherent Neutrino Scattering Experiment (ICNSE) at BARC, (*iv*) scintillation detectors for reactor monitoring and the search for possible sterile neutrinos, and (*v*) the deuterated liquid scintillator detector for low-energy solar neutrinos. In addition, opportunities exist for the study of the ^{7}Be line in the solar neutrino sector using Indium as the target material, for exploring the violation of parity/time reversal symmetries via the measurement of the electric dipole moment of the electron, and for a satellite mission for detecting medium-energy gamma rays, but no concrete steps have been taken on these fronts as yet.

Many of the above experiments need to be in a location where the cosmic ray background is minimal. India is geographically situated at a latitude where this occurs naturally, and we should take advantage of this circumstance to build underground laboratories that would allow the Indian HEP community to conceive of and execute MSPs at medium scale in such niche areas. If a suitable large underground laboratory can be built, the R&D carried out in the INO project would be invaluable for developing a neutrino detector at such a location.

An important aspect of developing a scientific ecosystem which can lead to sustained activities in Mega Science is the existence of smaller-scale ‘feeder’ projects, which consider new or more focussed aspects of an existing or potential MSP and study their experimental feasibility and scientific viability. It is often seen that such a small project has the potential to grow into a MSP. The Indian Mega Science Vision should not neglect this important aspect of research and should, in fact, actively nurture such projects.

Organisation and Planning: In view of the large investments in money and human resource, and the national prestige involved, MSPs need to be implemented in a planned, focussed and professional manner. Since most of the projects will involve international collaborations, the standard of output, both material and intellectual, must be compatible with the best international standards. This calls for a well-coordinated programme of training, implementation and feedback into the system, so that it can be sustained over several decades.

India has many strengths, including human resource, quality education and a tradition of doing MSPs, but also weaknesses that stem mainly from the fact that we are still a developing nation. Some of the pre-requisites for being able to carry out MSPs from inception to successful conclusion are skilled and trained human resource, a strong scientific ecosystem and the willpower and stamina to carry out sustained activities for a long time. Given the rate of growth of scientific knowledge and advanced technology, specialised training in state-of-the-art techniques is of paramount importance. It is also essential to induce the talented youth of the country to take up science as a career, and further to get them involved in MSP activities, for a strong base of trained and knowledgeable personnel lies at the core of technological prowess.

In addition, for ensuring successful, high-quality research that competes with the best in the world, one needs strong industrial involvement, timely availability of adequate funds and sustained governmental support. The industry must be convinced that developing customised high-end products will be profitable in the long run, and this will require some vigorous persuasion by the scientific community. One of the best ways to do this would be to involve industries as partners in MSPs from the inception. Since this kind of initiative will be new to India, proper modalities will need to be developed for government-industry partnerships in conceptualising and setting up MSPs.

The effectiveness of governmental support may be enhanced by making official procedures simpler. For example, there should be a single-window system for submission and evaluation of MSPs in a given area. A common evaluating body for all HEP MSPs would be useful in creating directions for the HEP community as well as ensuring that all MSPs are assessed on an even level. It would also be desirable if funding agencies can have a separate line in their budgets for MSPs.

In order to be able to play a major role in the future HEP MSPs, one would need common laboratory-cum-training facilities, with strong links to other institutions around the country, on the lines of the major HEP laboratories around the world. While individual universities and institutes will continue to carry out R&D in their own laboratories, such a *common* facility should act as a user centre. This is where we can locate infrastructure which is too big or too expensive to create multiple copies across the country and ensure that scientific personnel from multiple institutions can come and go freely in order to contribute to the design and development of MSPs. At such a facility, researchers could carry out coordinated developmental work in HEP-related instrumentation and high-end electronics. In addition, such a facility could house specialised laboratories and workshops for development and testing, and provide user support for high-end computation.

These would not be limited to HEP, but could be used by other areas as well, e.g., nuclear physics. Finally, specialised training programmes related to MSP activities could be run for students and industry partners.

The need for science communication and outreach cannot be overstated. Every MSP should mandatorily allocate some fraction of resources on Outreach activities. A centralised outreach unit for HEP Mega Science activities could help coordinate these activities in an efficient manner.

In summary, **the recommendations of MSV-2035 in High Energy Physics are**:

A. Scientific Recommendations:

1. ***Top priority projects:*** This includes those MSPs that are in progress or activities that are ready to be launched, and should be fully supported.

   a) *Collider experiments*: The current HEP MSPs in collider physics should be (i) CMS and (ii) Belle II. Planning and R&D efforts for experiments at future colliders such as FCC-ee/FCC-pp and/or a muon collider should start in a coordinated manner. Instrumentation R&D for new technologies for future detectors (e.g. quantum sensors) should be a priority.

   b) *Underground experiments*: Efforts to establish an underground observatory in the country (similar to that envisaged for INO), for experiments in HEP, Nuclear Physics and Astrophysics should be supported. Given the front-ranking status of dark matter searches in current particle physics, a dark matter search experiment that uses emerging technologies (such as the prototype at JUSL) could be developed to become a flagship experiment at such a site.

   c) *Neutrino experiments:* Participation in a top-of-the-line international neutrino experiment such as DUNE is strongly desirable, especially if the possibility of participation in building an important component of detector hardware is envisaged. There is also an opportunity for contributing detector components to IceCube-Gen2.

   d) *Cosmic ray experiments*: Support for the astroparticle physics experiments GRAPES-3 and MACE, and the neutrino scattering experiment ICNSE should continue. The upcoming Stereo MACE has great potential and should be aggressively pursued. Indian participation in the CTA Observatory is strongly recommended, given the importance of the experiment, the level of interest of Indian scientists, and its synergy with MACE.

2. ***Forthcoming prospects***: This includes those MSPs that appear promising and where initial steps need to be taken now.

   a) Possibilities of getting involved in a smaller collider physics experiment, viz. MATHUSLA, right from its R&D stage, should be explored.

   b) The areas of Indian contribution to HK should be clarified and defined in consultation with the HK collaboration, based on which a formal India-HK Collaboration may be considered.

   c) There is an opportunity for contributing significantly to the construction of IceCube-Gen2; however, the number of scientists involved in this activity needs to increase.

3. ***Minor-investment projects***: This includes projects that are a part of frontline international MSPs and should be encouraged, even though the Indian participation is envisaged to be small and the financial investment is not expected to reach the scale of MSPs:

   a) Gamma-ray observatory MAGIC (and, in the future, SWGO)

b) WIMP dark matter detection experiments PICO and Super-CDMS

c) Axion dark matter experiments GNOME, ADMX

4. ***Niche prospects:*** This refers to indigenous projects that are currently small scale, but may grow into MSPs in future, and hence should be encouraged and nurtured[2].

   a) Dark matter detection experiment at Jaduguda (JUSL);

   b) Neutrinoless double beta decay experiment (TinTin);

   c) Reactor monitoring and sterile neutrino search experiment (ISMRAN);

   d) Observation of low-energy solar neutrinos using deuterated liquid scintillator (DLS);

   e) Satellite-based experiments exploring the Universe in medium-energy gamma rays;

   f) Development of precision and sensitive detectors based on emerging quantum technologies.

B. Organisational Recommendations:

1. ***Infrastructure:*** To be successful, all workers on MSPs must have access to some of the following infrastructure.

   a) Common facilities for detector development which can host state-of-the-art laboratories and/or workshops for instrumentation, testing and computation (to be available for all MSPs in HEP), should be set up at suitable locations.

   b) Universities and institutes should continue their present level of activities in Mega Science, but their researchers must be able to use (or continue to use) common facilities to carry out coordinated instrumentation and training activities.

   c) It is crucial that a concerted effort be made to create a large multipurpose underground facility that could host experiments that look for rare events (e.g. neutrinos, dark matter, rare nuclear processes) and hence need a location that is relatively free from the cosmic ray background.

   d) Industries should be incentivised to get involved in MSPs from the inception stage and participate in the development of new technologies, with possible commercialisation in mind.

2. ***Funding:*** Research in and leading to MSPs must be adequately funded both in the short and long term.

   a) There should be a separate line in the budgets of funding agencies for MSPs, since the MSPs have special funding requirements given their multi-institutional and long-term nature.

   b) Experiments that do not reach the level of an MSP at the moment but have the potential to develop into MSPs over a longer duration — the so-called `feeder projects' — should be considered for funding under the Mega-Science activities.

   c) The funding structure must incorporate resources for networking and mobility of scientists by having special calls for proposals on focussed topics in frontier areas, on a regular basis.

3. ***Monitoring:*** It is important to have a systematic process for monitoring, so that every MSP has proper guidance and accountability. Such a scheme might consist, *mutatis mutandis*, of the following.

   a) Every MSP should have a *Scientific Review Committee* (SRC), to monitor and report on its progress.

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[2] Items 4(b), 4(c) and 4(d) are described in detail in [MSV-2035-NP].

b) A common *Inter-Agency Committee* (IAC-HEP) should look after the appraisal and funding of all HEP MSPs.

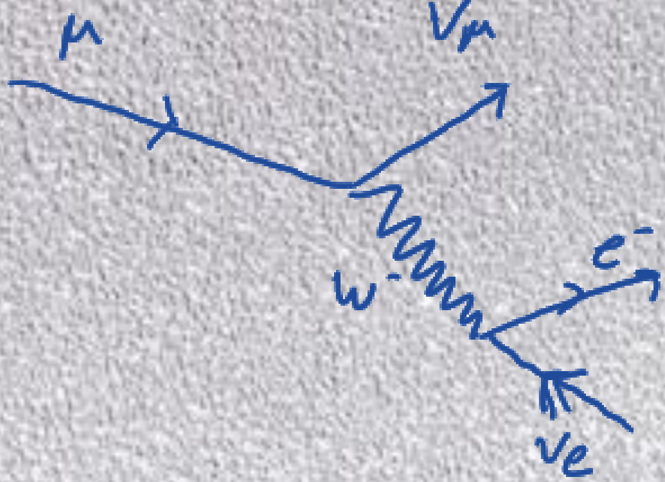
c) A *Mega Science Coordination Unit* (MSCU) should be formed in, e.g., the PSA's office or any other suitable agency, which will serve as a single-window system for all communications between the proposers and/or the SRCs and the IAC-HEP.

The future of, and the Indian participation in, many of the projects is still unclear due to the changing economic, geopolitical, and hence scientific funding situation worldwide. Though this is a vision for 2035, the situation on the ground may need to be reassessed periodically to decide on which projects to invest the financial and human resources in. The document therefore may need to be updated periodically at appropriate time intervals, leaving a scope to accommodate possible unexpected developments in the field as and when they arise.

The detailed report follows.

MEGA SCIENCE VISION - 2035

High Energy Physics



Detailed Report

Contents

The Standard Model Lagrangian : the current theory of everything terrestrial

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$
$$\frac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu\partial_\nu W^-_\mu -$$
$$M^2W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu - \frac{1}{2}\partial_\mu H\partial_\mu H -$$
$$\frac{1}{2}m_h^2H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} +$$
$$\frac{2M}{g}H + \frac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu -$$
$$W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu -$$
$$W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac{1}{2}g^2W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\frac{1}{2}g^2W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$
$$g^2s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2s_wc_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$
$$\frac{1}{8}g^2\alpha_h[H^4+(\phi^0)^4+4(\phi^+\phi^-)^2+4(\phi^0)^2\phi^+\phi^-+4H^2\phi^+\phi^-+2(\phi^0)^2H^2] -$$
$$gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$
$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$
$$\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) +$$
$$igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$
$$igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2W^+_\mu W^-_\mu[H^2+(\phi^0)^2+2\phi^+\phi^-] -$$
$$\frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \frac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^1s_w^2A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial+m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial+m_u^\lambda)u^\lambda_j -$$
$$\bar{d}^\lambda_j(\gamma\partial+m_d^\lambda)d^\lambda_j + igs_wA_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda)+\frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j)-\frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] +$$
$$\frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda)+(\bar{e}^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda)+(\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 -$$
$$1-\gamma^5)u^\lambda_j)+(\bar{d}^\lambda_j\gamma^\mu(1-\frac{8}{3}s_w^2-\gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) +$$
$$(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda)+(\bar{d}^\kappa_jC^\dagger_{\lambda\kappa}\gamma^\mu(1+$$
$$\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda)+\phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] -$$
$$\frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda)+i\phi^0(\bar{e}^\lambda\gamma^5e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_jC_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) +$$
$$m_u^\lambda(\bar{u}^\lambda_jC_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1-$$
$$\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_ju^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_jd^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5u^\lambda_j) -$$
$$\frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5d^\lambda_j) + \bar{X}^+(\partial^2-M^2)X^+ + \bar{X}^-(\partial^2-M^2)X^- + \bar{X}^0(\partial^2 -$$
$$\frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- -$$
$$\partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y -$$
$$\partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+X^+ -$$
$$\partial_\mu\bar{X}^-X^-) - \frac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \frac{1}{c_w^2}\bar{X}^0X^0H] +$$
$$\frac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] +$$
$$igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]$$

1. Status of the Field and Scientific Goals

Equipped with his five senses, Man explores the Universe around him and calls the adventure Science
— Edwin P. Hubble

The field of High Energy Physics or Particle Physics is concerned with elementary particles and their interactions at the most fundamental level.

1.1 Current Understanding of Elementary Particles

High Energy Physics deals with particles at the quantum (subnuclear) scales with relativistic energies. As such, the field is always poised at the frontier of subatomic length scales as well as the highest energy scale achievable, depending on the most advanced technologies available at the time. Over the past half-century, our knowledge of this field has been consolidated into a theory called the *Standard Model of Particle Physics* (SM). The SM describes Nature in terms of the elementary particles, or the so-called building blocks, and interactions between them at the most fundamental level [Khalil 2022]. These consist of fermions called *quarks* and *leptons* spread over three generations and a solitary scalar field called the *Higgs boson*. These are illustrated in Figure 1.1. The masses of these fermions are hierarchical, increasing over successive generations. The quarks take part in strong, weak and electromagnetic interactions, whereas the charged leptons take part in weak and electromagnetic interactions. The neutral leptons – *neutrinos* – take part only in the weak interactions. The quarks are never free, always forming bound states – most often, quark-antiquark bound states or *mesons*, and three-quark bound states or *baryons*. However, exotic bound states such as *tetraquarks* and *pentaquarks* [Cowan 2018] have recently been observed and more exotics are being discovered at ongoing experiments. Of the baryonic bound states, only the lightest ones, viz., the neutrons and protons, are found to be stable. All the other exotic bound states are produced ephemerally during high energy processes, and are seen to decay rapidly, with neutrons and protons being the end results of the decay chain. All the fermions of the Standard Model, except the neutrinos, are described in terms of Dirac fermions, which have particle and anti-particle states, each having left-chiral and right-chiral projections. The neutrinos are traditionally described in terms of Weyl fermions with only left-chiral particle and right-chiral anti-particle states. The interactions between elementary particles are described in terms of the force carriers, viz., the eight *gluons* for the strong nuclear interactions, the photon for the electromagnetic interactions and the $W^{\pm}$ and Z bosons for the weak interactions.

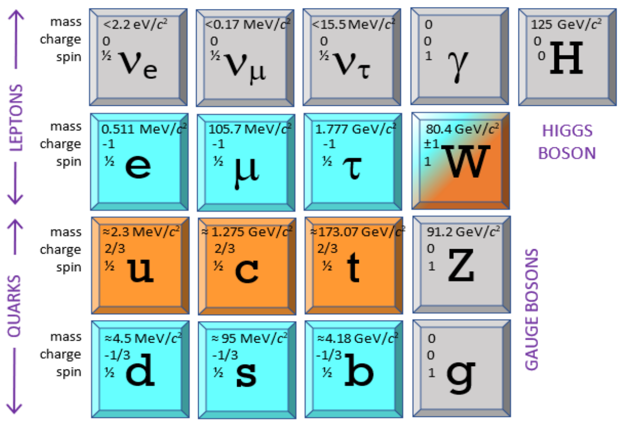


Figure 1.1 The particle spectrum of the Standard Model, including the matter fermions, the force carriers and the Higgs boson. Each of the first three columns corresponds to a 'generation'. The boxes are coloured orange, cyan and grey for particles which are positively charged, negatively charged and neutral, respectively. [*Technical note*: The figure shows flavour eigenstates rather than mass eigenstates and hence the indicated mass values are to be understood as expectation values.]

Theoretically, the Standard Model is described in terms of a nonabelian gauged quantum field theory. The strong interactions are described by an unbroken gauge theory called *Quantum Chromodynamics* (QCD), with the defining gauge group being $SU(3)_C$. Weak and electromagnetic interactions are described in a unified 'electroweak' theory, which is based on the group $SU(2)_L \times U(1)_Y$. The weak interaction part of this is a parity-violating theory where only the left-chiral particle (or right-chiral anti-particle) projections take part. Unlike QCD, the electroweak interactions are described by a broken symmetry to explain the existence of pointlike interactions and massive gauge bosons. The gauge group $SU(2)_L \times U(1)_Y$ gets *spontaneously broken* to $U(1)_Q$ of electromagnetism, which remains unbroken, and the photon remains massless. The $W^{\pm}$ and Z bosons, however, become massive and their interactions reduce, in the low energy limit, to the old Fermi theory of weak interactions. The spontaneous symmetry-breaking part of the Standard Model is driven by the Higgs sector, and it is this which generates masses of the gauge bosons $W^{\pm}$ and Z, as well as for the Higgs boson H. The Higgs mechanism also generates the masses of the fermions through their Yukawa interactions. Moreover, flavour violation and CP violation are induced by the non-diagonal complex Yukawa couplings of the fermions with the Higgs boson.

In addition to its successes in describing the broad structure of elementary particles and their interactions, the Standard Model turns out to be a renormalizable theory, making calculations possible at higher orders, and thereby making the theory testable at the quantum level in experiments [tHooft 1971]. In fact, the construction of the Standard Model has been a tremendous achievement, a culmination of experimental, phenomenological and theoretical efforts taken up by scientists across the world over several decades. A chronological description of the important discoveries and the role of large projects (the "Mega Science" of the past) therein are presented in the next subsection. We also describe there the Indian involvement in these exciting developments.

As mentioned above, the Standard Model has been tested at the quantum level in various sectors. In the flavour sector, rare processes induced by flavour-changing neutral currents in B and K decays have been studied. The gauge sector has been measured at a very high precision in the experiments at the LEP collider of CERN. Overall, the Standard Model has been tested to a very high accuracy over the last few decades – and so far, except for a few tantalising anomalies, no significant deviations from its predictions have been found [Freitas 2021]. This extraordinary success of the Standard Model actually makes it a formidable challenge to identify new physics required for a deeper understanding of phenomena at these scales. For it is now very well established that there *are* phenomena in Nature which cannot be explained by the Standard Model [Nagashima 2014]. The most prominent of the questions include the particle nature of *dark matter*, the stability of the Higgs boson mass, the origin of neutrino masses and mixing angles, the *baryon asymmetry* of the Universe, etc. In addition, there are several anomalies in flavour and precision physics experimental measurements which are not yet resolved. There are also many unaswered questions, e.g. those related to the origins and nature of hierarchies of the interaction strengths and of the fermion masses, those relating to the further unification of forces, etc. Many of these questions will be detailed in the following subsections.

It is important to note that any new theory which seeks to explain these conundrums must also incorporate within itself the successes of the Standard Model and be compatible with the tremendous amount of data and constraints collected over the past several decades. At the same time, our lack of deeper understanding in these areas can be attributed to several things, of which the lack of enough experimental data in those sectors, especially at higher energy and precision regimes, is the principal one. This makes new experimental inputs and discoveries absolutely crucial for any further significant breakthrough in our understanding of Nature. Thus, the importance of the next generation of Mega Science Projects (MSPs) cannot be understated.

1.2 The Standard Model and Mega Science Projects: a Chronological Perspective

The expression Mega Science corresponds to a collective endeavour where scientists and scientific institutions pool their strengths, in terms of technical, human and financial resources, to tackle some of the most challenging and difficult scientific problems. In high energy physics (HEP), this usually refers to large experimental collaborations taking up important problems of the field which cannot be otherwise tackled. This collegial approach has had significant successes. It was the deep insights and information that arose from collaborative experimental activities, together with penetrating analyses of them by theorists and phenomenologists alike, that led to the development of the Standard Model and culminated in the discovery of the Higgs boson in 2012. Today, as we perhaps stand at the cusp of history – with brand new directions waiting to be discovered – it might be useful to take a brief ride into the past to see how the Standard Model was built and mark the role which large laboratories played in the process [Cahn 2009].

1.2.1 Development of the Standard Model through Experimental Discoveries

Experience never errs; it is only your judgments that err by promising themselves effects such as are not caused by your experiments

— Leonardo da Vinci

The idea of bringing excellent scientists and engineers together for the purpose of solving a major scientific or technical problem is one of the biggest innovations of the 20th century. Historically, perhaps the best-known example is the *Manhattan Project* during World War II, which developed the atomic bomb [Rhodes 2012]. Since then, several scientific and technological collaborations have been created around the world, including the Human Genome Project or the International Space Station. However, High Energy Physics, which by its very nature requires large detectors, accelerators and colliders, and correspondingly large computational facilities, together with the human resources to manage these, has almost become synonymous with "Mega Science". The establishment of major laboratories, such as the BNL (1947) in the USA, CERN (1954) in Europe, FRASCATI (1954) in Italy, DESY (1959) in Germany, SLAC (1962) and FERMILAB (1967), both in the USA, KEK (1997, reorganisation of institutes formed in 1955, 1971 and 1988) in Japan, were all crucial for the development of the Standard Model [Jayakumar 2012].

As a matter of fact, the most important chapter of the Standard Model story began with the discovery of the neutral currents at the Gargamelle Bubble Chamber Experiment at CERN in 1973. By 1966-67, building on the ideas of François Englert, Robert Brout, Peter Higgs and Tom Kibble, theorists Sheldon Glashow, Abdus Salam and Steven Weinberg had already created a model describing unified electroweak interactions. In 1971, Martinus Veltman and Gerhard 'tHooft showed this theory to be renormalizable to all orders. However, an experimental verification was very much required. It was the Gargamelle Collaboration, which by discovering the neutral current – an important prediction of the Glashow-Salam-Weinberg model – provided the impetus required towards the establishment of the Standard Model. The very next year – 1974 – was the year of the so-called 'November Revolution' when the charm quark was discovered at both the BNL and SLAC laboratories. The tau lepton was discovered a year later, confirming the notion of three generations and setting up searches for the bottom and top quarks. These met with success in 1977 and 1994 respectively.

On the strong interaction front, following pioneering work by Struminsky (1965), and by Moo-Young Han and Yoichiro Nambu (1965), Murray Gell-Mann and his collaborators Harald Fritzsch and Heinrich Leutwyler, at Caltech, proposed what is now known as the QCD theory (1973), and were soon followed by David Gross, Frank Wilczek and David Politzer, who showed the theory to have the property of *asymptotic freedom*, making calculations and predictions possible in this theory using standard techniques. In 1979, the *gluon* – the mediator of the strong interactions and the heart of QCD – was discovered by the TASSO collaboration using the PETRA collider at DESY. The mediators of the weak interactions, the W and Z bosons were discovered by the UA1 and UA2 collaborations using the $Sp\bar{p}S$ collider at CERN in 1982 and 1983 respectively, thereby firmly establishing the gauge sector of the Standard Model. In the following decade, the LEP collider at CERN probed the Standard Model at the quantum level, and also established the existence of three light neutrinos.

The discovery of the top quark at Fermilab in 1994, and evidence for the tau neutrino, found at DoNUT at Fermilab in 2000, completed the fermionic content of the Standard Model. All that remained was the elusive Higgs boson, which also yielded to the Large Hadron Collider (LHC) in 2012.

1.2.2 Indian Involvement in the Development of the Standard Model

I tell my countrymen that so far, they have done well — now is the time to do better.

— Swami Vivekananda

During the 1950s and 1960s, Indian groups were not just a part of important experimental HEP collaborations but were competitive at the cutting edge. For example, the observation of atmospheric neutrinos was first reported (1965) by a TIFR-Osaka-Durham collaboration from the experiment at the Kolar Gold Fields (KGF). However, when high-energy colliders became the high-energy probes of choice during the 1970s, Indian participation waned, and we lost out on inclusion in the momentous discoveries of the period, including the discoveries of W and Z. It was only in the 1990s when India decided to join the collaboration for the L3 detector at the LEP collider at CERN, that India started participating in international collider experiments. An official agreement between CERN and India for cooperation in scientific and technical areas was signed during 1991. Within the next year, 1992, Indian scientists were also participating in the DØ experiment of the Tevatron at Fermilab. Both these collaborations paid off very well for the Indian High Energy Physics community.

The LEP experiment established the Standard Model at the quantum level. Several precision observables including the masses and widths of the Z-boson were measured with a precision at the per mille level or better. Apart from probing the Standard Model, this also put significant constraints on the possible symmetry-breaking mechanisms of the Standard Model. For example, dynamical symmetry-breaking mechanisms like walking technicolor, which, at that point of time, were considered more natural than the Higgs mechanism were ruled out by these measurements. The LEP was also instrumental in demonstrating the existence of three generations of the Standard Model. At the Fermilab, DØ and CDF experiments discovered the top quark in 1994.

Indian scientists were deeply involved in the measurement and interpretation of W and Z boson properties and in establishing the asymptotic freedom of QCD from the LEP collider data. Several groups from India were a part of the DØ collaboration, which went on to win the EPS prize recently for the top quark discovery. Indian groups also participated actively in the Belle Collaboration, which played a crucial role in confirming the mechanism for CP violation in the Standard Model. This led to the award of the 2008 Nobel Prize to Kobayashi and Maskawa, who proposed the mechanism in 1973.

The LEP was shut down in 2001 and was succeeded by the Large Hadron Collider (LHC) at CERN, which became operational from 2009. It has completed Run I and Run II operations so far. During the Run I, the Higgs boson was discovered by the two experimental collaborations, CMS and ATLAS, in 2012. This was a remarkable result as it established the symmetry-breaking mechanism of the Standard Model, which, in a way, was the holy grail of Particle Physics for the previous half-century. The importance of this discovery was promptly recognised by a Nobel Prize to the theorists and the New Horizon Prize to the experimentalists.

India was one of the first few countries to promise support to the LHC project [Maity 2023]. Subsequently, India was granted an Observer status at CERN as early as 2002 and became an Associate Member in 2016.

Currently, about forty groups from India are a part of the CERN-India collaboration, which includes the ALICE as well as the CMS Collaborations.

1.3 Scientific Goals

Nothing in life is to be feared, it is only to be understood. Now is the time to understand more, so that we may fear less

– Marie Curie

Significant understanding of the dynamics of different particles of the Standard Model has been achieved in the last few decades. However, there are several other areas where our understanding is not comparable. In Figure 1.2, we present a knowledge matrix of our present understanding and goals in high energy physics. The rows correspond to the different frontiers in which the current efforts are going on. The columns represent the nature of the knowledge which is being sought.[3]

The first row represents the so-called 'Energy Frontier', which incorporates studies related to the Higgs boson and direct searches for physics beyond the Standard Model (BSM) at highest energy particle colliders available at the present (or in the near future). In this row the box on the left indicate the searches for the so-called 'Quantum Realm' either through precision measurements of the Higgs boson properties or other electroweak parameters. The central box refers to the 'Invisible Universe', i.e. through canonical 'bump hunting' of resonant states of new, heavy particles, or of hitherto undiscovered physics that can modify the electroweak vacuum. The box on the right refers to 'New Paradigms', which would involve currently-unknown fields and their interactions. Similar considerations hold for the next three rows, marked 'Intensity Frontier', 'Cosmic Frontier' and 'Theory Frontier' respectively. In each case, the left box describes effects that arise from the quantum nature of the field(s), the central box mentions new phenomena or new contributions to known phenomena, and the last box on the right indicates possible directions in which the previous two may lead us. These programmes are described somewhat more elaborately in the following.

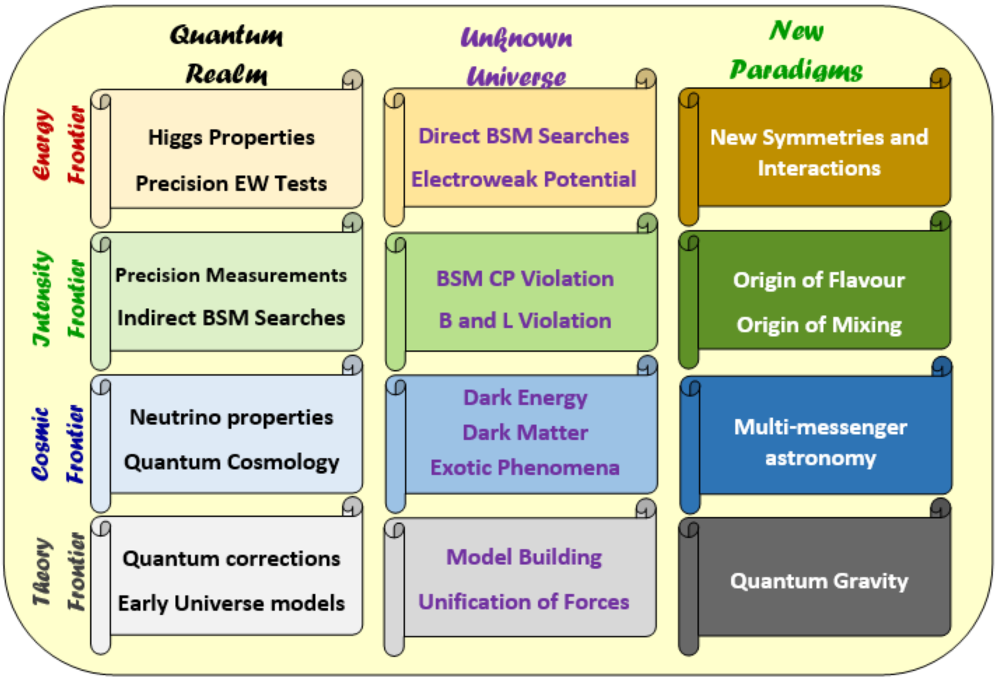


Figure 1.2 The present knowledge map and goals for the High Energy Physics community. The rows correspond to the different frontiers in which the current efforts are going on, and the columns represent the nature of the knowledge that is being sought [P5 2023].

[3] The columns correspond to the science themes of the US P5 report [P5 2023].

Energy Frontier: A key idea of the Standard Model is broken gauge symmetries. In the Standard Model, the symmetry breaking is implemented through the Higgs mechanism. For the mechanism to work, the Higgs particle should not just couple to all the fermions and gauge bosons, it should also have self-interactions with specific coupling constants. The Higgs boson has, of course, been found at the LHC, and its couplings to the gauge bosons and heavier fermions have been measured to be close to the SM predictions. In the SM, the coupling of every particle to the Higgs boson is proportional to its mass, and hence each individual coupling requires to be measured accurately to confirm the SM mechanism of electroweak symmetry-breaking. However, Higgs measurements are limited by the amount of data available and the challenging experimental conditions. As a result, important couplings like the quartic or triple Higgs vertices have not yet been measured with anywhere near the precision required to test the SM. While the LHC, in its current configuration, might not be able to measure these couplings with much precision, that should be possible at the HL-LHC and in future colliders like ILC, FCC-ee, FCC-hh and the muon collider. The pattern of electroweak symmetry-breaking calls forth a number of questions which require BSM physics to explain. A major thrust at the Energy Frontier would therefore be to make direct searches for the new particles and couplings predicted in such BSM scenarios. This is where the future colliders could act as 'discovery machines'.

Intensity Frontier: Experiments at low energies may be sensitive to new physics at high energies through quantum effects. These effects are naturally small but can be observed if the intensity of the initial beams is high enough. Thus, the intensity frontier can be used to probe BSM physics in an energy regime which cannot be accessed at the Energy Frontier. Some of the most obvious effects would come from flavour physics which also probes the pattern of fermion masses and mixings. The quarks have masses which are hierarchical with small mixing angles enshrined in the Cabibbo-Kobayashi-Maskawa (CKM) matrix. The recently discovered neutrino mass differences and the associated large mixing angles in the leptonic sector shed light on some possibilities of mass generation beyond the Higgs model. There are, however, several other areas where more precise experimental investigations and/or theoretical computations are required. These include CP violation and rare decays in the K, D and B meson systems, hadron spectroscopy including exotic hadrons, magnetic moments of the muon and heavier systems like atoms and nuclei, atomic parity violation, etc.

Cosmic Frontier: Cosmic rays have been studied for more than a century and some of the pioneering work has been done in India and by Indians. Cosmic rays, which impinge upon the Earth from a variety of galactic and extra-galactic sources, contain a plethora of information about the nature and structure of the Universe. Therefore, studies of cosmic rays, including very high energy gamma rays and astrophysical neutrinos, form a very important component of high energy physics. There is also strong evidence for the existence of dark matter, starting from galactic scales all the way up to the Universe as a whole. While we are more-or-less sure that dark matter exists, and there is good reason to believe that it is particulate in nature, no clear picture has emerged as yet. There are, of course, several proposed candidates, including the most popular ones, viz., Weakly Interacting Massive Particles or WIMPs, which arise in many well-known extensions of the Standard Model, as well as axions, axion-like particles, dark photons, etc. Over the coming years, several experiments in astroparticle physics, including those which are satellite based, will probe several aspects of these dark matter candidates. An exciting synergy with Astrophysics lies in the future of multi-messenger astronomy, where observations of not just electromagnetic waves covering a broad spectrum of energies, but also cosmic rays (including neutrinos) and gravitational waves, can be used in combination to gather information about different extraterrestrial objects. This would tie in well with the ideas presented in the MSV-2035 Report on Astronomy and Astrophysics [MSV-2035-A&A].

Theory Frontier: Apart from details like the fermion masses and mixings, the major questions which arise out of the Standard Model are the possibility of unification of all three of the gauge couplings and also unification with gravity. Currently, there is a large community of theorists examining string theory and related ideas which attempt to quantise gravity and also achieve its unification with the other forces. In fact, though theoretical models for Grand Unification, the quantum nature of gravitational interactions, etc. remain speculative, they have overlaps with current particle physics through models conceived at high energy scales, like supersymmetry, extra dimensions, etc. The theoretical tool of choice to connect these ideas with experimental data is through Effective Field Theories, evaluated against measurements of effective couplings at the accessible energy scales. In fact, the couplings and masses of the gauge bosons, W and Z, have already been measured rather precisely. More improvement, especially in the W mass measurement, is expected at the upcoming HL-LHC (High Luminosity LHC). An important facet of the theory frontier tries to construct theoretically and phenomenologically consistent extensions beyond the Standard Model, which may be probed by direct searches for new physics either at the HL-LHC or the future colliders. The Indian particle physics community has produced a large body of work on topics like supersymmetry, extra dimensions, neutrino mass models and their possible signatures either at colliders or other indirect experiments. New approaches using effective field theory techniques are also being employed to understand heavy new physics in a model-independent manner.

A significant amount of theory effort goes into computing the various possible experimental signatures and estimating their possible backgrounds. Such computations have played an important role in the discovery of the Higgs boson, the determination of top quark mass, etc. The current era is one of higher loop computations, viz., at two loop level for electroweak interactions and more than two loop level in QCD. New techniques lying at the intersection of physics and mathematics are being discovered. Artificial Intelligence (AI) and Machine Learning techniques (ML) are also being used to better simulate experimental environments and extract useful information from a plethora of data [Calafiura 2022]. Such theoretical computations and predictions play a major role in shaping the nature of all new MSPs, each of which requires a detailed Technical Design Report (TDR) — including the physics prospects — before the project is taken up for serious consideration.

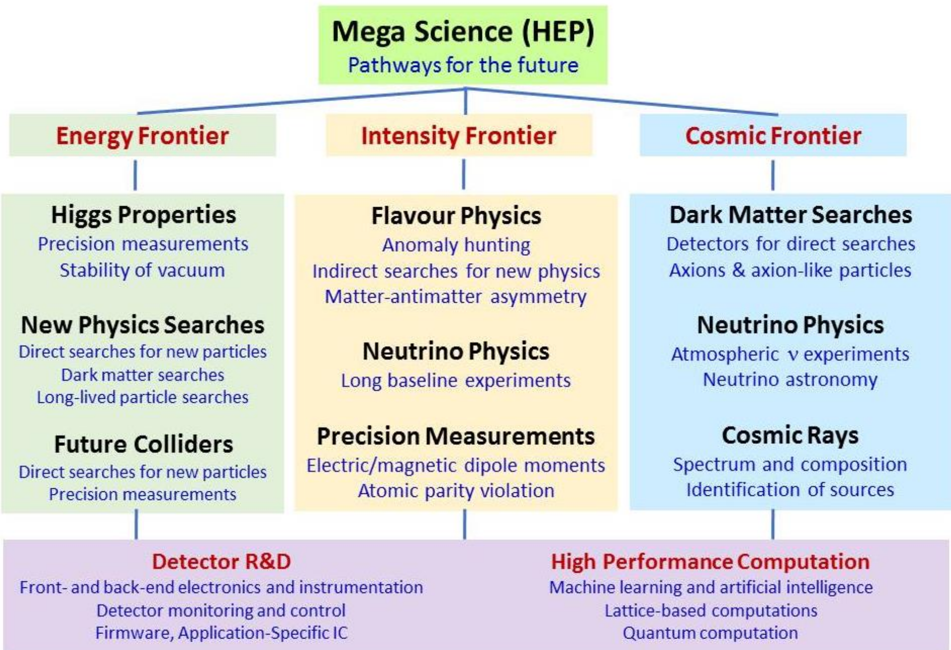


Figure 1.3 Summarising some of the important scientific goals of the High Energy Physics community.

Broadly then, the experimental questions raised above can be grouped into the three classes displayed in Figure 1.3, viz. (a) the Energy Frontier, (b) the Intensity Frontier and (c) the Cosmic Frontier. Mega Science Projects can approach specific scientific goals in each of these directions. In Figure 1.3, we have summarised, in terms of these three frontiers, some of the issues which the world-wide HEP community hopes to pursue in the coming decade. It is worth noting that High-Performance Computation will be common to all of these approaches. In the coming sections we elaborate on these points.

1.4 The Energy Frontier

The Energy Frontier probes the high energy limits of the Standard Model — which would correspond to low energy limits of new physics at higher scales. The flagship machine for this is the LHC, currently running at 13.6 TeV, after earlier runs at 7, 8 and 13 TeV respectively. The power of this machine as a probe of fundamental interactions is well described by the diagram reproduced in Figure 1.4, reproduced from the CMS Collaboration. A variety of processes possible in the SM have been measured, and their cross-sections are presented in decreasing order from left to right, along with the theory predictions from the SM, including QCD corrections. The figure makes it clear that at this level there is universal agreement of the experimental data with the SM predictions, and is, therefore a testament to the phenomenal success of the SM.

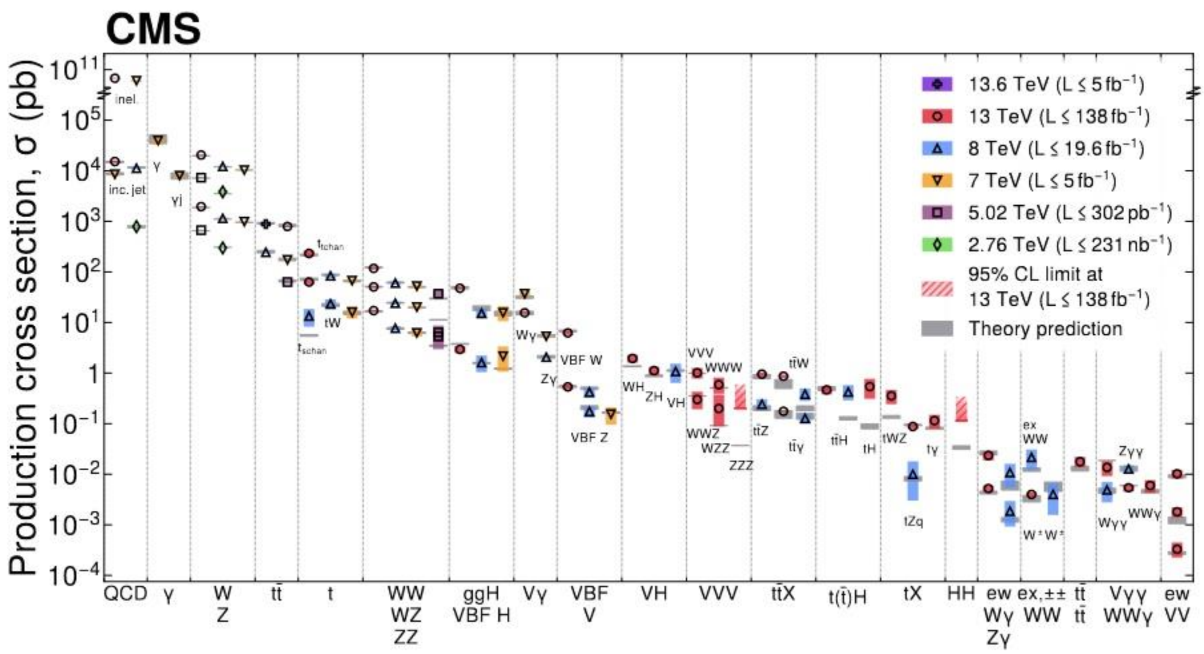


Figure 1.4 CMS measurements of cross-sections for a variety of different processes at the LHC operating at different energies, compared with the theoretical (Standard Model) predictions. Such measurements, spanning more than 10 orders of magnitude, show a remarkable agreement with the theory for the entire set of processes [CMS-CS 2024].

After experimental searches spanning five decades, the SM was completed by the discovery of the Higgs boson in 2012. Since this discovery, the energy frontier has focussed on (a) high-precision measurements of Higgs couplings, which would require copious production of Higgs particles at high energies in the two-Higgs and three-Higgs channels, (b) precise measurements of the mass and couplings of the top quark and (c) further searches for new physics particles. The upgraded LHC and the new colliders under discussion would also be performing along these lines.

The importance of knowing the precise values of the Higgs couplings cannot be understated. They would help to unravel exactly how the symmetry-breaking mechanism incorporated in the Standard Model is realised in Nature. At the same time, a large variety of the new physics models will be directly probed at the upgraded LHC as well as at new upcoming colliders. These would include supersymmetric models, multi-Higgs models like the two-Higgs doublet models, extra-dimensional models, vector-like particles which are ubiquitous in a large class of new physics models, leptoquarks, long-lived particles, etc., as well as more exotic objects such as magnetic monopoles and dark mesons. All these models would be probed up to energies ranging from a few hundred GeV to several TeV in the coming decades [Barr 2016], something which would require setting up giant multi-TeV particle accelerators. Some of the planned efforts in this direction are discussed in Chapter 3.

1.4.1 Higgs Physics, Precision Measurements and Future Colliders

The Higgs mechanism forms an essential part of the electroweak symmetry breaking mechanism. While the ATLAS and CMS indeed discovered the Higgs particle in 2012 [ATLAS 2012, CMS 2012], initially very little information was empirically known about the particle except its mass, which has been measured with increasing precision over the years (Figure 1.3). Over the years, however, we have now identified some more properties of the Higgs boson. In particular, the CMS and ATLAS measurements have established that it is a spinless particle of even intrinsic parity, exactly as predicted in the Standard Model. Further, its couplings to the gauge bosons have been measured and they seem to be matching reasonably well with the expectations from the Standard Model [ATLAS 2022, CMS 2022]. The LHC is, at present, measuring the fermion couplings of the Higgs boson, so that the Standard Model Higgs-fermion couplings can be verified. Currently, however, very high precision has not been attained, except in the case of the top quark. It may be reasonably stated that none of the measurements so far have shown any deviation from the Standard Model predictions (see Figure 1.5).

High-precision measurement of the dominant Higgs couplings is extremely important to verify whether the Higgs mechanism realised in Nature is the minimal one – with one Higgs – as proposed in the Standard Model. For this, it is very important to measure the couplings of the Higgs field not just with gauge bosons and fermions but also with itself. This self-interaction of the Higgs field determines the form of the potential required to generate the spontaneous symmetry breaking. However, the shape of the potential is also subject to quantum corrections of the Higgs field through the fermions, the gauge bosons and itself. The value of the Higgs boson self-coupling also decides the lifetime of the Universe in the minimal Higgs model. A precise measurement of its value along with precise measurements of other parameters like the top quark mass would determine whether the Standard Model resides in the deepest (stable) minima or in a metastable one [Plehn 2014].

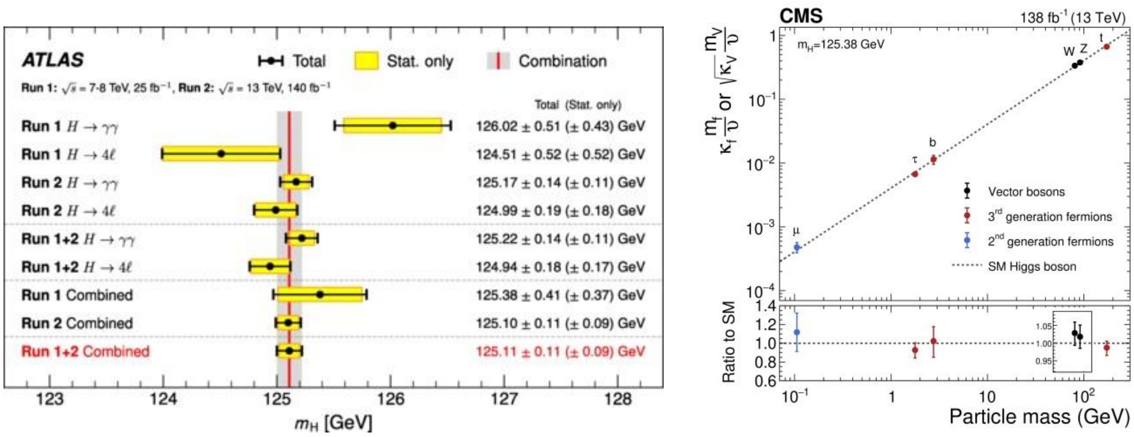


Figure 1.5 Measurements of Higgs boson properties at the LHC. The left side shows the Higgs boson mass [ATLAS 2023] as obtained from different decay channels while the right-hand side shows Higgs boson couplings to particle pairs and their comparison with the SM predictions [CMS 2022].

Experimentally it would thus be very important to measure the triple-Higgs coupling as well as the quartic-Higgs coupling. These measurements have been recognised as the most important measurements by the international HEP community and Indian scientists have also been involved in these crucial measurements. A precise measurement of these couplings will, in all probability, lie beyond the reach of the upcoming energy upgrade of the LHC and even HL-LHC [deBlas 2020]. This underlines the need for a next generation of colliders for precision Higgs physics. While HL-LHC is already approved, most of the future colliders are still at the discussion stage, and they will need further upgrades to enter the realm of precision Higgs physics.

1.4.2 Physics Beyond the Standard Model (BSM)

While the Higgs couplings form the most important of the questions that need to be addressed by the community, there are other issues which are equally pressing, and which are also being keenly pursued. These are related to the other open questions in the Standard Model listed earlier, like the naturalness of the Higgs mass, dark matter and its associated particles, neutrino masses and the associated particles, etc.

Most models of BSM physics like supersymmetry, extra dimensions, composite Higgs, etc., and/or variations of them, contain solutions to these problems while predicting a profusion of new particles. These can be simply classified into extra chiral/vector fermions, scalars and gauge bosons, in terms of their spin and parity. The quantum numbers carried by these particles vary depending on the BSM model they belong to. Given that the detection of the particles would primarily be through their direct or indirect interactions with known particles, search techniques for such new particles are a matter of great complexity. A model-independent approach on the other hand, would consider using the so-called Standard Model Effective Field Theory (SMEFT) to understand the implications [Falkowski 2023]. Different types of colliders have been proposed to search for new particles, based on the theories which predict them. For example, in models with new leptonic degrees of freedom, it is natural to consider leptonic colliders. Analogously, for models with new coloured degrees of freedom, hadronic colliders are far superior.

The Large Hadron Collider has, till the present, collected $\sim 10\%$ of the total data which it would be collecting in its entire lifetime. As is well-known, there is no evidence in these data for any new particles. However, several new particles which are proposed in theories such as supersymmetry, extra-dimensional models, neutrino mass models, dark matter models, etc. could be probed at the planned upgrades of the LHC. Of particular interest are, for instance, extra scalars or pseudoscalars, new heavy gauge bosons, leptoquarks, vectorlike fermions, superpartners or Kaluza-Klein excitations of SM particles, and composite particles, which are predicted in specific BSM theories. There is much better hope for finding coloured particles in hadronic colliders like LHC, HL-LHC and the proposed VLHC and its variants. The leptonic colliders are mostly precision machines, especially the ones with electron and/or positron beamlines. They are efficient to measure the couplings of the Higgs boson, analyse the anomalies, hunt for deviations from Standard Model Higgs sector and discover low-lying new particles below a few hundred GeV. Supersymmetric theories, neutrino mass models or dark matter models all predict the existence of new particles within this range. The muon colliders on the other hand could act as spectacular discovery machines if the currently-significant technological challenges can be overcome. Another interesting area to probe would be long-lived particles which could be present in many BSM models − especially those with dark matter candidates. In addition to the particles which are considered to be stable in the Standard Model, several models that go beyond the SM predict long-lived particles (LLP) with varying lifetimes, whose long lives might be due to approximate symmetries in the model, phase space suppression, or the smallness of the relevant interaction or a combination of these. Future experiments like MATHUSLA, etc. would be probing these particles.

The future colliders including the LHC upgrades would require some completely new kinds of detector technology. These would be at the forefront of the existing technology and innovations. India is involved in the development of these technologies, in partnership with international collaborators. Detector technology is, in itself, a broad subject and could help to nurture future experts, who could then contribute to a multitude of areas including condensed matter and astrophysics in addition to high energy physics [Shiltsev 2023].

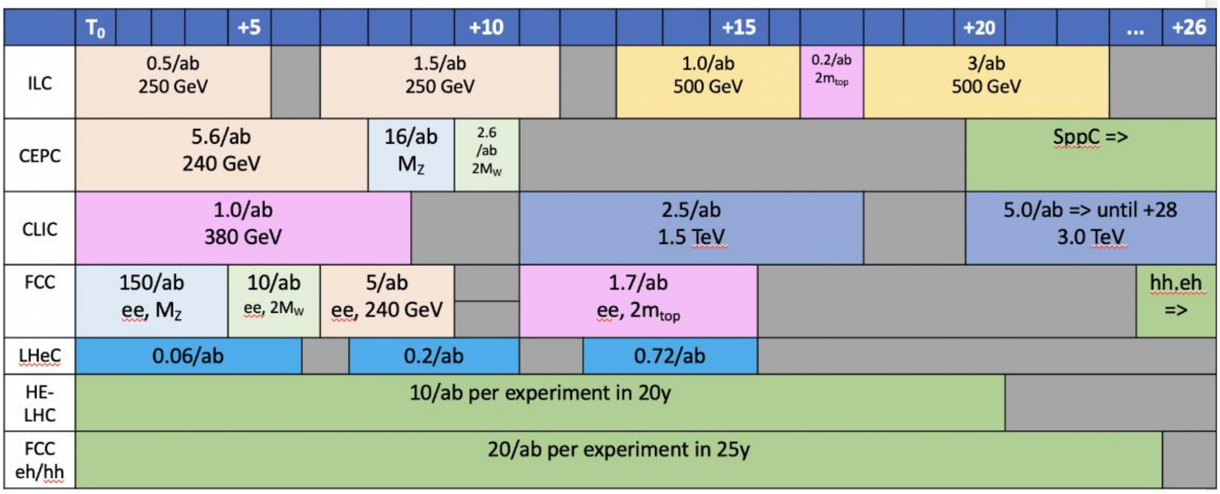


Figure 1.6 Possible scenarios and timelines of future colliders in the upcoming decades, as presented in [deBlas 2020]. Here T_0 may be taken as the starting time of the data-taking phase of the experiment.

In summary, the Energy Frontier addresses significant questions related to the Higgs boson, collider physics and new discoveries. While the dust is not yet settled on the choice of the new collider, it would be prudent for India to join the efforts which the community as a whole decides.

1.5 The Intensity Frontier

The Intensity Frontier probes the Standard Model and physics beyond by searching for rare processes which are normally deemed to be extremely difficult to detect. Typically, these processes would also probe the quantum structure of the Standard Model and its smaller coupling constants. These experiments typically focus on producing large numbers (luminosity) of short-lived particles at a focussed energy and studying their decays. Specialised experiments, e.g., B-factories like BaBar [Boutigny 1998], Belle, Belle II [Abe 2010] dedicated flavour physics experiments like LHCb [Amato 1998], and high intensity neutrino experiments like DUNE, fall in this category.

Many of the rare processes are well understood within the context of the Standard Model and thus any deviation from their expected values would immediately signal the existence of new physics. Typical rare processes include rare Kaon decays, including $K \to \pi\nu\bar{\nu}$, CP-violation in neutral Kaon oscillations, B-meson oscillations and CP violation therein, magnetic and electric dipole moments of fundamental and composite particles, CP violation in the neutrino sector, etc. Similarly, searches for rare processes which are typically not expected in the Standard Model, like $\mu \to e\gamma$ *and* related decays of the tau in the lepton sector, can provide hints of new physics. So can discoveries in the neutrino sector. While the B-factories like BaBAR and Belle are sensitive to the rare decays also in the tau sector, specialised experiments such as MEG [Baldini 2018], PRISM [Andre 2014], etc. are designed to search for rare processes in the muon sector. In the leptonic sector, the magnetic moment of the muon is also a very important probe of the Standard Model and beyond. The present experimental results on the muon anomalous magnetic moment [Aguillard 2023] do not match with the Standard Model predictions, indicating a strong tension between theory and the experiments. Whether this tension is due to new physics or some ill-understood effect in the Standard Model, will only be known in the coming years.

1.5.1 Flavour Physics and BSM Searches

Flavour physics, working at the intensity frontier, tries to push the discovery limit in energy higher by two to three orders of magnitude, through the observation of tiny quantum effects mediated by the heavy BSM particles. Here, by flavour physics, we will mostly mean B physics, i.e., physics of the hadrons containing a b-quark. Physics of the hadrons with the charm or the strange quark is also interesting in its own right, but we will not go into details on this. However, we will discuss the physics of the charged leptons. The three major goals of flavour physics are as follows.

- *Better understanding of the Standard Model*: The SM has 19 arbitrary parameters − which is unacceptably large for a fundamental theory − and the majority of them are in the flavour sector. They include the quark and lepton masses, and the elements of the quark mixing matrix, also known as the CKM matrix. We do not know why there are three generations of quarks and leptons, why the mass pattern is hierarchical, and why the CKM matrix is almost diagonal with small off-diagonal elements. In other words, we have no idea whether there is any fundamental symmetry behind this pattern. The first goal of flavour physics is to look for indications of such underlying symmetries.
- *Understanding the puzzle of CP violation*: Violation of the combined symmetry CP in weak interaction still remains an enigma. While experiments have identified the CKM matrix as the source of CP violation in low-energy experiments, the extent of CP violation in the CKM matrix is nowhere near enough to explain the matter-antimatter asymmetry of the Universe. In fact, the prediction from the SM falls short by about nine orders of magnitude. This remains one of the strongest motivations to look for BSM physics.
- *Indirect search for BSM physics, including violation of discrete symmetries*: If the SM happens to be an effective theory valid up to a scale beyond the reach of LHC, the only way to find BSM physics is to look for its indirect effects on low-energy observables. The observables include branching fractions, CP asymmetries, and decay distributions. They also include looking for decays of the B hadrons that are either forbidden, or unobservably small, in the SM. Extending the scope to charged leptons takes one to the highly interesting lepton flavour violating decays, as well as to the anomalous magnetic moments $(g-2)$ of charged leptons.

The first important results in B-physics came from the ARGUS experiment at DESY [Albrecht 1987], which studied the oscillation of neutral B mesons and the CLEO experiment at Cornell [Artuso 1989] which studied the Υ resonances, i.e., bound states of b and $\bar{b}$ quarks. Then started the first golden era of flavour physics in the first decade of this century, when two B−factories, i.e., asymmetric electron-positron collider-based experiments, BaBar (1999−2008) at SLAC, USA and Belle (1999−2010) at KEK, Japan made an exhaustive study of the two lowest-mass B mesons, and thereby established the CKM matrix as the dominant, if not only, source of all CP-conserving and violating flavour-changing processes. The mantle has been taken up successfully by the LHCb experiment at CERN, and recently by the Belle II experiment at KEK, Japan. Indian participation was significant in Belle, and continues to be in Belle II, more details of which may be found later.

Figure 1.7 is a summary [Charles 2005, CKMfitter 2021] of the wonderful work done by the B-factories for the construction of the so-called `CKM unitarity triangle', with angles α, β and γ. The sides and angles of this triangle have been determined by multiple independent measurements. There is a tiny red circle that is common to all the bands and where the tip of the unitarity triangle falls. The existence of a common overlap region vindicates the CKM picture, and its small area demonstrated the high precision achieved by the B −factories. Unfortunately, as mentioned above, the CKM picture established so firmly comes nowhere close to solving the matter-antimatter asymmetry.

In spite of the beautiful agreement with the Standard Model, over the last few years some points of tension have come up, which might well be the first indirect evidence of BSM physics [London 2021]. Most significant of them is the apparent violation of lepton flavour universality in semileptonic and leptonic B-decays. This anomalous behaviour was confirmed by all the past and present B-factories, and the combined disagreement with the SM is now more than 3σ. Some tension also exists for the direct CP violation measurements for some nonleptonic D and B decays. With the upcoming high luminosity B factories, one hopes to explore these anomalies in detail and identify the new physics, if any, which is their underlying cause.

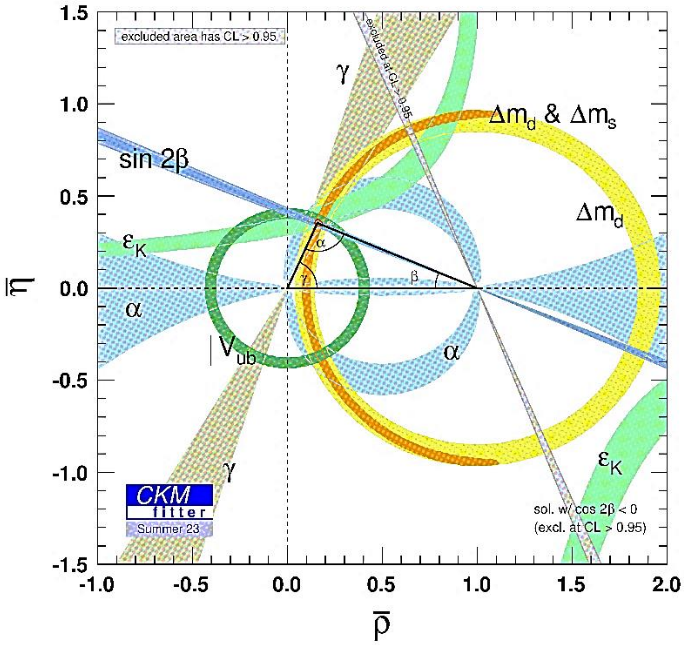


Figure 1.7 Experimental constraints on the unitarity triangle from flavour physics measurements [CKMfitter group, http://ckmfitter.in2p3.fr]

One also must not forget to explore the properties of the heavier leptons, μ and τ, in detail, if the hint of lepton flavour universality violation persists. While the anomalous magnetic moment of the $\tau^{\pm}$ has a rather loose bound and needs to be improved by orders of magnitude, that for the muon is already precise and has a distinct tension with the SM prediction. If leptons do not have a universal coupling with the weak gauge bosons, the lepton flavour-violating processes may have a detectable branching fraction. In the SM, it is immeasurably small, thanks to the very tiny mass of the neutrinos.

In short, one can create a 'shopping list' for the next decade:

- At what level can the branching fractions, CP asymmetries, and decay distributions for the rare processes, particularly the neutral current ones, be measured? The Belle II upgrade may have an integrated luminosity as high as $50\ \mathrm{ab}^{-1}$, which will enable us to measure very rare processes.
- Can we measure the higher-order corrections to the CKM matrix? In other words, can we measure the so-called 'squashed unitarity triangles'?
- How precisely can we measure the final states involving one or more τ leptons?
- How cleanly can we measure the neutral-current decays with neutrinos in the final state?

Whatever the successes in these endeavours, it is clear that flavour physics at the intensity frontier will remain a thrust area in high energy physics for many years to come.

1.5.2 Lattice QCD: BSM Searches, and Spectroscopy of Hadrons

Searches for Beyond Standard Model (BSM) physics at precision frontiers are closely tied to uncertainties in hadronic physics, which is governed by strong interactions among quarks and gluons. Quantum Chromodynamics (QCD), the theory of strong interactions, becomes highly non-perturbative at low energies, lacking an analytical solution for many crucial aspects. As a result, large-scale numerical computations on space-time lattices — Lattice QCD — addressing the challenges posed by the non-perturbative nature of QCD in the low-energy domain, have become vital for BSM physics investigations.

In order to estimate the non-perturbative effects in various possible decay modes of hadrons, it is crucial to parametrise and calculate the associated non-perturbative form factors and decay constants in a systematic way. Lattice QCD is uniquely poised to compute those from first principles with controlled systematics [Banuls 2020]. However, achieving the high-accuracy results for these observables which are necessary for BSM searches is currently hindered by factors like finite volume effects, discretisation errors, and associated renormalisations. This challenge intensifies for hadrons with heavy flavours, particularly in the investigation of lepton-flavour anomalies. Addressing these issues requires finer lattices with larger volumes, demanding access to very large-scale computing resources.

Apart from constraining the parameter space for BSM searches, lattice QCD calculations are also required for predicting the spectroscopy of hadrons. Such studies are passing through exciting times with the discovery of a large number of subatomic particles in recent years. It is anticipated that many more hadrons will be discovered in the near future in HEP laboratories, such as LHCb, BES III, Belle II, JPARC and JLAB. While some of the newly- discovered particles could be understood as regular mesons and baryons in terms of the quark model, many of them do not fit in this conventional picture. In fact, observed decay channels for some of these states manifestly demand interpretation through four, five and even six valence quark configurations and also states with exotic spin quantum numbers [Brambilla 2019, Chen 2023]. Though a number of theories have been put forward to interpret these new exotic states — compact tetraquarks, loosely-bound molecules, hadroquarkonia and hybrids, etc., — a coherent picture of the formation, structure and properties of these new states is yet to emerge. Nevertheless, the existence of such subatomic particles is allowed in QCD and therefore lattice QCD is an obvious tool for studying these new subatomic particles theoretically. As a matter of fact, recent lattice QCD advancements in computing the excited-state energy spectra in the finite volume as well as in extracting the hadron-hadron scattering amplitudes have led to the prediction of new exotic states, which have triggered ongoing search programmes at high energy laboratories.

Indian scientists are very much at the forefront of these developments. To perform cutting-edge research and to maintain international competitiveness in lattice QCD works involving BSM searches and exotic hadrons it is essential to have access to multi-petaflop computing resources. Thus, high performance computation would have to be an important facet of the Mega Science effort in the Indian context.

1.5.3 Neutrino Physics

Neutrinos are perhaps the most difficult and challenging particles to study in the Standard Model, as well as some of the most intriguing objects in the Universe. In the past two decades, various experimental collaborations probing solar, atmospheric, astrophysical, reactor and geophysical neutrinos have established the standard three-flavour oscillation framework. The mass-squared differences ($\Delta m_{ij}^2 = m_i^2 - m_j^2$) and the mixing angles (θ_{ij}) of the neutrinos are reasonably well established, so much so that the field has entered a precision era. The present knowledge of the neutrino mass mixing parameters is summarised in Table 1.1. However, the very success of the neutrino oscillation hypothesis has raised several questions towards understanding of the fundamental properties of the neutrinos.

One of the most fundamental open questions in neutrino physics is the absolute mass scale of neutrinos. The oscillation experiments determine the mass-squared differences among neutrinos and guarantee that all the neutrinos are within 0.1 eV of each other. The Standard Model of Cosmology puts reasonable limits on the sum of neutrino masses to be less than 1 eV. The absolute scale for neutrino masses is expected to be partially addressed by the ongoing KATRIN experiment [Aker 2021] which is trying to measure the effective neutrino mass in tritium beta decay.

	best fit	
parameter	**Best fit** $\pm 1\sigma$	3σ **range**
$\Delta m^2_{21}\ [10^{-5}\ eV^2]$	$7.42^{+0.21}_{-0.20}$	$6.82 \rightarrow 8.04$
$\Delta m^2_{31}\ [10^{-3}\ eV^2]$ (NO)	$2.517^{+0.026}_{-0.028}$	$2.435 \rightarrow 2.598$
$\Delta m^2_{31}\ [10^{-3}\ eV^2]$ (IO)	$-2.498^{+0.028}_{-0.028}$	$-2.581 \rightarrow -2.414$
θ_{12}	$0.304^{+0.012}_{-0.012}$	$0.269 \rightarrow 0.343$
$\theta_{12}/^0$	$33.44^{+0.77}_{-0.74}$	$31.27 \rightarrow 35.86$
θ_{23} (NO)	$0.573^{+0.016}_{-0.020}$	$0.415 \rightarrow 0.616$
$\theta_{23}/^0$(NO)	$49.2^{+0.9}_{-1.2}$	$40.1 \rightarrow 51.7$
θ_{23} (IO)	$0.575^{+0.016}_{-0.019}$	$0.419 \rightarrow 0.617$
$\theta_{23}/^0$(IO)	$49.3^{+0.9}_{-1.1}$	$40.3 \rightarrow 51.8$
$\sin^2\theta_{13}$ (NO)	$0.02210^{+0.00062}_{-0.00063}$	$0.02032 \rightarrow 0.02410$
$\theta_{13}/^0$(NO)	$8.57^{+0.12}_{-0.12}$	$8.20 \rightarrow 8.93$
θ_{13} (IO)	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \rightarrow 0.02428$
$\theta_{13}/^0$(IO)	$8.60^{+0.12}_{-0.12}$	$8.24 \rightarrow 8.96$
$\delta/^0$(NO)	197^{+27}_{-24}	$120 \rightarrow 369$
$\delta/^0$(IO)	282^{+26}_{-30}	$193 \rightarrow 352$

Table 1.1 The present ranges of the allowed neutrino oscillation parameters as a result of a global fit to all available data [Esteban 2020]. NO means Normal Ordering and IO means Inverted Ordering.

The mechanism of mass generation crucially depends on whether neutrinos are of Majorana or Dirac type. The associated phenomenology is also different in both the cases. Several international experiments are planned to address this issue, such as GERDA [Agostini 2023], CUORE [Alduino 2016], MAJORANA [Arnquist 2023], etc. These projects are of great interest and if there is any Indian group which would want to participate, they should certainly be supported. Efforts are, in fact, under way to have an experiment in India to study neutrinoless double-beta decay (NDBD).

In the precision sector of neutrino oscillations, the main questions which remain to be addressed are (i) the neutrino mass-ordering, and (ii) the value of the CP violating phase in the lepton sector. While these are independent parameters, their effect on the oscillation observables would be intertwined. Several experiments like Hyper-K, DUNE, NOvA would be probing oscillation observables with high precision. Within India, the India-based Neutrino Observatory (INO) represented a step in that direction. With its capacity to detect energetic muons and identify their charge, it could have been in a good position to identify the neutrino mass ordering.

Beyond the measurement of neutrino properties, the neutrinos coming from astrophysical objects or phenomena can give us information about the processes taking place inside stars, or inside dense media like AGNs, from where light cannot reach us directly. Precision measurements of solar neutrinos can help us monitor the nuclear reactions taking place inside the Sun, and thus directly probe the solar core.

Neutrinos are ubiquitous in Nature: from the Earth, the atmosphere, and the stars from the Main Sequence ones to the ones in their end stages, like supernovae, as well as in man-made reactors and accelerators, etc. This leads to a significant level of synergy between various branches of science with interesting applications. For example, the experiments like Hyper-K [Abe 2018] and DUNE [Abi 2020] are sensitive also to supernova neutrinos. Detection of these neutrinos would lead to a deeper understanding of the stellar life cycle. Neutrino tomography of the Earth can reveal the size and composition of the core of the Earth. Neutrinos can also be used to detect man-made nuclear activity on our planet. All the above would require large-scale experiments to be performed over many years.

1.5.4 Precision Physics

Some of the strongest constraints on physics beyond Standard Model come from the precision measurements of fundamental properties of elementary particles such as their electric and magnetic dipole moments. For example, leptonic and atomic magnetic moments form extremely sensitive tests of the quantum nature of the Standard Model and beyond. Similarly, measurements of electric dipole moments of elementary particles constitute extremely delicate probes of their CP properties. In recent times, there has been particular focus on the measurements of anomalous magnetic moment of the muon at BNL [Bennett 2006] and Fermilab [Aguillard 2023]. Both these measurements, while consistent with each other, indicate that Standard Model contributions are not enough to explain the measured values, i.e., additional contributions from new physics might be required. While further theoretical and experimental explorations are required to establish the source of this discrepancy, this promises to be one of the important tests of the Standard Model. Experiments at CERN like MUonE [Abbiendi 2022] would further help in resolving this mystery.

Other precision probes of the Standard Model would include Atomic Parity Violation (APV) which would probe the chiral structure of the weak interactions. These experiments have grown increasingly precise over the years, with the improved computation of the atomic wave functions of certain systems and have the potential to significantly change our understanding at those scales. Particle colliders and beam dump experiments too provide precision information about the gauge sector of the Standard Model, especially the masses, couplings and lifetimes of these particles. The experiments at LEP at CERN, SLD at SLAC etc., already gave significant information on this sector. The LHC is expected to improve these measurements significantly, especially those on the W-boson mass. These measurements provide the strongest limits on a variety of new physics models with extended gauge sectors, new fermions charged under the SM gauge group, etc.

In short, it may be said that precision measurements complete the search for quantum effects which is taken up in flavour physics, and have the same potential to extend the discovery reach in energy by an order of magnitude or two beyond the direct searches at the high energy frontier.

1.6 The Cosmic Frontier

The Cosmic Frontier refers to the cosmological and astrophysical probes of Standard Model particles and their interactions. In many cases, this could mean that there are phenomena occurring at cosmological and astrophysical scales which would require new particles or new interactions beyond the Standard Model, of which dark matter is the prime example.

1.6.1 Particle Interpretations of Dark Matter

There is now enough evidence for dark matter at more or less all astrophysical scales, starting from the galactic scale to galactic clusters to the truly cosmological scales [Arbey 2021]. The evidence is extremely strong for the existence of a non-collisional, electrically neutral, non-baryonic tenuous fluid which encompasses most of the matter density of the universe. Within the Standard Model of Cosmology, dark matter constitutes about 24% of all the energy density of the Universe. The biggest conundrum of the present time is the lack of any observable evidence or any clue about the particle nature of dark matter. Over the past decade or so, there has been an explosive rise in the study of dark matter through various experimental, astrophysical and theoretical channels. In fact, it would not be an understatement to say that the particle nature of dark matter is one of the most pursued research topics today [Bauer 2017].

The principal probes of dark matter may be listed as

i) relic density measurements;

ii) direct detection experiments;

iii) indirect detection experiments.

The relic density is a cosmological observation determined predominantly by the measurements of tiny anisotropies in the Cosmic Microwave Background Radiation (CMBR). These measurements are most accurately done by satellite-based experiments like COBE, WMAP and PLANCK. Together with optical and other probes of Type 1A Supernovae, the dark matter relic density of the Universe is now accurately pinpointed up to a percent level.

The direct detection experiments, on the other hand, are ground-based, typically employing deep underground detectors. These can identify direct interactions of dark matter with the ordinary matter in the detector. Such experiments have already produced very high-quality results — putting strong constraints on thermal dark matter. The weakly interacting massive particle (WIMP) hypothesis has also received significantly strong constraints from the direct detection experiments.

Indirect detection of dark matter is the attempt to measure dark matter properties within the galaxy or nearby, by looking at the indirect products of dark matter decay or annihilation. There are both ground-based and satellite-based probes which look for antimatter content, gamma and Cherenkov radiation and other signatures like X-rays. This subject is closely linked to the study of cosmic ray physics and astrophysics like X-ray astronomy etc. Currently experiments like AMS 02, FERMI, PAMELA as well as balloon-based experiments like ATIC have measured antimatter content and the spectrum of gamma rays from space. In future, ground-based experiments like CTA and Tibet AS gamma would also lead to significant constraints on indirect detection of dark matter. More details of the relevant cosmic ray experiments are given in the next subsection.

Weakly Interacting Massive Particles (WIMPs) are a class of dark matter candidates which are theoretically well-motivated by several extensions of physics beyond the Standard Model, such as, for example, supersymmetry. These particles could be detected in high-energy collisions, such as those at the LHC (collider searches), or via annihilation products of particle-antiparticle pairs (indirect detection), or via their elastic scattering with matter showing up as nuclear recoil signals (direct detection). The availability of so many channels of detection means, however, that WIMP scenarios, especially with higher masses, are highly constrained — as can be seen from the summary of WIMP-nucleon interaction cross-sections as measured by various experiments (Figure 1.7). The experiments like CDMS, Xenon 1T and LUX, etc., have provided limits which are almost touching the neutrino floor for some dark matter masses. In India, there is a proposal to build a direct detection experiment called InDEx. There are other several approved direct detection experiments like LZ, Xenon NT, etc., which will improve the limits significantly in the coming years. At a future stage, when the direct detection limits begin to breach the neutrino floor, developing methods for distinguishing between dark matter and neutrinos would become a major challenge.

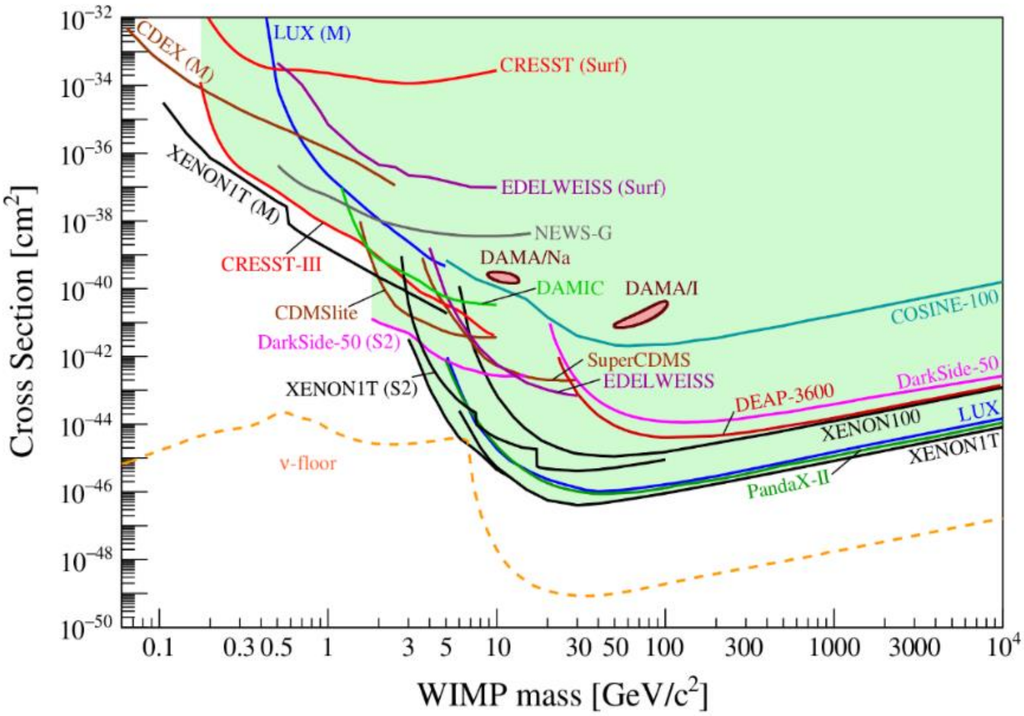


Figure 1.8 Experimental constraints on WIMP dark matter scenarios, as presented in [Billard 2021].

Another set of candidates for the dark matter particles are axions or axion-like particles (ALPs), light pseudoscalars that couple weakly with photons. While axion was originally proposed to resolve the so-called `strong-CP' problem and has a fixed relation between its mass and coupling, ALPs span a wider parameter space in their masses and couplings and can constitute the bulk of dark matter in the Universe. ALPs can convert to photons in the presence of strong magnetic fields, which is the principle used for their search, for example, superconducting magnets at the CERN Axion Solar Telescope (CAST), or microwave cavities at the Axion Dark Matter Experiment (ADMX). The possibilities associated with the existence of other light scalar particles such as dilatons, chameleons, etc. are also under investigation.

Dark matter interacts very feebly with the SM particles. However, relatively stronger interactions of dark matter particles among themselves cannot be ruled out. Such a possibility allows the presence of gauge symmetries under which the dark matter particles are charged, but the SM particles are singlets. This could lead to the formation of bound states of dark matter particles, which could have specific signatures at collider experiments. Furthermore, the mediators of forces among the dark matter particles, the `dark photons', can have astrophysical consequences like the central density profiles of galaxies, the abundance of satellite galaxies of the Milky way, etc., Dark matter thus forms another bridge between high energy physics and astrophysics.

Overall, the future of dark matter research has the potential of opening up an entirely new sector of particles and interactions for us to study.

1.6.2 Cosmic Ray Physics

The origin of cosmic rays (CR) has always been a mystifying problem in astrophysics, ever since their discovery in 1912 by Victor Hess. Even today, after a century of intense research, a complete understanding of CR is still lacking. Nevertheless, various properties of cosmic rays as regards to their spectrum, elemental composition and angular distributions have been studied extensively [Drury 2012]. We also understand the basic energetic requirements of cosmic ray production in the (Milky Way) Galaxy [Horandel 2008, Blasi 2013]. The energy density of cosmic rays in the Galaxy is known to be comparable to the energy density in Galactic magnetic fields and in the thermal energy of the interstellar gas, from which it is clear that cosmic rays play a non-negligible role in shaping the evolution of galaxies. However, cosmic rays are charged particles and are therefore deflected in the interstellar magnetic field. Therefore, cosmic rays cannot be traced back to their sources, the so-called cosmic particle accelerators, except for energies beyond 10^{20} eV, where the bending effects of galactic magnetic fields become minimal. However, the flux of CR goes down dramatically beyond this, due to the so-called GZK cutoff. Thus, much of the current effort goes into identifying and quantitatively describing these cosmic accelerators [Mollerach 2018]. Shocks in supernova remnants and/or pulsar wind nebulae systems are thought to be the dominant sources of Galactic cosmic rays.

At energies below 10^{14} eV, cosmic rays have been primarily studied using space-based instruments where detectors primarily used are magnetic spectrometers and/or calorimeters for momentum/energy determination along with transition radiation detectors and Cherenkov detectors. Examples of such experiments include PAMELA [Galper 2017], AMS-02 [Aguilar 2013], TRACER [Ave 2011], CALET [Torii 2011] and DAMPE [Chang 2017]. While direct detection mechanisms in space provided many important results on elemental and isotopic composition, the steep fall in flux of cosmic rays with energy, along with the limited size of space-based detectors, restricts the energy range of detection. Thus, at higher energies, ground-based instruments have a distinct advantage where the Earth's atmosphere acts as a vast calorimeter in which particle cascades are created when a primary particle or a photon interacts with the atmosphere. These instruments detect the secondary and tertiary shower particles or Cherenkov photons reaching the observational level and can have an effective detection area as large as a few thousand square km. Some of the important ground-based cosmic ray experiments are KASKADE [Apel 2010], Pierre Auger Observatory [Aab 2015], IceTop [Abbasi 2013], GRAPES-3 [Gupta 2010], Telescope Array (TA) [Abu-Zayyad 2012], Tibet AS-gamma [AS-gamma 2013] and under construction experiment LHAASO [Amenomori 2009]. GRAPES-3 represents the only major operational facility in India.

Even though many interesting and ground-breaking results have been obtained from the above-mentioned experiments, we have explained that it is very difficult to identify the sources of charged cosmic ray particles. Therefore, high energy gamma-ray observations both from space and ground and neutrino observations from the ground are of prime importance in order to establish the directionality of cosmic ray sources. Very High Energy (VHE) gamma-ray astrophysics started primarily in the context of sources of cosmic ray particles which are the progenitors of gamma-rays [Bose1 2022]. More than 170 high energy gamma ray sources of various classes have been discovered in the last decade. Acceleration of charged particles inside these objects to such high energies produces gamma rays through various processes. Therefore, the study of VHE gamma ray emission from these objects will not only provide clues about the origin of cosmic rays, but also lead to insights into emission regions and mechanisms in these enigmatic objects.

To cut a long story short, the few outstanding questions of TeV γ-ray astrophysics today are:

- Origin of cosmic rays and their acceleration to energies way beyond that is achieved in man-made accelerators.

- Understanding how transparent our universe is, i.e., cosmology with TeV gamma rays and understanding the Extragalactic Background Light (EBL) leading to an estimation of the Hubble parameter.
- Indirect detection of dark matter through observations of dark matter-dominated galaxies.
- Role of cosmic rays in star forming systems.
- Understanding the nature of the central engine in very high energy gamma-ray bursts (GRBs).
- Probing fundamental physics through studies of Lorentz invariance violation and search for axion-like particles.

The most sensitive satellite-based gamma-ray detector currently operating is the Fermi Large Area Telescope (LAT) [Atwood 2009] which has revolutionised the field by discovering hundreds of high energy sources including several new source classes. However, at higher energies beyond a few tens of GeV photon statistics drops and one needs to start observing from the ground. The most sensitive ground-based approach is the Imaging Atmospheric Cherenkov Technique (IACT), which uses the Cherenkov light produced by the electromagnetic cascade of electrons and positrons in the atmosphere to establish the properties of the primary gamma-ray photon. The direction of the primary gamma ray is determined by imaging the cascade, the gamma-ray energy is then derived from the Cherenkov light yield. The current generation of IACT instruments include MAGIC [Aleksic 2016], H.E.S.S. [Aharonian 2006], and VERITAS [Weekes 2002] and these have already yielded many ground-breaking results in the field of very high energy gamma-ray astrophysics.

Another technique called the wavefront sampling technique has been used with limited success as the sensitivity of the technique is very limited. HAGAR at Hanle [Britto 2011] uses this technique and in the late 1990s and early 2000s, a couple of experiments in Europe and USA (CELESTE in France [Pare 2002] and STACEE in USA [Gingrich 2004] operated briefly using this technique.

Currently, over 3000 sources of GeV gamma rays have been detected using the space-based instruments Fermi-LAT [Fermi-LAT 2024] and AGILE [Agile 2018], and over 200 sources of TeV gamma rays have been detected with ground-based instruments, showing the abundance and indeed ubiquity of cosmic particle accelerators. However, there is no clear consensus regarding the nature of these accelerators even though from the available data, supernova remnants and pulsar wind nebulae seem to be the most prominent sources of galactic cosmic rays. The current interesting physics results and the confidence obtained in building successful telescopes to probe the very-high-energy sky has triggered an initiative of scientists all over the world to build the next-generation ground-based gamma-ray telescopes called Cherenkov Telescope Array (CTA) [Bernloehr 2013] with an increase in sensitivity by a factor of 10 or more.

Research on cosmic rays (CR) that span a wide energy range (10^8—10^{20} eV) has been carried out in India since the 1940s. Today, there are seven groups in India that operate(d) experiments for Astroparticle studies at very-high-energy (VHE) or ultra-high-energy (UHE). Two groups, one from TIFR (Hanle), and one from BARC (Mount Abu) detect VHE gamma-rays by the atmospheric Cherenkov technique. The BARC group has installed a new telescope, MACE, at Hanle. MACE will add to the impressive list of current generation of imaging telescopes and its longitude allows it to make observations that are complementary to most other telescopes in the world. A third group from the Bose Institute has set-up an Extensive Air Shower (EAS) array in Darjeeling. Two groups, from Guwahati and North-Bengal used to operate EAS arrays that were used for educational purposes. A sixth group, from DEI, Agra has set-up an EAS array. These EAS arrays have been set up with help from TIFR's GRAPES-3 experiment which is a major operational facility in India aimed at Astroparticle physics.

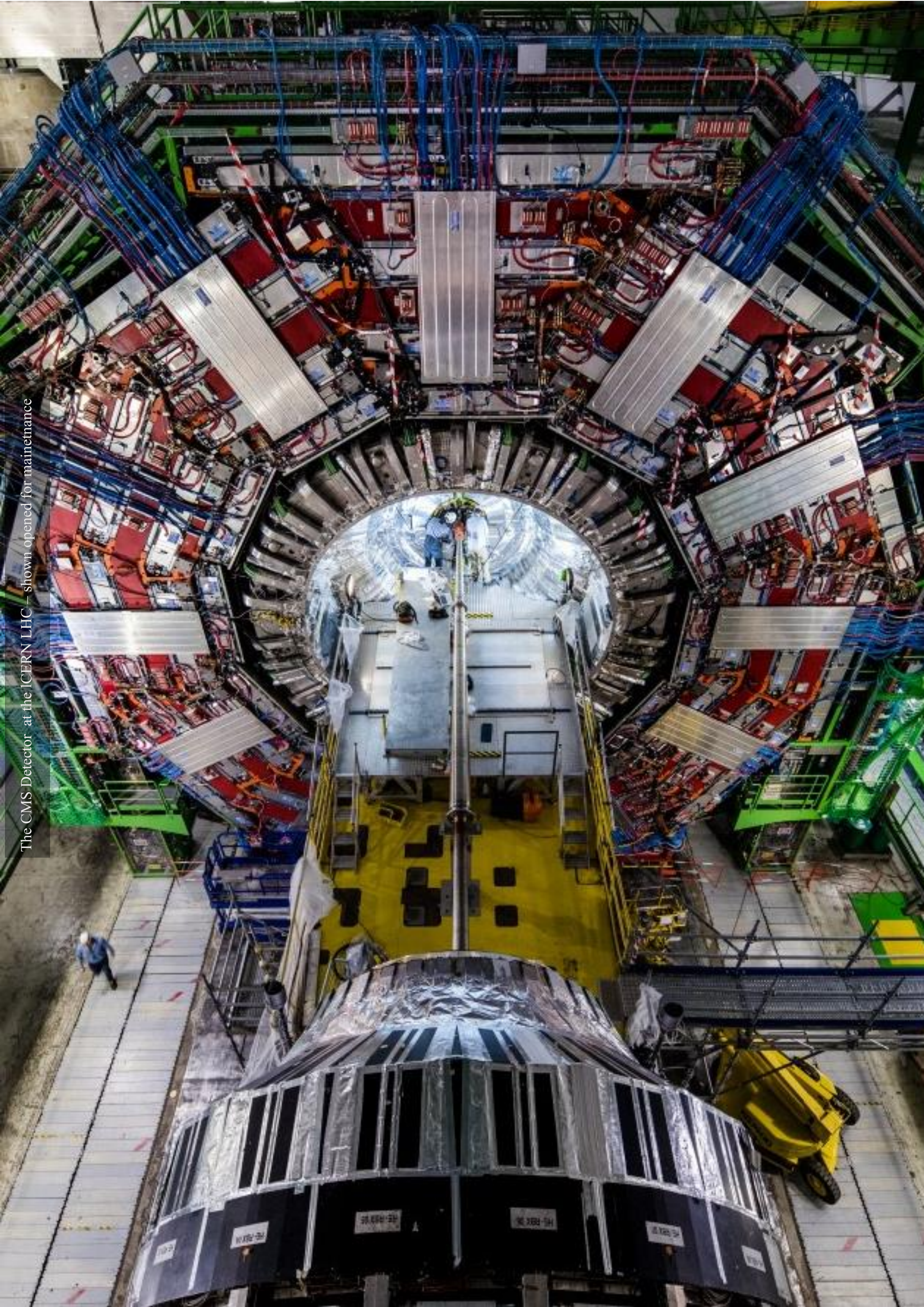
1.7 Summary

You can't use up creativity. The more you use, the more you'll have.

— Maya Angelou

Since the discovery of the Higgs boson and the running of the first phase of LHC, high energy physics is currently poised at a crossroads, with several different interesting directions being actively pursued. These directions can be clubbed as the a) Energy Frontier b) Intensity Frontier and the c) Cosmic Frontier.

India is nicely placed to take a significant part in explorations in all the three directions. While Mega Science Projects which are international are being pursued vigorously, homegrown efforts would help our budding scientific community in a big way. Further help in this direction would be facilitated with the establishment of a centralised facility dedicated to training and innovations focussing on High Energy Physics (see Section 4.4).



The CMS Detector at the lCERN LHC – shown opened for mainetnance

2. Current Projects and Their Upgrades

A story has no beginning or end: arbitrarily one chooses that moment of experience from which to look back or from which to look ahead.
— Graham Greene

In this Section, we would like to give a brief overview of the ongoing Mega Science HEP Projects with Indian participation. These projects have already started and their future goals and possible upgrades are more or less clearly defined. For those established outside India (listed in Subsection 2.1), either the Government of India has already committed financial and other support, or such support would be highly desirable in order to have a successful Indian participation.

2.1 Participation in International Projects

Nothing exists until it is measured.
— Niels Bohr

Indian scientists are involved in some major international Mega Science Projects (*a*) on the Energy Frontier, such as the CMS Experiment at the Large Hadron Collider at CERN, Geneva; (*b*) on the Intensity Frontier, such as the Belle II Experiment at KEK, Tsukuba, as well as neutrino experiments like NOνA and MINERνA at Fermilab, and (*c*) on the Cosmic Frontier, in experiments such as PICO/PICASSO at Sudbury and MAGIC at La Palma. Some details of these experiments and the Indian involvement therein are given below.

2.1.1 Energy Frontier: CMS Collaboration (CERN)

It was already emphasized in Section 1 that one must look beyond the Standard Model for the questions still unanswered, and the Large Hadron Collider (LHC) [Evans 2008] at CERN, Geneva, is one of the best tools to do so. LHC operates on the energy frontier and aims at direct production of new particles. There are two multipurpose detectors that look for such direct signals of new physics, and there has been a significant Indian participation in one of them, namely, the CMS experiment. These experiments have already discovered the Higgs boson and are expected to help in direct detection of new particles lying in the TeV range. They are also expected to shed light on the nature of Dark Matter.

The CMS experiment [CMS 2008] is a general-purpose detector designed to serve a broad physics program of precision measurements of SM processes and searches for the BSM phenomena. Thus, the choices of various particle detection techniques are optimized to identify and measure four momenta of particles ranging from a few hundred MeV to a few TeV originating in the proton-proton collisions via SM and BSM processes. The presence of neutrinos and dark matter candidates could only be inferred from an imbalance in measured momenta in the plane orthogonal to the proton beams, and hence require a hermetic detector. The detectors close to the beam pipe are continuously exposed to the harsh radiation environment and the choice of detector material is severely constrained by the requirement of radiation hardness. The CMS experiment has collected close to 25 fb^{-1} at 8 TeV and 6 fb^{-1} at 7 TeV (Run-1) during 2012 and 2011 respectively, then 150 fb^{-1} integrated luminosity at 13 TeV during the years 2015-2018 (Run-2) and it plans to collect additional 250 fb^{-1}data during 2022-2025 (Run-3). To enhance its discovery potential, the LHC machine is being upgraded to start its high luminosity operations (HL-LHC) from 2029 [Contardo 2015] and is expected to accumulate 3000 fb^{-1} data in the next decade. This larger data set will be used to search for new fundamental particles predicted by various BSM theories; it will also allow the reduction of uncertainties in the measurements of Higgs properties, including the all-important Higgs self-coupling, which could be a window to new physics phenomena.

Current status: Indian physicists have made immense contributions to the CMS experimental program in the last 25 years [Maity 2023] and will continue to do so with the data to be collected during the HL-LHC phase, complementing their effort in building some crucial components of the detector. The Indian community has delivered detector modules and electronics readout components for silicon-based pre-shower detectors, the scintillator-based outer hadron calorimeter, SiPM readout boards, resistive plate chambers, and gas electron multiplier (GEM) detector modules for muon detection. Starting from the testing of the prototype detectors in in-house laboratories, the community has participated in manufacturing R&D with Indian industries and in test beam experiments with energetic single particles at CERN and Fermilab. The physicists have played a key role in the development of GEANT4-based dedicated simulations of these detectors and their validation using the data collected in test beam experiments and pp collisions. This has been followed up by participation in the installation and integration of these detectors at the CMS site and their commissioning using cosmic muons as well as first collision data.

Indian faculty members and students have been significantly contributing to the low-level preparation of the data to be usable for inferring physics measurements. This requires a multifaceted engagement during the data collection, calibration of the detectors, trigger designing, physics object calibrations, and data quality monitoring in real time and offline. India-CMS members have been contributing to many of these aspects, which provide inputs to practically every physics paper published by the collaboration.

The CMS Grid Tier-2 and Tier-3 centres are hosted in TIFR, serving the CMS grid infrastructure round the clock as well as the India-CMS community for direct access to the data via grid [Jashal 2022]. Under the world-wide LHC computing grid (WLCG) structure, India provides a Tier-2 computing centre to the international CMS Collaboration with suitable support for a wide-area research network as the backbone. It is both an international and a national facility with about 40% of the resources being utilized by CMS central computing. Along with the TIFR facilities, several analysis-computing clusters across the India-CMS institutions support CMS analysis activities on a continuous basis.

The Indian community has played a leading role in the discovery of the Higgs boson and continues to make measurements of its properties using its decays to a pair of photons or W/Z bosons, to a pair of tau leptons, as well as the measurement of its coupling to the top, bottom and charm quarks. Indian scientists have made key contributions to the physics of associated Higgs ($t\bar{t}H$) production, which is a challenging analysis owing to its small production cross-section and large SM backgrounds. In addition, there have been key contributions in the measurement of the invisible width of the Higgs boson, in studies of rare production modes involving single top quarks and in Higgs pair production via both resonant and non-resonant processes.

There are major Indian contributions to the searches for various types of new physics. Indian physicists have played a leading role in searches for charged Higgs particles**.** Indian contributions range from all-hadronic multijet final states to multilepton final states for a wide range of SM measurements and new physics searches [Maity 2023]. The India-CMS group has made significant contributions to the heavy ion collision programme, complementing the work of Indian colleagues participating in the ALICE experiment [Aamodt 2008] at CERN. The India-CMS physicists have been regularly leading the various physics and detector groups in formally elected convener positions. The HL-LHC program will extend through 2040's, and the data analysis for another few years.

The CMS experiment started collecting data in 2009 and the CMS collaboration has published more than 1300 physics papers [CMS-pub 2024] using the pp collision data Indian scientists have been strongly involved in the data collection, analysis, result dissemination as well as detector construction, maintenance, operation and upgrade activities. The India-CMS collaboration currently consists of approximately 35 Ph.D. faculty/scientists, 10 postdocs and 60 Ph.D. students from 14 institutes, namely Delhi U, Hyderabad U, IISc, IISER-Pune, IIT-Bhubaneswar, IITM, IOP, NISER, Panjab U, GHG Khalsa College, SINP, TIFR, UIET and Visva-Bharati. In addition, about 10 engineers/technical personnel are directly involved in the CMS activities. Eight of the current faculty members did their PhD in India on the CMS experiment. So far, more than 100 students from India have received their Ph.D. working on CMS, many of whom are working as postdoctoral researchers in very reputed institutions.

- *Human Resource Development:* The Mega Science Projects offer a wide range of exposure to the students right from the beginning of their PhD program. The India-CMS has played a key role in detector construction, installation and performance measurements, in particular for RPC, GEM, silicon and scintillator-based detection technologies. These provide an unparalleled opportunity for students to work with state-of-the-art technologies and various aspects of data acquisition and debugging the system. Tools used in handling large data volumes and distributed computing over GRID have widespread applications in finance and banking industries. The students graduating now are mostly well-equipped with machine learning and artificial intelligence. In summary, the India-CMS students get trained in detector physics as well as collision data analysis.

  In addition, students are required to make regular presentations in India-CMS meetings as well as in CMS meetings. The India-CMS faculty members regularly organize physics lecture series for the benefit of the students. They also have to present physics talks which give them an opportunity to discuss with their peers and get guidance from more experienced people.

- *Industry Connections:* Detector technologies developed for collider experiments involve high-end electronics and communication technologies, which, with their wide dynamic range of signal size, radiation hardness and fast timing, find usage across a variety of societal and cross-disciplinary applications (e.g., defence and finance). Among the ones for which R&D is extensively carried out in India, Resistive Plate Chambers (RPCs) and Gas Electron Multipliers (GEMs) have potential to be used in cargo tomography, X-ray imaging, medical imaging for cancer treatment, neutron imaging, space sciences and other medical and national security applications. Silicon detectors could be very useful for defence applications and medical sensors. The experience gained with handling large data volumes and advanced modelling algorithms (including artificial intelligence) could have wide applications in banking, finance and medical research.

  The India-CMS team has been collaborating with various industries for developing various state-of-the-art technologies. Further connections with industry could be established by starting fresh collaborative industry projects for indigenously developing new technologies. For example, SINP and VECC have initiated work on medical applications of particle detectors under the CERN detector R&D programmes. BARC has developed single-sided silicon strip detectors for the CMS experiment, which it uses to build many variations of radiation monitoring devices. These, and similar developments, could well find use in industry and have commercial applications.

- *Funding Requirements:* The project cycle for CMS funding in India is for 5 years unlike other regular projects under DST/CSIR/BRNS. However, the experiment will continue to run till the 2040's, and the physics extraction will continue till the middle of this century. Thus, a long-term plan encompassing 10 to 20 years is needed. This should also account for a transition of the leadership from the present generation to the future generation of scientists. Also, it has to be recognised that the project has to be coordinated with scientists from different parts of the world. A detailed mechanism should be in place for timely action.

  A large emphasis would be on analysing the data and harnessing the physics especially after the detector upgrades are completed in the next 5 years. Indian groups have already been provided funding for the setting up of the CMS Grid Tier-2 centre. With the ageing of the computing resources and to meet the new data analysis challenges all the grid centres need upgrade and capacity enhancement. The Tier-2 centre at TIFR as well as prospective Tier-3 centres and computing clusters at the other collaborating institutions would require budgets for new machines and hardware peripherals, including GPUs. The National Knowledge Network (NKN) bandwidth also needs enhancement and better connectivity to cope up with the data analysis demands. A dedicated network bandwidth of 10 Gbps or more for each institute is required to efficiently carry out the data analysis.

The funding for FY 2020-2025 is about Rs. 120 Cr. It is expected that, with further expansion of the collaboration within India and increased cost, India-CMS will need about Rs. 200 Cr. between FY 2025-2030. For FY 2030-2035, the funding requirement is expected to be around Rs. 225 Cr.

- **Overall Appraisal:** Given the young profile of faculty members and interest among younger physicists to return to India, a total of 25 – 30 new faculty are expected to join India-CMS efforts in the next 15 years. The India-CMS collaboration has graduated more than 100 students since its inception and about 150 new PhD students are expected to graduate in the next 15 years. If funding allows, 40-45 postdocs are expected to join Indian institutions. In addition, a continued India-CMS collaboration for the next two decades is expected to produce a large pool of trained human resources having expertise in contemporary detector technologies and software/computing models, in the field of collider experiments. This will be readily available for the future colliders (e.g., ILC, CLIC, CEPC, FCC-*ee*, FCC-*hh* and FCC-*eh*). Based on this strength of faculty members and postdocs, India-CMS has immense potential to play a major role in the CMS program in next 15 years and beyond, i.e., through the HL-LHC and further in future collider projects. However, to be able to play a meaningful role in operations and maintenance, one needs support for deploying people at CERN for longer duration, especially during data collection.

2.1.2 Intensity Frontier: Belle II Collaboration (KEK)

The Belle II experiment [Abe 2010] follows on from the success of the Belle and BaBar experiments that discovered CP violation – different behaviour of matter and antimatter – in *B* meson decays. This discovery confirmed the Kobayashi-Maskawa mechanism [Kobayashi 1973] within the SM. The principal goal of Belle II is to make precise measurements of the decays of beauty and charm mesons, as well as tau leptons, which are potentially sensitive to mass scales of the order of tens of TeV. In other words, Belle II will look for indirect signals of new physics, including potential new sources of *CP* violation, and play a role complementary to that of the LHC. Through such quantum effects, Belle II can probe mass scales which are well beyond the reach of the LHC. For this, Belle II plans to collect data with integrated luminosity of 50 ab^{-1}, till the mid-2030's. While the LHC works at the energy frontier, Belle II may be said to work at the intensity frontier.

Belle II may well be the first collider experiment to confirm deviations from SM expectations, in particular measurements of lepton flavour universality violation and electroweak penguin decays. In addition, there is a rich programme of world-leading measurements in several areas: *CP* violation, rare B, D and τ decays, heavy hadron spectroscopy and the search for new exotic multi-quark states. Belle II has strong complementarity with the flavour physics programme at the LHC. While the high energy at LHC experiments results in larger production of B mesons, Belle II has unique capabilities to reconstruct missing energy, as well as significantly better reconstruction performance for photons, neutral pions, neutral kaons and electrons.

- *Current Status:* India has been a part of the Belle and Belle II projects for over 20 years, and has contributed to building part of the silicon vertex detector (SVD) of Belle II. Indian collaborators have made significant contributions to over 50 Belle and Belle II papers. They are involved in the operation of the

SVD, detector calibration and distributed computing. Some of them hold elected positions in the management, such as Conveners of working groups related to physics analyses. Continued involvement in the project is envisaged, including detector R&D for the upgrade which is expected by 2028-29. The hardware aim will be the development of a replacement double-sided silicon strip detector (DSSD) with thinner sensors and finer pitch, which would improve background tolerance and performance. The involvement should last till 2035, when the data analysis is expected to be complete.

The current Indian involvement in Belle II comes from eleven institutions (IISc, IIT-BBS, IIT-G, IIT-H, IIT-M, IISER- Mohali, IMSc, MNIT-Jaipur, Panjab U, Punjab Agricultural U. and TIFR) with 13 faculty members (median age 45), 25 PhD students and five technical staff. This corresponds to approximately 5% of the Belle II collaboration. There have been 7 postdocs mentored over the years, some of whom may be expected to join the collaboration. (Five of the current faculty members have been PhD students in Belle.)

In the absence of its inclusion in the Mega Science stream, there is currently no formal "India-Belle II" collaboration structure. However, it is envisaged that such a structure, and a monitoring mechanism, when formalized, would allow the Indian research groups to increase their impact within the Belle II project internationally.

- *Human Resource Development:* Indian Belle II groups are heavily involved in both SVD hardware and software. In particular, TIFR has played an important role in the design, prototyping and construction of one of the four layers of this detector, having delivered 12 state-of-the-art modules. The data analysis required to make measurements at Belle II relies upon machine learning algorithms and big data analytics. IIT-G, IIT-H and TIFR are contributing to the Belle II GRID Computing. The students and postdocs involved in these tasks get trained in the building and testing of SVD modules, as well as in the software for data analysis.

  Indian research groups involved in Belle and Belle II have made special efforts towards the training of students in the project, by organising annual Belle II Analysis Workshop (BAW), which has been taking place since 2011. The BAW brings together all Indian collaborators, as well as a few international ones, for pedagogical lectures, hands-on tutorials and student presentations over the course of a week to ten days. These workshops are invaluable for the Ph.D. students, resulting in a strong ecosystem of collaboration among them and their institutions.

- *Industry Connections:* The work on silicon detectors has resulted in a successful R&D program with Bharat Electronics Limited, Bangalore in developing silicon microstrip sensors. Other Indian industries may also be encouraged to take part in the SVD upgrade, as well as in longer term international and home-grown projects that follow thereafter. There are also potential societal applications of silicon strip detectors in muon tomography and medical imaging. During the SVD upgrade, it is also possible to explore possibilities of utilizing indigenous technologies like LYSO crystals and plastic scintillators.

- *Funding Requirements:* Belle II participation from India does not receive funding under the Mega Science stream currently. Some individual research groups get their funding separately, e.g., the TIFR group is funded to the extent of about Rs. 1.5 Cr. per annum, including contributions to Belle II maintenance and operation (M&O). It is expected that the funding needed during 2020 – 2035 would be a total of Rs. 47.5 Cr. (7.5 + 25 + 15 in 5-year slabs), including operations, upgrade and GRID computing infrastructure.

- **Overall Appraisal:** *Given* the young profile of the faculty members currently involved in Belle II, and the prospective new members on the horizon, the Indian Belle II community has the potential to be a major contributor for the whole lifetime of the Belle II project, i.e., till about 2035. This could naturally develop into closer Indo-Japanese collaboration, either for additional upgrades of Belle II, or in the longer term, the International Linear Collider that may be hosted in Japan. A very important prospect is that the R&D proposed for the Belle II upgrade will naturally feed into the requirements for detectors for other possible future e^+e^- colliders such as CLIC and FCC-ee. While the technology needed for these future projects is still not achieved, the high energy physics community as a whole is invested in the success of the SuperKEKB accelerator technology.

2.1.3 Neutrino Experiments: NOνA and MINERνA (Fermilab)

The NOνA (NuMI Off-axis ν_e Appearance) experiment [Ayres 2007] at Fermilab, USA, was built for observing $\nu_\mu \rightarrow \nu_e$ oscillations to measure the neutrino mixing angle θ_{13}, determine the neutrino mass ordering, measure the CP violating phase δ, measure precisely the other oscillation parameters and establish the octant of the angle θ_{23}. It can also measure the Earth matter effects, shed light on the existence of sterile neutrinos and measure non-standard interaction (NSI) effects. It has been collecting data since 2012.

The MINERνA (Main INjector Experiment for $V-\mathrm{A}$) experiment [Aliaga 2014], also at Fermilab, USA, is a high statistics (anti)neutrino experiment dedicated to study neutrino cross sections with a variety of nuclear targets (C, Fe, Pb, He, H_2O) and to understand nuclear medium effects. It has completed its low and medium energy mode runs between 2009 and 2019. The experiment has set a foundation for future neutrino oscillation experiments by improving the present interaction models.

- *Current status:* A consortium of nine Indian Institutions -- Aligarh Muslim University, Banaras Hindu University, Cochin University of Science and Technology, University of Delhi, IIT Guwahati, IIT Hyderabad, University of Hyderabad, NISER and Panjab University -- has been actively participating in the Fermilab neutrino program since 2010. They have collaborated on several experiments such as Main Injector Particle Production (MIPP) [Isenhower 2006], Main Injector Neutrino Oscillation Search (MINOS) [Ambats 1998], and MINOS+ [Tzanankos 2011], and are currently a part of NOνA and MINERνA. The participation of all the above institutions is under the IIFC-νP (Indian institutions – Fermilab Collaboration in Neutrino Physics) programme.

  The group members have been involved in beam studies, detector operation and maintenance, software/code development, data analyses and data saving for future use. The group has been instrumental in adapting Deep Convolutional Neural Network (DCNN) techniques for particle identification and in classifying the vertex location along the direction of the (anti)neutrino beam. The group has helped in improving the overall flux prediction and reducing the uncertainty associated with NOνA results, in calibrating the NOνA detectors and in measuring $\nu_\mu \rightarrow \nu_e$ oscillations.

  An oscillation analysis framework to analyse the muon and electron neutrino events observed in the near and far detectors has been developed to implement signal and background event selections. With the event rate in the near detector being largely unaffected by oscillations, this can be extrapolated to make accurate predictions for those in the far detector, thereby removing effects of much of the systematic errors. This has led to improved searches for sterile neutrinos, NSI effects, Lorentz violation and CPT violation.

  Oscillation studies for the MINOS+ experiment and studies of pion and kaon production in proton-induced interactions in the MIPP experiment have been carried out. Some of these may also be helpful in improving GEANT4 models of pion and kaon productions for the future DUNE experiment (Deep Underground Neutrino Experiment) [Abi 2020].

  In the MINERνA experiment, the prime focus is to obtain the differential and total cross-section and the ratio of the cross-sections for the (anti)neutrino modes for the nuclei in the deep inelastic scattering region. A comparison of different machine learning (ML) techniques is being made by the AMU group using the antineutrino data. Polarization studies as well as studies of perturbative and non-perturbative effects in the deep inelastic scattering (DIS) region have been carried out. The plan is to further extend this study to understand associated particle production processes and nuclear medium effects in the inelastic induced reactions.

- *Human Resource Development:* As mentioned above, there are nine institutions involved in NOνA, of which Aligarh Muslim University also participates in MINERνA. Most of the students and postdocs are under the age of 35 years and most of the faculty members are between 40 and 55 years. A faculty member of the collaboration is a member of the Neutrino Panel of International Union of Pure and Applied Physics (IUPAP) as well as the International Collaboration of Neutrino Experimental-Theory Collaboration (NUSTEC) Board.

  About 20 students from the above institutions have been awarded their Ph.D. degrees based on their work in this project, and 20 more are currently working as Ph.D. students. The students typically spend a few years at Fermilab, and after coming back to India help in training their younger colleagues. More than half of the graduating students have landed postdoc positions in prestigious institutions around the world involved in neutrino physics.

- *Funding requirements:* The IIFC-νP collaboration will last till 2026. It is funded till 2024 and an additional Rs. 6 Cr. will be needed. The effort put in this collaboration by Indian physicists could be synchronized with the Indian efforts in the DUNE Collaboration.

- **Overall Appraisal:** Since the Indian neutrino physics community is already collaborating with the Fermilab through the IIFC-νP collaboration, it can naturally move on to a collaboration with the DUNE experiment in the next two decades. The Indian groups plan to be involved in designing the DUNE Near Detector and are contributing to the R&D for the Straw Tube-based Tracking (STT) system.

2.1.4 Direct Searches for Dark Matter: PICASSO/PICO (Sudbury)

PICO is a direct Dark Matter (DM) detection experiment [PICO 2024] located at the SNOLAB underground laboratory in Sudbury, Canada. It is optimized to search for weakly interacting massive particles (WIMPs) with special sensitivity to the spin-dependent WIMP-nucleus interaction sector. The detection technology is based on bubble chambers with superheated liquid chlorofluorocarbon as the active detector material. The PICO is built upon the success of previous generation experiments PICO-2L and PICO-60L which have yielded the most stringent upper limits on the WIMP-nuclei spin-dependent (SD) cross-section to date. The latest results released in 2019 based on PICO-60L experiment with 52 kg of C_3F_8 as active medium and a total exposure of 1404 kg-day give an upper limit of 3.2×10^{-41} cm^2 (90% C.L.) on the WIMP-proton SD cross section at 25 GeV WIMP mass. At present, PICO-40L with a modified bubble chamber design is in operating phase. Construction and testing of various components of the upgraded PICO-500L experiment are well under way with a view to eventually develop a multi-ton experiment.

- *Current Status:* From India, the SINP group has been participating in the PICASSO/PICO collaboration since 2009, contributing to detector fabrication, R&D for the next generation detector, simulation of the backgrounds such as alpha particles as intrinsic background and cosmic ray muon induced neutrons as external background, analysis of the data collected by experiments at SNOLAB, calibration and characterization experiments at the SINP lab, online shifts of detector operation during the experiments, etc. The SINP group has developed in-house facilities for fabrication of prototype superheated liquid detectors for R&D work. Also, the design and fabrication of the Camera Mount system for the PICO experiment has been done at SINP.

- *Human Resource Development:* The SINP group currently consists of one faculty, one engineer and three PhD students. Earlier, one other senior faculty and three post-doctoral fellows in the SINP group also worked in this experiment. Young researchers are being trained on various aspects of direct dark matter detection experiments and are doing well in their subsequent academic positions. One student has already completed her PhD, and is currently a postdoctoral fellow working in the DARKSIDE experiment in Ontario, Canada.

  This experience and expertise gained from working in a leading experiment on direct dark matter detection will be useful in setting up and executing the proposed InDEx dark matter search experiment in India.

- *Industry Connections:* The superheated liquid detectors can also be used as high accuracy neutron dosimeters for neutron monitoring at various accelerator sites and for environmental radiation monitoring. This kind of detector can also potentially be used for neutron monitoring in cancer radiation therapy, a possibility that the SINP group is already in the process of exploring.

- *Funding Requirements:* The SINP group is interested to continue its participation in the PICO experiment as it progresses towards a multi-ton scale experiment. During the plan period 2012-2017, the funding requirement of the SINP group consisted of a monetary contribution of CAD 60,000 per year for annual operational cost sharing and Rs. 20 lakh per year for travel to the experimental site as well as R&D work at SINP. This does not include personnel requirements. Funding at a similar level will be required to continue the PICO related research activities in the future at SINP.

- **Overall appraisal:** The PICO collaboration is bi-annually reviewed by an Experimental Advisory Committee (EAC), SNOLAB. There are also regular PICO collaboration meetings (3 to 4 per year) for monitoring the progress of the activities by the different group members and organization. Thus, the project is closely monitored for its progress within the approved budget and timelines and is well on track.

  The SINP group has been successfully participating and usefully contributing to the PICASSO/PICO experiments since 2009, including successfully graduating PhD and Master's students. The group's strength lies in detector fabrication, simulation, detector characterization and data analysis. The main weakness is the insufficient availability of trained manpower for hardware development.

2.1.5 Gamma-ray Astrophysics: MAGIC (La Palma)

Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescope system [Aleksic 2016] is a system of two 17m-diameter, Imaging Atmospheric Cherenkov Telescopes (IACT) performing observations of gamma rays from galactic and extragalactic sources in the very high energy range (VHE, 30 GeV to 100 TeV). The telescopes are located in El Roque de los Muchachos Observatory in La Palma, Canary Islands, Spain at an altitude of 2200 m above sea level. The MAGIC telescopes are currently run by an international collaboration of about 165 astroparticle physicists from 24 institutions belonging to 12 countries from Europe, Asia and South America. India has been a full member of the MAGIC experiment since 2015. MAGIC is currently one of the leading installations in the world which boasts of a very low energy threshold ($\sim$ 30 GeV) with unprecedented sensitivity ($<$ 1% of the Crab nebula flux), thus ideally bridging the gap between the satellite detectors like Fermi-LAT and the ground-based ones. Owing to its low energy threshold, MAGIC is the only telescope system which can detect high energy gamma rays from pulsars, pulsar wind nebula systems, gamma-ray bursts and active galactic nuclei at energies below 100 GeV.

- *Current Status:* The Indian involvement in the MAGIC experiment is expected to run till 2025 through an approval of the Department of Atomic Energy (DAE) with periodic institutional reviews. The current involvement in MAGIC comes from two institutions, SINP as a full member, and IIT-Jodhpur and Presidency University as associate members. The primary objective of the Indian participation in MAGIC is to perform coordinated multi-wavelength observations with the currently running Indian observatories like Himalayan Chandra Telescope (HCT) at Hanle, Giant Metrewave Radio Telescope (GMRT) at Pune and the first Indian multi-wavelength satellite, ASTROSAT. Scientists from SINP and Presidency University, Kolkata, are actively involved in several such coordinated observation proposals of very high energy gamma-ray sources between ASTROSAT and MAGIC, and are also serving in responsible positions at MAGIC.
- *Human Resource Development:* Currently five faculty members from ARIES, IIT Jodhpur, Presidency University, RRI and SINP are involved in this project from India. Two students have already completed their PhD and are postdocs in renowned institutes abroad and in the country. There are three more Ph.D. students and a few Master's students currently working in the project. The involvement in MAGIC project enables one to develop and train manpower for future upcoming experiments like Major Atmospheric Cherenkov Experiment (MACE) at Hanle and the international Cherenkov Telescope Array (CTA) project.
- *Funding Requirements:* The project is approved for funding till 2027 by DAE beyond which funding will be requested for continuation of the project till 2030 when the project is expected to be completed. The projected funding requirement from 2025 till 2030 is approximately 1.0 Cr. (20 lakhs per year) and includes the upgrade of an already existing High Performance Computing Cluster at SINP with adequate storage for data analysis.
- **Overall Appraisal:** The scientific activities undertaken through participation in MAGIC experiment will help scientists, students and postdocs in India to pursue and engage in various outstanding problems in the field of TeV gamma-ray astronomy and also give them an opportunity to work with one of the most advanced telescope systems in the world. This will be extremely beneficial for training skilled human resources in the field. In the context of understanding the nature of these exotic sources, data from one or two instruments is not always sufficient to make conclusive statements. Multi-wavelength observations with X-ray satellites, radio observatories and optical telescopes would be of immense importance.

  The results from measurements in different regions of the electromagnetic spectrum along with the elusive neutrinos can be combined to obtain clues about the origin of galactic and extragalactic cosmic rays. At the same time, it will help to identify many sources otherwise unresolved and understand their phenomenology. There are currently several accepted and planned proposals for observations of extragalactic sources with the successfully operating Indian X-ray satellite ASTROSAT [ASTROSAT 2024], optical telescope (HCT) [HCT 2024] operating at Hanle and MAGIC. Such observations will go a long way in building up the ecosystem for future simultaneous observations with state-of-the-art telescope systems like Square Kilometre Array (SKA) [SKA 2024], Thirty Meter Telescope (TMT) [TMT 2024] and Cherenkov Telescope Array (CTA) [Bernloehr 2013]. Additionally, the knowledge gained in operating MAGIC telescopes and developing various analysis tools for data analysis can be successfully utilized and implemented during the operational phase of Major Atmospheric Cherenkov Experiment (MACE) telescope [Yadav 2022], which has recently been constructed by BARC at Hanle and, in future, for the Cherenkov Telescope Array (CTA).

2.2 Projects Located in India

In addition to involvement in international Mega Science Projects, the Indian HEP community is also involved in envisioning, constructing and operating some experiments in India. These include, the India-based Neutrino Observatory (INO), the high-energy cosmic ray experiment GRAPES at Udhagamandalam (Ooty) and the gamma-ray observatories HAGAR and MACE in Ladakh. Some details of these experiments are given below.

2.2.1 Ultra-high Energy Cosmic-ray Experiment (GRAPES-3)

GRAPES-3 is a major high-altitude, near-equator astroparticle physics experiment [Gupta 2010] at Udhagamandalam. It is an expanded version of the original GRAPES experiment, which started running more than 30 years ago. It consists of 400 large-area detectors made from scintillators, as well as 4000 massive sealed proportional-counters, making it the world's largest muon telescope. It is sensitive to the spectrum and composition of cosmic rays over the range $10^{13} - 10^{17}$eV and is well-suited for exploring the “knee” region in the energy spectrum of cosmic rays as well as for observing accelerated particles in atmospheric, solar, galactic and extragalactic domains. In fact, recently GRAPES-3 has observed some novel features in the spectra of cosmic rays at $E \sim 10^{14}$ eV [Varsi 2024].

GRAPES-3 can also search for gamma ray sources in the multi-TeV to PeV range, diffuse gamma ray emission from the galactic disk, and can look for decaying dark matter in the galaxy. The resolution for multi-TeV gamma ray sources could be as low as 10 arc minutes.

In addition to the cosmic ray observations, GRAPES-3 can be sensitive to particle acceleration by electric potentials generated in thunderstorms and take measurements relevant for space weather and heliospheric studies. GRAPES-3 scientists have also demonstrated that cosmic ray (CR) muons can be a powerful tool to measure arrival time of solar storms at Earth with great precision [Hariharan 2023]. Such studies are vital for protecting worldwide telecommunication and electrical grids from disruption.

- *Current Status:* GRAPES-3 Collaboration includes 12 Indian institutions (TIFR, Bose Institute, Aligarh Muslim University, Utkal University, Dibrugarh University, North-Bengal University, Tezpur University, VIIT Pune, IISER Pune, IIT Kanpur, IIT Indore, IIT Jodhpur) and 7 Japanese institutions (Osaka-City University, Chubu University, ICRR Tokyo University, Nagoya University, Kochi University, Hiroshima-City University, Aichi Institute). A Memorandum of Cooperation (MOC) proposed to be signed between India and Japan is under consideration in DAE. It would enhance Japanese participation in GRAPES-3.

  DAE has approved funding for a 3-year project to develop and produce scintillator-based radiation detectors in Ooty, jointly with the Radiation and Photochemistry Division (RPD) of the Chemistry Group in BARC. Discussions are going on for a collaboration between SAC, ISRO and GRAPES-3 to exploit complementary capabilities of GRAPES-3 and Aditya L1 Mission on the ground and in deep space for unprecedented studies of solar storms.

  Key objectives of GRAPES-3 are sensitive measurements of (1) acceleration of muons in the atmospheric electric field inside thunderstorms, (2) space-weather in interplanetary-space, including interaction of magnetosphere – extreme solar-storms can disrupt technological infrastructure on Earth and in space, (3) gamma-rays with energies >100 TeV through rejection of CR background (~7σ CRAB detection in 1-year), in order to address origin, acceleration and propagation of cosmic rays.

  An expansion of GRAPES-3 over the next five years is proposed, which would double the areas of the scintillator array and the muon-telescope.

- *Human Resource Development:* The GRAPES-3 project currently has 24 faculty members, with their median age around 55. In addition, there are about 20 engineers / technicians, and 10 students. This number is expected to reach 50 faculty members and 40 engineering and technical personnel, over the next 15 years.

  The project has trained hundreds of young physicists and engineers through winter schools and projects. The winter schools, which are being conducted since 2006, have benefitted about 250 students, and about 150 students have done B.E. projects under the TIFR-VIIT MOU. Over the years, more than 6500 students and teachers from schools and colleges have visited the GRAPES site.

- *Technology Development:* Over the years, GRAPES has succeeded in making high-quality plastic scintillators with high light-output and timing comparable to imported ones, but at a fraction of their cost. It has also manufactured thousands of large rugged, sealed proportional counters (6m x 0.1m x 0.1m). Ultra-fast amplifiers, discriminators and time-to-digital converters (TDCs) have been made at 10-20% of the cost of imported ones. FPGA-based signal processing and data-recording electronics have also been developed.

  In the absence of indigenous manufacturers of high-quality scintillators and ultra-fast electronics, GRAPES has provided technical support to national institutes and universities including BARC, Bose Institute, IISER Pune, Utkal University, Dayalbagh Educational Institute, Agra, etc. Since much of the equipment used is fabricated in-house, GRAPES-3 provides a unique facility for hands-on training of highly skilled human resources in detectors and electronics for nuclear, high-energy and astroparticle physics. The detector technology developed have a potential strategic value.

- *Funding Requirements:* The projected budget of the project is about Rs. 25 Cr. for the period 2020 – 2025, Rs. 37.5 Cr. for the period 2025 – 2030, and Rs. 50 Cr. for the period 2030 – 2035.

- **Overall Appraisal:** Due to its dense array of scintillators and the large-area muon telescope, both located at a relatively high altitude, the GRAPES-3 setup offers several advantages over other arrays in sensitivity to cosmic ray composition and episodic phenomena. A near-equator location offers unprecedented views of both northern and southern skies, including the galactic centre. Longitude differences of ~5 and ~10 hours relative to Europe and USA allow monitoring of transient sources when they cannot be viewed by instruments in Europe and Americas. This makes GRAPES-3 a valuable part of the network of international gamma-ray telescopes, with a potential to contribute to multi-messenger studies in astrophysics.

2.2.2 Gamma-ray Astrophysics (HAGAR/MACE)

Indian groups started activities in VHE gamma ray astronomy when the field was still in its infancy [Bose2 2022]. TIFR entered this field in 1969 with initial activities near Ooty (and then in Pachmarhi), whereas the BARC group started activities in the 1970s at Gulmarg (and then at Mt. Abu). Globally, there was a major advancement in the field in the late 1980's with the advent of imaging techniques successfully demonstrated by the Whipple Telescope in Arizona. In the next decade or so, further innovations carried out by European and American groups paved the way for the present generation of stereoscopic arrays of imaging telescopes like H.E.S.S. [Aharonian 2006], MAGIC [Aleksic 2016] and VERITAS [Weekes 2002].

- *Current Status:* In the last twenty years, there has been a worldwide attempt to lower the energy thresholds of Cherenkov telescopes to 100 GeV or lower, the motivation being to have an overlap with satellite-based experiments like Fermi-LAT. There are two main ways to reduce the energy threshold, either by using large mirrors in telescopes or by installing telescopes at high altitude locations.

Considering the cost-effectiveness of the second option, TIFR and IIA together decided to set up atmospheric Cherenkov telescopes at Hanle in Ladakh at an altitude of 4.3 kms, where IIA has been operating the Himalayan Chandra Telescope (HCT) since 2000. As a result, the High-Altitude GAmma Ray (HAGAR) telescope array [Britto 2011] was proposed. Installation of HAGAR began at Hanle in 2005 and was completed in 2007. SINP joined this effort in 2007.

The HAGAR array consists of seven telescopes, each consisting of an array of seven para-axially mounted parabolic mirrors of diameter about 1m, with UV sensitive PMT mounted at the focus of each mirror. The pulses from PMTs are brought to the control room and processed there. HAGAR is based on wavefront sampling technique consisting of an array of small size telescopes that records arrival time of Cherenkov shower front and Cherenkov photon density at various locations in Cherenkov pool.

Regular observations with the HAGAR array are being performed since 2007. Well-known TeV blazars Mrk 421 and Mrk 501 were observed during several flaring states and moderately high states of the source. Coordinated multi-wavelength campaigns with Swift and other X-ray and optical observatories have been carried out. Very high energy gamma-ray emission from the Crab pulsar has already been detected.

In the second stage of the project, a large 21 m imaging telescope called MACE [Yadav 2022] has been constructed at Hanle under the leadership of BARC. The energy threshold of MACE is expected to be ~ 30 GeV, which would make it one of the few experiments in the world with a low energy threshold. MACE has completed its commissioning phase and has started its science operations [Borwankar 2024].

Stereo MACE: A single telescope is limited in its sensitivity owing to the poorer angular resolution and poorer gamma-hadron separation especially at lower energies below 100 GeV. Stereoscopic observations vastly improve the angular resolution, energy resolution and gamma-hadron separation which in turn translates to improved sensitivity of the telescope system. After the successful commissioning of the MACE telescope, the group has started to work on the feasibility of constructing more telescope(s) close to the MACE telescope to perform stereoscopic observations. Currently simulations are underway to estimate the performance of stereo MACE and details about funding for the second telescope are being worked upon.

Technology Development: Several technological challenges have been overcome during the construction of MACE. The telescope deploys a 21m diameter tracking light collector made up of about 1400 aluminium mirror facets. These mirror facets which have been developed within the country are of 50 cm × 50 cm size. The imaging camera is designed to be a compact array of 1088 photomultiplier tubes arranged in a triangular pitch of 55 mm corresponding to a pixel resolution of 0.125 degrees. MACE is expected to have a sensitivity of about 3% of the Crab nebula flux in 50 hours for 5 sigma detection.

As a part of the second phase of HAGAR, the TIFR group has built a Silicon PM camera [Kumar 2023, Rao 2023], which will be the first of its kind in the country. The camera has 256 pixels of 0.3 deg each, covering the field of view of 5 deg x 5 deg. It is mounted in the focal plane of one of the vertex elements of TACTIC telescopes at Mt Abu. After successful completion of tests, the camera and vertex element will be shifted to Hanle. This telescope will be dedicated for monitoring of known bright blazars. Apart from giving long duration coverage of blazars, it will also serve the purpose of alerting MACE and other observatories to conduct deeper observations whenever a blazar is seen in a high state.

- *Human Resource Development:* Currently, there is one TIFR faculty member involved in the HAGAR project, with about 5 engineers and 2 technicians. Two Ph.D. students and a postdoc have worked on

HAGAR analysis and the development of the SiPM camera. There are about 20 scientists from BARC working on the MACE project and towards MACE Stereo.

- *Funding Requirements:* The HAGAR project and the SiPM camera have been funded by DAE through plan budgets. The SiPM camera project was first proposed during mid-term review of the 12th Plan. The MACE project, with the construction cost of nearly Rs. 90 Cr. and operations cost of about 2 Cr. per year, is fully funded by DAE. The MACE Stereo project is expected to cost about Rs. 500 Cr. over the next 10 years.

- **Overall Appraisal:** Even though the sensitivity of MACE may be worse than the current generation of imaging Cherenkov telescopes, MACE is expected to discover very high energy gamma rays from several pulsars and high-redshift active galactic nuclei (AGNs). Additionally, the longitudinal location of MACE is complementary to that of other major Cherenkov telescopes in the world, which will allow scientists to perform observations of transient sources for several hours in a night. MACE can also be used as a testbed for future technologies to be used in the upcoming international project, Cherenkov Telescope Array. In fact, the site at Hanle has several advantages due to its height and geographical location which may be exploited for future experiments; more details may be found in the MSV-2035 Report on Astronomy and Astrophysics [MSV-2035-A&A].

  Stereoscopic observations of MACE will significantly improve the angular resolution and energy resolution of the system as well as the gamma-hadron separation, especially at lower energies where a single telescope has limited capability. This in turn will improve the sensitivity of the system which will translate to shorter detection times for the observed sources and a better estimation of the parameters of the source.

  The scientific activities undertaken through the MACE experiment will help scientists, students and postdocs in India to pursue and engage in various important problems in the field of TeV gamma-ray astronomy. This can be used as a launching pad for making very important contributions to the upcoming array of Cherenkov telescopes, namely CTA.

2.2.3 Indian Coherent Nuclear Scattering Experiment (ICNSE)

The Indian Coherent Neutrino Scattering Experiment (ICNSE) at the Apsara-U research reactor at BARC aims to study neutrino-nucleus scattering at energies of about a MeV. At such energies, coherent elastic neutrino-nucleus scattering (CEνNS) occurs, in which a neutrino interacts with a nucleus through the neutral-current interaction and the nucleus is not excited to a higher energy state. Such a process is favourable as long as the momentum exchanged remains smaller than the inverse of the nuclear size, which means that the neutrino energies are typically below a few tens of MeV. The scattering cross section is enhanced by the square of the number of nucleons. Even though the process was predicted more than 40 years ago, it was detected only recently (2017) by the COHERENT experiment [Akimov 2017]. Several ideas, based on the above cross section enhancement, have been put forward to use CEνNS to deepen our understanding of various facets of particle and nuclear physics. These include searching for non-standard neutrino interactions, determination of the relevant nuclear form factors, precise measurement of the Weinberg angle, sterile neutrino searches [Behera 2023] and measurement of the neutrino magnetic moment [Dutta 2016], to name a few.

- *Current status:* There are several experiments around the world utilizing reactors to detect CEνNS. Examples of these experiments are RICOCHET [Augier 2021], CONNIE [Aguilar-Arevalo 2019], CONUS [Bonet 2021], Dresden-II [Colaresi 2021], NUCLEUS [Wagner 2021], NuGEN [Alekseev

2022] and RED-100 [Akimov 2020]. They use several competing technologies like Charge Coupled Devices (CCD), dual-phase noble gases, and low temperature semiconductor crystals. The ICNSE experiment at BARC has been approved and funded recently.

- *Technology development:* CEνNS experiments fall into the category of rare-event search experiments, which need detectors of the highest quality in order to reduce background due to inherent radioactive impurities. High purity crystal fabrication is an area upon which India can focus for developing such detectors. Facilities such as the Crystal Technology Lab, BARC have already grown crystals for their use in radiation detection. Such facilities could be empowered and exploited to fabricate crystals for use in ICNSE. Another important aspect of such detectors is the patterning of Transition Edge Sensors (TES), numbering several thousand on an area of approximately 30 cm^2, on their surface that serve as phonon detectors. The patterning is done on the crystals using photolithographic techniques which constitute a technology familiar to the Indian community. However, patterning such sensors on uncommon crystals may need the development of other techniques.

- *Human Resource Development:* The human resource requirements for setting up the ICNSE experiment are envisaged as follows. Over the first 5 years, the requirement would be about 10 personnel, including scientists, engineers, students and postdocs. In the subsequent 5 (10) years, this requirement would grow to about 15 (20) personnel.

- *Funding requirements:* The major cost for running the ICNSE experiment would stem from the necessary cryogenic infrastructure, which will amount to about Rs. 100 Cr. for the first 5 years, and an annual cost of Rs. 5 Cr. for the subsequent 5 years, followed by Rs. 3 Cr. p.a. for the next 5 years.

- **Overall appraisal:** The CEνNS experiments offer a novel way to probe neutrino-nucleus interactions and associated ideas. As the neutrinos produced in nuclear reactors have energies in the range of 0-8 MeV, the search for CEνNS using reactors is most opportune given the availability of a good number of research reactors in India. In fact, the ICNSE experiment at BARC has already been funded and is expected to come up within the next few years. Apart from its purely scientific interest, it will enhance the visibility of the Indian HEP and NP community and open up a prospective channel for non-intrusive reactor monitoring to assess the operational state of reactors. The development of high-purity crystals and cryogenic infrastructure will also help the country to grow and attain expertise that can be used in fields like semiconductor devices, quantum computing etc.

2.2.4 Atmospheric Neutrino Experiment

Over the last two decades, the Indian high energy physics community has been working on a projected facility, the India-based Neutrino Observatory (INO) [Athar 2006], which would consist of a 51 kt magnetized iron calorimeter detector (ICAL) for observing atmospheric neutrinos. Currently, however, the project is not active, but the technology developed (see below) could have significant applications in future mega science projects to be developed in India. Some of the plans and details of the erstwhile project are given below.

The ICAL detector was envisaged to consist of about 30,000 resistive plate chambers (RPCs) of dimension 2 m × 2 m as the active detector elements, 151 layers of which would alternate with 150 layers of iron plates (4 m × 2 m × 5.6 cm). The detector would have excellent energy and directional resolution for muons, as well as charge identification capability due to the magnetic field of 1.5 T. This would make the detector unique in being able to distinguish between neutrino and antineutrino in every event.

The major question that a detector like ICAL would be able to address [Ahmed 2017] is the determination of the neutrino mass ordering, whether it is normal ($m_1 < m_2 < m_3$) or inverted ($m_3 < m_1 < m_2$). This is one of the crucial ingredients needed for understanding the origin of neutrino masses. The current experiments (T2K [Abe 2020], NOνA [Ayres 2007]) may not reach a resolution on this in their lifetime, and while the JUNO reactor experiment [Adam 2015], which is expected to start in 2024-25, aims to achieve this in about 5 years, its success depends on being able to reach an unprecedented resolution in neutrino energy. Two large long-baseline experiments, Hyper-Kamiokande [Abe 2018] and DUNE [Abi 2020], expected to start by the end of this decade, will also be able to address this important issue. In any case, the results from ICAL would be the first using atmospheric neutrinos at multi-GeV energies and the first based on Earth-matter effects over a wide range of distances travelled through the Earth.

Apart from the neutrino mass ordering, a detector like ICAL would also be able to make a precise determination of atmospheric neutrino mixing parameters, and probe new physics scenarios such as non-standard neutrino interactions, possible CPT violation or long-range forces, neutrino decay or decoherence, the presence of sterile neutrinos, etc. Using the neutrinos that have passed through the mantle and core of the Earth, it can also do Earth tomography. It can look for specific signals of physics beyond the Standard Model that may not be directly linked to neutrinos, like magnetic monopoles, long-lived particles and products of dark matter annihilation. In the long term, it could act as a detector looking for astrophysical or atmospheric phenomena and be a participant in the global multi-messenger astronomy network. It would be in a unique position of being sensitive to any neutrino observations where the event-by-event identification of neutrinos versus anti-neutrinos would be relevant.

- *Current Status:* The INO project proposal included (a) construction of an underground laboratory and associated surface facilities, which would be a national facility, (b) construction of the ICAL detector, and (c) setting up of an Inter-Institutional Centre for High Energy Physics (IICHEP) for human resource development, operation and maintenance of the underground laboratory and for detector R&D. Over the last two decades, nearly 100 scientists from more than 20 Institutes, IITs and Universities in India have carried out activities such as (i) detector design and development, with the construction of a prototype, (ii) front-end electronics and data acquisition, (iii) detector simulations, (iv) physics potential studies, as well as (v) site selection and obtaining necessary clearances.

  A prototype magnet of 85 tons iron, with 11 layers of iron plates in 1:700 scale version, the mini-ICAL, has been built and tested. It has been installed at the IICHEP Transit Campus at Madurai. The RPCs for the prototype have been made by industry in collaboration with different institutions. The prototype 1.5 T magnet has been commissioned and regular data-taking has started in mid-2018. The construction of the magnet, as well as in-situ measurements of the magnetic field, has been achieved with custom-built instrumentation. The data have been used to test and validate the numerical simulations software developed for track reconstruction and magnet design parameters. This mini-ICAL has been taking data of cosmic ray muons ever since, which has already resulted in the Ph.D. theses of multiple INO students. The experience gained during the construction of mini-ICAL should be very useful in constructing a larger scale iron calorimeter detector.

  The project has been periodically evaluated by a set of international experts and by the erstwhile SAC-PM. A Scientific Management Board set up jointly by DAE and DST has monitored the scientific progress of the project on a regular basis. However, the project has so far been unable to obtain the necessary clearances needed for the construction of the underground tunnel and caverns, for various reasons. Since these are absolutely essential for the success of the project, the project is stalled. If a suitable location with proper clearances becomes available in future, the project may see a revival, perhaps in a new/modified form.

- *Human Resource Development:* The running of a large facility like INO would have needed more than a hundred people on site in the long term, including faculty members, scientific officers and technical personnel, including experts in experimental and theoretical high energy physics, nuclear physics, detector physics, electronics and computer science. Realizing the need for developing the large trained human resource, INO had started its own Graduate Training Programme (INO GTP) in 2008, to train students in particle physics, neutrino physics, experimental methods and simulation techniques in high energy physics and instrumentation. Till now, around 30 students have completed their Ph.D. from INO GTP. In addition, every year INO has trained 10 to 30 summer interns, many of whom choose their career in high energy physics within the country or abroad. Some students have also worked on spinoffs and applications of RPC technologies such as in PET, tomography, etc. The ICAL collaboration has developed the basic detector simulation, digitisation and reconstruction code from scratch. This has helped in training newcomers in the use of complex software used in HEP experiments.

  In the process of design and characterization of large-area glass RPCs, several RPC laboratories have been set up in universities and research centres in India, where more than a hundred students, scientists and engineers have been trained in the RPC detector technology. The R&D on RPCs as well as the magnet have resulted in around 100 publications and many invited talks in prestigious conferences. These developments have also fed into teaching labs for graduate students and a large number of summer/winter students, who have eventually joined many national/international labs for their Ph.D.

- *Industry Connections:* The R&D activities for the ICAL detector have been carried out in-house in various participating institutions using locally available material and components to the extent possible. A conscious and consistent effort at developing local solutions, for needs as diverse as raw materials like glass and Bakelite, electronics, gas-mixing units and RPC construction, has been made.

  The particle detectors developed over the years by high energy and nuclear physicists have found wide applications in areas such as medical imaging, materials science, industrial control processes and geological surveys. The detector development for the ICAL experiment may find large-scale use in applications like PET-based medical imaging and the detection of contraband materials.

- *Funding Requirements:* A funding of approximately Rs. 1,500 Cr. had been sanctioned by the GOI in 2015 for the construction of the cavern, construction of the detector and running of the facility for the first 5 years. Since the project could not take off, most of this funding could not be put to use and no further funding is projected.

- **Overall Appraisal:** The INO had immense promise from the neutrino physics point of view and its importance as a unique facility for doing science underground cannot be overstated. Unfortunately, despite the enormous amount of background R&D done by the scientists and the financial sanction by the Government of India, the construction of INO could not be taken up because of local opposition to the project based on misconceptions about the nature of the experiment.

  The study of atmospheric neutrinos remains important, however, for the study of neutrino properties as well as for the long-term goal of Earth tomography. The physics question that the INO project was conceived to solve is still open; the quest for the neutrino mass ordering is expected to continue beyond the current decade. On the other hand, once the competing experiments start taking data, it would become impossible to catch up with them in the race for determining the neutrino mass ordering. The scientific goals of the project, therefore, require a major reassessment. Nevertheless, there is a strong consensus among the scientific community that a laboratory underground, or beneath a mountain, must exist as a long-term science facility. Such infrastructure would also be useful for other experiments, in high energy physics as well as in nuclear physics, astroparticle physics, materials science, geology and biology wherever a radiation-free environment is crucial. In fact, there are already plans for such experiments to detect neutrinoless double beta decay and dark matter. This would be a great opportunity for India to reclaim the position on the world-map of science at underground facilities, which had been earned with the Kolar Gold Field facility.

The idea of building an Inter-Institutional Centre for High Energy Physics (IICHEP) is also stalled due to the discontinuation of the INO project. Such a Centre would offer unique opportunities for participating in Mega Science activities to a wide section of Indian high energy community and is crucial for its sustenance as well as growth. The role of such a facility and its envisaged structure have been detailed later in Sec. 4.4.

2.3 Summary

Be not afraid of growing too slowly. Be afraid only of standing still

— Benjamin Franklin

India and Indian scientists are involved at the Energy, Intensity and Cosmic frontiers, with participation in international experiments such as CMS at CERN, Belle II at KEK, neutrino experiments at Fermilab, dark matter experiments in Canada and gamma ray experiments in Spain, as well as in home-grown experiments such as the GRAPES-3 experiment in Udhagamandalam, the HAGAR and MACE experiments in Ladakh and the erstwhile INO. This participation has been going on for the past few decades and has helped establish a base of expertise in India for Mega Science Projects. This expertise needs to be nurtured and utilized for participating in, planning and executing future projects. This will form the subject of the next section.

The MACE telescope at Hanle, Ladakh, on a starry night

3. From Current Expertise to Future Experiments

One never notices what has been done; one can only see what remains to be done
— Marie Curie

This Section will sketch a few upcoming Mega HEP projects, including some that are only at a conceptual stage, where interest has been expressed by some members of the Indian HEP community. This Section is divided into three parts: Subsection 3.1 describes the Indian expertise in HEP experiments and emphasizes why India should strive to be a major player in the next decades; Subsection 3.2 is on the upcoming international projects with a possibility of Indian participation; and Subsection 3.3 is on projects that could be located in India.

3.1 Building on Experience

Excellence is a continuous process and not an accident.
— A.P.J. Abdul Kalam

Indian scientists have been participating in Mega HEP Projects for a long time. The past experience has been described in Section 1.2.2, while the present involvement has been discussed in Section 2. For the experiments situated abroad, this has been in the form of building, installing and commissioning detectors; providing accelerator components; as well as construction and operation of the electronics components, trigger and data acquisition systems. For India-based project(s), in addition to the above, setting-up, construction, installation, and operation of the entire experiment(s) have also been carried out by Indian scientists.

We still have lots of ground to cover to compete with the first-world countries, but we have an ecosystem, which, if properly sustained and upgraded, can do the job. We have enough interested young people, either here or abroad (the Indian diaspora who may want to come back, given suitable opportunity), which ensures a steady supply of person-power to these experimental endeavours. We also have a large number of competent theoreticians who can contribute to such efforts. The linkage with industries is encouraging.

In this Subsection, we will provide a brief description of our experience and strong points on which the HEP activities in India should be planned and built. In this document, we focus on the detector aspects; the accelerator aspects have been covered in detail in the MSV-2035 Accelerator Science & Technology and Applications Report [MSV-2035-ASTA].

3.1.1 Technology and Detector Building Capabilities

Since the early days of cosmic ray research, the Indian HEP community has a long-standing tradition of building particle detectors, gradually evolving into a strong participation in Mega Science Projects in HEP like the L3 experiment at LEP, the DØ experiment at the Tevatron, the CMS experiment at LHC as well as astrophysics experiments like GRAPES at Udhagamandalam (Ooty) and MAGIC at La Palma in the Canary Islands, to name a few. These large-scale complex detectors, with millions of readout channels, generally consist of state-of-the-art detection technologies and cutting-edge data acquisition systems. R&D for particle detectors collectively refer to both active sensing elements as well as the associated data acquisition and trigger electronics, which take a centre-stage especially in the experiments involving large background rejection in real time to reduce the amount of data to be saved permanently.

The active components of detectors in which the Indian HEP community has extensive experience could be broadly divided in four categories:

- *Plastic Scintillators*: The community has delivered plastic scintillator-based units for calorimeter detectors in the CMS and D0 experiments. Although the scintillators themselves were imported from common vendors selected by the collaborations, the mechanical grooving to insert wavelength-shifting fibres in these tiles, each a few meters long and a centimetre thick, were done locally along with the full assembly of modules. The assembly and fabrication were followed by characterization of the tiles using cosmic muons and a radioactive wire source before shipping these to the final installation site at CERN or FermiLab [CMS-HO 2008]. The scintillation light produced is further converted to an electronic signal using photomultipliers (PMTs), hybrid photodiodes (HPDs) or silicon photomultipliers (SiPMs).

  The Cosmic Ray Laboratory at Ooty has been at the forefront of development of plastic scintillators and now has the in-house capability of making high quality plastic scintillators with long attenuation length and high light-output [Mohanty 2009]. These detectors constitute a key component of experiments that study cosmic rays and very high energy gamma-rays. A cosmic ray air shower detector system using these devices was set up at CERN in the 1990s in connection with the L3 experiment [Adriani 2002]. The scintillator detectors as well as full DAQ and electronics were developed and manufactured in India and shipped to CERN by a team led by TIFR.

- *Silicon Detectors*: Given their excellent signal-to-noise separation, radiation endurance, industrial ease in fabrication in the form of micro-pixels and micro-strips and developments in integrating the on-detector readout electronics, the silicon-based detectors are heavily used in collider experiments. These are the detectors that are usually placed closest to the beam and are used to measure the point of interaction as well as the momenta of charged particles via tracking. Particle multiplicity is highest close to the interaction vertices and this places heavy demands on the reaction and quenching time of the detectors. Such charge-coupled devices (CCDs) are also widely used in astrophysics and cosmology experiments.

  The Indian community supplied 1,100 silicon-strip modules based on 320 micron-thick 4-inch sensor technology for the pre-shower detector of the CMS experiment, and these correspond to almost half of the modules required for the system [CMS 2008]. These detectors were fabricated by BEL at Bengaluru and thoroughly tested in India for their quality and radiation hardness. The community also delivered part of the silicon vertex detectors for the Belle II experiment in Japan. In the near future, the community is committed to deliver silicon-based detector modules for the outer tracker upgrade of the CMS experiment for the high luminosity LHC (HL-LHC), and to develop thin sensor strip detectors with a finer pitch for the Belle II experiment. R&D for a prototype SiPM-based camera for a small 4 m class imaging Cherenkov telescope is also well under way.

- *Gas Detectors*: India has a legacy of building gaseous detectors for many decades and Indian scientists have successfully installed many large, rugged, sealed proportional counters for cosmic ray experiments at Ooty and elsewhere. The community has supplied large-area Resistive Plate Chambers (RPCs) for the CMS experiment [CMS-RPC 2012]. These detectors are useful because of their good spatial resolution as well as fast timing for triggering on single muons. These RPCs were to be heavily used in our indigenous project INO. These are also popular choices for several Astrophysics experiments.

  The Gas Electron Multipliers (GEMs) are advanced detectors to handle the fast-triggering rates and higher backgrounds expected in the CMS experiment during high luminosity operations of the HL-LHC. The detectors supplied to CMS as a part of the ongoing detector upgrade, along with associated electronics boards, were fabricated in India in collaboration with the Indian industry Micropack at Bengaluru [CMS-GEM 2018, CMS-GEM 2019].

Several detector development projects aimed towards achieving a superheated droplet detector, and studying neutron and gamma-ray induced nucleation events in such a detector, are going on. These are potential candidates for active material for an underground dark matter detection experiment.

- *Cherenkov telescope*: A Large Imaging Cherenkov telescope has been built at BARC. While ECIL has built the structure, the camera and electronics have been built by BARC Electronics Division. BARC has collaborated with a government industrial partner, Mechvac, which has built the mirrors and done their coating. This was possible after a technology transfer from Italy. The telescope, MACE, has already been commissioned at Hanle.

3.1.2 Electronics, Trigger and Data Acquisition

All the advancements in detection techniques and active (sensing) materials have to be matched with the required electronics readout, achieving efficient signal triggering while rejecting backgrounds, and a data acquisition system capable of increasing the purity and precision of measurements.

- *Cosmic Ray Data*: The cosmic ray laboratory at Ooty excels in indigenous development and production of ultra-fast amplifiers, discriminators, fan-in/fan-out modules, time-to-digital converters (TDCs), FPGA-based signal-processing and data-recording electronics at a fraction of the cost of the imported modules. The groups involved in various experimental setups for cosmic ray and collider-based research have broad experience with CAMAC- and VME-based data acquisition systems, trigger logic, several controller cards and development of a RTC (real time clock) synchronized with GPS.
- *Collider Data*: The high energy accelerator-based experiments generally come with the daunting task of processing very high data volumes. For example, with the LHC collisions at 40 MHz and each event at CMS of the order of a few megabytes, the data is generated at the rate of a few TB/s. Out of these, less than a GB/s can be stored permanently for further analyses, as limited by current electronics. This rejection of events happens online in real time and requires processing of detector signal recorded in millions of channels using high speed electronics as close as possible to the detector ("front end readout"). In collaboration with the Indian industry, the Indian HEP community has supplied a large fraction of SiPM readout boards, control systems and calibration modules for the CMS hadron calorimeter. The group has also developed trigger and readout boards for the new generation data acquisition systems based on micro-TCA protocols, replacing the old VME-based systems for the forward hadron calorimeter upgrades.
- *Fast Triggers*: The India-CMS group is heavily involved in the development of next-generation trigger readout boards to adapt to much larger particle multiplicity at the high luminosity HL-LHC, with technology based on high-speed optical links and fast FPGAs. This includes development of the central trigger system as well as high-granularity calorimeters, which will also be the basis for experiments at the future linear and circular colliders, like the planned ILC and FCC.
- *Integrated Circuits*: Many different kinds of Application-Specific Integrated Circuits (ASICs) have been developed and their large-scale production has been achieved for the INO and other in-house experimental setups.

The experience and expertise gained over the last many decades, as described above, must be kept in mind while choosing the international experiments which one can join and where one can contribute meaningfully and significantly. The scientific and technological expertise that one can gain from our participation in such international projects should also be an important factor in taking such decisions.

3.2 Participation in International Projects

The nations may be divided in everything else, but they all share a single body of science.
— Isaac Asimov

Since some of the major experimental efforts in High Energy Physics are taking place in foreign countries, as large international projects with large international participation, Indian scientists too have joined or expressed interest in joining many such experiments and international collaborations. An appraisal of the Indian involvement envisaged in these high-profile Mega Science endeavours follows.

3.2.1 Detectors at Future Colliders (ILC / CLIC / μC / FCC-ee/pp)

The legacy of the first decade of LHC Physics could be summarized by the discovery of the Higgs boson of mass 125 GeV and the absence of any direct evidence of new physics phenomena. There are, however, a few tantalizing hints, a recent one from LHCb, which could lead to a complete paradigm shift in our understanding of elementary particles if confirmed. The next decade-and-a-half of precision measurements and direct searches at the LHC (Run-3 and HL-LHC) will certainly add valuable inputs to build upon, but it is still limited by the available beam energy to find statistically conclusive direct signatures of particles of masses of several TeV. New results from Belle II are also expected to further our understanding of these hints but they will certainly not solve the puzzles completely. Hence, more powerful machines are certainly needed.

Several proposals for future energy-frontier machines are being considered, namely the International Linear Collider (ILC) in Japan [Behnke 2013], Compact Linear Collider (CLIC) at CERN [Aicheler 2013], Future Circular Collider (FCC) at CERN [Benedikt-ee 2019, Benedikt-hh 2019] and Circular Electron Positron Collider (CEPC) in China [CEPC 2018]. The first stage of any of these proposals is envisaged to be an e^+e^- collider operating at a centre of mass energy (denoted by $\sqrt{s}$) optimized for Higgs production associated with Z or via WW fusion processes. Over a span of 20-25 years, ILC plans to operate at $\sqrt{s}$ = 250 - 1000 GeV and CLIC at $\sqrt{s}$ = 380 - 3000 GeV. The FCC at CERN plans to start as an electron-positron collider (FCC-ee) [Benedikt-ee 2019] at $\sqrt{s} = M_Z$ and increase to $\sqrt{s}$ = 365 GeV (top quark pair production) in 10-15 years, and then upgrade to a hadron collider machine (FCC-hh) [Benedikt-hh 2019] colliding protons at $\sqrt{s}$ = 100 TeV. An electron-hadron mode (FCC-eh), colliding 60 GeV electrons with protons or heavy ions, is also projected to have concurrent operation with the FCC-hh.

Higher energies are easily achievable in circular machines as compared to the linear ones and these offer prospects for measurements with well-defined polarization of the beams. Precision measurements in the Higgs sector allow probing indirect effects due to new particles of masses a few tens of TeV, depending on their coupling strength. The circular colliders offer very strong electroweak, QCD and flavour physics programs at an e^+e^- machine, which is upgradable to a hadron collider, a discovery machine to directly probe the unknown mass scales at unprecedented high energies. Hadron machines are, in fact, indispensable in order to directly access physics phenomena at such high energies.

Hosting a 3 TeV or 14 TeV $\mu^+\mu^-$ collider (μC) in the existing 27 km LHC ring [Accettura 2023] is an interesting proposal for a Higgs factory. The muons are elementary particles and all of the beam energy is available for hard collisions, and hence, it offers a reach in the energy available to produce massive particles that is similar to a 100 TeV hadron collider. However, the short proper lifetime of muons (2.2 μs) makes it challenging to achieve high beam luminosity, and the detector designs also need to be optimized for resultant large beam backgrounds. The muon collider offers unique possibilities for accurately measuring the Higgs line shape given the very small spread in beam energy, and also for measurement of Higgs self-couplings, making a precise determination of the shape of the Higgs potential a real possibility.

The current resources allocated for particle physics experiments imply that only one — or at best two — of the above programs will be realised in the next two decades. However, the long timelines (Fig. 1.6) required to complete these projects (e^+e^- and hh) mean that engagement is required decades in advance to define the physics goals and select the appropriate technologies.

- *Current Status:* At present, the Indian community has been largely invested in the ILC project (and a small group in physics at the $\mu^+\mu^-$collider), which is the most mature of the projects listed above as of now. Phenomenology groups in Ahmedabad, Bengaluru, Cuttack, Delhi, Guwahati, Kolkata, Mumbai and Prayagraj, have worked on various aspects of precision SM measurements and new physics searches. On the experimental front, there have been some detector R&D and physics simulation studies, especially by groups in Delhi and Mumbai. However, as the groups committed to deliver detectors for the HL-LHC upgrade will be freed in a few years, R&D activities for the next generation experiments are foreseen to increase significantly.

- *Human Resource Development:* Apart from the current faculty members across India working on collider-based experiments (around 45), in the coming years we expect the diaspora of recent graduates to return to either join the existing groups or set up new ones. Therefore, the community may grow by 50-100% over the next decade. The current groups are spread across DAE institutes, IITs, IISERs and universities.

  Following the trend of India-CMS and Belle II (Section 2), training and subsequent absorption of young researchers are envisaged. Researchers trained at future collider facilities will further assist technological developments in many fields in ways that are unimaginable and will continue to serve the society in multiple ways.

- *Technology Development:* Thanks to our pursuits with CMS and Belle II collaborations, India has developed indigenous capabilities in scintillator, silicon and GEM-based detector technologies; the latter (GEM) was acquired through the transfer of technology agreement signed with CERN in 2013. In addition, Indian scientists have worked closely with Indian industry partners for electronics readout and data acquisition boards. In the coming decades, we expect much more success in bringing the Indian industries closer to the technologically advanced field of particle physics. This is also crucial in order for the Indian industry to reap the maximum benefit from our current status as an Associate Member of CERN.

- *Funding Requirements:* The start of the ILC is currently expected to be about 13 years from the time of approval by the Japanese government, i.e., around 2035. The CLIC has a similar timeline, whereas FCC-ee would be expected to start a few years later once the HL-HLC program is complete. These timelines nicely complement the Belle II physics program, which would be in the physics harvesting phase from the early 2030s, after the data taking has stopped. In addition, various upgrades of the CMS experiment would have concluded by 2026, freeing up instrumentation expertise to work on future detectors.

  We estimate the capital cost of a future detector for an electron-positron collider to be around Rs. 4000 Cr., i.e., the same as CMS. A 5% contribution to such a detector from India would be approximately Rs. 200 Cr. capital plus another Rs. 200 Cr. revenue. This need will arise only in the 2030s but some seed R&D funding prior to that would be necessary. The estimated resources required over time are (i) Rs. 15 Cr. per year for R&D prior to conceptual design report and for pre-construction R&D during 2026 – 2030 and (ii) Rs. 125 Cr. on construction during 2030 – 2035. In the near future, assured financial support under the R&D head will be vital to invigorate and expand existing efforts and to initiate new ones.

For the muon collider project, a ballpark funding of around Rs. 10 Cr. should be adequate in the initial five years as the collaboration is formed. The funding requirements will evolve at a later stage to a ballpark figure of Rs. 5 Cr. per year depending on how the project evolves and the nature of hardware commitments that can be made.

- **Overall Appraisal:** The existing India-CMS and India-Belle groups have a proven track record in building detector instrumentation, training next-generation physicists and engineers, making leading contributions to scientific publications and playing key roles in the international collaborations. So, they are well poised for undertaking a leading role in future collider facilities. Involvement in these projects will allow India to be a significant player in the future collider program, which should solve some of the outstanding problems in fundamental sciences. Being involved in the R&D from an early stage will enhance the possibilities to engage Indian industry, which will be particularly advantageous for any future CERN-based projects given India's Associate Membership.

  On the other hand, the trained pool is not big enough to participate significantly in more than 2-3 such efforts, if they come up. As it is not certain which projects will ultimately be realised, one needs to initially perform generic detector R&D and physics simulation studies that can be suitably adapted to the chosen project. A further threat to Indian high energy physics is the absence of a concrete proposal for involvement in collider R&D beyond 2025. Such plans must be tabled now, for otherwise India may end up squandering the considerable human resources and industrial linkages built up for the current programmes.

3.2.2 Detectors for Long-lived Particles (FPF/MATHUSLA)

Many BSM models (including dark matter models) propose the existence of particles with ultra-low masses and ultra-long lifetimes, which would decay outside detectors, or particles with very small electric charges (e.g., milli-charged particles), neither of which can be probed easily at the LHC detectors. Hence, several dedicated experiments are being proposed to extend the sensitivity of the current experiments to these long-lived particles (LLPs) and other exotics produced at the main LHC interaction points (Figure 3.1). In fact, two detectors FASER [Feng 2018] and SND [SND 2022], which are placed off-axis on either side of the ATLAS detector, have already made the first direct observations of neutrinos produced in *pp* collisions at the LHC.

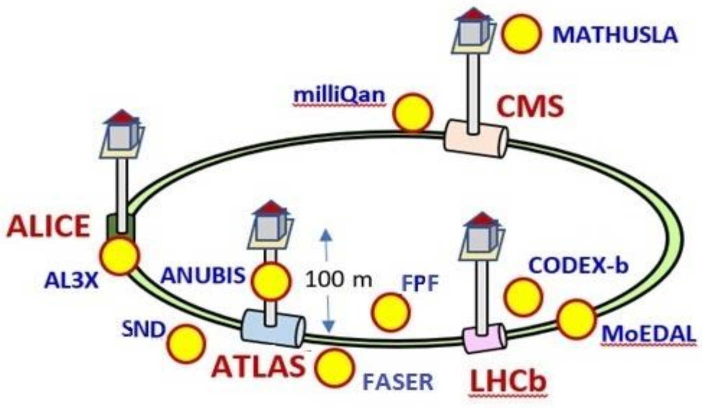


Figure 3.1 Schematic diagram (not to scale) of the LHC ring, showing the major experiments (labelled in red) along with the vertical shafts descending to the ring at a depth of 100 m below the surface. Some of the current/proposed smaller experiments looking for LLPs (yellow circles, labelled in blue) are also indicated.

Further planned experiments include the MATHUSLA surface detector [Alpigiani 2018] for ultra-long lifetimes and the milliQan detector [Ball 2016] for milli-charged particles, both located close to the CMS detector; the ANUBIS [Bauer 2019] close to the ATLAS detector, MoEDAL [Pinfold 2017] for monopole searches and CODEX-b [Aielli 2022] with the LHCb experiment. In addition, there are beam dump experiments like ShiP [Ahdida 2021] at CERN and SeaQuest [SeaQuest 2010] at Fermilab, as well as the proposed Forward Physics Facility (FPF), to be located 617 – 682 metres from the ATLAS interaction point along the beam collision axis [FPF 2022]. The FPF will be shielded by concrete and rock and will host a suite of experiments to probe SM processes and search for BSM physics.

Of the above proposals, the MATHUSLA and the FPF are the experiments where an interest has been shown by the Indian HEP community, and hence the following discussion focuses on these two. However, the other LLP detectors would be similar in essentials, and the same considerations will be relevant for those as well.

MATHUSLA: the MATHUSLA (MAssive Timing Hodoscope for Ultra Stable Neutral pArticle), would be a dedicated large-volume displaced-vertex detector to be placed on the surface at the CMS site [Alpigiani 2018]. This detector can be built using the existing technologies with a reasonable budget, in synchronization with HL-LHC (High Luminosity LHC) upgrade, to search for neutral LLPs without trigger limitations and with very low or zero backgrounds. This allows it to probe LLP cross sections and lifetimes up to several orders of magnitude beyond the reach of CMS and ATLAS. MATHUSLA will also act as a cutting-edge cosmic ray detector exploring many questions in cosmic ray and astroparticle physics. It is a large and robust tracking system monitoring an empty decay volume (100m length x 100m breadth x 20 m height) on the surface to reconstruct LLP decays. It is shielded from the CMS interaction point by more than 100 meters of rock. This project is aimed to start data taking around 2026; the R&D for detector building has already started.

Forward Physics Facility: At present, five experiments are being proposed for the FPF, viz., FASER2, FASERν2, Advanced SND, FLArE and FORMOSA [FPF 2022]. FASER2 will be a large volume detector consisting of a spectrometer, electromagnetic and hadronic calorimeters, veto detectors and a muon detector. The detector is designed for sensitivity to a wide variety of models of BSM physics and for precise muon reconstruction. The Advanced SND project will extend the physics case of the SND@LHC experiment. It will consist of two detectors: one (called FAR) placed in the same range of pseudorapidity η as SND@LHC, i.e., $7.2 < \eta < 8.4$, and the other (called NEAR) in the range $4 < \eta < 5$. FLArE is planned to be a modularized liquid argon time projection detector, the technical design of which is helped by the considerable investment in liquid noble gas detectors over the last decade, such as ICARUS, MicroBooNE, SBND and protoDUNE. A liquid argon detector offers the possibility of precise particle identification and accurate measurements of track angle and kinetic energy over a large dynamic range (from ~ 10 MeV to many hundreds of GeV). Finally, FORMOSA would be a milliQan-type detector designed to search for milli-charged particles at the FPF, but with a significantly larger active area and a more optimal location with respect to the expected milli-charged particle flux.

- *Current Status:* Currently a few Indian institutes/universities, *viz.* NISER-Bhubaneswar and University of Hyderabad, are participating or have shown interest in MATHUSLA. It is a natural choice for these CMS collaborating institutes to participate in such an experiment. In addition, the Indian phenomenology community, many of whom have extensive experience in studies involving LLPs, can play a crucial role by mapping the physics reach of MATHUSLA in various well-motivated new physics scenarios and by providing benchmark points as targets for discovery and exclusion. The Indian participation in the FPF programme is still in a very nascent stage, with only IIT Guwahati being a part of the collaboration currently. However, there is an ongoing effort to involve more institutions from India into the collaboration.
- *Human Resource Development:* As the experiment is in an early stage of planning and is yet to be approved by the CERN Management, it is hoped that more and more CMS (and India-CMS) institutes

will participate in this pursuit. Given that most of the CMS participants from India are in the age group of 40-50 or below, the time-scale of the experiment suits the community very well to take a leadership role. Due to the relative simplicity of this experiment, this will be a great platform for training students and younger physicists for physics measurements across the experiments.

- *Technology Development:* MATHUSLA will primarily be based on scintillators and RPCs. Indian institutes have experience in both detector technologies because of their earlier participation in different experiments such those at the LHC, Tevatron etc. Also, the electronic readouts would be simpler than those at current high-end experiments such as CMS. Therefore, several Indian industries may already possess (or can readily acquire) the capability of designing and building output electronics in addition to building detector components.
- *Funding Requirements:* The MATHUSLA detector cost will depend on the final approved design. However, given that a large part of the decay volume is air, with a few layers of tracking detector and readout electronics along with data acquisition systems, the total expected budget is less than about Rs. 900 Cr., which is small in comparison to most modern-day accelerator-based experiments or neutrino experiments. In fact, an Indian contribution of the order of Rs. 90 Cr. over about a decade would already be a worthwhile investment, which will enable us to play a leading role in the experiment. Similarly, the total estimated cost of the FPF facility (including all five experiments) is about Rs. 1,700 Cr., as per the 2023 cost estimation. Here too, even with a modest 10% contribution, India can play an important role in this emerging experimental program.

  For both the above projects, the requirements for funding at any significant scale would come only after a decade or so. During the interim period, only small grants for R&D would be called for.

- **Overall Appraisal:** The Associate Membership of CERN provides India with a unique opportunity to participate in some of the smaller experiments right from the initial stages and exploit their exciting science potential. Among these options, although very much in the planning stage, MATHUSLA stands out due to its size and potential scientific impact, as well as its technical feasibility and low construction/maintenance costs. As the Indian particle physics community is already working in the CMS experiment and as it includes many researchers having expertise in LLP searches using the CMS detector itself, it is a natural choice for the current India-CMS community to seize this opportunity. This detector does not need any sophisticated construction; thus, from a technical point of view, many institutes within India can easily participate and contribute to each part of the experiment. Nevertheless, the FPF is also an attractive option, and, as shown in Figure 3.1, there are several proposed experiments that will be dedicated to LLP search. The Indian HEP community should be ready to participate in whichever of these experiments finally materializes.

3.2.3 Long-Baseline Neutrino Oscillation Experiment (DUNE)

Deep Underground Neutrino Experiment (DUNE) is an international particle physics experiment [Abi 2020], located in USA, that aims to answer fundamental questions about the neutrinos and the Universe. The experimental facility consists of neutrino beam produced at Fermilab, a near detector (ND) complex located at the Fermilab site, and a far detector (FD) located about 1.5 km underground at the Sanford Underground Research Facility (SURF) in South Dakota, at a distance of 1300 km from Fermilab. The FD will consist of a modular, large, liquid argon time-projection chamber (LArTPC) with a total mass of 70 kiloton. The ND is to be located approximately 600 m from the source of neutrinos, which will be the world's most intense neutrino beam. The ND will consist of several different components: a highly-modular LArTPC, a magnetized gaseous argon time projection chamber (TPC), and a large magnetized beam monitor detector, called SAND.

The primary science objectives of DUNE are to carry out a comprehensive investigation of neutrino oscillations to test CP violation in the lepton sector, determine the neutrino mass ordering and to test the three-neutrino paradigm. By measuring the propagation of neutrinos and antineutrinos through matter independently, DUNE will be able to observe neutrino oscillations with the precision required to determine the CP-violating phase and the neutrino mass ordering.

The Long Baseline Neutrino Facility (LBNF) and DUNE will also support a high-priority ancillary science program, such as precision measurements of neutrino interactions and cross-sections, studies of nuclear effects in such interactions, measurements related to the structure of nucleons, as well as precise tests of the electroweak theory. These measurements of the properties of neutrino interactions are also necessary to achieve the best sensitivities in the long-baseline neutrino oscillation program.

The DUNE far detector, consisting of four LArTPC modules, will offer unique capabilities for addressing non-accelerator physics topics like atmospheric neutrinos, proton decay, astrophysical neutrinos — possibly even the neutrino burst from a core collapse supernova. Further developments in LArTPC technology during the course of the DUNE Far Detector construction may open up the opportunity to observe very low-energy phenomena such as solar neutrinos or even the diffuse supernova neutrino flux.

The LBNF will provide the technical and conventional facilities for a powerful 1.2-MW neutrino beam utilizing the PIP-II upgrade of the Fermilab accelerator complex, which is expected to become operational by 2025, and will be upgradable to 2.4 MW with the proposed PIP-III upgrade. Several Indian institutions and Fermilab are already collaborating on the upgrade of the PIP-II facility through joint development of superconducting radio frequency (SRF) technologies as applied to high-intensity proton linear accelerators.

- *Current Status:* An "Implementing Agreement (IA) between the Department of Energy, USA and the Department of Atomic Energy, India for Cooperation in the area of accelerator and particle detector research and development for Discovery Science" was signed by the above two parties in July 2011. The Implementing Agreement is written under the 2005 "Agreement on Science and Technology Cooperation between USA and India" and serves as an umbrella for the creation of annexes that define the scope of specific cooperative activities.

  Project "Annex I to the IA" provides the formal framework for U.S. and India collaboration on high-intensity superconducting proton accelerators, including the PIP-II project at Fermilab and two accelerators to be constructed in India. This framework covers both the R&D and construction phases of these accelerators, all of which are identified as being based on SRF technologies. Annex I was signed in November 2014 by the U.S. Secretary of Energy and the Chairman, AEC & Secretary, DAE.

  Similarly, Project "Annex II to the IA" was signed in April 2018 to further enhance the collaboration between Fermilab and Indian institutions on INO and DUNE, with matching in-kind contributions to each other's projects of up to USD 10M, respectively. A beginning was already made by Fermilab by contributing, at no cost, extruded plastic scintillator strips made in the Fermilab facility, for an efficient cosmic muon veto detector surrounding the mini-ICAL detector. This will give hands-on experience in operating a large plastic scintillator array that can be used to enhance the capabilities of the ICAL detector.

  There is an ongoing collaboration with Fermilab on the current generation of neutrino experiments, such as NOνA and MINERνA, executed through "Indian Institutions and Fermilab Neutrino Collaboration". Participation in DUNE may be a natural continuation of this.

- *Human Resource:* The current generation of neutrino experiments at Fermilab are expected to wind up their data collection period by the middle of this decade and DUNE is expected to start its operation by 2028-2029 and will continue to collect data at least till 2040. It is expected that for many Indian participants in NOνA or MINERνA, this will be a natural extension of their activities. Currently, the DUNE-India group has about 15 faculty members, three post-doctoral fellows, five Ph.D. students from 10 different institutions. It is envisioned that an additional 50 Ph.D. students would be completing their Ph.D. by 2035, by participating in the hardware, software and GRID computing activities of DUNE.

- *Technology Development:* Project Annex II has already been signed for the participation of Indian physicists in the DUNE experiment. Project Annex II clearly defines the areas of technical and scientific cooperation on DUNE, viz. the development of detector technology like LArTPC components, magnet design and fabrication, detectors for high precision charged particle tracking, electromagnetic and hadronic calorimeters, muon detectors, high performance electronics, high performance computing and high-power particle beam systems.

  Indian participants are already contributing to the development of the Straw Tube Tracking (STT) detector and the development of the external muon detector for the SAND near detector, the design and fabrication of magnets for the LBNF primary beamline, large diameter superconducting magnet and the pressure vessel for one of the near detectors. This may be extended to the development of Resistive Plate Chamber (RPC) detector for external muon detector and readout electronics. There are plans to set up a STT production and testing facility for the production of STT modules for the SAND near detector. A distributed computing site may also be set up as a part of the DUNE worldwide computing GRID infrastructure.

  The above technology development can have many important spinoffs. Boron-coated straws can be effectively used for neutron detection, which may have security applications. The development of magnets may be useful for hadron therapy machines for cancer treatment, for high energy synchrotrons and for future high energy accelerator programmes. It would also provide opportunities for Indian industry to develop infrastructure for large-size superconducting magnets.

- *Funding Requirements:* In the next 5 years of R&D and construction phase, DUNE-India group will require Rs. 35 Cr. for the construction of STT modules in India, Rs. 35 Cr. for the design and construction of the magnet and pressure vessel and Rs. 10 Cr. for setting up the DUNE-INDIA GRID computing site. The average funding requirement for other requirements such as personnel, travel, contingency and consumables is expected to be about Rs. 5 Cr. per annum for the next five years. In total, the requirement is about Rs. 85 Cr. in the next five years. Afterwards, in the O&M phase, it will go down to about Rs. 15 Cr. per year for about 10 years.

- **Overall Appraisal:** The most important strength of the DUNE-INDIA group is the existence of the IIFC-νP collaboration, which is collaborating with the current generation of the neutrino experiments at Fermilab. In addition, since the Govt. of India is already contributing significantly towards the construction of the PIP-II facility at Fermilab that will produce the most intense neutrino beam in the world, India will certainly miss the science discovery potential of the DUNE experiment if we do not participate in the experiment in a big way. Several institutions from India are already actively contributing to the SAND near detector and have made commitments towards the construction of the detector. Since such large international projects function with a definite timeline for various deliverables, any delay in making the resources available for the Indian contribution can jeopardize the project.

3.2.4 Water Cherenkov Neutrino Experiment (Hyper-Kamiokande)

Hyper-Kamiokande (HK) experiment [Abe 2018] will be a 260-kiloton water Cherenkov detector, expected to address fundamental questions related to mass ordering and CP-violation in neutrino sector, proton decay and astrophysical neutrinos. HK is the future upgrade of the long line of Kamioka neutrino detectors, the present one being the Super-Kamiokande (SK). The SK was instrumental in discovering neutrino oscillations, which received the 2015 Nobel Prize in Physics. The HK will be among the most important upcoming experiments in particle & astroparticle physics.

- *Current Status:* The construction of the detector has already started in the Kamioka mine, Japan. The HK collaboration involves about 400 scientists from 19 countries around the globe. Some of the Indian institutes and Universities are already part of this collaboration and planning to contribute significantly in hardware and software development of this project.

  To explore the possibility of Indian groups being willing to contribute to the HK project, the first formal India-HK mini-collaboration meeting was held virtually in August 2020, in which about 160 participants from research institutes like TIFR, IOP, IITs, NITs, and from universities in India, Japan, UK and Canada participated. It was decided that a formal India-HK collaboration be formed, and a joint pan-India Expression of Interest (EOI) be submitted to the HK collaboration on behalf of all Indian participants, highlighting possible contributions in hardware, software and physics analysis. So far around 30 faculty members from various universities and institutions have expressed their willingness to join the HK project.

  In hardware, the contributions of Indian scientists could be in (i) simulation, mechanical and structural studies of the water tank for the Water Cherenkov Test Experiment (WCTE) and Intermediate Water Cherenkov Detector (IWCD), (ii) design and testing of waterproof feedthrough for a CAT5e cable into the photomultiplier tubes in WCTE and IWCD, (iii) designing black sheets to reduce noise due to Cherenkov light reflecting from the stainless-steel structure and tank, and (iv) concept circuit designing and hardware simulation for high-voltage monitoring, and slow control & monitoring. Some of the Indian engineering students have already worked in (i) and (ii) for their M. Tech. projects. At present, attempts are on to find a couple of common facilities for hardware activities, which are accessible to all collaborators, so that available resources may be optimally utilised.

  In software, possible areas are (i) detector response study with GEANT4-based simulations (using WCSim framework) for different upgraded configurations (e.g. gamma-ray background in the detector, response of the 20’ multi-PMT detectors at the active element, etc.) (ii) event reconstruction in HK using Machine Learning techniques (iii) development of software for DAQ and other slow control / monitoring, and (iv) DRS ADC - development of software for readout / testing and debugging.

  A proposal for contributing high energy neutrino event generation has been presented to the HK collaboration. It includes (i) risetime analysis of the supernovae neutrinos for mass ordering, and (ii) simulation of neutrinos at HK with energies of hundreds of GeV to TeV, for different classes of astrophysical objects.

- *Human Resource Development:* Indian members already in the HK Collaboration have committed on an average 40% of FTE (Full Time Equivalent) for a proposed India-HK project. Any new member joining the collaboration will be encouraged to commit 25% or more FTE. Each member will have to present the status of their task to the corresponding working group regularly (at least once every month) over teleconferencing. A three-member advisory board is expected to review the proposal before it is submitted to the funding agency.

The current collaboration includes many engineering institutions like IITG, IITKGP, VIIT, etc., which could play a role in harnessing the large pool of engineers in India for mega projects. VIIT is already participating in the 50-ton WCTE (Water Cherenkov Test Experiment) activity and could help in manufacture and deployment of the mechanical structure at CERN. Engineering colleges are also expected to bring in their connections with, and exposure to, the industrial sector.

- *Funding Requirements:* In the next 5 years of R&D and construction phase, Indian participation in Hyper-Kamiokande will require about Rs. 20 Cr. per year. Afterwards, in the O&M phase, it will go down to about Rs. 15 Cr. per year for the next 5 years.

- **Overall appraisal:** Activities around the India-based Neutrino Observatory (INO) in the last decade have created a substantial human-resource pool in neutrino physics, some of whom will be able to contribute significantly to HK. The median age of faculty members who have expressed interest in HK is about 45, so they could stay associated with this project for more than 15-20 years of their active career. However, a concrete nationwide collaboration is yet to emerge.

3.2.5 Ultra-high Energy Neutrino Telescope (IceCube Gen-2)

Over the last decade, neutrinos have emerged as a new window to the Universe, and thus a thrust area in astroparticle physics, driven primarily by the discoveries of the IceCube Neutrino Observatory in Antarctica. This is a 1 km^3 ice Cherenkov detector for neutrinos with energies of 100 GeV and higher. In the last decade of operation, a diffused flux of astrophysical neutrinos and a few candidate-extragalactic sources have already been identified. Neutrinos with energies more than 10^{15} eV have been observed for the first time, and a blazar has been observed before its indication from optical experiments. The promise of neutrino astronomy is that, while mapping the sky with high-energy sources, it will serve as a unique probe of the mechanisms by which particles are accelerated to the highest energies in the Universe. For this, IceCube-Gen2 [Aartsen 2019], which increases the in-ice instrumented volume by a factor of eight and the energy range by several orders of magnitude by incorporating surface radio arrays, is being planned. It is expected to begin deployment in 2028 and be completed by 2035. It will be a one-of-its-kind detector.

- *Current Status:* Indian activity on this front is still in its inception. The immediate plan is to formally join IceCube while the Gen2 design phase is going on. A preliminary proposal has been submitted, which will provide for computational resources for the design phase, while also enabling the R&D towards assembly, integration and testing of detectors for IceCube Gen2.

- *Human Resource Development:* A collaboration of interested physicists from India needs to be built. Currently the activity has started only in TIFR, with a few faculty members and up to 5 students/postdocs and engineers at any given time.

- *Technology Development:* The GRAPES-3 experiment has proven our capability of making large-area scintillation detectors, with the help of industries around Coimbatore. This capacity can be leveraged and improved, possibly with the help of new commercially available technologies, to be able to provide scintillation detectors with a larger area in large numbers. Additional muon counters may also be set up, which opens up the possibility of having an air shower detector at the South pole.

- *Funding Requirements:* If India joins IceCube-Gen2 collaboration most of the Indian contribution is envisaged to be in-kind, in the form of detector development and computational resources. Depending on the size of the eventual Indian collaboration, and the extent to which it will undertake the activity, this contribution may be about Rs. 20 Cr. during 2025 – 2030 and further about Rs. 100 Cr. during 2030 – 2035 in the construction phase.

- **Overall appraisal:** There is clear synergy with other astroparticle physics experiments within India (e.g., GRAPES-3), from the point of view of multi-messenger astronomy as well as expertise in detector manufacturing. There is also a large community of theorists working on the phenomenological aspects of astrophysical neutrinos. However, delays in starting a new external collaboration could be a major showstopper for the entry of India in this one-of-a-kind experiment, where we should be able to play a prominent role from the very beginning.

3.2.6 Gamma-ray Astrophysics (CTA)

The importance of Cosmic Ray (CR) physics has already been pointed out in Section 2. The current generation of telescopes (H.E.S.S. [Aharonian 2006] in the southern hemisphere and MAGIC [Aleksic 2016] and VERITAS [Weekes 2002] in the northern hemisphere) have made tremendous progress in understanding the nature of CR. The Cherenkov Telescope Array (CTA) is the proposed next-generation ground-based gamma-ray telescope [Bernloehr 2013] which will surpass the sensitivity of earlier telescopes by an order of magnitude. It will consist of a hybrid array of three different types of Cherenkov telescopes, viz. Large Size Telescope (LST, 23 m class), Medium Size Telescopes (MST, 12 m class) and Small Size Telescopes (SST, 3-5 m class) in order to access the wide energy, ranging from 20 GeV to beyond 300 TeV. It will allow the detection of a significantly larger number of sources with high quality spectra and time variation measurements.

- *Current Status:* An International CTA collaboration was established in 2010, and currently it has expanded to participation from institutions in more than 30 countries and more than 1000 scientists. At present, CTA is going through prototyping and pre-production phase where different telescope sub-consortia within the CTA consortium have taken up the responsibility of building different types of telescopes in terms of structure, camera, different front-end electronics, global trigger and array control, etc., in order to demonstrate the feasibility of a mixed array. Soon, it is expected to enter into its construction phase, which will continue till 2030-2032 in a staged manner. At this time, full science operations are expected to begin.

  Several Indian institutes have been participating in the CTA experiment since 2011. Indeed, Hanle was initially proposed to be the northern hemisphere site. Since 2015, SINP and TIFR have been involved in the design and development of a prototype calibration system for the camera of a prototype Large Size Telescope (LST) of CTA. India has been formally invited to be one of the stakeholders of the project.

  The CTA-India Consortium was formed in August 2019 with approximately 30 faculty members and 10 engineers/technicians to facilitate the participation of Indian physicists and engineers in the CTA project. The Consortium set up a 5-member Advisory Board, which reviewed the proposal and gave important feedback, which is currently being implemented. Once finished, the proposal is expected to be submitted to the funding agency. A one-day online workshop on "Science with CTA" was organised by CTA-India Consortium at the 39th Astronomical Society of India meeting in February, 2021, which was attended by about 40 participants. Several talks on ground-based gamma-ray astronomy in India and prospects of scientific cooperation with CTA were delivered by Indian gamma-ray astroparticle physicists and CTA Consortium members.

  The Indian participation in CTA is expected to be in R&D for the detectors, building detector hardware, actual detector operation and in developing analysis pipelines. There is a three-stage plan:

  - An initial period of about 3 years for prototyping and pre-production phase. In this phase, one prototype structure and drive system of a Medium Size Telescope (MST), one calibration system and

R&D of Silicon-PM (SiPM) camera will be undertaken. Additionally, the Indian scientists would like to build a large and scalable data centre (both conventional CPU-based and GPU-based) for running massive simulations and analysis of the early science data.

  - Contributing to various hardware and software activities during the construction phase that would last for about 4 more years. In this phase, exploiting India's expertise in heavy engineering, the construction of structure and drive systems for several MSTs along with calibration systems and SiPM camera for Small Size Telescopes (SSTs) will be taken up.
  - Operations and science observations, physics analyses, interpretation of the data and theoretical modelling over a period of about 15 years.

- *Human Resource Development:* The CTA-India Consortium comprises approximately 30 faculty members and about 8-10 engineers/technicians from about 15 scientific and engineering institutions in the country. At this moment, students (both engineering and physics) and postdocs are not accounted for; this number should increase to about 2-3 per institution, once funding is ensured.

- *Technology Development:* The calibration box for the camera of a prototype LST was designed at SINP, developed and tested at TIFR and later at SINP. Control and access of the calibration box with OPC/UA interface was developed at TIFR.

  The CTA-India Consortium wishes to contribute to the development of a SiPM camera for the Small Size Telescopes (SSTs) of CTA. The SSTs in CTA will be built on the concept of dual mirror technology with SiPM cameras at the foci of the secondary mirrors. In future, there is a strong possibility of technology knowledge transfer especially related to aspheric mirror development of the SSTs. A similar small array of SSTs (either mid-size or small size) can be built at Hanle which would focus on very specific cosmic ray astrophysics problems. Currently, the technology to build imaging telescopes based on dual mirror technology does not exist in the country. Participation in CTA and working with such state-of-the-art systems will enable the Indian groups to gather valuable knowledge and experience to build such challenging telescope systems in India.

  Every hardware contribution to CTA will have to pass a Critical Design Review and satisfy the Requirement and Maintenance Service Document before deliverables are accepted by the CTA-Observatory. Several key components of the telescope which CTA-India wishes to construct and deliver would require very strong participation of industrial partners. The engineering faculty members associated with the project have a wealth of experience to take up this challenge and deliver various subsystem products within the time frame of the project.

  The novel semiconductor photodetectors can find wide applications in other particle physics and astroparticle physics experiments where high granularity scintillators are used. They can also be used in scintillation detection in WIMP searches in dark matter experiments and can find huge applications in Positron Emission Tomography (PET) in medical research.

- *Funding Requirement:* It is envisaged that at least 2-3 engineers and about 7-8 technicians would be entirely dedicated to the project. It is essential to build a large computing centre hosting resources of about 20-30 TeraFlop-year with approximately 1 PetaByte of storage facility for efficiently running Monte Carlo simulations and data analysis and storing the data. Depending on the stage at which India decides to join the experiment, the funding requirement would be anywhere between Rs. 100 Cr. to 175 Cr. over a 10-year period. In fact, an investment around Rs. 20 Cr. for the next 5 years is absolutely necessary to get a foothold in the project.

- **Overall appraisal:** The CTA would be the largest gamma ray detector in the world, made with collaboration and participation of the scientific community in all major nations, quite similar to what is being done at CERN for collider physics experiments. The scientific activities undertaken in the project will help India in maintaining and improving its international standing in the field of TeV gamma-ray astrophysics. Considerable expertise in the area of cosmology, multi-wavelength/ multi-messenger astrophysics, astroparticle physics and particle physics is available in many Indian institutions, with scientists interested in probing important astrophysics and fundamental physics questions through observations of astrophysical sources. The project will give them an opportunity to work with one of the most advanced telescope systems in the world. The CTA-India Consortium has several faculty members from renowned engineering institutions in the country who have got involved in the project at a relatively early stage, and have sufficient knowledge of and exposure to working in collaboration with various international organisations.

  There are strong synergies with several Mega Science astro/astroparticle physics facilities. India is part of SKA, TMT and LIGO, and has complementary interests in the proposed direct detection dark matter experiments and dark matter searches at the colliders (LHC). Once operational, the MACE experiment at Hanle can indeed act as a pathfinder in India to CTA by building up and training a vigorous community of users who would be ready to contribute to the development of data analysis tools and also use the data coming from CTA in future.

  Since large international projects like CTA function with a definite timeline for various deliverables and CTA is expected to enter into Phase-I of the construction phase by summer 2025-26, any delays in decision-making can jeopardize Indian participation in the project.

3.2.7 Ultra-high Energy Gamma Rays (SWGO)

The ground-based gamma ray detectors HAWC [Abeysekara 2017] and ARGO [Bartoli 2015] have demonstrated the scientific potential of a wide field-of-view and a very high duty cycle in gamma-ray astronomy. This potential is being exploited in the northern hemisphere by LHAASO [Amenomori 2009], which recently detected a number of beyond-100 TeV sources. Currently, no such instrument exists in the southern hemisphere. The availability of gamma-ray telescopes in both hemispheres will provide access to the full sky for observing transient and variable multi-wavelength and multi-messenger phenomena. The southern hemisphere will be a perfect place to make deeper probes into our galaxy as the whole galactic plane is visible from the south. A very large array of particle detectors, such as the proposed Southern Wide-field Gamma-ray Observatory (SWGO) [Albert 2019], will be well suited to perform observations at and above a few tens of TeV to PeV energies complementing the ongoing installations/ observations in the northern hemisphere. Additional studies like cosmic ray anisotropy and the follow-up of several transient phenomena as potential electromagnetic counterparts to neutrinos detected by ANTARES, IceCube and upcoming KM3Net will be of prime importance for this array.

- *Current Status:* On July 1, 2019, thirty-nine research institutions from nine countries, viz. Argentina, Brazil, Czech Republic, Germany, Italy, Mexico, Portugal, the United Kingdom and the United States of America signed an agreement for the creation of a new international R&D collaboration for the SWGO. The aim of the collaboration is to develop a detailed proposal for the implementation of such an observatory, including site selection and technology choices.

- *Technology Development:* This is still at the inception stage but such an array can be built using scintillator detectors and water Cherenkov detectors, possibly with muon counters. They can be quite cheap and robust and can be built in a relatively short time.

- *Funding Requirements:* The funding for such an array is expected to be modest and the technical knowhow to build such an array exists within the country.

- **Overall Appraisal:** Indian expertise in cosmic-ray experiments is a point of enormous strength. Fruitful collaboration with international partners will be of immense benefit for the project and also building the ecosystem in the country. Finding a suitable site in the southern hemisphere for such an array has been undertaken by astroparticle physicists in several institutions all over the world (primarily USA, Brazil, Argentina, Germany and Italy). India can play a very important role in the design and development of such an array in the South and has the capability to lead this effort in the world.

3.2.8 Direct Search for Dark Matter (SuperCDMS)

The SuperCDMS [Agnese 2018] is a planned deep underground experiment for direct detection of dark matter. It is designed to be sensitive to WIMPs of masses of a few GeV which result in very small nuclear recoil signal, which is quite hard to differentiate from backgrounds. Typical nuclear recoil energies are $1-100$ keV for WIMP mass ranging from $1-1000$ GeV. The CDMS low ionization threshold experiment (CDMSlite) [Agnese2 2018] at the Soudan Mine in Minnesota, USA has already opened up a yet-unexplored low-mass parameter space (< 10 GeV). Building on this success, SuperCDMS is preparing for the next phase of the experiment, with a provision of up to ~200 kg of target mass, to be located at SNOLAB near Sudbury, Ontario.

- *Current Status:* The Indian efforts are presently led by the group at NISER Bhubaneswar in close collaboration with the Texas A&M group, USA (both parts of the SuperCDMS Collaboration). Currently, from the Indian side, about 7 PhD students, postdoctoral fellows and scientists all below the age of 50 years are involved. There are many opportunities for building collaborations with other Indian groups, and this is being explored. The discovery of DM candidates is one of the key open questions in science, it is important that there is Indian participation in this area of fundamental science.

- *Human Resource Development:* SuperCDMS was selected as one of the next-generation (G2) direct dark matter search experiments by the funding agency in the USA in the year 2014. Prototype detectors have been produced and tested successfully. The production of the final detector, which will operate at 15 mK temperatures, is in an advanced phase. Concurrently, testing, installation and setting up of the experiment at the site are going on. The science run is scheduled to take place in the years 2025-2030. To make it a feasible endeavour, it will require an involvement of 10 full-time equivalent scientists to begin with. With multiple institutions in India joining the effort, the number of participants will easily grow to 50. The experiment brings a concrete platform to train young students not only on fundamental physics measurements but also in novel detection techniques related to solid state physics. Hence, the trained person power generated via this program could be the key leaders of the next generation of direct dark matter detection experiments.

- *Technology Development:* The challenges involved in such very sensitive detectors require continuous and evolving R&D for (i) reducing the recoil energy threshold including improved phonon energy resolution; (ii) extending signal-to background discrimination to lower recoil energy; and (iii) reducing dark counts by the reduction of ionization leakage at high bias voltages. These goals require improvements in phonon-mediated signal detection over a wide range of voltages in monolithic Si detectors which should be scalable for mass production. The industries, therefore, could be involved from the initial phases of R&D till the final delivery of these novel detection systems.

- *Funding Requirements:* Typical hardware resources required for an experimental setup for such a rare event search using cryogenic semiconductor detectors needs a dilution fridge, SQUIDS, shielding material (borated rubber, lead and water) and 64-channel digitizer. Along with the detector and fabrication costs, the full setup may require up to Rs. 15 Cr.

- **Overall appraisal:** Preparations for the SuperCDMS experiment is in an advanced stage, built on the successful completion of earlier phases, viz. the CDMS and CDMSlite experiments. This is the leading experiment to search for WIMP dark matter candidates of masses below a few GeV. Undoubtedly, SuperCDMS will be one of the most important and crucial experiments given its size and remarkable sensitivity to low mass dark matter candidates. Given that the community has the experience of building sophisticated detection systems and analysing data, many institutes within India can easily participate and contribute to various aspects of the experiment.

  The facility-specific backgrounds for nuclear recoil are of the order of $2 - 3x10^{-3}$ /kg/keV/yr and those for the electron recoils are of the order of $25 - 100$ /kg/keV/yr. The experiment expects to be limited by higher backgrounds from cosmogenic activation. Depending on the observation of a dark matter signal or the lack thereof, the experiment will upgrade to enhance the signal over background or attempt to increase sensitivity to masses as low as 0.05 GeV. Hence, any investments made in coming years in terms of experimental developments actually promise long-term benefits and returns.

3.2.9 Search for Axions and Axion-like Particles (GNOME, ADMX)

The QCD axion was first proposed by Peccei and Quinn in 1977 to solve the strong CP problem [Peccei 1977, Kim 2008]. Even beyond the strong CP problem, various extensions of the Standard Model, such as the extra dimensional theories, generically predict such particles, often called Axion Like Particles (ALPs) in the literature [Marsh 2015, Choi 2020]. It was later realized that ALPs can also be candidates for Dark Matter (DM) in our Universe. Interaction of axions with usual matter is predominantly via their coupling to two photons. Unfortunately, since ALPs generically have very weak interactions with the SM particles, their experimental detection is challenging. A huge amount of effort is being made towards their experimental discovery at colliders and in neutrino experiments at reactors. Direct detection experiments using helioscopes and haloscopes such as the CERN Axion Solar Telescope (CAST), Tokyo Axion Helioscope (SMICO) and ADMX are in progress. Indirect inferences about axion masses and couplings can also be obtained from astrophysical observations via measurements of photons or energy loss rates. On a smaller scale, table-top experiments can also probe coupling of (virtual) axions that influence spectroscopic observables in atomic physics. However, the required scale and/or technical complexity of experiments is very high in all these approaches.

- *Current Status:* There is an interest building up in the Indian community to participate in the ongoing international projects, and also develop in-house capabilities. A group at IIT-Tirupati is officially a part of the GNOME (Global Network of Optical Magnetometers for Exotic Physics) Collaboration [Afach 2023], which is a set of synchronized and connected nodes searching for correlated signals of a transient clump of axions passing through their optical magnetometers. On a short time-scale (1-3 years), one can aim to build an indigenous detector that forms a node of a global network like GNOME, while carrying out research and development for newer standalone detectors, e.g., using precision atomic spectroscopy, eventually leading to a precision physics facility. One can also think of delivering a key technology for a project like ADMX (Axion Dark Matter eXperiment) [Khatiwada 2021], for example quantum-noise mitigating measurement protocols and devices. The other option in India would be to use precision atomic spectroscopy to identify new forces mediated by axions, and probe nuclear effects on variation of electronic transition energies, *i.e.*, the isotope shifts. For lower axion masses, the required technologies involving improvements in magnets and cavity etc. will allow a probe of axion masses as low as 0.2 micro-eV.

- *Technology Development:* For GNOME and the atomic physics-based experiments, there will be development of technologies like atomic clocks, useful for better physical standards, navigation, communications, etc. For ADMX, there is an overlap with techniques used in quantum computing, in particular quantum noise defeating technologies. The aims align with the goals of the National Quantum Mission (NQM) of India [NQM 2024], and it can be expected to bring rich strategic and commercial dividends in a field that is believed to hold tremendous promise.

- *Funding Requirements:* Participating in GNOME with an in-house node of global network may need a modest investment of around Rs. 10-12 Cr. over a period of 10 years. The resources required for methods based on quantum technologies will need a dedicated facility and may need investments, similar to that of a cutting-edge quantum computing laboratory.

- **Overall Appraisal:** With progress on quantum technology research across the country, enough expertise could be built here to take a lead in international projects and pave the way for indigenous large-scale and high-technology efforts, which will also benefit NQM immensely.

The 9 possible future projects described above (3.2.1-3.2.2 in collider physics, 3.2.3-3.2.5 in neutrino physics and 3.2.6-3.2.9 in astroparticle physics) are international ones that will be taking place independent of Indian participation. Which of these collaborations actually work out will depend upon a number of other factors, like availability of necessary resources, details of collaboration and a well-thought-out cost-benefit analysis. It would be up to us to decide where our participation will be significant, and also bring us dividends in terms of science, technology, training and the opportunity to do cutting-edge research in frontier areas to address fundamental questions. At the same time, it must also be added that the participation in some of the above experiments should not be seen as a replacement for setting up a major national facility / experiment such as an underground laboratory of the kind described in section 4.4.3. A judicious mix of national as well as international programmes is the call of the hour.

3.3 Opportunities for India-based Projects

Never lose your faith in the destiny of India.
– Subhas Chandra Bose

Thus far, we have mostly discussed large-scale HEP projects based in foreign countries where India can be a significant partner. We do have the potential as a nation to initiate our own HEP projects (the initial progress of INO is already an example). For building a large-scale accelerator, the financial constraints might be insurmountable, but building the detectors should not be that formidable a challenge. In this Section, we will list a few such detector-based projects, which can be completely indigenous, on all three fronts of R&D, personnel and industry-linkage. However, the importance of having international participation, even for such projects, cannot be overemphasized.

Fundamentally, India has no dearth of interested and competent human resource. However, many of our HEP experimentalists now choose to settle abroad to pursue their careers — a trend which needs to be reversed for the enhanced growth of HEP activities in India. This can be achieved if and *only* if we have our own experiments, a model successfully followed by Japan and China. We also have to keep in mind the unfortunate situation in India where only a tiny fraction of the student population gets the opportunity to be acquainted with large-scale science.

Once these proposed HEP experiments start, this brain drain may be expected to partially taper off as our highly competent younger generation will then find satisfying and challenging opportunities even in India. The interested undergraduate students will also get a chance to have hands-on training on exciting experiments. This will motivate them further, leading to positive feedback and ultimately enriching our pool of top-level scientific personnel. Such training can also benefit the budding experimentalists from other developing countries, and give India a bigger leadership role.

In India, dark matter detection experiments have already been initiated, and the seeds have been sown for neutrinoless double beta decay (NDBD) experiments, while satellite-based HEP experiments, as well as low-energy solar neutrino detection experiments are being discussed. These experiments do not require a large budget, and we do have some young and competent people who could take these ideas forward. Most of these ideas have a lot in common with the areas covered by other Mega Science groups, and that is how it should be — an interdisciplinary effort. While we may not have enough people to start all these projects within a year or two, they must be kept in focus for a somewhat longer-term vision, since we expect more and more young people entering the field in the years to come.

One must not also discard so-called wild or crazy ideas, i.e., ideas that no one has probably thought of till now, and which are therefore not part of any such vision document. The lead can come from the experimentalists (like the discovery of neutrino oscillations), or from the theoreticians (like the prediction of the neutral current, or the charm quark), but history tells us that this can be completely unexpected, and therefore, we must not be caught napping. In fact, a timely start can make us a leader on the global front. The Mega Science Vision allows for such unexpected breakthroughs.

One must also take into account the benefits reaped from industrial linkage. First, industries that can cater to such precision experiments will be either set-up, or upgraded, and that will be a benefit on the global scale. While we have to depend a lot now on importing sophisticated instruments, the situation can significantly improve if proper impetus is provided by the Government. Second, the R&D section of these industries can absorb many HEP-trained personnel, which is a pretty regular phenomenon in western countries, and this will prove profitable for both the industries and the experiments.

We now provide brief sketches of some of the proposed India-based experiments which should be kept in focus during the next 15 years. Not all of them are as yet out of the drawing board stage, so this document is providing only the scientific importance of those projects.

3.3.1 Direct Dark Matter Search Experiments (JUSL/InDEx)

As explained earlier, the direct and the indirect searches for the dark matter candidates, the WIMPs, have made very significant progress across various terrestrial, underground and space-based experiments. However, a large phase space concerning low mass (few GeV) WIMPs is yet unexplored. The InDEx (Indian Dark matter search Experiment) is a nascent experiment in India for direct detection of such WIMP dark matter candidates in the less-explored low mass region. It is envisaged to be eventually set up in a deep underground laboratory, where, with an active target detector mass of a tonne, InDEx would be sensitive to dark matter particles in a wide mass range of a few GeV to a few hundred GeV. This will provide a platform for competing with the present and future experiments worldwide.

The superheated liquid detector (SLD) technique is one of the proven technologies being used for experimental efforts towards direct detection of WIMPs. Low detection threshold, sensitivity to low mass WIMPs, interchangeability of the target fluid, operation without cryogenics, intrinsic background rejection capability and complementarity to the physics capabilities of other dark matter search experiments, make SLD technology unique in the field of WIMP direct detection experiments. An alternative proposal is to use a suitable scintillator or semiconductor material. This simultaneous information could help to substantially increase the significance of a WIMP signal against the background.

- *Current Status:*

The SINP group has initiated a low mass (< 20 GeV) WIMP dark matter search experiment in the Jaduguda Underground Science Laboratory (JUSL), located at the Jaduguda mines of the Uranium Corporation of India (UCIL), at a depth of 555 metres underground [JUSL 2024]. This may be considered as the first phase of InDEx. Currently the experiment is taking data with two 500 ml detectors fabricated at SINP using the superheated liquid detector (SLD) technique. In future, more detectors are envisaged to be added to this set-up, which is expected to bring down the operating threshold of the experiment and enable the probing of lower dark matter masses.

Significant R&D work towards this goal has been undertaken at SINP, VECC and NISER, where prototype detector fabrication, instrumentation, DAQ and calibration experiments have been performed. Along with it, studies of background rejection through shielding of the active detector volume are also being carried out. A test run was carried out during September 2019 with a small SLD fabricated at SINP. A small prototype setup using scintillators was used to measure the cosmic muon flux as well as the gamma ray and radon backgrounds present in the underground laboratory [Ghosh 2022]. Systematic investigations into detector performance and response including simulation will be conducted in the near future, and the detailed design of the next generation detectors will be developed. In parallel, the underground physics program will run with operating detectors that will collect valuable physics data and will allow the detector technology to be further refined. The ultimate goal is to build a large-scale low background detector with low threshold sensitivity that will probe the phase space for low-mass dark matter interactions.

The expected sensitivity of one of such low-mass targets, namely, liquid $C_2H_2F_4$, has been estimated for 1000 kg-day of exposure with zero background, and the results show that $C_2H_2F_4$ has the potentiality to probe the sub-GeV WIMP mass region if operated at a low threshold. The investigations for optimizing the scintillating material for phonon detection, and hence developing a strategy for cryogenic experiment, are also going on. Once these technologies are refined for the operation of the detector at very low threshold, the same detector can, in principle, be suitably modified in future to detect the possible DM-induced electron recoils and to make the detector sensitive to axions. The SLD technology can, in principle, also be used for the detection of supernova neutrinos through the process of coherent elastic neutrino-nucleus scattering.

As mentioned earlier, one could also utilise other technologies like scintillators and semiconductor detectors. The semiconductor detectors can provide very low recoil energy thresholds enabling dark matter search in the low-mass region, which has so far remained unexplored. Simulation studies have been performed by NISER together with SINP to estimate the muon and neutron backgrounds inside the cavern. They show that the background levels at JUSL (depth of ~555 metres) are comparable to that of existing dark matter experiments worldwide. Initial sensitivity estimates considering neutron-only background suggest that a dark matter experiment is indeed feasible at JUSL.

A small-scale underground laboratory has been set up at JUSL with a plan to expand it further as the experiment moves towards larger mass. The cosmic ray background will be lower when the experiment shifts to a location that is deeper underground, in its next phases. The sensitivity will also improve by lowering the intrinsic backgrounds and scaling up the size of the active mass of the detector.

- *Human Resource Development:* At present, research groups from SINP, VECC and UCIL are involved in the experiment using the SLD technology. The JUSL group has already organized national level meetings both at SINP and UCIL with different organizations in India. It is planned to have reviews of the activities and future directions in this regard with national and international experts. A large number of graduate and undergraduate students are expected to participate in the hardware and simulation studies, and gain experience in carrying out an experiment starting from its conceptualization stage.
- *Technology Development:* The SLDs can also be used as high accuracy neutron dosimeters for neutron monitoring at various accelerator sites and for environmental radiation monitoring. This kind of detector can also potentially be used for neutron monitoring in cancer radiation therapy. It should be noted that such an experiment involves interdisciplinary efforts across several areas of experimental physics including particle physics, nuclear physics, condensed matter physics and low-temperature physics.
- *Funding Requirements:* The major budget consists of the R&D activities at the laboratories, infrastructure setup at JUSL, and technical personnel (scientific officers and engineers) to operate the experiment. A total expenditure of Rs. 75 Cr. is projected during 2025 – 35 out of which some may be used for infrastructure development at JUSL for expansion at a depth of 555 metres and followed by a laboratory setup at 880 metres. Moreover, the development of an underground clean room of class 10,000 of approximate dimensions 50 ft x 50 ft x 10 ft would also be needed in this time scale.
- **Overall appraisal:** The SINP group has already been successfully participating and usefully contributing to the international collaboration, PICASSO/PICO (using SLD technology to search for WIMP DM candidates) at SNOLab since 2009. Several Indian groups are experienced in developing scintillation-based experiments as well as in readouts of low strength signals. The group's strength lies in detector fabrication, simulation, detector characterization and data analysis. On the other hand, NISER has been an active member of the SuperCDMS and MINER collaborations. It has been involved in the development of large-mass low-threshold semiconductor detectors for dark matter and rare event searches. Currently, the main hindrance is the lack of enough dedicated human resource for running the DM search activities at JUSL.

3.3.2 Quantum Sensors for High Energy Physics Applications

In addition to the high energy and intensity frontiers in terrestrial experiments, there is also another frontier of sorts, and that is the so-called *precision frontier*. Closely related to the intensity frontier, it involves making measurements at unprecedented levels of accuracy. For this, one approach that is rapidly gaining traction is where devices are engineered that exploit the extreme sensitivity of quantum mechanical phenomena — referred to as quantum sensors [Schneider 2021]. Such an approach can be complementary to current approaches in high energy colliders and other experiments, for example large-scale detectors that search for the existence of dark matter of particle origin, or look for Axion Like Particles (ALPs) in those regions of phase space which can only be tackled efficiently using the novel properties of quantum sensors. There is also a wider-use case of quantum sensors, which can significantly improve the capabilities of instrumentation by augmenting existing timing detectors and calorimeters used primarily in, but not limited to, particle physics experiments. This would be in sync with the goals of the National Quantum Mission (NQM) of India [NQM 2024].

Some of the promising quantum sensor platforms include superconducting devices such as Superconducting Quantum Interference Devices (SQUIDs), Transition Edge Sensors (TES) and Superconducting Nanowire

Single-Photon Detectors (SNSPDs) as well as 0-, 1- or 2-dimensional Metamaterials. In beam dump experiments at future colliders and haloscopes that search for axions, the two classes of quantum sensors that hold the most promise are superconducting devices (particularly SNSPDs) and metamaterials (particularly perovskite nano-crystals and quantum dot-based scintillators).

- *Current status:* Over the last two decades SNSPD based detectors have demonstrated high (~98%) system detection efficiencies to single photons, extremely low (6×10^{-6} counts per second) dark count rates, a temporal resolution of better than 3 ps and very high (~ 1 Giga counts per second) event rates, and have been fabricated into large-sized (~ 500 kpixels) arrays. While these best-in-class characteristics have been demonstrated for SNSPDs till date there is no device that has shown to have all these properties simultaneously, which makes it an open field of research. The BREAD Collaboration [Liu 2022] has proposed to use a SNSPD-based haloscope to search for axions in the mass range 1 meV to 1 eV. Similar SNSPD-based detector platforms that can tackle masses ~10 to 100 eVs have been proposed for the "light-shining-through-wall" class of ALPs detection experiment. Several particle physics groups are already organizing themselves into international collaborations to study some of the above technologies. Some of their plans and programmes may be found in the ECFA detector R&D roadmap [ECFA 2021] and in the Snowmass 2021 report [Snowmass 2021].

  A new international collaboration named RDq, anchored at CERN, is being formed to break down the R&D activities of different classes of quantum sensors into distinct work packages so that groups from across the world can participate. From India, IISc, RRI and TIFR have been represented during the planning phase of this collaboration.

- *Technology Development:* Any quantum detector would need fast timing resolution (better than 30 ps), high radiation tolerance (better than 20 MRads) and a high detection efficiency for photons as well as charged particles. Another requirement to mainstream these detector classes is to enhance the operating temperature to beyond liquid Helium temperatures (> 4K) so that relatively more cost-effective closed cycle cryostats can be utilized. This requires fabricating and characterizing SNSPDs from high T_c materials, such as bismuth-strontium-calcium-copper oxide (BSCCO)-based nanowires. These detectors have to be scaled up from their current sizes of tens of microns per pixel to several cm with thousands of pixels and dedicated front-end electronics also needs to be developed. Commercial off-the shelf electronics based on Radio Frequency-System On Chips (RF-SOC) has been customized for such applications.

- *Human Resource Development:* The superconducting quantum sensor class of detectors inherently requires interdisciplinary expertise in device fabrication, cryogenics, setting up test stands to qualify the sensor, designing the readout electronics and finally scaling up to meet the requirements of the current state-of-the-art in particle physics instrumentation and experiments. Additionally, irradiation and beam test facilities are also needed for ensuring that the detectors meet the requirements of particular experiments. Fortunately, such expertise is already available in India, spread across condensed matter/materials science, high energy physics and nuclear physics departments. In fact, the nanoelectronics group at TIFR has in the recent past grown nanowires with the BSCCO material. Hence, by forming cross-disciplinary working groups, rapid progress can be made in setting up small-scale experiments. Subsequently, the scaling-up challenge will require getting a critical mass of scientists interested in this class of detectors.

- *Funding Requirements:* To initiate a programme for fabrication and characterization of SNSPDs, funding of around Rs. 2 Cr. is needed to set up a cryogenic test stand that can go down to 3 K and to develop the readout electronics. Once this initial fabrication and characterization chain is demonstrated, the next target, viz. scaling up both the detector and the readout to the size of a repeatable unit/detector module of a haloscope scale of experiment, would require around Rs. 15 Cr. over a period of 5 years. In the final step to carry out the systems engineering of a haloscope-class experiment, an additional Rs. 35 Cr. would be needed over another 5-year period, provided a cosmic background-free underground laboratory is already available.

- **Overall appraisal:** Quantum sensors, with their extreme sensitivity, hold the promise to upstage contemporary HEP detectors by making it possible to achieve in a 'tabletop' detector what would have otherwise required a much larger apparatus. This field, in terms of applications in HEP, is relatively nascent, as a result of which significant intellectual contributions can be made in India even with device characterisation test stands. In order to get started in this direction with different materials, sufficient expertise already exists in India. However, in order to achieve our ultimate goal of an end-to-end HEP experiment using this technology platform, we need to get more scientists interested in this area and secure adequate funding over the next 10 years. Participation of Indian scientists in the RDq Collaboration would secure benefits from the CERN-India knowledge transfer in the fields of advanced quantum materials, cryogenic readout electronics, etc. and also permit the use of beam test facilities at CERN to characterise India-made detectors.

3.3.3 Testing Violations of Global Symmetries

Neutrino physics involves both nuclear physics and high energy physics. The topics like neutrinoless double beta decay, reactor neutrino monitoring, sterile neutrino search, low energy solar neutrino physics, and neutrino-nucleus interactions, are of crucial importance and interest to high energy physics. However, the knowledge of nuclear structure and spectroscopy, as well as the experimental techniques needed, need the expertise of the nuclear physics community. Therefore, it is envisaged that these projects will be led and executed by nuclear physicists, and therefore are treated in greater detail in the MSV-2035 Nuclear Physics Report [MSV-2035-NP].

- **Neutrinoless Double Beta Decay:** The origin of neutrino masses is a fundamental question, the answer to which is unknown so far. One of the important steps in this quest is to determine whether neutrinos are Majorana or Dirac particles, that is, if they are their own antiparticles or not. The only concrete, feasible and unambiguous way of determining this is to look for a neutrinoless double beta decay (NDBD) reaction in any nucleus. Such a reaction can only occur if neutrinos are Majorana particles. There are more than a dozen experiments worldwide, using different nuclei and different techniques, which are trying to reduce their background to levels where such a process may be observed. The lack of knowledge of the values of relevant nuclear matrix elements makes it difficult to predict which nuclei will be able to show the first evidence of such a decay.

  An Indian experiment to explore NDBD in the tin isotope Sn-124 (Tin.Tin) has been proposed. For this, a custom-built cryogen-free dilution refrigerator, having a large cooling power of 1.4 mW at 120 mK, has been installed at TIFR. A low background counting setup, TiLES, with a high efficiency, low background HPGe detector has also been set up, which is shielded with inner 5 cm low activity OFHC Cu, outer 10 cm low activity Pb, a radon exclusion box, and plastic scintillators for an active veto system. The sensitivity of the setup has been obtained to be ~1 mBq/g for Th-232 and ~2 mBq/g for K-40. The actual experiment will need to be located underground, with about a kilometre of rock coverage on all sides.

The Tin.Tin collaboration currently involves around 15 faculty members from TIFR, BARC, VECC, PRL, IIT-Kharagpur, IIT-Ropar, and University of Lucknow. More than 10 students and postdocs have already worked on various aspects of the experiment, and will be prospective members of the collaboration when it grows to a larger size.

- **Search for Sterile Neutrinos:** There are three species of active neutrinos in the Standard Model – electron neutrino, muon neutrino and tau neutrino. However, the presence of one more light neutrino, which does not interact via weak interactions but mixes with the active neutrinos, has not been ruled out. These sterile neutrinos, of masses ~eV, may explain some of the anomalies at accelerator experiments like LSND or MiniBooNE. They may also help in accounting for the formation of supermassive stars and may form part of the dark matter. Since sterile neutrinos with eV masses lead to neutrino oscillations at very short distances, experiments to look for sterile neutrinos are set up close to nuclear reactors or as near detectors in long-baseline experiments.

  Scintillation detectors set up close to nuclear reactors (at 10-100 m from the core) would be able to measure the deficit in the expected number of electron antineutrinos produced in the reactors, and hence the extent of their oscillations into sterile neutrinos. Multiple detectors at different distances would give us better control over the measurements of neutrino masses and mixing. The same setup would also be useful for monitoring of reactor antineutrinos. The project, called the Indian Scintillator array for Monitoring Reactor ANtineutrinos (ISMRAN), has already started in BARC, and a prototype setup has already been designed.

- **Electric Dipole Moments:** Electric dipole moment (EDM) of an electron would be a result of parity (P) or time-reversal (T) violating interactions. Though these discrete symmetries are broken by weak interactions, the values of EDMs predicted in the SM are orders of magnitude smaller than the current upper bounds determined experimentally. Certain extensions of the SM predict higher EDMs, and these could be tested by future experiments trying to measure this quantity very precisely. These indirect tests of the SM, though in principle unable to identify the underlying fundamental theory, are sensitive to physics at a much higher energy scale than that accessible at colliders.

  An atom or a molecule could also possess an EDM due to the possible existence of (i) the electron EDM, (ii) P and T violating (P, T-odd) electron-nucleus interactions, and (iii) the hadronic CP violation. Limits on electron EDM can also be obtained by measurements on atomic or molecular systems like the paramagnetic Tl atom or diamagnetic Hg-199 atom. Precise calculations of these atomic or molecular environments, that use the state-of-the-art relativistic many-body methods, have been undertaken by some Indian groups. Expertise on such many-body theory calculations is currently available at IISER-Kolkata, IIT Kharagpur, Guru Nanak Dev University, Amritsar and IIT Delhi. However extensive computational facilities needed for this may need a funding of about Rs. 20 Cr. over the next 15 years.

  On the experimental front, there is some interest in the search for electron EDM in cold polar molecules, from experimentalists in IIT Delhi. A coordinated multi-institution collaboration is yet to be developed.

3.3.4 Low Energy Solar Neutrinos

With the solar neutrino problem now having a consistent resolution through neutrino oscillations, further neutrino observations focusing on specific aspects of solar neutrino would enrich our knowledge of the interior of the Sun. For example, the standard solar model predicts a line spectrum of Be-7 electron capture neutrinos. Such a line spectrum cannot be observed at any of the current neutrino detectors like Borexino or JUNO, since they are based on Compton scattering where the electron carries only an unknown fraction of the neutrino energy in each interaction.

- **An Indium-based Detector:** An Indium-based low energy electron neutrino detector could measure, in real time, solar neutrinos using the charged current interaction with a "peak" response to Be-7 neutrinos. Apart from an accurate measurement of the solar neutrino spectrum at low energies, it could be the first one to directly measure the temperature at the core of the Sun, by determining the width of the Be-7 spectral line.
  - *Current Status:* While such a detector was envisaged in 1976, it poses many challenges, including the reduction of background from the radioactivity occurring in In-115 itself. However, these appear to be surmountable. In fact, a small prototype had been successfully built in the shallow Kimbleton mine in the US. There does not seem to be any international progress on this front in the recent past.
  - *Technology Development:* The Indium detector could be based on In-doped liquid scintillator (LS) at ~10% or a cryogenic In-bolometer. It could be built at a depth of 500-1000 m. Expertise exists at Virginia Tech and BNL (USA) on metal-doped LS including water soluble LS, and a collaboration to help develop this technology in Indian industry is possible. Development of a very different approach using quasiparticles in a superconductor of Indium is also possible, at a Facility like the proposed INFHEP (see chapter 5.4).
  - *Funding Requirements:* The estimated budget would be about Rs. 250 Cr. for the In-LS detector and about Rs. 500 Cr. for a cryogenic In detector. For R&D and prototype construction, one would need about 15% of the above costs, plus about 2 faculty + 5 technical staff assuming an appropriate eco-system already in place.
  - **Overall appraisal:** The technologies of liquid scintillator, metal loaded liquid scintillators, cryogenic detectors and LAPSD will find wide application in many other areas such as security, low noise electronics and photon counting. Since nobody has built such a detector(s) before, it will not only be one-of-its-kind in the world, but will also produce frontier science. A conscious effort to build as much of the cryogenics as possible in India will also help in other areas such as SQUID arrays for medical research and diagnostic applications and quantum computers.
- **Deuterated Liquid Scintillator***:* The status of India as the largest producer of heavy water in the world may be leveraged to construct a deuterated liquid scintillator detector. Such a detector would have all the advantages of having a deuterium nucleus instead of hydrogen, which were used in the Sudbury Neutrino Observatory (SNO) experiment that put to rest the long-standing solar neutrino problem. Moreover, the scintillator would allow the reduction of the detector threshold to about 200 keV from 5 MeV. This opens up the possibility of measuring the "survival" probability of electron neutrinos from the Sun's core as a function of neutrino energy very precisely.
  - A precise measurement over an energy range from about 3 MeV to 8 MeV would test the current paradigm of matter effects in the sun quite stringently, and also throw light on alternate non-standard scenarios in a matter of a few years of measurement. Such a 1 kt detector located at a suitable site with a rock overburden of at least 1 km, preferably larger, could also measure the day-night effect (a near-equatorial site in India would be a major advantage), and provide a unique measurement of Supernova neutrinos (should we get lucky). It must be emphasized that a DLS detector can measure both electron neutrinos and antineutrinos through the charged current interaction (due to the presence of both the proton and the neutron in deuterium), as well as the

sum of all types of neutrinos and antineutrinos irrespective of their flavour, through the neutral current process.

– As a first stage of the above project, a prototype 1–5-ton detector would need to be developed. This could be gainfully deployed at a nuclear power reactor *on the surface* to remotely monitor the reactor. A new detector facility with such a novel detection technique could form the basis of a leading international scientific collaboration with India as the host nation.

– **Overall appraisal:** The dual scientific advantage of scintillator for better energy threshold and deuterium for sensitivity to all neutrino species, combined with the technological advantage of India being able to produce a sufficient quantity of heavy water, would make the DLS detector one of the frontrunner ideas to be pursued. The technical feasibility of the preparation of deuterated scintillator of the required purity, and the ability of take care of the backgrounds, need focussed activity.

3.3.5 Medium Energy Gamma Rays from the Universe

The field of multi-messenger astrophysics has burst into prominence in the last few years with the observations of electromagnetic counterparts (optical, X-rays and high energy gamma rays) of both gravitational waves and high energy sources of astrophysical neutrinos. By the end of the decade, it will not be sufficient to just identify and localise these electromagnetic counterparts, the focus will be on leveraging joint campaigns in all the available bands to address the compelling questions regarding the nature of these enigmatic sources. Most of the current observations have been performed using telescopes and detectors from the ground (IceCube, LIGO, MAGIC, H.E.S.S and VERITAS) with the exception of LAT on board the Fermi observatory in space. Below a few GeV, gamma rays cannot penetrate deep into the Earth's atmosphere and so they cannot be detected. Instead, one has to rely on detectors flown in satellites or balloons to perform such observations. Hence there is a growing need to build and commission a particle physics detector in space which would carry out observations of astrophysical sources from several hundred keV to a few GeV as currently there is no such detector operational in this energy range. Apart from addressing several traditional astrophysics questions, this sort of a mission can be very effectively used to probe several fundamental physics questions, for example, the possible existence of sub-GeV dark matter.

- *Technology Development:* This sort of a particle physics detector will consist of a tracker using silicon sensors, a calorimeter and an anti-coincidence shield. A strong synergy as regards to detector development exists with experimental particle physicists participating in the LHC at CERN.
- *Funding Requirements:* The long-term funding for such a mission is estimated to be around USD 500 million, including the payload, satellite mission and detectors. However, for the initial R&D, about Rs. 10 Cr. over the next 5 years and Rs. 25 Cr. over the subsequent 5-year period may be envisaged.
- **Overall appraisal:** Enough expertise should be available in the country due to the presence of a good number of experimental particle physicists who have the required knowledge to undertake detector development. This project will benefit a lot from having international partners in development of several components of detector, but the project can be carried out in India with India being the leading member of the project. Since this is a satellite-based project, participation of ISRO will be of paramount importance. This would lead to an enhanced synergy between the HEP programme and the Space programme.

3.4 Summary

We must not only be good; we must be good for something
— Sarojini Naidu

This Section has discussed several possibilities where Indian scientists can get involved or take up positions of leadership in upcoming national as well as international Mega Science projects, in addition to the current involvement described in Section 2. However, in order for this to be a success, we will have to overcome the current limitations in terms of trained personnel, R&D infrastructure, funding processes and industrial support. A more detailed blueprint for providing these essentials to Mega Science Projects in HEP is laid out in the next Section.

Detail from *Civilisation* by K.K. Hebbar [TIFR Art Collection]

4 BUILDING AN ECOSYSTEM: INVESTING AND PLANNING FOR THE FUTURE

In view of their technological complexity, requirements of large investments in money and human resource, and their scientific significance resulting in India's enhanced global scientific standing in the concerned fields of research Mega Science Projects need to be implemented in a planned, focussed and professional manner, with top priority being given to the scientific goals. As these projects are largely international collaborations, the scientific output, both material and intellectual, must necessarily be compatible with international benchmarks and best practices. This calls for a well-coordinated programme of training, implementation and feedback into our system, so that the national capacity can be sustained, generally over several decades. While there are past international experiences to learn from, we cannot copy them blindly, but must tune our programmes to the needs, capabilities and working ethos of our own country. A happy synthesis of the two approaches is vital if we are to make a success of our Mega Science endeavours. This has, indeed, been the approach taken by India's most successful scientific enterprises after Independence, and it should be followed in the present case as well.

4.1 SWOT Analysis of India's Potential for Mega Science Projects

Know thyself, and thou wilt know the Universe

— Pythagoras

If India is to succeed in joining and/or building Mega Science Projects, and eventually become a world leader, we need to first assess where India stands vis-á-vis the required Mega Science ecosystem, i.e., perform a SWOT analysis. Elementary Particle Physics continues to attract some of the brightest young people in India. However, when we compare India with the western world, we still do not have a critical number of experimentalists. This is exacerbated by the fact that a large number of competent experimentalists of Indian origin have so far largely chosen to work and settle down abroad. However, a reasonable number of them may prefer to eventually settle down in India if provided with the right research environment. A positive change in this regard is being seen in recent times with the growing number of Higher Educational Institutions (HEIs). The success of the MSV-2035 Vision in HEP will depend very crucially on our ability to increase the number of experimentalists in the country to a critical number. Quite naturally, then, this will figure as a major component in our SWOT analysis below.

4.1.1 Strengths

It is a matter of pride that in India as a country, we have several strengths to rely on, when it comes to developing Mega Science in the area of HEP, which it is well to recall at this stage.

- *Numbers***:** India's large population has often been described as her greatest strength. With competent training in HEIs, and given proper motivation, India can easily create an endless supply of talented, enthusiastic and ambitious young people who would seamlessly merge with the experimental groups envisaged in our plan.
- *Education:* India has a strong tradition of education in science and engineering, exemplified by the IITs and IISERs, apart from several premier universities. The basic training required for Mega Science participation is, therefore, already available in the country. Moreover, the prevalence of English as the medium of higher education in India provides our students with a ready-made platform to comfortably engage at the international level, since English is the *lingua franca* of science around the world.

- *Tradition*: India has a strong tradition of cosmic ray studies which started a century ago and are still continuing. Since the field of High Energy Physics originated in cosmic ray studies and is still intimately linked with cosmic ray experiments, this can be a major motivation for young people to join in the Mega Science efforts related to this area.
- *Experience:* Compared to many developing countries, India has considerable experience of participating in and contributing to major international collaborations and giant experiments across the world. In HEP alone, the culture of international collaboration was initiated in the KGF experiment, carried forward by the L3, DØ and BELLE collaborations, and is now being taken forward in the CMS and other experimental collaborations. There is now enough experience available in conducting international collaborations for India to start taking a lead role in the organisation and setting up of a Mega Science experiment.
- *Computation Power*: Today, Indian strength in computation and IT is recognised all over the world, and yet what has been tapped is the mere surface of our potential in this direction. Since HEP Mega Science is largely computer-driven, it is a major strength of India. In fact, currently we already have significant expertise in grid and high-performance computing and data handling. We also have major ongoing efforts on the quantum computation front.
- *Geographical Diversity*: It has been famously said that India is an epitome of the world, and its high mountains, deserts, plateaus and stable geological formations, make it ideal to set up Mega Science experiments of different kinds. India's position in the tropical zone makes it one of the few countries located close to the Equator which can sustain Mega Science, and complement northern (or southern) regions in experiments where the latitude makes a difference.
- *Freedom:* The democratic structure of our polity permits young people to choose the careers they wish and does not force anyone into any occupation which they do not want to take up. It is thus possible to attract personnel who will take up the projects with passion and dedication.
- *Economy:* Last, but not the least, is our growing economy, which is strong enough to permit professionals like scientists, engineers and technicians to make a decent living with the earnings they can make in their individual professions. Economic progress also opens up the possibility of increasing investments in scientific research.

  Complementary to the possibility of a large number of experts mentioned above, is the availability in India of a large labour force. This provides affordable labour and enables the construction of large facilities at a relatively lower cost than what would be required in other countries with a comparable level of scientific development.

In India we often take these things for granted and compare ourselves unfavourably with more developed countries, but one only has to look around at other developing nations to understand the extraordinary potential our own country possesses for scientific and industrial development.

4.1.2 Weaknesses

Despite having so many advantages, India is yet to become a leader in Mega Science, and our overall impact in Mega Science is not commensurate with our economic and intellectual resources. This arises principally from the fact that in India the availability of resources required for Mega Science is a more recent phenomenon. Thus, much of the country's immense potential remains untapped. This can also be traced to some inherent weaknesses, which are listed below.

- *Postcolonial Legacy:* When India attained Independence, the country was faced with serious developmental and socioeconomic challenges. The past 75 years have seen a slow but steady progress despite a burgeoning population, and economic competition in the international arena. Even noting the successes of early efforts like the KGF experiment, it is only now that India has some of the required resources available to take up Mega Science Projects with full commitment.
- *Protracted Brain-drain*: In continuation of the above point, India saw major 'brain drain' during the latter half of the twentieth century. Though this has been partially reversed during the past two decades or so, it is still happening to a lesser extent. In HEP, this is particularly true of experimentalists. While there are a large number of competent experimentalists of Indian origin who are settled abroad, the number working in India is severely limited. Even where some are working, it is often just a single scientist at an institution, whereas experience shows that one needs a critical number to form a successful group. It is something of a Catch-22 situation, where challenging projects cannot be developed without the necessary experts, and unless there are challenging projects, experts will prefer to go where they can find such challenges.
- *Lack of Opportunities*: As in every other country where Mega Science has developed, a great deal of the scientific and intellectual contributions must come from all the universities scattered across the country. However, a young researcher trying to work on Mega Science Projects in an Indian university has to face problems like (a) teaching overload, (b) lack of funds, (c) isolation and (d) limited opportunities for travel and interaction with peers. There is often very little support from the authorities in the universities, who either fail to treat research as an integral part of the academic activities or are unfamiliar with the requirements of collaborative research.
- *Procedural challenges*: While the Government largely understands and appreciates the importance of fostering a scientific culture and of nurturing Mega Science Projects, scientific proposals often face procedural issues like unexpected delays, sudden cuts in pre-approved budgets, etc. Long gestation periods for infrastructural facilities, logjams in procurement of equipment, delays in payment of fellowships, etc., can seriously dampen the enthusiasm for research among scientists and students. In case of international collaborative projects, delays in getting visas can create operational problems in implementation of projects. 'Ease of Business' is as much necessary for science as for commercial enterprises.
- *Excessive Individualism*: The culture of 'collaborative research' is yet to fully sink into the scientific community in India. One of the issues faced by researchers participating in Indian Mega Science Projects is that every faculty member in an HEI is expected to build an independent research programme. In fact, a team player in India often finds it difficult to get credit as an independent researcher for matters involving career progression or other incentives. This is really a hangover from the past, when tabletop experiments dominated and it was normal for each scientist to have his/her own laboratory. It is still possible for an individual theorist, working alone or with a few students and postdocs, to come up with outstanding contributions, but hardly so for experimentalists, who need to work in large teams, especially in areas like HEP.
- *Confining Activity to Silos*: Another major weakness of Indian scientists is a disconnect among disciplines and lack of engagement with society in general. There is an overwhelming tendency among scientists to confine themselves to the laboratory and the classroom and make little or no efforts to communicate with scientists in other fields or with the general public. This carries the danger that the public may come to regard scientists as a group of people who seek to be supported by taxpayer's money

to pursue things of interest only to themselves.

- *Disconnect with Industry*: Last, but not the least, is another crucial disconnect, viz. between science and industry. In developed countries, there is a strong positive feedback loop between science and industry. Scientific breakthroughs lead to new, and often commercially exploitable, technologies, while sophisticated technologies enable scientists to probe aspects of Nature which cannot be done with more primitive tools. In India, industries do not, in general, have strong R&D departments. This particularly affects the engagement between industry and HEP Mega Science Projects, which require sizable upfront R&D efforts and expenditure as one needs to push the technology frontiers to achieve the goals of such projects. In the current scenario, Indian laboratories are often dependent on imported technologies.

  A related issue is the lack of career opportunities for scientists and the research-minded in Indian industry. Industrial houses are generally eager to pick up bright people with a basic technological degree but sooner-or-later these individuals find themselves channelled into the management streams rather than scientific R&D.

4.1.3 Opportunities

Opportunities arise naturally when there are strengths, and we have seen that India has many.

- *Human Resource*: Assuming that the fraction of talented and meritorious youngsters in any human population is roughly the same everywhere in the world, it stands to reason that India has an enormous advantage over most countries because of the sheer size of our population. With proper training and opportunities, therefore, it should be possible to build a massive HR base in India in almost every field, including HEP Mega Science. This will not only sustain future experimental efforts but also provide a continuous supply line for the R&D sections of many industries, some existing and some which will surely come up in the future.

- *HEP Centre*: With her current economic and HR strengths, India is fully capable of creating a major HEP experimental centre. This would be especially useful for scientists scattered all around the country, especially in smaller institutions. It might also act as a major HEP lab for the developing countries, and scientists from other developed nations may also benefit from it. This could establish India as a leader of the developing world in HEP and help in propagating HEP across such countries. More details on this theme are presented in Section 4.4.

- *Indigenous Hi-Tech*: Development of Mega Science will go hand-in-hand with the development of cutting-edge technologies in areas like electronics, materials science, data processing and AI, all within the country. This will also be instrumental in making the dream of *Atmanirbhar Bharat* into a reality. Using Mega Science as a motivation to drive such developments may be a good way to seed the activity, since commercial successes may take some time in coming.

- *Spinoffs*: As everywhere else in the world, technological development has spinoffs for areas as diverse as, among others, the health industry, agriculture and the IT industry. This is particularly true of Mega Science Projects. Some of these are discussed in more detail in Section 4.2.4.

- *Scientific Awareness*: There is an excitement about fundamental science, with its declared aims of probing the deepest secrets of Nature. In fact, this greatly appeals to the imagination of the man-in-the-street as it is intimately connected with the innate human desire to solve such mysteries. With proper channelisation, bringing these ideas to the public via Mega Science activities can play a major role in developing not just interest in science, but trust in scientific methods among the larger population.

4.1.4 Threats

Just as opportunities arise when there are strengths, threats arise when there are weaknesses, or when there is competition. This is a serious matter for a country like India, which aspires to establish and grow its Mega Science footprint.

- *International competition*: Science – including Mega Science – is a global enterprise. Similar ideas occur to experts across the globe and are often taken up in countries which have the necessary experience and/or resources. Mega Science is often carried out in a spirit of international cooperation as well as competition. Therefore, inordinate delays may considerably hurt the 'discovery potential' of a Mega Science Project, despite all efforts and finances, especially if the major discoveries are made by scientific competitors in the meantime.
- *Migration of Talent*: In continuation of the above, and the point about 'brain-drain' made under 'Weaknesses', bright young people, in significant numbers, leaving for what they perceive to be greener pastures is a major threat to Mega Science, not merely because they deplete the skilled human resource in India, but also because the same bright individuals go on to make significant contributions to parallel efforts in foreign countries. Pursuing science and Mega Science in India must be made both challenging and fulfilling to arrest this trend.
- *Overzealous Activism*: A more recent phenomenon has been the stalling of Mega Science Projects in the name of protecting the environment, citing threats which have little or no scientific basis, but nevertheless generate considerable emotional appeal among the public. The burden, therefore, falls on scientists to carry out a vigorous outreach programme to convince the community-at-large of the safety as well as the benefits of pursuing Mega Science Projects.

4.2 Pre-requisites for HEP Mega Science

A prudent man will always try to follow in the footsteps of great men and imitate those who have been truly outstanding, so that, if he is not quite as skilful as they, at least some of their ability may rub off on him.

— Niccolo Machiavelli in *The Prince*

If we look around the world, focussing on countries where Mega Science projects have been conceived and are running, we will notice that most of the leading countries have one or more dedicated HEP laboratories, such as the SLAC, Fermilab and BNL (USA), TRIUMF and Sudbury (Canada), DESY (Germany), CERN (Europe), Frascati and Gran Sasso (Italy), JINR (Russia), KEK and Super-Kamiokande (Japan) and IHEP (China). Most of these labs have originally developed around a Mega Science Project, and the bulk of discoveries in elementary particle physics after the 1960s have, in fact, come from these institutions. Examining the ground reality shows that there are **6 basic pre-requisites** to build such facilities and take Mega Science projects forward. These are

- The presence of a large body of skilled and properly *trained manpower*, who can take these programmes forward in a sustainable manner.
- The overall presence of a strong *scientific ecosystem,* which includes a system of education in which the importance of science, and especially Mega Science, is recognised and supported by the society, including the rest of the academic community.

- The mindset in the community for maintaining *sustained activities* in Mega Science Projects over many years, sometimes decades.
- The timely availability of *adequate funds,* from both national and international sources, to carry out these highly-expensive projects.
- The presence of strong *industrial backup*, where manufacture of a large fraction of the apparatus for high-tech science experiments can be done in the country.
- A strong level of *governmental support*, not just in funding, but in laying down appropriate funding and implementation processes, in facilitating international participation and in generating career opportunities.

These points, in the Indian context, are taken up in more detail in the following subsections.

4.2.1 Manpower Involvement and Development

> *Every art must be learnt by training with a master; when you are sick, you do not look for the physician who is most well-born, or most good-looking, or most eloquent, but for the man who possesses the skill to cure you.* — Plato in *The Republic*

To reconstruct Plato's example in a more modern context, one cannot build an international-level football team by putting together a group of enthusiastic persons with an eye to achieving even distribution across age, geographical, societal and gender parameters. Instead, it requires selection of individuals with talent and suitability, followed by rigorous training under experienced coaches in a camp where these players can concentrate fully on preparing themselves for the game. The situation is analogous in Mega Science. We will require a dedicated team, where the personnel selected after a careful merit-based process will have a solid training, no distractions from the goal and adequate support in their task. The leadership also cannot be a part-time task assigned to an eminent person who is busy with many projects. It has to be done by a person or persons who can make it his/her/their *primary* scientific goal.

The typical HR structure for a Mega Science Project (MSP) involves some established scientists, as well as a team of postdocs, students, engineers, technicians and support staff in order to function properly. We can classify their involvement as Primary, Secondary and Peripheral. For lack of a more accurate metric, these categories can be broadly delineated in terms of the R&D time devoted to the MSP by the individual, as follows.

- *Primary***:** 50% or more of the R&D time. For such individuals, the MSP will be their main scientific interest, with perhaps a peripheral interest in some other project(s).
- *Secondary***:** between 25% and 50% of the R&D time. Those with secondary-level involvement typically have the MSP as only one of their multiple research interests, or will have a different MSP as their primary interest.
- *Peripheral***:** less than 25% of the R&D time. This can be for various reasons, e.g., involvement in only a specific part of the MSP, or primary involvement with one or more different MSPs.

The corresponding requirements in terms of the participation of established scientists and/or engineers for a typical MSP to be viable is roughly as follows:

— There must be one or two Project Leaders who may devote at least 75% of their research time to the MSP, including science and management.

— The number of persons with Primary-level involvement should not be less than 5 to 10.

— The number of persons with Secondary-level and Peripheral-level involvement will depend very strongly on the size and nature of the MSP, but must be commensurate with the demands of the MSP.

The HR requirements mentioned above apply to a single MSP, and therefore, the country's requirements in the area of HEP alone must be multiplied by the number of MSPs taken up. The number of scientific personnel employed in MSPs around the world vary from a few thousands (as in the CERN LHC experiments) to a few tens (as in the Sloan Digital Sky Survey). Currently, the Indian HEP community-does not have the bench strength, especially in the experimental area, to take up a pivotal role in more than 2-3 such MSPs. Moreover, the availability of engineers and technicians is severely limited in most of the universities across India. The future will depend entirely on how many experts can be trained in India (with help, if necessary, from other countries) to run these projects. Here we must note that the word 'experts' denotes scientists, technicians and engineers, all of whom have a major role to play in setting up an MSP. With proper planning, existing MSPs can train the HR required for future MSPs and this must become a continuous process.

India is not in the same situation as the USA and European nations, which have a long tradition of excellence in science and engineering, and where the best experts can be hired from all over the world, taking full advantage of the basic training they have received *in their own countries*. Even the policy followed by some other Asian countries, viz. that of inviting their non-resident or ethnic nationals back from the Western countries with significantly higher financial inducements, would not be workable within the Indian setup. Nevertheless, given the conditions mentioned above, it should not be difficult, in principle, to find suitably educated young people and impart to them the specific training needed to participate in MSPs, and take them ahead. For HEP MSPs, these students will need training in the following broad areas, viz.

- *Science*: The basic ideas of HEP, so that they will understand the scientific goals of the MSPs they will be involved in; this is also vital if they are eventually to become leaders and start new MSPs.
- *Techniques*: The basic techniques of HEP experiments, from electronics to vacuum technology, so that they can both build and assemble the highly sophisticated instrumentation required for HEP studies. Even if India makes partial contributions to large internationally built and funded experiments, the parts built by our scientists must satisfy internationally-acceptable criteria of performance. Such equipment can only be created by workers having the necessary knowhow.
- *Computation*: A core set of software and computational skills, since HEP experiments are extremely computer-intensive, requiring not just highly sophisticated analysis, but also massive number-crunching power. The specialised software packages that do this, even if readily available, require to be learnt and adapted before they can become useful. Given its tradition of developing strong software tools for HEP experiments, the Indian community should continue to take a lead in building such software tools which could be adapted and used globally.
- *Engineering*: Specialised skills in engineering and product development, which are specific to HEP experiments. These are vital if any form of advanced hardware is to be developed in India. While bright engineers are not difficult to find, they will require to be trained in these specifics— sometimes by overseas experts if the requisite skill is not available in India.
- *Management*: The management and coordination of MSPs is quite different from running a tabletop experiment or even a Department/Institute, and it also requires to be learnt. This is not a skill which can be taught in a classroom, but can only be acquired by experience, and by observing how it is done in countries where MSPs are routinely executed.

Training, as envisaged above, can be imparted either in a distributed model, or in a centralised model.

- In a *distributed model*, such as is widely seen in developed countries, the specific training for MSP participation is readily available due to the presence of experts and necessary facilities at multiple institutions across these countries.
- In a *centralised model*, the specific training for an MSP will be available at one particular institution in the country, where all those desirous of acquiring these specific skills will have to go, or to spend a substantial part of their training period there.
- A *mixed model*, where some part of the training is imparted in a distributed mode, and some part in a centralised mode, is also possible and may be the most pragmatic way forward. This issue is discussed in greater detail in the next section.

4.2.2 Training and Outreach: Fostering a Scientific Ecosystem

> *I am sure my fellow-scientists will agree with me if I say that whatever we were able to achieve in our later years had its origin in the experiences of our youth and in the hopes and wishes which were formed before and during our time as students.*
> — Felix Bloch

Training: Among the many reasons why stand-alone Mega Science programmes have flourished in countries like the USA, is their ability to attract outstanding candidates from around the world, who come with the requisite talents and training. This mechanism nicely complements the considerable skills and expertise already existing in the country. This has turned out to be a suitable model for the USA, but is not workable in India, where we would wish – for a multitude of reasons – to have the programmes run entirely (or almost entirely) by our own people. There is thus no alternative to creating our own ecosystem. As mentioned above, in India today we have several good educational institutions and, thanks to the large population, no lack of talented youth eager to devote their careers to fundamental science. However, we do need to worry about a lack of adequate training and counselling for those who wish to do fundamental science. Even more important is the need to attract some of our best brains to tackle the intellectual challenges involved in understanding the natural world.

In order for the youth to acquire the training and motivation to take up careers in science, proper teaching at the college and university levels is essential. In India the number of institutions providing this is incommensurate with the size of the population. Sometimes even in the best institutions, there is an undue stress on rote learning with little or no connection with the real world, as well as repetitive and unimaginative laboratory teaching.–Due to the lack of intellectual challenges in college/university laboratories many of the brighter students seek to work on theoretical science. Involvement of these students in some of the direct or peripheral aspects of Mega Science Projects has started in a small way in the country, but this needs to increase substantially.

However, it is neither possible nor practical for the Mega Science Vision-2035 to address the inadequacies of India's science education system, which need to be looked at in a much bigger context. Therefore, the following focussed suggestions are being made only to enthuse young people about Mega Science. If these can ameliorate the larger problems in a small way, it could perhaps set an example to be emulated and/or adapted by educationists on a broader canvas. The suggestions are as follows.

- To organise and host a 2-3 month workshop every year during the summer, where college and university students from all over the country will be given intensive training in theoretical and experimental topics and learn to do hands-on experimental work, all related to Mega Science. Active scientists, college and university teachers from across the country, as well as retired faculty/scientists of high repute, may be invited as instructors. The programme should be carefully set up by a national-level committee on the lines of the SERB Schools. In fact, the SERB Schools in theoretical and experimental HEP form an excellent example of the utility of such a programme, since a majority of Indian HEP scientists of the current generation owe some part of their training to these very successful schools.

- To create a set of video lectures which cover topics relevant to Mega Science including demonstrations which are necessary for basic understanding, and which can be accessed by any interested student. There should be particular focus on laboratory methods. This will require top-level scientists to generate the content, and a team of facilitators with proper computer skills to create the graphic visualisations. It may be noted that the idea of recording blackboard lectures and broadcasting them has been tried for some time, but has not met with much success, since students typically find them boring and/or uninspiring. As in the previous item, this will require a national-level committee to monitor the process, since good lectures are obtained by specific solicitation rather than sending out open invitations.
- To run short (2-3 week) teachers training programmes relevant to Mega Science, which can be attended by college and university teachers across the country, on the lines of the 'refresher' programmes being run by universities and the Academies. If these can be considered for career purposes as a 'refresher' course, it will certainly motivate the college and university teachers to attend it. These will feature lectures at a higher level, visits to major experimental facilities and interactions among the participants. All this may lead to crosstalk at the college and University level, which is now utterly lacking. After all, enthused teachers make enthused students.

  A side element could be a quota for students and teachers from other countries, especially developing countries, to attend the above programmes. One could also have visiting schemes by which established scientists from other countries could spend some time in India. Obviously, the effort in India would be enormously benefitted if a few top-quality scientists from around the world can be persuaded to visit India and interact with Indian scientists.

Science Communication and Outreach:

Science communication is an imperative part of all MSP's. In fact, promoting public awareness and understanding of MSP's through effective science communication strategies and active science outreach programmes is a must. However, this task cannot be left to the scientists alone but should also involve professional science communicators and dedicated media personnel. It is important to convey to the taxpayers, the scientific excitement as well as the potential benefits and breakthroughs which an MSP can generate. An active presence in print, electronic, and social media is of utmost importance in reaching all sections of society. MSPs should organise outreach seminars at schools, colleges and educational institutions, public lectures, articles in newspapers and magazines, participation in exhibitions as well as open houses in scientific institutions. Encouraging citizen science initiatives where the public can actively participate in scientific research would foster a culture of scientific inquiry and community involvement sensitising the public towards the goals of Indian development in the sciences. Every MSP should mandatorily allocate some fraction of resources for such activities.

A centralised outreach unit for HEP Mega Science activities could help coordinate these activities in an efficient manner. Large-scale multi-city events such as *Vigyan Samagam* [VS 2019] conducted by DAE and DST in 2019, should be repeated at regular intervals in different parts of the country. Close collaboration with international HEP groups like the International Particle Physics Outreach Group (IPPOG) at CERN is strongly recommended.

4.2.3 Sustainability

It's not that I'm so smart, it's just that I stay with problems longer.
– Albert Einstein

Mega Science projects will repay the time, effort and money spent in creating them only if they can attain a level of scientific sustainability, which will enable new projects to grow and flourish even as the older ones become obsolete and close down. Some of the policy initiatives, which would be crucial for this, are as follows.

- The establishment of a national level think-tank, consisting of different domain experts, which will coordinate among potential MSPs as well as feeder projects that Indian scientists are interested in. It could also be on the lookout for opportunities of initiating or participating in future MSPs that India would benefit from, and may coordinate with external agencies in the preliminary stages. The goal of such a body would be to prepare the ground for future possibilities well in advance, so that the relevant community of Indian scientists will find itself in a position to play a leadership role and not just a participatory role.
- A judicious choice of the science goals, such that when one project is completed, the expertise acquired in that can promptly be channelised into a fresh project. It will be good if the main effort is restricted to 2-3 big projects with large demands on money and manpower, and a set of smaller projects with a flux of people moving between these two categories. Ideally, every student should be exposed to projects of two kinds – those which are being constructed and others which are giving data. This would provide an experimentalist with a holistic training.
- A regular flux of youngsters who will work in different projects and acquire the expertise to become the next generation of leaders. Those trained in these areas should be able to find (a) academic positions in Universities, IITs, etc., (b) positions in Industry as skilled experts, and (c) positions in academia as scientific staff, where they are assured of a career progression commensurate with their talents. It may be mentioned in this context that engineers and skilled technicians form the backbone of Mega Science setups in developed countries, and they are respected as such. In India, such recognition is largely accorded to engineers and technicians in the mission agencies and CSIR laboratories, but is rarely observed in the academic system.
- A large expansion of postdoctoral positions across the different institutions is needed to groom and sustain the scientific talent pool. At present, only some of the research institutes have regular postdoctoral schemes and there are a few offered by Central agencies, such as the DST and CSIR. Postdocs, the world around, play a very important role in the R&D and running of MSPs, taking responsibilities for specific tasks. If India is to harness and utilise their skills in similar ways, this may need a cultural transformation — that will take a conscious effort and some time to happen, but it needs to start now. In particular, providing special scholarships, fellowships, and attractive career opportunities may serve to retain domestic talent and attract international scientists and researchers to work in India.
- A proper system by which leadership is passed from senior to junior scientists and managers. This will require a special effort by the seniors to groom their successors and ensure that the baton can be handed over at the proper time in a smooth manner.
- Regular and planned outreach programmes which will bring to the public the excitement of Mega Science and the quest for the fundamental constituents and principles of the Universe. This will also serve to enthuse young minds to take up careers in science, and thus infuse new blood into the country's scientific effort.

Ultimately, a Mega Science programme will be sustained by three things. The first and most important one is success at achieving the proposed *scientific goals*, or even beyond. The second is the ability to use the experience gained in international collaborations to gradually build the *infrastructure* required inside the country, or to develop designs which can work with the infrastructure/facilities already existing in the country. The third is a more long-time requirement that India develop *leadership* in Mega Science projects, for no country can sustain a derivative programme for ever. For this, it is required to build a whole ecosystem of smaller size 'feeder projects' in the country which would provide the directions in which a Mega Science Project could be developed.

4.2.4 Adequate Funding

I believe in innovation and that the way you get innovation is you fund research and you get the basic facts.
— Bill Gates

If technical competence provides the backbone of any project, then funding provides the flesh and blood. Given the heavy requirement of high-end technology, substantial skilled manpower and international involvement, substantial funding will be required to carry out Mega Science project-related activities in HEP in India. Since private funding of R&D in India is still relatively small and noting the difficulty of monetising Mega Science achievements in a short time frame, almost all of the funding for Mega Science would need to come from government sources.

In view of the above, it would be desirable for a separate budget line to be created for the pursuit of Mega Science Projects within each of the budgets allocated to overarching agencies like the DAE, DST, CSIR, UGC, etc. The reason is that there are many calls on these organisations, as they have been formed to cater to the needs of the country in other specific directions too. It may be noted that the beneficiaries of an investment in Mega Science are not just the scientists involved, but a vibrant Mega Science programme will have a long-term impact on industry, education and nation-building in general.

There are three important aspects of the funding policies, which are described below.

- *Modality*: There must be a simple and well-defined process by which scientists can apply for and get access to funding. There are three different kinds of projects, viz.,
  - those that will require regular or *long-term funding* of a major nature, such as large international collaborations like India-CMS, or the proposed INFHEP centre (see Section 4.4), etc.
  - those that will require a *large initial outlay* to set up and thereafter smaller amounts of maintenance funds to keep it going., e.g., setting up a testing facility.
  - those that will require a *one-time funding*, e.g., pilot projects, feasibility studies, educational/outreach projects, etc; or *small periodic grants* for repeated activities. This is discussed in more detail in Section 4.6.

  The process of getting these funds must be made simple and transparent. Some of the desirable features of this are

  - The *proforma* for application must be simple and non-repetitive. The design should be such that the proposals become precise and pointed, in addition to being scientifically comprehensive, i.e., they stay confined to scientific goals and methods, the scientific credibility of the proposer(s) and budgetary requirements.
  - There must be a pre-assigned *time frame*. Typically, a small 'feeder' project (up to, say, Rs. 10 Cr.) should be evaluated and approved (or otherwise) within 4–6 months from the date of submission, and

a middle-size project (Rs. 10–50 Cr.) within 6–9 months. For really major or long-term proposals, a period of up to 1 year may be required to get the necessary approvals (or otherwise). These benchmark timelines would naturally be extended if the proposal has to be returned for revision and resubmission.

- The sanctioning process must be *transparent*. For example, if there are budgetary cuts, these must be justified. Similarly, if a project proposal is rejected, or deferred, a clear *explanation* must be given for doing so. This must be based on scientific and/or technical reasons, unless it is a matter of unavailability of budget. Such a procedure will help the proposers to re-formulate their proposal, or, if that is not possible, point out what is required of a proper proposal.

- *Distribution*: The types of grants for Mega Science may be divided into three classes.
  - *Committed grants*: Grants for major facilities being developed/run in India would be the primary target of such grants. This category would also include funds to pay membership fees in major international collaborations, and also support India's contribution, as per the agreements signed with these collaborations. In the latter case, the funds are often non-negotiable and generally substantial.
  - *Solicited grants*: These would include funds granted against specific academic proposals at regular times. They may include medium or short-term projects, pilot projects, or testing facilities. Such grants would be necessary to create an ecosystem of 'feeder projects' for current and future Mega Science activities.
  - *Manufacturing grants*: It is often seen that some scientific devices required for Indian participation in Mega Science programmes may be required in fairly large numbers, but may not have enough commercial demand to interest bigger industrial players in their manufacture. In such cases, financial support may be required, either to get them custom-made at some existing facility (in India, or elsewhere), or to give the initial support to any entrepreneur who wishes to branch out from HEP research to industrial manufacture of such devices. In fact, such schemes would be excellent examples of public-private partnership.
  - *Mobility and Networking Funds:* India is a large country with a limited number of high energy physicists geographically scattered over a large number of academic/research institutions, including universities, IITs, IISERs, research institutions, etc. To strengthen the Indian HEP community, it is important to facilitate mutual interactions on a frequent basis. While online communication channels are generally available, experience shows that in-person interactions are more effective for creative brainstorming and focussed collaborations. In fact, for tangible experimental development, such interactions are indispensable. Such interactions can also foster healthy growth of the younger section of the HEP community and bring more breadth to their scientific activities. Therefore, the funding structure must incorporate resources for networking and mobility of scientists. Special calls for such networking proposals, focussed on specific topics in frontier areas, should be made on a regular basis.

  Perhaps the most important aspect of fund distribution is that there must be a mechanism to ensure that adequate funding is provided to persons or groups having proven competence, but at the same time there must be a provision to provide smaller amounts for newcomers, or those who want to try out new technologies in India, or those who want to try out-of-the-box ideas. This calls for a proper evaluation process, and brings up the next and perhaps most critical issue.

- *Scientific Accountability*: Scientific Accountability in a scientific project would basically involve achievement of the scientific goals of the project in the prescribed time frame and cost. It must, however, be borne in mind that these are R&D projects at the very frontiers of science and technology and there are inherent uncertainties and risks associated with these projects. As a consequence, the judgment whether a project has scientifically succeeded or not can only be made by a group of experts.

4.2.5 Partnership with Industry

Science and everyday life cannot and should not be separated.
— Rosalind Franklin

If we consider the list of leading HEP laboratories in the world, as listed at the beginning of Section 4.1, it may not come as a surprise to see that they are all located in industrially-developed nations as such as the USA, Canada, Germany, Italy, Russia, Japan and finally China. For science and technology have gone hand-in-hand since ancient times, more so since the Industrial Revolution, and almost exclusively so in the post-World War II period. In a classic bootstrap picture, it is the requirements of scientific experiments which lead to the development of sophisticated technologies and applications, and then it is the development of sophisticated instrumentation which drives science to greater heights, and this, in turn, spawns a need for even better technologies. It has been the same story with HEP Mega Science projects, which is illustrated below with a few specific examples.

- Perhaps the single most influential technological development due to HEP experiments today is something which does not involve elementary particles at all. This is the World Wide Web, invented at CERN in 1989 by Tim (now Sir Timothy) Berners-Lee to enable researchers to access HEP data through a common database. Berners-Lee also introduced the concept of a web browser, to provides the interface between a user and the database. Released to the world in 1991, this has spawned the Internet, which now embraces everything from buying real estate to watching movies to getting vaccinated. During the current pandemic and sporadic lockdowns across the globe, it is the Internet which has kept the world moving.

  The Internet and WWW have also brought about the widespread use of wireless LAN, or WLAN devices. The original concept was developed by John O'Sullivan in 1977 to sharpen images from radio telescopes. Today it is a household device.

- On the hardware side, one of the major medical applications of high energy accelerators has been to provide proton and ion beams for radiation therapy to treat tumours, especially deep-seated ones. The property of protons and ion beams, that they deposit most of their energy towards the end of their path in the material, helps to minimize damage to healthy cells on the way. Scientists trained in particle detection and data acquisition systems are crucial for the development and deployment of such technologies.

  Many HEP experiments like dark matter searches and neutrino physics studies require very sensitive detectors, and the technologies could be further adapted to such medical applications. Semiconductor pixel detectors with capabilities to count single photons, almost noise free, have provided a boost to X-ray imaging. Gaseous detectors like resistive plate chambers and gas electron multiplier detectors, with their large area adaptations and high time and spatial resolutions, provide unique opportunities for rapid cargo scanning at affordable prices. These technologies have high potential for security applications as these could be used to spot materials of varying densities by reconstructing the images. Large area detectors with high spatial resolution could also be used to model the underground density profile, and hence spot anomalous material densities, for mineral exploration, oil and gas reservoirs estimation and other geotechnical applications. These will essentially measure the directional attenuation of the cosmic muon flux in a process called muon geotomography.

- Another important aspect of HEP Mega Science has been computer simulation. GEANT4 is a well-established software package for simulating interaction of particles with matter for high and low energy physics research. It has been widely used for space applications to study effects of natural radiation on various instruments. The GEANT4 has also been extensively developed for medical applications to study the effect of beams on biological samples. The same GEANT4 is heavily used in nuclear physics applications e.g., to develop more efficient neutron monitoring detectors to be used in reactors or simulate the effect of radiation on electronic instrumentation. OpenGATE is an open-source extension of GEANT4 which can also model time-dependent phenomena such as detector movements or source decay kinetics to allow simulation of time profiles close to realistic conditions.

Two other software packages primarily developed for astrophysics work are IDL (Interactive Data language) and IRAF (an image processing algorithm used primarily by optical astronomers) which are now used in medical industries regularly, e.g., PET scanners, cardiac angiography and X-ray computer tomography. IDL is also being used by big oil industries.

Recording and processing large datasets in real time is imperative for HEP, especially the collider experiments. The need to share LHC data globally has led to the World-Wide LHC Computing Grid (WLCG) for data distribution and its analyses. The basic idea is to have a global distribution of arrays of computational nodes, with each such array being maintained locally, which will collectively form a vast supercomputer, processing data through whichever node(s) is free at that point in time. Such data-intensive computing and accessing huge databases are also some of the key challenges for drug design projects, since these involve screening of millions of molecules to identify their properties. Similar applications are also relevant for earth and climate science applications.

With burgeoning real-time data rates expected in the next phases of the LHC, artificial intelligence (AI) and machine learning (ML) will become crucial to select and save the collision events for detailed scrutiny offline. The plan is to implement these advanced algorithms at the front-end readout using Field Programmable Gate Arrays (FPGAs). Such FPGAs are widely used in military applications like automated missile guidance because of their low latency, in radio astronomy applications for specialized I/O on the detection system, etc. The personnel trained in conventional grid computing as well as data handling e.g., on FPGAs, could be an asset to non-HEP endeavours both for further developments of the system as well as application expertise.

Like the World Wide Web, grid computation has the potential to change the way the whole world operates. One can easily envisage a futuristic scenario where all computers and cell phones will be connected to a universal grid, so that smart homes, smart transport and smart cities around the world will essentially be run by one universal AI programme (or set of programmes), running on a few billion CPUs spread across the world.

In recent years, cloud computing, i.e., storing, managing, and processing large data by utilising a network of remote servers hosted on the internet rather than a local server, has been gaining popularity. One major advantage is that the end-user does not have to perform any active management of the resources. Recently the IceCube collaboration carried out a two-hour computing experiment running simulations in which about 50,000 GPU processors were used on cloud, marshalling resources from Amazon Web Services, Microsoft Azure and Google Cloud Platform. The results showed that the cloud-based cluster delivered a performance of almost 90% of what could be achieved in a localised high-performance computing (HPC) cluster called SUMMIT at the Oak Ridge National Laboratory, which has a nominal performance of 400 PFLOPS 32. A similar effort was undertaken by the computing group in the Cherenkov Telescope Array (CTA), who proposed an innovative cloud computing architecture in order to reduce the time for simulations. The CMS experiment also developed tools and infrastructure capabilities to utilize the cloud resources (provided by the same agencies as above). Detailed real-world proof-of-concept workflows were carried out on all these infrastructures wherein thousands of compute resources were added on the fly to the Worldwide LHC

Computing Grid (WLCG) and realistic Monte Carlo simulations were carried out for CMS physics analyses. Various CMS partner institutes, including TIFR, have participated in developing and demonstrating these capabilities. As a response to the increasing demand for transparency and access to data by policy makers and society, the CMS Collaboration has now provided open access to data, along with the recently-released statistical analysis and combination tool COMBINE [Combine 2024], to make it possible for others to perform their own analyses.

In general, cloud computation is quite cost-effective, especially if the computing requirements are short-term or intermittent. However, the cloud is distributed over diverse geographical locations and hence data transfer, which depends on the internet speed, may be considerably slower than that in a local cluster. At the same time, availability and costs may fluctuate with the changing geopolitical situation. Moreover, when relying on cloud resources, one should be mindful not to lose local computing system expertise in handling such large and complex systems. Thus, cloud computing has the potential to become a very useful tool for HEP computation so long as it is used judiciously.

Implementation of advanced technology in India will require a strong backup from Indian industry. Currently, much of India's high-technology equipment is imported at an enormous cost to the exchequer. Even if these products are assembled in India, the process is often more cost-effective and would definitely result in useful technology transfer. In fact, it may be said that if there is a proper synergy between industry on the one hand and Mega Science on the other, both sides will benefit considerably. For Industry, it may enhance their own R&D programmes and enable them to come up with sophisticated products that are internationally competitive, as well as involve them in the investigation of new ideas which are of high risk, but nevertheless of great commercial potential. It may also introduce them to a pool of bright young minds who may, in principle, be absorbed for increased science-based R&D. For Mega Science, it will not only enable the indigenous production of equipment which would otherwise require to be imported, but may also lead to the development of instrumentation which could lead the world in terms of precision, etc., and enable India to participate in technology-led science in a bigger way.

To bring all this into practice, it will be necessary for industry to engage with scientists, have their own strong R&D wings and make the necessary investments to develop high quality products. Therefore, industries must become convinced that developing high-end products will be profitable in the long run, and this will require some vigorous persuasion by the scientific community, e.g., by pointing to developed countries. At the same time, it is desirable that a certain fraction of scientists and engineers eventually move into industry from fundamental research. These transitions happen readily in developed countries and are an important factor in their dominance over the technological progress in the world, with which, as mentioned above, scientific progress is intimately connected.

Keeping the above in mind, we suggest the following initiatives.

- Involve industries as partners in Mega Science Projects from the inception. To take an example, the Kamiokande experiment in Japan was based on collaboration with Hamamatsu Photonics and their ability to make large photomultiplier tubes. Since this kind of initiative will be new to India, proper modalities will need to be developed for government-industry partnerships in conceptualising and setting up Mega Science Projects;
- Encourage industries to commercialise the results of the research, subject to adequate IPR conditions which can be initially agreed with the MSP;
- Have continued engagement of experts from the industry all the way from the planning stage to the running of the MSP, so that a more synergetic roadmap can be created and followed;

- Project the capabilities of Indian industry internationally by participating in technical exhibitions and industrial fairs; the Government could create an Industrial Liaison Office to encourage and capitalise on such involvement;
- Provide for a flux of young people, e.g., students, postdocs, interns, trainees, to move from a MSP to industry and vice versa, so that they may get a holistic training and be able to contribute to either.

Indian engagement in MSPs so far has led to close interactions with the industry, where industry has contributed in delivering high-quality, cost-effective products for detector instrumentation and electronics as well as magnets and other engineering products for accelerators. Some of these partnerships are listed in Annexure A.3. Thus there is potential to develop further in these areas, but much more capacity-building will be necessary as India enters into a new era of MSP participation.

4.2.6 Governmental Support

> *There is nothing which can better deserve your patronage than the promotion of science and literature. Knowledge is in every country the surest basis of public happiness.* — George Washington

As mentioned above, Mega Science Projects require to be funded by the government. In order to thrive, a Mega Science programme in HEP will depend on the Government for some of the following items.

- *Ease of Transactions*: It is important to simplify the processes of funding and project implementation without compromising with the basic requirements of transparency and financial rectitude.
- *Single-window System*: Often, in setting up projects, it becomes necessary for the scientists to approach different agencies of the State and Central Governments. This occupies a great deal of the time and effort they could otherwise have devoted to scientific matters. A single-window system of approach would be of great help to the scientists, so that they do not need to make multiple submissions of their project proposals and interim reports. Overall, an improved project management system and strategy is definitely called for. Further details may be found in Section 4.5.
- *Prompt Action*: Applications to the Government, varying from land acquisition to permission for travel, need to be processed faster. A typical time frame for funding proposals has been suggested in Section 4.5.1. Similar reasonable time frames should also be defined for approval of other MSP-related requests.
- *Facilitating Interactions*: Travel within and outside the country is an essential part of Mega Science and requires to be facilitated. As a part of this, there should be adequate opportunities for Indian scientists and engineers involved in HEP projects to travel inside the country as well as internationally, to present their work, to learn new skills and to interact with the top experts in the world. There should also be opportunities to invite experts from other countries to visit different institutions and laboratories in India and share their skills with Indians. This should be facilitated in all possible ways.

  The Covid-19 pandemic has brought to the fore the fact that a certain basic level of scientific and other interactions can be carried out through video conferencing. While this is certainly a positive step, it must be emphasised that no amount of video conferencing can substitute meetings/discussions in person, teaching in a classroom, or working together in a laboratory.
- *Industrial Liaison*: Scientists often do not know what is available in industry, or are themselves unknown to industrialists. There is an urgent need to build bridges with industry, and governmental endorsement in this regard would be really helpful.

The Government may also consider providing appropriate incentives to industry for setting up partnerships with scientists which would utilise the expertise of both sides. The move to permit CSR funds to be allocated for research is a right step in this direction. However, more direct Government mediation in the early stages of a Mega Science Project would certainly facilitate the setting up of active science-industry collaborations.

There are many other small ways in which Mega Science Projects may require Government help, some of which will be known only when they come up. The important thing at that time is for the Governments at both State and Central levels to retain a positive attitude towards Mega Science Projects and their practitioners.

4.3 Past Achievements, Present Status and a Wish List

If you worry about yesterday's failures, then today's successes will be few. The future depends on what we do in the present.
— Mahatma Gandhi

At this point it is worth making a quick appraisal of where we stand today in terms of High Energy Physics and Mega Science. Though somewhat at the periphery, India has not been a passive watcher of the great developments of 20th century science, and today there is considerable expertise in the country in some aspects of this great enterprise. However, it lacks consolidation, and there is a long – but not impossible – wish list which can be achieved with dedication and support. These are touched upon in this subsection.

4.3.1 The Historical Context

In the nineteenth century and the first half of the twentieth century, the nature of physics research was such that an individual scientist, working alone or, perhaps, with one assistant, could investigate fundamental aspects of Nature at the cutting edge and produce results of great consequence. Most experiments were of the tabletop variety, with the highest budget going for experiments which involved travel (such as the famous 1919 British expedition to observe bending of light in a solar eclipse in South America). Compared to an MSP today, the cost of these was negligible. Under such a backdrop, it was possible for Indian scientists, even in pre-independence days or in challenging times post-independence, to do fundamental research and come up with results crucial to the advancement of science. Some of the shining examples (in physics) are listed below.

- We can go all the way back to the 1890s, when J.C. Bose achieved the crucial breakthrough which made wireless communication a reality — a feat which did not get its proper recognition till 2012. The race was on between different European experts to develop a practical use of Hertzian waves, and yet it was the Indian savant who made the difference.
- Within two decades, M.N. Saha had applied statistical thermodynamics to stellar dynamics (1919), thereby opening up the new field of astrophysics (complementing the ancient science of astronomy) in general.
- While the whole world puzzled over the peculiar statistical properties of photons, it was S.N. Bose who found the explanation (1923), creating the whole subject of quantum statistics.
- C.V. Raman and K.S. Krishnan (1928) discovered the effect named after the former and created the entire subject of Raman spectroscopy.
- A.K. Raychaudhuri made (1955) important advances in general relativity which culminated in the Hawking-Penrose theorems on singularities.
- The Kolar Gold Field experiment, led by M.G.K. Menon and others, discovered atmospheric neutrinos (1965) two weeks before a rival US-South American group led by future Nobel Laureate F. Reines could do so.

However, such front-ranking work has been more limited in more recent times, with a few exceptions such as, for example, Ashoke Sen's work in string theory.

The reason for this paucity of landmark discoveries in contemporary Indian science in general, and HEP in particular, is not any fundamental deficiency in Indian scientists, for some of the brightest sparks have come — and do continue to come — to science, and a not-unreasonable fraction of them do stay and work in the country. The reason must be sought in the changing nature of science and scientific research in the post-World War II era, which has tilted the balance firmly in favour of the Western countries. The roots of this go back to the Manhattan project, i.e., the American atom-bomb project, which was run on corporate-cum-military lines, with great success. It proved that miracles can be achieved in science if several sharp minds can be brought together to work in collaboration, along with the necessary finances and other resources. Therefore, by and large, the post-war organisation of science has moved in the direction of teamwork, and MSPs that require the marshalling of technological and industrial resources in the interest of science. It took several decades for the Indian community to catch up with this. Apart from a few isolated examples like Homi Bhabha and Vikram Sarabhai, the Indian community was firmly set in the nineteenth-century mould of a 'professor' conducting research in isolation within the confines of his own laboratory. Only since the 1990s has the idea of teamwork caught on in a small way, but it still has a long way to go (see under 'Excessive Individualism' in Section 4.1.2).

4.3.2 Where We Stand

When it comes to specifics, the HEP community in India today has a very broad experience of R&D for detector components and subsystems, which includes fabricating the active material and electronics components indigenously as well as assembling the imported components on final working systems like silicon photomultipliers, sensors and FPGAs. In the context of the CMS Collaboration, Indian R&D efforts have included ECAL-related studies for crystals, fabrication of the Outer Hadron Calorimeter, pre-shower detector modules, RPC and GEM muon detectors (currently in operation), and ongoing hardware development for the HL-LHC. For the BELLE II detector, one layer of the silicon vertex detector was delivered by the Indian group. Large area scintillation detectors and RPCs have been developed for the GRAPES-3 and INO experiments. India has also contributed several accelerator components, especially to CERN, and more recently, to FAIR [MSV-2035-NP].

With this kind of multi-pronged experience in delivering high-end systems to international experiments (e.g., CMS & BELLE II), combined with the creation of in-house experimental setups (e.g., GRAPES-3 & INO) — and with many new projects (e.g., FCC, ILC, ICECUBE-GEN2) on the horizon — it is actually high time to consolidate and expand our efforts and expertise in order to seize a leadership role on the international front and build some scientifically-competitive facilities on Indian soil. The most recent advancements in detector technology centre around fast readout of the signal from the detectors and achieving unprecedented timing and spatial resolution. India thus needs to strengthen capabilities in electronics and systems based on plastic scintillators, silicon and other solid-state detectors for high granularity detectors, and also the gas detectors, already planned to be used for the CMS endcap calorimeters at the high luminosity LHC starting 2027 and being discussed for future projects, e.g., FCC.

4.3.3 Wish List for the Future

The Indian experimental groups have been successfully delivering the various detection and electronics components of very complex state-of-the-art particle physics and astrophysics experiments on the international front. Even though our current participation has mostly taken the form of contributions to external experiments, the experience gained so far has actually enabled us to take up indigenous projects like INO, MACE, etc. This experience should be built upon for constructing Mega Science experiments based in

India with possible international participation. On the other hand, the Associate Membership of India at CERN should also be leveraged for initiating novel experiments utilising the expertise and facilities available at CERN.

The next generation of breakthroughs in answering the fundamental questions in particle physics will be hugely governed by innovations in the detection technologies to measure very small signals, fast timing measurements, radiation hardness, scalability and related instrumentation, be it to exceed the current sensitivities of dark matter experiments or to prepare for the future collider-based experiments. The R&D for all these are already going on in various centres like CERN, DESY, KEK, Fermilab, etc. while none of the Indian groups hold a centre-stage role in these developments. In order to leapfrog to a more central role, commensurate with our aspirations to be at the forefront of knowledge-creation, India will first need to achieve self-sufficiency in the relevant technologies. In addition, we should have in-house capabilities to quickly pick up any relevant technological breakthrough, e.g., in 2D materials and/or quantum materials, and apply it to particle detection devices. Such research projects would require high-end tools and facilities, and advanced engineering capabilities, which are not available to the Indian HEP community at the moment, except at overseas facilities.

- The collider physics experiments of the next generation are expected to perform in an unprecedented environment of very high particle energies and numbers. Thus, proton-proton collisions at centre-of-mass energies beyond the LHC will require detectors to satisfy very stringent demands as regards radiation hardness as well as granularity, and high-precision timing performance of individual detector readout units. Stability against radiation doses makes an important benchmark for detectors as well as front-end electronics. It is therefore of utmost importance to have an access to suitable irradiation facilities within India, which could, for example, be low energy beams with high intensity.
- The Silicon photomultiplier (SiPM) is an established photodetector device which is finding a wide range of applications in high energy particle and astroparticle physics experiments, and even in medical physics, such as PET, fluorescence spectroscopy, etc. SiPMs can be used to detect single photons and have several other advantages such as operations at low voltage, compactness, radiation hardness and robustness. All these make the SiPM an attractive technology for use in high-energy astroparticle experiments, e.g., searches for dark matter, neutrinoless double beta decay and imaging atmospheric Cherenkov telescopes. It is thus of paramount importance to start developing expertise and laboratory infrastructure towards coupling SiPMs with the front-end electronics of such experiments.
- To develop, characterize and assemble the state-of-the-art detectors for such future experiments would require a facility which will concentrate on developing different types of detectors like design and synthesis of new ultrapure crystals, characterizations of their structure and properties, growth and application study of synthetic crystals that will form the materials basis for future technologies. Such a facility should host all the tools and expertise needed to realize a single working detector unit starting from a concept, and possibly scale it up to massive production. For example, for silicon detectors, the requirements are high-end clean rooms, lithography systems for making pixillated detectors, metal deposition systems for electrical contacts, probe stations for making connections, spectroscopy tools to study crystal defects and various high end X-ray sources.
- Dark matter and neutrinoless double beta decay experiments need extremely low background radiation detectors since the expected event rate is less than a few events per tonne of the detector mass in one year. To set up such experiments, deep underground laboratories at least 1.5 km from the surface are

needed in order to achieve the required experimental sensitivity. Such underground facilities would need clean rooms of Class 10000 which are large enough to accommodate the detector(s).

- Last, but by no means the least, are the computational requirements for HEP Mega Science, which is heavily dependent on computation. Large-scale computations enable us to access data-processing regimes and theoretical analyses which would have been unthinkable in the pre-computer era. Moreover, a paradigm shift in computation, with powerful artificial intelligence (AI) and machine-learning (ML) techniques is beginning to take over from old-fashioned number crunching methods, and we will surely see a rapid expansion in AI and computation-driven research in the coming years. More specifically, for HEP, the HL-LHC will generate about 100 Petabytes (Pb) of data over a decade and it will require multi-petaflop computing resources to analyse them for the study of hadronic jet structures, as well as searching for new physics through ML techniques. Lattice QCD calculations which are crucial to study various non-perturbative aspects in high energy physics, particularly in search for new physics, require access to large computing resources.

The computational requirements of HEP and Nuclear Physics communities in India are closely related, and have therefore been presented in a consolidated fashion in the MSV-2035 Nuclear Physics report [MSV-2035-NP]. In brief, a need is felt to build *four* major Data Centres in the country specifically for High Energy and Nuclear Physics, with a total computing power of 100 PFLOPS and storage of 250 PB. A tentative timeline for the growth of these resources is given below.

Item	2020 – 2025	2025 – 2030	2030 – 2035	15-year total
Computing Power (PFLOPS)	25	35	40	**100**
Storage (Pb)	50	75	125	**250**
Approximate Cost (Rs. Cr)	1,000	1,200	1,500	**3,700**

In addition to the high-performance computation (HPC) requirements detailed above, genuine mega science analysis work would require high-throughput computation (HTC), which means computation through nodes distributed across a network, whose geographic extent can cover the whole country or even extend beyond as a part of international collaborations. Federating of resources greatly enhances efficiency of utilization and return-on-investment (ROI) while reducing maintenance overheads. The technology for this is already developed and is being used by the major CERN collaborations under the head "Grid computation". The HTC requirements for HEP mega science projects would consist of (i) compute servers, (ii) storage servers, (iii) intranet and internet bandwidths, (iv) OS and software for computing, and (v) middleware for robust system of authorization, authenticating, auditing and secure data transmission.

While we invest in computing hardware, which has a limited lifetime, it is also important that we invest in acquiring and developing software –which stays longer and can span many generations of hardware. As a matter of fact, software has become a critical element for the full and long-term exploitation of large data sets in data-intensive science projects such as those in particle and nuclear physics, astrophysics and astronomy. Unlike hardware, software elements can often be shared across multiple experiments and can be passed from one generation of an experiment to the next. In addition, the use of, and inter-operability with, data science and machine learning tools developed by other parts of the academic and industrial world is becoming ever more important to science.

Once commitments for well-defined deliverables have been made for an MSP, the respective hardware and analysis activities are generally carried out independently across several institutes at a smaller scale.

However, in order to have a decisive role in upcoming MSPs, production, testing and assembly of single units need to be scaled up to match the requirements of future projects undertaken. It is, therefore, necessary to build up a facility(ies) where this phase of an MSP can be carried out. For example, such a facility should be able to foster R&D on silicon sensors, CCDs, SiPMs and their associated electronics, etc. for dark matter, astrophysics and future particle physics detectors. The actual equipment and priorities could be finalized based on the choice of Mega Science Projects.

4.4 Common Facility(ies) for High Energy and Related Physics

> *There are. scattered all over India, competent workers who are not doing as good work as they would do if brought together in one place under proper direction.* — Homi J. Bhabha

If we look across India, we will find that the bench strength of trained experimental HEP personnel is inadequate to run more than a few MSPs, and even they are scattered across the country in small numbers at individual places. It is true that communications have vastly improved in recent times (especially during the Covid-19 pandemic), but we have already mentioned that remote interactions cannot form a substitute for working together, especially in a laboratory. With a limited number of people distributed thinly over multiple institutions, it becomes difficult to focus efforts towards a Mega Science project.

In fact, the successful implementation and running of an MSP requires not just the participation and involvement of scientists who are experts in the relevant areas of the experiment but also the active involvement of a large number of engineers and technicians who can bring in different skills for the successful completion of the project. This is almost impossible in a typical HEI set-up (which includes the universities, IITs and IISERs) where available manpower, funding and infrastructure in terms of design, development and assembly is inadequate to successfully carry out the project. Moreover, the complexity of the experiment requires 24×7 involvement of people in the project — which is almost impossible in a university due to various other commitments of the faculty members, pertaining to teaching etc.

To explain this with a concrete example, let us take a small piece of instrumentation from a branch of astroparticle physics, viz., TeV γ-ray astrophysics. One of the key components of an atmospheric-imaging Cherenkov telescope to perform the high energy γ-ray observations of astrophysical sources is the camera of the telescope. This camera is made of hundreds of photomultiplier tubes, preamplifiers, trigger-interfacing among various pixels, low-voltage power supplies, high-voltage power supplies, cooling mechanisms of the camera and optical fibres to transport the signals with minimum loss. Constructing such a camera will require expertise not just from physicists but from several engineers and technicians proficient in analog and digital electronics, electrical systems, mechanical systems to build the frame of the camera and so on. It is almost impossible for the faculty members of the physics department at a HEI to carry out such a massive task successfully with the limited support available. Hence there is a need for a facility where physicists, engineers and technicians will work closely together to make the project a success. Many examples of what could be set up in such a facility are given above, in Section 4.3.3.

However, it must be noted that universities can (and definitely should) continue to build smaller local laboratories in order to perform specific tasks pertaining to the project in order to impart very critical and useful training to the students, such as, for example, measuring the quantum efficiency and gain of the photomultiplier tubes, understanding the mechanism of the trigger, performance studies of how to convert efficiently an electronic signal to an optical signal for transport through optical fibres etc. All these above-mentioned tasks, which are extremely important for the project, can be carried out in the local laboratories of a university.

In Section 4.2.1 we have introduced the concept of distributed, centralised and mixed modes for training. The same models could, in principle, be applicable to the entire pursuit of Mega Science. In a distributed model, the different parts of a Mega Science project are built at different institutions around the country, and their testing and assembly takes place at some common facility. Much of the existing MSPs are currently being done in this mode, e.g., the components being made for the CERN experiments are taken to Switzerland to be tested there, and the final assembly also takes place there. However, if India aspires to create her own MSPs, or to lead some international MSPs, then such a distributed model will require a location within the country for testing, assembly and running the experiment. On the other hand, it would be counter-productive to remove all the existing groups and facilities to a single location, even if that were possible. For many of them have been built up with great expense and effort over the years and now provide India with the springing board from which to launch the country into a higher level of participation in Mega Science. It is these groups and facilities in Universities and Institutes across the country which have created the scientific ecosystem for Mega Science. Therefore, it is a mixed model which India must go for, with the creation of a few common facilities, and leaving the rest distributed across the country. One example of this is the GMRT facility at TIFR's National Centre for Radio Astrophysics (NCRA) at Pune.

In view of the above arguments, what is required to take Mega Science forward in HEP is one or more common laboratory-cum-training facility(ies), with strong links to the other institutions around the country, on the lines of the major HEP laboratories around the world, as listed in Section 4.2.1. Such places would be invaluable to build high-end instrumentation, and train experimentalists in their design and use. Any common facility should act as a *user centre*, where scientific personnel from multiple institutions can come and go freely, making use of infrastructure which are too big to create multiple copies across the country, and contributing to their design and development. It is also important that such a user centre should not end up as just another research institute.

4.4.1 Role of a National Facility(ies)

In view of the above, it is felt that a national facility(ies) could be established– perhaps around one or more existing or upcoming MSPs (like the IICHEP that was proposed to be set up for the INO Project) – to fulfil these objectives. For the purposes of this document, we shall refer to this generically as the Indian National Facility for High Energy Physics (INFHEP), even if it is of a distributed nature. The role that such an INFHEP can play will comprise the following.

- *Independent Research in HEP, especially Related to MSPs*: Like its counterparts elsewhere in the world, the INFHEP may have a small but select faculty, who will conduct independent research in high energy physics, especially on the physics related to MSPs (though academic freedom should not be compromised). The Facility should be able to employ a significant number of postdocs, and permit both graduate students and postdocs from institutions all over the country to be stationed there for substantial periods of time. Other Indian institutions should be persuaded to encourage their faculty to spend sabbatical leave periods there rather than in foreign institutions. This is a feature which works very successfully at places like Fermilab, CERN and KEK.
- *An Incubation Centre for future MSPs:* INFHEP can serve as a facility encouraging the initiation of feeder projects, some of which could eventually set a foundation for future MSPs. Exchange of state-of-the-art technical knowhow with incubation centres in other leading laboratories around the world, and active participation in the international Detector R&D collaborations (DRD's) may be facilitated at this centre.

- *Running Training Programmes for Students*: HEP students from all over the country, working on Mega Science programmes, will then be encouraged to spend at least one year at this facility to get a dedicated and focussed training in some of the following areas:
  - Advanced training in particle theory, including the Standard Model, calculation of basic processes, introduction to physics beyond the Standard Model and the astroparticle frontier. This will give them a perspective on the purposes for which their research work will be done.
  - Intensive courses on instrumentation relevant to high energy experiments, with adequate hands-on training.
  - Intensive courses on numerical simulation and data analysis, with introduction to modern techniques like deep learning, with adequate hands-on training.
  - Frequent interaction sessions to prepare them to present their views and work in a professional manner.

At this Facility, instruction will be provided by the small core team of scientists who are integrally part of the Facility plus a large number of visiting faculty, including visitors from overseas. Such visiting faculty may include retired faculty who are still academically active.

Universities should be encouraged to make some of these courses a part of their curriculum and allow their students to accumulate credits towards their respective degrees. This would be in consonance with the spirit of skill-enhancement courses as envisaged in the National Education Policy 2020 [NEP 2020].

- *Organising Meetings, Conferences and Workshops in HEP*: There are two major Indian conferences in HEP, viz., the national-level DAE-HEP Symposium and the Workshop on High Energy Physics Phenomenology (WHEPP), which have traditionally been held in alternate years. The particle physics community was brought together with those working on more formal aspects of quantum gravity, super-unification, etc. through a series of workshops called '*From Strings to LHC*'. A centre like the INFHEP could become the regular organiser of such major events, and at the same time hold smaller satellite workshops round the year on specific topics. Small, focussed workshops could play a major role in disseminating new ideas across the country. In any case, conferences and workshops form a vital part of scientific engagement, and this should be an important part of the mandate of INFHEP.
- *Housing Specialised Labs and Workshops for Development and Testing*: As mentioned above, a great deal of the testing and assembly for MSPs is currently being done by taking the material abroad and using some foreign laboratory/facility to carry out the necessary activities. The INFHEP could house some state-of-the-art laboratories and workshops where this work could be carried out in-house. Only the largest of assembly, or the most difficult testing should require the prototypes to be taken abroad. The existence of such a facility in the country will provide a big boost to smaller centres (e.g., colleges and universities) which could then assume bigger responsibilities in Mega Science projects, including international ones, by ramping up their hardware contributions. It may be noted that the development of high-end detector technology does not need to be focussed on a particular/sanctioned experiment, but can take place in the spirit of capacity-building for the next generation of HEP experiments.
- *Development of High-end Electronics*: A great deal of the instrumentation for HEP Mega Science involves very high-end electronics, such as are neither available in the market, nor easily fabricated in a small laboratory without specialised equipment. The INFHEP could house such a specialised laboratory, with the requisite equipment, where researchers could come from around the nation and develop the equipment which they can then take back to their own laboratories for further work.

- *High-end Computation with User Support*: Another requirement of MSPs in HEP is the requirement of the computational power to handle huge quantities of data and do super-fast number crunching. Most universities do not possess such computational facilities. The INFHEP could act as a facility where HEP workers across the country could run their codes– in fact, it could be one of the Data Centres proposed in the MSV-2035 Nuclear Physics report [MSV-2035-NP]. It could also participate in the Grid computation project of CERN and similar enterprises which may come up elsewhere. The INFHEP could also develop and maintain a virtual advanced technological platform for all HEP Experiments with databases that support large-scale scientific research and collaboration. The INFHEP could have a small team of system administrators and computational experts who would provide the user support for users scattered all over the country.
- *Visitor Centre for Other Countries*: At a later state, the INFHEP could also function as a visitor centre for scientists from other developing countries. Of course, this should not be at the expense of researchers from Indian institutions, but rather be regarded as a part of India's outreach to other countries.

4.4.2 Structure and Organisation

In setting up a common facility(ies) like the INFHEP, some of the important considerations would be as follows.

- It is important that the INFHEP should permit participation from across the country in an equitable manner, so that it possesses a truly national character. This egalitarian nature should not be sacrificed even if the INFHEP grows around a particular MSP or is part of an existing institution.
- One or more dynamic persons in late middle career could be chosen to lead the effort, with a few senior, experienced persons in advisory roles. The example of other institutions shows that such a centre generally nucleates around one (or at most two) dynamic leader(s), with a group of competent lieutenants who can carry out the vision of their leader. A distributed leadership, even with good relations among the top scientists, often leads to a lack of focus and non-optimal use of the available resources.
- The INFHEP should be permitted to hire not just faculty but high-quality scientific and technical staff. The skills of scientific and technical staff will fundamentally impact the scientific output. This is seen at well-known laboratories like CERN and Fermilab, where a significant part of their reputation arises from the engineers and technical experts at these places. In fact, the crucial role of engineers and technicians in setting up and running a major experimental facility is given full credit in such institutions, on par with the academic personnel. This is also, to some extent, already the case in Indian facilities such as ARIES Nainital, IIA Bengaluru, etc. and in the mission-oriented organisations such as DAE, ISRO and DRDO.
- Long- or middle-term hiring of foreign nationals should be made possible, as has been permitted for Institutions of Eminence. Not only will this widen the pool of talent for the institution, but it will also permit the bringing-in of new skills without necessarily making a permanent hire.
- There should be separate legal, financial, and procurement departments at such a facility, as for example is the case at CERN. This would take a large burden of administration from the backs of the scientists leading the work. A separate department to handle contracts and contract workers would also be required.
- The site should be chosen *in or around a metropolis*, or the outskirts of a metropolis, with a view to accessibility to industry and both domestic and international travel. The latter is a *very serious requirement* if the facility is to be widely used by researchers across the country. Moreover, such a location

will automatically provide the researchers with access to better medical facilities, wider opportunities for spouse employment and good educational opportunities for children.

Once set up, the INFHEP should have MOUs with organisations and institutions across India, including umbrella organisations like the UGC, CSIR, etc. The purpose of these MOUs would be to permit freedom of mutual interactions regarding personnel, funds, equipment and IPR. Under such MOUs, it should be possible for researchers from all over India to consider the INFHEP as their second academic home and carry out there the experiments and testing which they may not be able to do in their home institutions. The MOU must allow them to get the appropriate leave and permissions to do this. Such a programme will permit those who would otherwise not be able to contribute to Mega Science Projects, to do so with comparative ease. At the same time, the INFHEP will benefit vastly by having access to a larger pool of talent across the country, whose scientific energies can be channelised into MSPs. We already have the highly-successful mode of Inter-University Centres like IUAC and IUCAA.

In the initial 5 years, the funding will be primarily used to create the infrastructure and logistics of the centre, including buildings to house laboratories and offices, as well as rooms for seminars/lectures/discussions. In this phase, setting up a large mechanical workshop, a large electronics workshop, and high-end clean rooms would be the first priority. It would highly beneficial to set up a powerful microelectronics group, with highly competent engineers, familiar with modern but constantly evolving micro-electronics design technologies. Computing facilities would also be on the high priority list. There will be a need for housing for permanent staff, a suitable guest house for visiting scientists, engineers, technicians and students/postdocs from other institutions, and a suitable canteen. All this will typically require an average funding of around Rs. 40 Cr. per annum. It is expected that specific experiments will bring in project funds for equipment and experiment-specific running costs for themselves. In the second 5-year phase, it is envisaged that other facilities, such as those enumerated in the wishlist of section 4.3.3, would be built up. This would need an average funding of about Rs. 20 Cr. per annum. Once up and running, the entire facility would be expected to continue operations over several years, with a core staff, a large flux of visiting scientists and some regular funding of a few Cr. every year.

4.4.3 Underground Facility for Cosmic Background-free Experiments

An underground facility with a rock overburden of about a km provides a suitable location for performing sensitive experiments where the filtering of cosmic ray backgrounds would be crucial. Indian scientists have already performed experiments in such a facility (the Kolar Gold Fields) in 1960's to 1990's and have obtained pathbreaking results like the first observation of neutrinos produced in the Earth's atmosphere [Achar 1965]. While this facility has now become unusable, dark matter search experiments such as JUSL (section 3.3.1) have been ongoing in the Jaduguda mines. Over the last two decades, there have been concerted efforts towards creating large deep underground facility for the proposed INO project (section 2.2.3) by constructing a tunnel under a mountain. While extensive studies have been carried out, requisite permissions for the selected sites have not been obtained till date.

As is clear from the success of underground experimental facilities in many countries (for example, Homestake and Soudan mines in USA, Baksan Neutrino Observatory in Russia, Kamioka mines in Japan, Gran Sasso National Laboratory in Italy, Sudbury mines in Canada, Jinping Underground Laboratory in China), underground experimental facilities allow the scientific community, across a broad range of disciplines, to pursue a variety of challenging science problems that would be impossible to address otherwise. There is already a large interest in the Indian scientific community across the fields of high energy physics, nuclear physics and astroparticle physics in performing experiments at such a facility. The availability of such a facility would also enable the Indian scientists to conceive of projects that could not be imagined earlier, and hence would add a new dimension to the national scientific programme.

Many of the projects described in this document would be enabled by, or have their scientific potential significantly enhanced by, an underground facility. Some of these projects and their science goals are:

- **Atmospheric neutrino detection:** the Iron Calorimeter (ICAL) experiment at the erstwhile INO project, for identifying the neutrino mass ordering, observing Earth matter effects on neutrino oscillations, looking for physics beyond the Standard Model in neutrino oscillations, etc. (section 2.2.3),
- **Direct detection of WIMP dark matter:** the proposed InDEx experiment, which would be the next stage of the ongoing dark matter search experiment at the Jaduguda Underground Science Laboratory (JUSL), which looks for possible signals of dark matter particles passing through the detector (section 3.3.1),
- **Axion detection:** the proposed haloscope experiments using indigenously developed quantum sensors such as SNSPDs (section 3.3.2)
- **Low energy solar neutrino measurements:** the Deuterated Liquid Scintillator (DLS) experiment that could leverage the heavy water production capability of India to measure the solar neutrino spectra in the energy range 2-5 MeV with unprecedented precision and would be able to detect neutrinos and antineutrinos of all flavors from a future galactic supernova (section 3.3.4),
- **Indium-based detector for solar neutrino observations:** an indium-based solar neutrino detector that can measure the width of the Be-7 line from the neutrino spectrum from the Sun, and hence make the only direct measurement of the temperature of the core of the Sun (section 3.3.4),

In addition, some of the projects described in the Mega Science Vision-2035 in Nuclear Physics [MSV-2035-NP] also need an underground facility as one of their crucial ingredients:

- **Search for the neutrinoless double beta ($0\nu\beta\beta$) decay:** the TIN.TIN experiment that aims to search for Dirac vs. Majorana nature of neutrinos by looking for the $0\nu\beta\beta$ signal in ^{124}Sn,
- **Low-energy underground accelerator for nuclear astrophysics:** a MV-scale accelerator which can enable the exploration of many reactions of interest to nuclear astrophysics, such as those relevant to He and C burning, BBN reactions, capture reactions with p-nuclei, etc. which have very low cross sections, and perform measurements of fission gamma rays relevant to fundamental nuclear physics,
- **Rare nuclear decays with novel detectors:** studies of rare gamma decays in atomic nuclei for testing the exponential decay law of radioactivity to extremely short time intervals, searches for as-yet undiscovered alpha or two-photon decays, or electron capture decay studies for measurements of neutrino mass,
- **Ultra-low energy gamma ray spectroscopy:** for material selection and testing of micro-electronic components that will be used in, for example, astroparticle physics experiments.

Further, such a facility would open up doors for as-yet uncharted research in related areas of

- **Geophysics:** for the quantification of noise while performing seismological measurements, by simultaneous measurements at the surface and underground.
- **Biology:** for understanding the effect of natural background radiation on living cells and their metabolism.

Taking into account the requirements of the projects mentioned above, the underground facility may be envisaged to consist of

- One large cavern of 100 m (L) x 25 m (W) x 30 m (H)
- Multiple caverns, typically of the size 30-50m (L) x 20 m (W) x 15m (H) for various experiments
- Some of the experiments may require clean rooms of class 100- 1000
- Projected power: ~5 MW (3 MW for the large cavern, 2 MW for the smaller caverns combined)
- Projected water consumption for cooling of instruments: ~400 KLD
- Radon-free circulation system
- Additional space for basic amenities, services and auxiliary systems.

The funding needed for establishing such a facility would depend primarily on its location and the length of the tunnel that needs to be excavated in order to get the required overburden. If the facility is built in synchronization with one of the tunnels being built for road/rail transport, the additional cost would be minimised. Once a suitable site has been located and the required permissions obtained, one would need about Rs. 500 Cr. over the first 5 years for the creation of the tunnel and the major caverns, and a further Rs. 250 Cr. over the next 5 years for completing the construction and making the standard amenities available.

Such a facility would need dedicated trained staff with specialized expertise for maintaining and operating underground facilities. It is therefore essential to create a pool of trained scientific and technical personnel for operation and maintenance of the world class underground facility over a prolonged period of a couple of decades or more. The underground science community in India would need to develop a coordinated roadmap for this purpose. The roadmap should include periodic workshops, summer/winter schools, training sessions, and networking opportunities for scientists and engineers interested in underground experiments. The INFHEP Centre (section 4.4.1) may take the responsibility for coordinating many of these activities.

An underground facility is a long-term investment and should provide sustained support to the science programmes over decades. There should be opportunities for international collaboration in the proposed projects, and for hosting of international experiments at such a facility. For successful implementation of these ambitious scientific proposals the industry participation is essential, which will further the development of advanced technology in the country. Such a facility will not only boost the national scientific programme but will also stimulate the advanced detector and associated technology development in the country and provide an ideal training ground for ambitious young scientists and engineers.

4.5 Accountability and Monitoring Mechanisms

It is not just what we do, but what we do not do, for which we are all accountable.

— Jean-Baptiste Moliére

A key issue in any programme, especially in a Mega Science programme where a great deal of time, money and effort will be expended is that of *accountability*. It is important that such a programme has something to show as results — even if they may not always be the results originally hoped for. At the same time, a programme in fundamental science cannot be held to commercial or industrial standards of accountability, nor even to the same standards as applied science. Research into the secrets of Nature is essentially a tentative process, and therefore, the 'product' in fundamental science is of a very different kind, and it is generally not possible to monetise this within a short time scale. It is, therefore, necessary to propose and develop an appropriate system of monitoring and accountability for the Mega Science Vision-2035. Such governance structures should be transparent, efficient, and capable of making timely decisions. We need to develop and enforce a robust regulatory framework that facilitates smooth execution of Mega Science projects, addressing key aspects such as funding, international collaboration, and intellectual property rights. An attempt to formulate this for the HEP component is presented below.

We propose that the Mega Science projects in HEP should be monitored by *two* committees and a common portal. All the MSPs in HEP should be monitored by a common **Inter-Agency Committee for HEP (IAC-HEP)** consisting of well-known domain experts and heads / senior representatives of the funding agencies. It may be also useful to call upon the services of leading international experts to advise the committee on scientific and technical aspects. The IAC-HEP will evaluate and recommend project proposals and if they are funded, oversee the resultant projects. It will constitute a **Scientific Review Committee (SRC)** for every MSP for its scientific and technical evaluation, based on the recommendations of which the project will be approved and, upon approval and funding, be periodically monitored.

- The SRC for each MSP would consist one or more domain experts not directly participating in the project and representatives of the funding agencies. This body will be constituted at the time of sanction of the project, and will automatically be dissolved when the project is closed. For longer-running MSPs, it may be reconstituted from time to time by the IAC-HEP.
- The PIs will present periodic reports on the project to the SRC. Each SRC will take stock of the progress in the MSP at regular intervals and prepare a report to be passed on to the IAC-HEP. The progress reports will take into account all aspects of the project, including science, HR, budget issues and sustainability.
- There should be a common **Mega Science Coordination Unit** (**MSCU**) where prospective MSP proposals can be submitted. This Unit, after preliminary scrutiny, will pass the proposals on to the IAC-HEP for evaluation. The decisions of the IAC-HEP will be communicated to the prospective project leader(s) by this Unit. The MSCU will also serve as a portal for inquiries regarding the progress of the proposal and updates on financial grants. All this can be done impersonally through a web portal. Periodic reports from the PIs, as well as the SRC reports, may be uploaded here for onward transmission as appropriate.

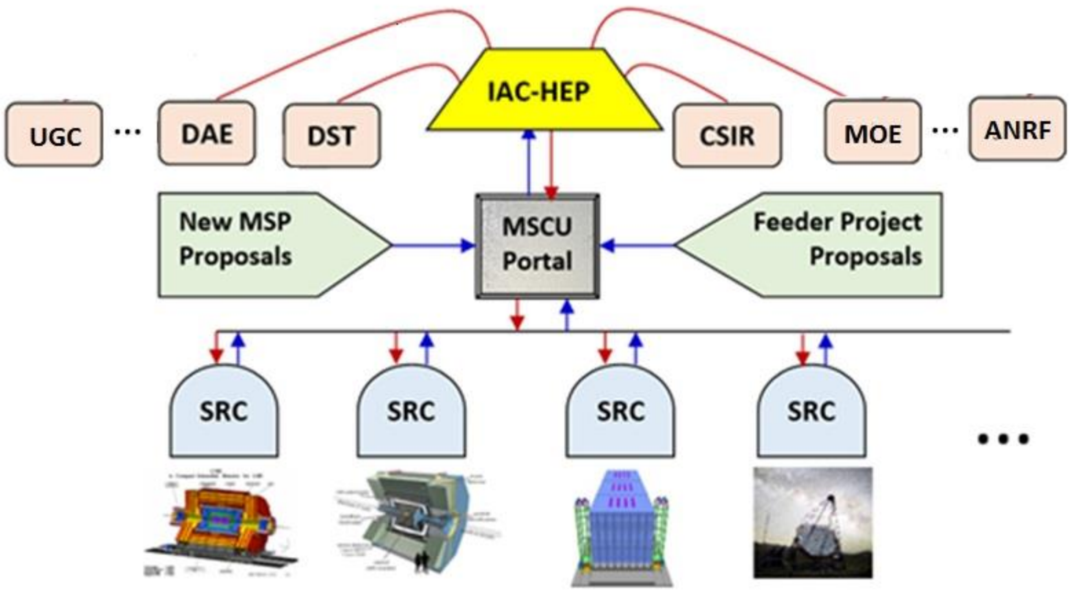


Figure 4.1 Rough sketch Illustrating the proposed single-window process for approval and updates on a HEP MSP.

The hierarchy of these suggested committees and authorities is illustrated in Figure 4.1.

4.5.1 Preliminary Steps Building up to a Mega Science Project Proposal

One day I went up to my mom and I said, 'Mom, can I have permission to build a 2.3-million electron-volt atom smasher - a betatron - in the garage?' And my mom stared at me, and she said, 'Sure. Why not? And don't forget to take out the garbage.
— Michio Kaku

Mega Science Projects, by their very nature, have a large element of community participation, i.e., scientists, engineers, technicians and students/postdocs, generally come together to work on development and running of the project(s). Since a typical MSP runs for a period of several decades, there must also be enough commitment from the community to ensure that the project sustains over the years. Therefore, an MSP must start with a wide acceptance across the country, and the science must be exciting enough to induce a reasonable number of scientists and others to devote the required amount of time and effort to the MSP.

Typically, an MSP – whether an India-based project or an international collaboration – would be initiated by one person or a small group of like-minded persons. The next step would be to invite the advice/opinion/criticisms of the HEP community in India (and elsewhere). This can be done by holding a national (or international) scientific meeting to have a preliminary discussion on the scientific goals and the feasibility of the project. This can also be an addendum to a more general conference, where opinions could be sought even from experts who are not quite in the specific field. After such a meeting (or meetings), a clearer picture may be expected to emerge, regarding (a) the interest of the HEP community in general, (b) the expertise and facilities already available in the country, (c) the number of interested persons, and (d) a crude estimate of the budget. If enough of these criteria are favourable, then one or two nodal persons may be decided by the community. They will take the proposal ahead, with the help of interested colleagues.

The nodal person(s), in consultation with the community-at-large, would set up a group of interested individuals who will then prepare a Detailed Project Report (DPR) for the proposed MSP, mentioning specifics like scientific goals, a proposed timeline, tentative budget and manpower requirements, etc. If necessary, feedback from the community could be incorporated into this DPR. At the next stage, a single-window system for submitting all HEP-related Mega Science proposals could be the MSCU described above. It would be the responsibility of this body to approve/reject the projects and decide the sources of funding, if approved.

4.5.2 Procedure for Continuation/Closure of a Project:

The season of failure is the best time for sowing the seeds of success.
— Paramahansa Yogananda

The procedure for continuation/closure of a project may be as follows.

- The schedule of IAC-HEP meetings will be announced every year on the MSCU portal. One month before the relevant IAC-HEP meeting, the SRC of every project coming up for review must upload their report on this portal.
- The SRC report will be discussed in the IAC-HEP, focussing on the achievements, progress and budgetary aspects of the project. If the IAC-HEP decides that the project is worth continuation, the same will be conveyed to the project leader(s) through the MSCU web portal.
- If the IAC-HEP feels that an MSP is not worth pursuing further, or has achieved all its planned goals, it may be decided to bring the project to a closure. In such cases the decision with reasons is to be communicated to the project leader(s) within one month after the date of the final decision.

Valid reasons for closure of a project might include the following:

a) The scientific goals of the project have been achieved and no further research in the same direction is warranted/contemplated.

b) The scientific goals of the project have been achieved as per the proposal, and for further research along the same lines, a fresh (perhaps larger) project proposal must be submitted.

c) The scientific goals of the project have become irrelevant, or appear unreachable, and there is nothing to be gained by further efforts in this direction.

d) There has been no progress during the period under review and/or it is unlikely that further progress can be made due to scientific/technological/human/budgetary reasons.

e) There are severe budgetary constraints which make further financial support impossible to sustain.

Of the above, the possibilities (a) and (b) would be regarded as normal closure and the rest as special/premature closure.

4.6 Feeder Projects

Wisdom demands a new orientation of science and technology toward the organic, the gentle, the elegant and beautiful.

— E. F. Schumacher

A major part of the scientific ecosystem which feeds MSPs consists of some small projects, which may not individually qualify as MSPs, but collectively form a pool of ideas, of which some can grow into a possible MSP. In developed countries, this has been an organic process, with a stream of new ideas and technologies being constantly developed in laboratories, workshops and factories, so that they are ready to be utilised by an MSP when it is taken up. In India, we have only a very rudimentary version of this, and hence our MSPs are very heavily dependent on importing not just technology, but also ideas from countries which have MSPs running. It is, therefore, necessary, for the Mega Science vision to include furtherance of small projects in related areas, out of which new and original ideas may be expected to grow. In this section, therefore, we describe (a) the need to foster the growth of multiple small-scale 'feeder' projects, (b) their synergy with MSPs, and (c) try to provide a prescription to convert successful ones to MSPs.

The typical project in this context will be smaller than a Mega Science project, but larger and more expensive than a typical tabletop experiment. Some of the experiments mentioned in Section 3.3 could themselves be regarded as 'feeder' projects, or as growing out of 'feeder' projects. It is important that such 'feeder' projects be recognised as an important part of the overall effort to initiate and run MSPs. The Mega Science programme should therefore create a scheme where these projects may be taken up with urgency through the same single-window processing scheme proposed for larger Mega Science Projects. In fact, the IAC-HEP mentioned above could play an even more proactive role in encouraging scientists to take up such projects or even to solicit proposals for what seem to be good ideas which are currently not being studied in India.

Before a group of scientists and allied experts can jump into the din and fury of an MSP, it is necessary that they have the competence as well as the confidence to do so. The lesson of history is that these attributes develop only in an environment where multiple small-scale projects have been tried out before and the necessary experience gained. The failure rate in such exploratory science is necessarily high. However, it is the small number of successes which then go on to develop into MSPs, and these, in turn, can foster more MSPs. Thus, a programme in Mega Science is always forged in the crucible of small-scale science. However, this does not refer to *all* of small-scale science, but only to those ideas which are known/surmised beforehand to have the potential to develop into an MSP. These will be referred to as 'feeder' projects.

- Where India is concerned, if we delve into the past again, we can find a medium-scale project (by the standards of the time) in India in the 40-inch cyclotron set up at the Institute of Nuclear Physics (now

Saha Institute of Nuclear Physics) under the leadership of M.N. Saha in 1948, only a year after Independence. Though the essential parts were all imported, from the accelerating components to the magnet to the vacuum pumps, they were set up entirely by Indian scientists and some of the front-end electronics was also designed and built locally. The cyclotron was famously used to provide accurate measurements of the fissile cross-section of U-235, a result whose importance in power generation cannot be over-emphasized.

- A similar project was the TIFRAC — the first digital computer built in India (1955) at TIFR, using 2,700 vacuum tubes. Once again, the basic components were imported, but the assembly was done entirely in India under the leadership of R. Narasimhan, and the patronage of Homi Bhabha. These early projects set the pattern for a hybrid mode of experimentation, where imported and indigenously-built components have been combined to set up experiments across the country.
- The GMRT, another success story of this kind, may also be mentioned in this context. In this case, the TIFR radio telescopes, first at Kalyan, near Mumbai and then at Udhagamandalam (Ooty), acted as 'feeder' projects before the larger enterprise of the GMRT could be taken up. Over the past few decades, the reverse has also been true, as described in Section 3.1.1, i.e., components have been indigenously built in India and incorporated in international experiments in a foreign country.
- Another example from overseas can be quoted in this context, and that is the measurement of the anomalous magnetic moment of the muon — the so-called $(g-2)_\mu$ measurement. These measurements started at CERN in the late 1950s, using small-scale accelerators, and have grown progressively more accurate with the development of larger experiments at Brookhaven and Fermilab. The highly-sophisticated experiment at Fermilab today is in a position to challenge the well-entrenched Standard Model of particle physics. If it had not been for the initial small-scale experiments and the dedication of scientists pursuing this experiment over decades, the present excitement would have been impossible. An analogous case was the Homestake experiment carried out under the leadership of Ray Davis Jr. from the 1960s onwards. Their perseverance in measurement of a deficit in the solar neutrino count eventually led to the discovery of neutrino oscillations and ended up with a couple of Nobel Prizes.

What is important to note here is that all these have started from small beginnings and developed into more ambitious projects. This required support and patronage for the initial small project, just as a small sapling requires care before it can grow into a mighty tree.

It is clear, therefore, that participation in and development of Mega Science projects requires the simultaneous development of multiple smaller-scale projects, which serve as a fertile breeding ground for ideas and an equally effective training ground to develop expertise in handling larger projects. This is especially needed in India, where the number of people with Mega Science experience and expertise is very small. Such moderate-size or small-size domestic projects could act as reservoirs of technological capacity from which the necessary expertise for MSPs would be sourced.

The history of science shows that often some idea, which is initially considered as being on the fringe or even outright wrong, later turns out to be a breakthrough in a new and promising direction. Therefore, it is worth nurturing, in a small way, multiple off-track ideas for that one spark of inspiration which may lie among them, just as we sieve tonnes of mud to find a single diamond. Moreover, the direction of research often does change and this happens with Mega Science projects as well, usually in the aftermath of a new/unexpected discovery. Thus, to maintain the required flexibility, the funding and general support for such 'feeder' projects requires to be brought under the umbrella of Mega Science.

To bring this section to a conclusion, it is strongly recommended that the Mega Science programme of the country should not neglect to include a provision to build up and nurture a culture of small and medium size projects.

5. Synergy with Other Areas

In the long history of species, only those who learnt to collaborate and improvise most effectively have prevailed.
— Charles Darwin

One of the most beautiful features of science is the presence of deep and often unsuspected interconnections between apparently disparate areas. For example, who could have predicted that two obscure Dutch opticians playing around with lenses would create an instrument that would one day revolutionise our understanding of diseases? Or that some purely mathematical attempts to reconcile electromagnetism with electrostatic equations would eventually lead to fantastic advances in the field of communications? In more recent times, we are seeing all earlier forms of domestic and city lighting being swept away by an invention arising from humble devices originally intended as opto-electronic switches. In the field of HEP itself, the fundamental idea of spontaneous symmetry-breaking has been imported from the physics of condensed matter systems. And then there is the World Wide Web, which grew out of a particle physicist's scheme to share data with colleagues, and has now come to dominate every moment of our lives.

All such connections cannot be predicted, of course, in advance, but it is important to recognise that the same or similar ideas, the same or similar equipment and the same operational methods which work in one area of science may also be applicable in others. This is certainly true for MSPs, where the large investment in money and human resource must be utilised to the fullest extent. In this section, therefore, we explore some of the synergies which seem feasible at the current juncture in time.

5.1 Synergy with Nuclear Physics

Atomic nuclei are often used in low-energy particle physics experiments where knowledge of the properties of these nuclei play an important part in interpretation of the outcome. The discovery of neutrinos and the identification of their flavour and helicity were achieved in such experiments through a detailed understanding of the properties of some specific nuclei. Even in the current and proposed experiments, such synergies with nuclear physics appear. Four examples are given below.

The first example consists of the experiments trying to detect dark matter, like SuperCDMS, JUSL, and InDEx. These experiments all involve the scattering of dark matter particles off atomic nuclei. Both spin-dependent and spin-independent scattering processes help us constrain the parameter space of dark matter models, be it a weakly interacting massive particle, or an axion-like particle. The participation of the Nuclear Physics (NP) community is needed because nuclear dynamics is involved in the evaluation of the scattering rates. It has already been emphasized in Section 4.3.3 that such experiments need an underground laboratory where background effects coming from cosmic rays can be minimized. Such a laboratory may also be used for purely NP-related experiments.

The next example is from the interface of NP and HEP, viz., the study of phase transitions in hadronic matter. During heavy-ion collisions at the LHC, extremely high temperatures are produced, approximating the temperature soon after the Big Bang when quarks and gluons were yet to get confined into hadrons. Such collisions, like Pb on Pb, help us to probe the hadronic phase transition and, thus, in a sense, have a glimpse of the very beginnings of the Universe. India is already involved in a dedicated heavy-ion experiment at the LHC, namely, ALICE, and even CMS can provide interesting results when LHC runs in the heavy-ion collision mode. There is also a possibility that the Indian high energy physics community would be joining the experiments at the upcoming Electron-Ion Collider (EIC). All these results, testing the theory of strong interaction under extreme conditions, will be equally interesting to the HEP and the NP communities.

The third example includes neutrino-related projects like the double beta decay experiments (e.g., TinTin which will try to observe $0\nu\beta\beta$ in Sn) and solar neutrino experiments that would use In or deuterated liquid scintillators. Results from these experiments would be of great interest to the HEP community in the context of the search for new physics. However, the techniques used would be standard ones used by nuclear physicists, and it must be carried out by them in collaboration with the HEP researchers.

The fourth and final example is that of large-scale computations using lattice QCD. These calculations are crucially needed in searches for violations of the symmetries of the Standard Model such as the lepton flavour. In the discovery of new exotic hadrons, including exotic nuclei, where various medium and high energy experiments are involved, lattice calculations offer valuable complementary insights. Lattice calculations are also essential to study the phases of quark-gluon plasma and the equation of states in nuclear matter and are beginning to provide essential inputs to low-energy nuclear physics covering areas such as neutrino-nucleus and dark-matter nucleus cross-sections crucial for dark matter direct detection experiments. Thus, lattice QCD naturally fosters synergy across multiple disciplines, including nuclear physics, high energy physics, astrophysics and cosmology.

Of the above examples, further details of dark matter experiments are given in the present document (Sections 3.2.8 and 3.3.1), while more details of heavy-ion and neutrino-related experiments may be found in the MSV-2035 Report on Nuclear Physics [MSV-2035-NP].

5.2 Synergy with Accelerator Physics

Many of the HEP experiments where Indian scientists play a major role are accelerator-based, and such experiments need dedicated detectors that have to be fabricated and tested before they can be put in the actual experiment. For such testing and development, both low- and high-energy accelerators play an important role. Prototypes of each of the detector elements as well as associated electronics have to be tested with accelerator beams to finalise the design choices for final mass production of detector modules.

Technical and physics performance of the prototype detectors have to be tested at dedicated test beam facilities e.g., those existing at CERN or Fermilab, which provide high-energy (10 GeV and above) single-particle beams of charged pions, electrons/positrons, and muons. The number of such facilities across the world is very small, and therefore prototypes built in most other countries, including India, must be taken for testing to these common international facilities.

Low energy beams — with energy of a GeV or less — are also used for a wide variety of tests during the detector R&D. For example, high granularity calorimeters based on silicon or on scintillators will play an important role in future collider experiments, where they are needed to cope with high pileup and high radiation environment at the detector. These can be tested using low energy beams and irradiation facilities with photons and a few-MeV neutrons. Electron/positron beams of 1-2 GeV can be used for studying ASIC performance, electronic noise stability and correlation among various channels, electronics gains and intercalibration, pulse shapes and signal reconstruction, time profiles and stability, efficiency of identifying minimum-ionising particles and position resolution, cross-talks among neighbouring channels, etc. All these measurements at the level of individual detector modules and channels must be passed on to the electronics simulation for a realistic modelling of the detector effects. A collaboration between Indian HEP and accelerator physicists could lead to such tests becoming possible in the country.

In fact, if we could build in India an accelerator with beam energies of a few GeV, we could even extend these studies to study the electromagnetic shower development characteristics at low energies with suitable use of absorbers in detectors. The X-ray beams available from such facilities could be used for detailed characterisation of the new detector material to be developed for the experiments with small signal expectation as well as those developed to meet high radiation tolerance requirements.

Low-energy high-flux neutron irradiation facilities would be vital for radiation hardness characterisation of the detectors to be developed for the future colliders. In addition, low energy neutrons are also needed for *in situ* characterisation of targets for dark matter searches where sensitivity to the nuclear recoil and its faithful modelling is of utmost importance.

For further details on the Indian capabilities for building and running accelerators, we refer to the MSV-2035 Report on Accelerator S&T and Applications [MSV-2035-ASTA].

5.3 Synergy with Astronomy and Astrophysics

There is a very strong synergy between high energy physics and astronomy and astrophysics. Cosmic rays, gamma rays and neutrinos from astrophysical sources can be used to probe particles at energies not attainable on Earth, and thereby help in understanding fundamental interactions. This, in turn, can be used to explain different astrophysical processes including particle acceleration mechanisms and cosmic evolution.

High energy gamma rays provide a unique view into the most extreme environments in the Universe, allowing one to probe particle acceleration processes and the origin of the galactic and extragalactic cosmic rays. For example, active galactic nuclei (AGN) are known to be sites of particle acceleration, emitting jets of highly relativistic particles. Outstanding questions regarding the acceleration processes include the nature of the accelerated particles (hadronic or leptonic), the role of shock acceleration and the mechanisms for the formation and collimation of astrophysical jets. Answers to these questions are expected to come from high-resolution measurements using multi-wavelength data with radio, optical, X-ray and gamma-ray instruments, from multi-messenger observations with gamma rays, ultra-high energy cosmic rays, neutrinos and, potentially, from gravitational waves. Participation in large international collaborations in these areas may be expected to generate significant R&D resources with scope for indigenous developments.

The two fields of cosmic rays and hadronic interactions are intimately related. High-energy cosmic rays can only be studied by detecting the showers they generate in the atmosphere, and the interpretation of the data requires precise modelling of hadronic interactions. Uncertainties in this modelling are an important limitation in cosmic ray studies. The cosmic ray spectrum extends to particle collisions with centre-of-mass energy approximately 50 times higher than the current LHC energy. Thus, cosmic ray studies offer the possibility to perform studies on the properties of hadronic interactions that are impossible at terrestrial accelerators.

Neutrinos complement observations of cosmic rays and gamma rays due to their weak couplings and their origin in the decays following high-energy hadronic interactions. Several important issues in particle physics and astrophysics can be addressed by neutrino experiments. For example, the IceCube collaboration has recently reported the detection of several high-energy neutrinos above a few tens of TeV, which are of astrophysical origin. These exciting results herald the beginning of high-energy neutrino astronomy and have initiated the study of neutrino oscillations at ultra-long baselines.

Dark Matter and Dark Energy are the most enigmatic mysteries of the Universe as they constitute more than 95% of the Universe's matter-energy content, but their nature and properties are far from fully understood. Currently substantial efforts are being undertaken to detect dark matter by building suitable experiments, including at high energy colliders, at non-accelerator underground laboratories and also through observations of astrophysical sources. For example, while searching for dark matter signatures from the galactic centre or other astrophysical objects, one must understand and measure the background from standard astrophysical processes.

Last but not the least, observations of highly energetic, variable distant sources like AGNs and gamma ray bursts (GRBs) provide a good opportunity to probe effects due to the emission and the propagation of high energy photons. A study of energy-dependent time lags in photons can be used to probe Lorentz symmetry-breaking as predicted in some quantum gravity models.

The physics issues related to dark matter and astrophysical phenomena like supernovae, AGNs, GRBs and nucleosynthesis are of as much interest to astrophysicists as they are to high energy physicists. More details regarding these can be found in the MSV-2035 Report on Astronomy and Astrophysics [MSV-2035-A&A].

Do not lower your goals to the level of your abilities. Instead, raise your abilities to the height of your goals.

— Swami Vivekananda

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References

[Aab 2015] Aab, A. et al. 2015. “The Pierre Auger Cosmic Ray Observatory.” Nucl. Instr. and Meth. A 798: 172-213. DOI:10.1016/j.nima.2015.06.058.

[Aamodt 2008] Aamodt, K. et al. 2008. “The ALICE experiment at the CERN LHC.” JINST 3: S08002. DOI: 10.1088/1748-0221/3/08/S08002.

[Aartsen 2019] Aartsen, M. G. et al. 2019. “Neutrino astronomy with the next generation IceCube Neutrino Observatory.” arXiv:1911.02561 [astro-ph.HE].

[Abbasi 2013] Abbasi, R. et al. (IceCube Collaboration) 2013. “IceTop: The surface component of IceCube.” Nucl. Instr. and Meth. A 700: 188-220. DOI: 10.1016/j.nima.2012.10.067.

[Abbiendi 2022] Abbiendi, G. 2022. “Status of the MUonE experiment.” Phys. Scripta 97: 054007. DOI: 10.1088/1402-4896/ac6297.

[Abe 2010] Abe, T. et al. 2010. “Belle II Technical Design Report.” arXiv:1011.0352 [physics.ins-det].

[Abe 2018] Abe, K. et al. 2018. “Hyper-Kamiokande Design Report.” arXiv:1805.04163 [physics.ins-det].

[Abe 2020] Abe, K. et al. 2020. “T2K ND280 Upgrade – Technical Design Report.” arXiv:1901.03750 [physics.ins-det].

[Abeysekara 2017] Abeysekara, A. U. et al. 2017. “Observation of the Crab Nebula with the HAWC Gamma-Ray Observatory.” Astrophys. J. 843: 39. DOI: 10.3847/1538-4357/aa7555.

[Abi 2020] Abi, B. et al. 2020. “Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume II: DUNE Physics.” arXiv:2002.03005 [hep-ex].

[Abu-Zayyad 2012] Abu-Zayyad, T. et al. 2012. “The surface detector array of the Telescope Array experiment.” Nucl. Instr. and Meth. A 689: 87-97. DOI: 10.1016/j.nima.2012.05.079.

[Accettura 2023] Accettura, C. et al. 2023. “Towards Muon Collider.” Eur. Phys. J. C 83 (9) 864. (Erratum: Eur. Phys. J. C 84 (1) 36.) arXiv:2303.08533 [hep-ex], DOI:10.1140/epjc/s10052-023-11889-x, Erratum: DOI: 10.1140/epjc/s10052-023-12257-5.

[Achar 1965] Achar, C. V. et al. 1965. “Detection of muons produced by cosmic ray neutrinos deep underground.” Phys. Lett. 18: 196-199. DOI: 10.1016/0031-9163(65)90712-2.

[Adam 2015] Adam, T. et al. 2015. “JUNO Conceptual Design Report.” arXiv:1508.07166 [physics.ins-det].

[Adriani 2002] Adriani, O. et al. 2002. “The L3+C detector, a unique tool-set to study cosmic rays.” Nucl. Instr. and Meth. A 488: 209-225. DOI: 10.1016/S0168-9002(02)00479-5.

[Afach 2023] Afach, S. et al. 2023. “What Can a GNOME Do? Search Targets for the Global Network of Optical Magnetometers for Exotic Physics Searches.” Ann. Der Physik 536: 2300083. DOI: 10.1002/andp.202300083.

[AGILE 2018] The AGILE website, http://agile.rm.iasf.cnr.it/

[Agnese 2018] Agnese, R. et al. 2018. “Results from the Super Cryogenic Dark Matter Search Experiment at Soudan.” Phys. Rev. Lett. 120: 061802. DOI: 10.1103/PhysRevLett.120.061802.

[Agnese2 2018] Agnese, R. et al. 2018. “Low-mass dark matter search with CDMSlite.” Phys. Rev. D 97: 022002. [arXiv:1707.01632v3 [astro-ph.CO]]. DOI: 10.1103/PhysRevD.97.022002

[Agostini 2023] Agostini, M. et al. 2023. “Final Results of GERDA on the Two-Neutrino Double beta Decay Half-Life of Ge76.” Phys. Rev. Lett. 131: 142501. DOI: 10.1103/PhysRevLett.131.142501.

[Aguilar 2013] Aguilar, M. et al. (A.M.S. Collaboration) 2013. “First Result from the Alpha Magnetic Spectrometer on the International Space Station: Precision Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5 – 350 GeV.” Phys. Rev. Lett 110: 141102. DOI: 10.1103/PhysRevLett.110.141102.

[Aguilar-Arevalo 2019] Alexis Aguilar-Arevalo et al. 2019. “Exploring low-energy neutrino physics with the Coherent Neutrino Nucleus Interaction Experiment.” Phys. Rev. D 100: 092005. [arXiv: 1906.02200 [physics.ins-det]]. DOI: 10.1103/PhysRevD.100.092005.

[Aguillard 2023] Aguillard, D. P. et al. 2023. “Measurement of the Positive Muon Anomalous Magnetic Moment to 0.20 ppm.” Phys. Rev. Lett. 131: 161802. DOI: 10.1103/PhysRevLett.131.161802.

[Aharonian 2006] Aharonian, F. et al. 2006. “Observations of the Crab nebula with HESS.” Astronomy and Astrophysics 457: 899-915. DOI: 10.1051/0004-6361:20065351.

[Ahdida 2021] Ahdida, C. et al. (The SHiP Collaboration) 2021. “The SHiP experiment at the proposed CERN SPS Beam Dump Facility." Eur. Phys. J. C 82: 486. DOI: 10.1140/epjc/s10052-022-10346-5. arXiv:2112.01487 [physics.ins-det].

[Ahmed 2017] Ahmed, S. et al. 2017. “Physics Potential of the ICAL detector at the India-based Neutrino Observatory (INO).” Pramana 88: 79. DOI: 10.1007/s12043-017-1373-4.

[Aicheler 2012] Aicheler, M. et al. 2012. “A Multi-TeV Linear Collider Based on CLIC Technology: CLIC Conceptual Design Report.” DOI: 10.5170/CERN-2012-007.

[Aielli 2022] Aielli, G. et al. 2022. “The Road Ahead for CODEX-b.” arXiv:2203.07316 [hep-ex].

[Aker 2021] Aker, M. et al. 2021. “The design, construction, and commissioning of the KATRIN experiment.” JINST 16: T08015. DOI: 10.1088/1748-0221/16/08/T08015.

[Akimov 2017] Akimov, D. et al. 2017. “Observation of Coherent Elastic Neutrino-Nucleus Scattering.” Science 357 : 1123–1126. arXiv: 1708.01294 [nucl-ex]. DOI: 10.1126/science.aao0990.

[Akimov 2020] D. Yu Akimov et al. 2020. “First ground-level laboratory test of the two-phase xenon emission detector RED-100”. JINST 15: P02020. [arXiv: 1910.06190[physics.ins-det]]. DOI: 10.1088/1748-0221/15/02/P02020.

[Albert 2019] Albert, A. et al. 2019. “Science Case for a Wide Field-of-View Very-High-Energy Gamma-Ray Observatory in the Southern Hemisphere.” arXiv:1902.08429 [astro-ph.HE].

[Albrecht 1987] Albrecht, H. et al. 1987. “Observation of B0 - anti-B0 Mixing.” Edited by J. Tran Thanh Van. Phys. Lett. B 192: 245–252. DOI: 10.1016/0370-2693(87)91177-4.

[Alduino 2016] Alduino, C. et al. 2016. “CUORE-0 detector: design, construction and operation.” JINST 11: P07009. DOI: 10.1088/1748-0221/11/07/P07009.

[Alekseev 2022] Alekseev, I. et al. 2022. “First results of the vGeN experiment on coherent elastic neutrino-nucleus scattering”. Phys. Rev. D 106 (2022), p. L05 1101. [arXiv: 2205.04305 [nucl-ex]]. DOI: 10.1103/PhysRevD.106.L051101.

[Aleksic 2016] Aleksic, J. et al. 2016. “The major upgrade of the MAGIC telescopes, Part II: A performance study using observations of the Crab Nebula.” Astropart. Phys. 72: 76-94. DOI: 10.1016/j.astropartphys.2015.02.005.

[Aliaga 2014] Aliaga, L. et al. 2014. “Design, calibration, and performance of the MINER☐A detector.” Nucl. Instr. and Meth. A 743: 130-159. DOI: 10.1016/j.nima.2013.12.053.

[Alpigiani 2018] Alpigiani, C. et al. 2018. “A Letter of Intent for MATHUSLA: a dedicated displaced vertex detector above ATLAS or CMS.” Tech. rep., CERN, Geneva. https://cds.cern.ch/record/2631491.

[Amato 1998] Amato, S. et al. 1998. “LHCb technical proposal: A Large Hadron Collider Beauty Experiment for Precision Measurements of CP Violation and Rare Decays.” https://api.semanticscholar.org/CorpusID:125412568

[Ambats 1998] Ambats, I. et al. 1998. "The MINOS Detectors Technical Design Report." DOI: 10.2172/1861363.

[Amenomori 2009] Amenomori, M. et al. 2009. "Multi-Tev Gamma-Ray Observation From The Crab Nebula Using The Tibet-Iii Air Shower Array Finely Tuned By The Cosmic Ray Moon's Shadow." Astrophys. J. 692: 61. DOI: 10.1088/0004-637X/692/1/61.

[Andre 2014] André, P. et al. 2014. "PRISM (Polarized Radiation Imaging and Spectroscopy Mission): An Extended White Paper." J. Cosmol. Astropart. Phys. 02: 006. DOI: 10.1088/1475-7516/2014/02/006.

[Apel 2010] Apel, W. D. et al. 2010. "The KASCADE-Grande experiment." Nucl. Instr. and Meth. A 620: 202-216. DOI: 10.1016/j.nima.2010.03.147.

[Apollinari 2015] Apollinari, G. et al. 2015. "High-Luminosity Large Hadron Collider (HL-LHC): Preliminary Design Report." DOI: 10.5170/CERN-2015-005.

[Arbey 2021] Arbey, A. and Mahmoudi, F. 2021. ``Dark matter and the early Universe: a review,'' Prog. Part. Nucl. Phys. 119: 103865. DOI: 10.1016/j.ppnp.2021.103865. [arXiv:2104.11488 [hep-ph]].

[Arnquist 2023] Arnquist, I. J. et al. (MAJORANA Collaboration) 2023. "Final Result of the Majorana Demonstrator's Search for Neutrinoless Double-β Decay in 76-Ge." Phys. Rev. Lett. 130: 062501. DOI: 10.1103/PhysRevLett.130.062501.

[Artuso 1989] Artuso, M. et al. 1989. "B0 anti-B0 Mixing at the Upsilon (4S)." Phys. Rev. Lett. 62: 2233. DOI: 10.1103/PhysRevLett.62.2233.

[AS-gamma 2013] Tibet AS-Gamma Experiment, https://www.icrr.u-tokyo.ac.jp/em/

[Astrosat 2024] The AstroSat mission, https://www.isro.gov.in/AstroSat.html

[Athar 2006] Athar, M. S. et al. 2006. "India-based Neutrino Observatory: Project Report. Volume I." Report INO-2006-01.

[ATLAS 2008] The ATLAS Collaboration 2008. "The ATLAS Experiment at the CERN Large Hadron Collider." JINST 3: S08003. DOI: 10.1088/1748-0221/3/08/S08003.

[ATLAS 2012] The ATLAS Collaboration 2012. "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC." Phys. Lett. B 716: 1-29. DOI: 10.1016/j.physletb.2012.08.020.

[ATLAS 2022] The ATLAS Collaboration 2022. "A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery." Nature 607, 52–59 (2022). DOI: 10.1038/s41586-022-04893-w

[ATLAS 2023] The ATLAS Collaboration 2023. "Combined Measurement of the Higgs Boson Mass from the $H \to ZZ^* \to 4\ell$ Decay Channels with the ATLAS Detector Using $\sqrt{s}$=7, 8, and 13 TeV *pp* Collision Data". Phys. Rev. Lett. **131**, 251802. DOI: 10.1103/PhysRevLett.131.251802.

[Atwood 2009] Atwood, W. B. et al. 2009. "The Large Area Telescope on the Fermi Gamma-ray Space Telescope Mission." Astrophys. J. 697: 1071-1102. DOI: 10.1088/0004-637X/697/2/1071.

[Augier 2021] Augier, C. et al. (Ricochet Collaboration) 2021. "Ricochet Progress and Status." J. Low Temp. Phys. 212, 127-137 (2023). [arXiv: 2111.06745[physics.ins-det]]. DOI: 10.1007/s10909-023-02971-5.

[Ave 2011] Ave, M. et al. 2011. "The TRACER instrument: A balloon-borne cosmic-ray detector." Nucl. Instr. and Meth. 654: 140-156. DOI: 10.1016/j.nima.2011.05.050.

[Ayres 2007] Ayres, D. S. et al. 2007. "The NO☐A Technical Design Report." DOI: 10.2172/935497.

[Baldini 2018] Baldini, A. M. et al. 2018. "The design of the MEG II experiment." Eur. Phys. J. C 78: 380. DOI: 10.1140/epjc/s10052-018-5845-6.

[Ball 2016] Ball, A. et al. 2016. "A Letter of Intent to Install a milli-charged Particle Detector at LHC P5." arXiv:arXiv:1607.04669 [physics.ins-det].

[Banuls 2020] Bañuls, M. C. and Cichy, K. 2020. “Review on novel methods for Lattice Gauge Theories.” *Rep. Prog. Phys.* 83: 024401. DOI: 10.1088/1361-6633/ab6311

[Barr 2016] Barr, G., Devenish, R., Walczak, R. and Weidberg, T. “Particle Physics in the LHC Era” (Oxford U. Press, 2016). ISBN: 9780198748564.

[Bartoli 2015] Bartoli, B. et al. 2015. “Crab Nebula: Five-Year Observation With Argo-Ybj.” Astrophys. J. 798: 119. DOI: 10.1088/0004-637X/798/2/119.

[Bauer 2017] Bauer, M. and Plehn, T. 2017. “Yet Another Introduction to Dark Matter: The Particle Physics Approach.” Lect. Notes Phys. 959. (Springer). arXiv:1705.01987 [hep-ph]. DOI: 10.1007/978-3-030-16234-4.

[Bauer 2019] Bauer, M. et al. 2019. “ANUBIS: Proposal to search for long-lived neutral particles in CERN service shafts.” arXiv:1909.13022 [physics.ins-det].

[Behera 2023] Behera, S. P. et al. 2023. “Sterile neutrino searches with reactor antineutrinos using coherent neutrino-nucleus scattering experiments.” Phys. Rev. D 108, 113002 (2023). [arXiv:2304.00912[hep-ph]]. DOI: 10.1103/PhysRevD.108.113002.

[Behnke 2013] Behnke, T. et al. 2013. “The International Linear Collider Technical Design Report - Volume 1: Executive Summary.” arXiv:1306.6327 [physics.acc-ph]

[Benedikt-ee 2019] Benedikt, M. et al. 2019. “Future Circular Collider - European Strategy Update Documents, The Lepton Collider (FCC-ee).” Tech. rep., CERN, Geneva. https://cds.cern.ch/record/2653669.

[Benedikt-hh 2019] Benedikt, M. et al. 2019. “Future Circular Collider - European Strategy Update Documents, The Hadron Collider (FCC-hh).” Tech. rep., CERN, Geneva. https://cds.cern.ch/record/2653674.

[Bennett 2006] Bennett, G. W. et al. 2006. “Final report of the E821 muon anomalous magnetic moment measurement at BNL.” Phys. Rev. D 73: 072003. DOI: 10.1103/PhysRevD.73.072003.

[Bernloehr 2013] Bernloehr, K. et al. 2013. “Monte Carlo design studies for the Cherenkov Telescope Array.” Astropart. Phys. 43: 171-188. DOI: 10.1016/j.astropartphys.2012.10.002.

[Billard 2021] Billard, J. et al. 2021. “Direct Detection of Dark Matter -- APPEC Committee Report.” arXiv:2104.07634 [hep-ex]. DOI: 10.1088/1361-6633/ac5754.

[Blasi 2013] Blasi, P. 2013. “The origin of galactic cosmic rays.” Astron. Astrophys. Rev. 21: 70. DOI: 10.1007/s00159-013-0070-7.

[Borwankar 2024] Borwankar, C. et al. 2024. “Observations of the Crab Nebula with MACE (Major Atmospheric Cherenkov Experiment).” Astropart. Phys. 159: 102960, DOI: 10.1016/j.astropartphys.2024.102960.

[Bose1 2022] Bose, D. et al 2022. “Galactic and extragalactic sources of very high energy gamma rays.” Eur. Phys. J. Special Topics 231: 27-66. DOI: 10.1140/epjs/s11734-022-00434-8.

[Bose2 2022] Bose, D. et al. 2022. “Ground-based gamma-ray astronomy: history and development of techniques.” Eur. Phys. J. Special Topics 231: 3-26. DOI: 10.1140/epjs/s11734-021-00396-3.

[Bonet 2021] Bonet, H. et al. 2021. “Constraints on elastic neutrino nucleus scattering in the fully coherent regime from the CONUS experiment.” Phys. Rev. Lett. 126: 041804. arXiv:2011.00210 [hep-ex]. DOI: 10.1103/PhysRevLett.126.041804.

[Boutigny 1998] Boutigny, D. et al. 1998. “The BABAR physics book: Physics at an asymmetric B factory.” DOI: 10.2172/979931.

[Brambilla 2020] Brambilla, N. 2020. “The XYZ states: experimental and theoretical status and perspectives,”. Phys. Rept. 873: 1-154. arXiv:1907.07583 [hep-ex]. DOI: 10.1016/j.physrep.2020.05.001.

[Britto 2011] Britto, R. J. et al. 2011. “Observations with the High-Altitude GAmma-Ray (HAGAR) telescope array in the Indian Himalayas.” Astrophysics and Space Sciences Transactions 7: 501. DOI: 10.5194/astra-7-501-2011.

[Cahn 2009] Cahn, R. N. and Goldhaber, G. 2009. “The Experimental Foundations of Particle Physics.” (Cambridge U. Press, 2nd ed.). ISBN 978-0-521-52147-5.

[Calafiura 2022] Calafiura, P., Rousseau, D. and Terao, K. 2022. “Artificial Intelligence For High Energy Physics” (World Scientific). DOI: 10.1142/9789811234033_0001.

[CEPC 2018] CEPC Study Group 2018. “CEPC Conceptual Design Report: Volume 2 - Physics and Detector.” arXiv:1811.10545 [hep-ex].

[Chang 2017] Chang, J. et al. 2017. “The DArk Matter Particle Explorer mission.” Astropart. Phys. 95: 6-24. DOI: 10.1016/j.astropartphys.2017.08.005.

[Charles 2005] Charles, J. et al. 2005, Eur. Phys. J. C41, 1-131 (2005) [arXiv: hep-ph/0406184]. DOI: 10.1140/epjc/s2005-02169-1

[Chen 2023] Chen, H.-X. et al. 2023. "An updated review of the new hadron states." Rept. Prog. Phys. 86: 026201. arXiv:2204.02649 [hep-lat]. DOI: 10.1088/1361-6633/aca3b6.

[Choi 2020] Choi, K., Im, S. H. and Sub Shin, C. 2020. ``Recent Progress in the Physics of Axions and Axion-Like Particles," Ann. Rev. Nucl. Part. Sci. 71: 225-252. DOI: 10.1146/annurev-nucl-120720-031147. arXiv:2012.05029 [hep-ph].

[CKMfitter 2021] CKMfitter Group 2021. http://ckmfitter.in2p3.fr

[CMS 2008] The CMS Collaboration 2008. “The CMS experiment at the CERN LHC.” JINST 3: S08004. DOI: 10.1088/1748-0221/3/08/S08004.

[CMS 2012] The CMS Collaboration 2012. “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC.” Physics Letters B 716: 30-61. DOI: 10.1016/j.physletb.2012.08.021.

[CMS 2022] The CMS Collaboration 2022. “A portrait of the Higgs boson by the CMS experiment ten years after the discovery.” Nature 607, 60–68 (2022). DOI: 10.1038/s41586-022-04892-x

[CMS 2024] CMS Physics Results 2024. https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

[CMS-CS 2024] The CMS Collaboration 2024. “Stairway to discovery: a report on the CMS programme of cross section measurements from millibarns to femtobarns.” arXiv: 2405.18661 [hep-ex] DOI: 10.48550/arXiv.2405.18661

[CMS-GEM 2018] Mohammad, A. et al. 2018. "Design of the Readout Boards for the GE21 upgrade of the CMS experiment at the LHC facility." Proc. of the DAE International Symp. on Nucl. Phys. 63. https://inspirehep.net/literature/1731477

[CMS-GEM 2019] Mocellin, G. "GEM detectors for the Upgrade of the CMS Muon Forward system", J. Phys. Conf. Ser.1390: 012116. DOI:10.1088/1742-6596/1390/1/012116.

[CMS-HO 2008] The CMS Collaboration 2008. "Design, performance, and calibration of the CMS hadron-outer calorimeter", Eur. Phys. J. C 57: 653–663. DOI: 10.1140/epjc/s10052-008-0756-6.

[CMS-pub 2024] CMS Public Results 2024. https://cms-results-search.web.cern.ch/

[CMS-RPC 2012] Pant, L. M. et al. 2012. "Characterization of CMS end-cap RPCs assembled in India." Nucl. Instr. and Meth. A 661, Supplement 1. DOI: 10.1016/j.nima.2010.08.082.

[Colaresi 2021] Colaresi, J. et al. 2021. “First results from a search for coherent elastic neutrino-nucleus scattering at a reactor site.” Phys. Rev. D 104: 072003. arXiv:2108.02880[hep-ex]. DOI: 10.1103/PhysRevD.104.072003.

[Combine 2024] Hayrapetyan, A. et al. 2024. “The CMS Statistical Analysis and Combination Tool: COMBINE.” arXiv: 2404.06614 [physics.data-an].

[Contardo 2015] Contardo, D. et al. 2015. "Technical Proposal for the Phase-II Upgrade of the CMS Detector." Tech. rep., Geneva. DOI: 10.17181/CERN.VU8I.D59J.

[Cowan 2018] Cowan, G. and Gershon, T. 2018. "Tetraquarks and pentaquarks", DOI: 10.1088/978-0-7503-1593-7, [arXiv:1808.04153 [physics.pop-ph]].

[deAngelis 2018] De Angelis, A. et al. 2018. "Science with e-ASTROGAM: A space mission for MeV-GeV gamma-ray astrophysics." J. High Energy Astrophys. 19: 1-106. DOI: 10.1016/j.jheap.2018.07.001.

[deBlas 2020] de Blas, J. et al. 2020. "Higgs Boson studies at future particle colliders." J. High Energy Phys. 01: 139. DOI: 10.1007/JHEP01(2020)139.

[Drury 2012] Drury, L. O'C. 2012. "Origin of cosmic rays." Astropart. Phys. 39: 52-60. DOI: 10.1016/j.astropartphys.2012.02.006.

[Dutta 2016] Dutta, B. et al. 2016, "Sensitivity to Z-prime and nonstandard neutrino interactions from ultralow threshold neutrino-nucleus coherent scattering." Phys. Rev. D 93, 013015. DOI: 10.1103/PhysRevD.93.013015.

[ECFA 2021] ECFA Detector R&D Roadmap Process Group 2021. "The 2021 ECFA detector research and development roadmap". CERN-ESU-017. DOI: 10.17181/CERN.XDPL.W2EX

[Esteban 2020] Esteban, I. et al. 2020. "The fate of hints: updated global analysis of three-flavor neutrino oscillations." J. High Energy Phys. 09: 178. DOI: 10.1007/JHEP09(2020)178, http://www.nu-fit.org.

[Evans 2008] Evans, L. and Bryant, P. 2008. "LHC Machine." JINST 3: S08001. DOI: 10.1088/1748-0221/3/08/S08001.

[Falkowski 2023] Falkowski, A. 2023. "Lectures on SMEFT." Eur. Phys. J. C83, 656 (2023). DOI: 10.1140/epjc/s10052-023-11821-3.

[Feng 2018] Feng, J.L. et al 2018. "ForwArd Search ExpeRiment at the LHC." Phys. Rev. D 97:035001. DOI: 10.1103/physrevd.97.035001.

[FPF 2022] Feng, J.L. et al. 2022. "The Forward Physics Facility at the High-Luminosity LHC." Snowmass Report . arXiv:2203.05090 [hep-ex]

[Fermi-LAT 2024] The Fermi Large Area Telescope, https://glast.sites.stanford.edu/

[Freitas 2021] Freitas, A. 2021. "Precision Tests of the Standard Model." TASI lectures 2020, arXiv: 2012.11642 [hep-ph].

[Galper 2017] Galper, A. M. et al. 2017. "The PAMELA experiment: a decade of Cosmic Ray Physics in space." J. Phys. Conf. Series 798: 012033. DOI: 10.1088/1742-6596/798/1/012033.

[Ghosh 2022] Ghosh, S. et al. 2022. "Measurements of gamma ray, cosmic muon and residual neutron background fluxes for rare event search experiments at an underground laboratory." Astropart. Phys. 139: 102700. DOI: 10.1016/j.astropartphys.2022.102700.

[Gingrich 2004] D. M. Gingrich et al. 2004, "The STACEE ground-based gamma-ray detector." IEEE Symposium Conference Record Nuclear Science 2004, pp. 50-54. DOI: 10.1109/NSSMIC.2004.1462067.

[Gupta 2010] Gupta, S. K. et al. 2010. "GRAPES-3: A high-density air shower array for studies on the structure in the cosmic-ray energy spectrum near the knee." Nucl. Instr. and Meth. A 540: 311-323. DOI: 10.1016/j.nima.2004.11.025.

[Hariharan 2023] Hariharan, B. et al. 2023. "Probing Solar storms with GRAPES-3 scintillator detectors." Journal of Atmospheric and Solar-Terrestrial Physics 243: 106005. DOI: 10.1016/j.jastp.2023.106005.

[HCT 2024] The Himalayan Chandra Telescope (HCT) 2024, https://www.iiap.res.in/iao/cycle.html.

[Horandel 2008] Horandel, J. 2008. "The origin of galactic cosmic rays." Nucl. Instr. and Meth. A 588: 181-188. DOI: 10.1016/j.nima.2008.01.036.

[Isenhower 2006] Isenhower, D. et al. 2006. "Proposal to upgrade the MIPP experiment." DOI:10.2172/900842.

[Jashal 2022] Jashal, B. K. et al. 2022. "Evolution of LHC Computing Grid for Run-III and Beyond with Emphasis on TIFR CMS Tier-II and Indian Contribution." Proceedings of the XXIV DAE-BRNS High Energy Physics Symposium, Jatni, India, eds. B. Mohanty, S.K. Swain et al., Singapore: Springer Nature Singapore. 781–785. ISBN: 981192354X, 9789811923548.

[Jayakumar 2012] Jayakumar, R. 2012. "Particle Accelerators, Colliders, and the Story of High Energy Physics" (Springer). DOI: 10.1007/978-3-642-22064-7

[JUSL 2024] The Jaduguda Underground Science Laboratory (JUSL) webpage 2024. https://www.saha.ac.in/web/about-InDEx

[Khalil 2022] Khalil, S. and Moretti, S. 2022. "Standard Model Phenomenology." (CRC Press, Boca Raton, 2022). :DOI10.1201/9780429443015

[Khatiwada 2021] R.Khatiwada, R. et al. (ADMX Collaboration) 2021. "Axion Dark Matter Experiment: Detailed design~and operations.'' Rev. Sci. Instrum. 92: 124502. DOI: 10.1063/5.0037857. [arXiv:2010.00169 [astro-ph.IM]].

[Kim 2008] Kim, J. E. and G.~Carosi 2008. ``Axions and the Strong CP Problem.'' Rev. Mod. Phys. 82: 557-602. [erratum: Rev. Mod. Phys. 91: 049902]. arXiv:0807.3125 [hep-ph]. DOI: 10.1103/RevModPhys.82.557.

[Kobayashi 1973] Kobayashi, M. and Maskawa, T. 1973. "CP Violation in the Renormalizable Theory of Weak Interaction." Prog. Theor. Phys. 49: 652–657. DOI: 10.1143/PTP.49.652.

[Kumar 2023] Kumar, S. et al. 2023. "Development of a prototype 16-channel dual gain waveform readout and data transfer system for IACT based telescope camera." Nucl. Instr. and Meth. A 1049: 168091. DOI: 10.1016/j.nima.2023.168091.

[Liu 2022] Liu, J. et al. (The BREAD Collaboration) 2022. "Broadband Solenoidal Haloscope for Terahertz Axion Detection.'' Phys. Rev. Lett. 128: 131801. DOI: 10.1103/PhysRevLett.128.131801. arXiv:2111.12103 [physics.ins-det].

[LlewellynS 2015] Llewellyn Smith C. 2015. "Genesis of the Large Hadron Collider." Phil. Trans. R. Soc. A 373: 20140037. DOI: 10.1098/rsta.2014.003.

[London 2022] London, D. and Matias, J. 2022. "B Flavour Anomalies: 2021 Theoretical Status Report.'' Ann. Rev. Nucl. Part. Sci. 72: 37-68, DOI: 10.1146/annurev-nucl-102020-090209

[Marsh 2015] Marsh, D. J. E. 2015. ``Axion Cosmology.'' Phys. Rept. 643: 1-79. arXiv:1510.07633 [astro-ph.CO]. DOI: 10.1016/j.physrep.2016.06.005.

[Maity 2023] Maity, M. (Ed.) 2023. "India and the Large Hadron Collider." Eur. Phys. J. Sp. Topics 232. DOI: 10.1140/epjs/s11734-023-01041-x.

[Mohanty 2009] Mohanty, P. K. et al. 2009. "Measurement of some EAS properties using new scintillator detectors developed for the GRAPES-3 experiment." Astropart. Phys. 31: 24-36. DOI: 10.1016/j.astropartphys.2008.11.004.

[Mollerach 2018] Mollerach, S. and Roulet, E. 2018. "Progress in high energy cosmic rays." Progress in Particle and Nuclear Physics 98: 85-118. DOI: 10.1016/j.ppnp.2017.10.002.

[MSV-2035-ASTA] The report "Mega Science Vision-2035 (Accelerator S&T and Applications)". A roadmap prepared by the Indian Accelerator Physics Community.

[MSV-2035-A&A] The report "Mega Science Vision-2035 (Astronomy and Astrophysics)". A roadmap prepared by the Indian Astronomy and Astrophysics Community.
https://psa.gov.in/CMS/web/sites/default/files/psa_custom_files/MSV__2035_AandA_Final_19%20Aug%202024.pdf

[MSV-2035-NP] The report “Mega Science Vision – 2035 (Nuclear Physics)”. A roadmap prepared by the Indian Nuclear Physics Community.
https://psa.gov.in/CMS/web/sites/default/files/psa_custom_files/MSV2035-NP-Final.pdf

[Nagashima 2014] Nagashima, Y. 2014. “Beyond the Standard Model of Elementary Particle Physics” (Wiley). ISBN: 978-3-527-41177-1.

[NEP 2020] National Education Policy 2020, Ministry of Human Resource Development, Govt. of India. https://www.education.gov.in/sites/upload_files/mhrd/files/NEP_Final_English_0.pdf

[NQM 2024] National Quantum Mission of India 2024. https://dst.gov.in/national-quantum-mission-nqm

[P5 2023] The report of the US Particle Physics Project Prioritization Panel 2023.
https://www.usparticlephysics.org/2023-p5-report/.

[Pare 2002] Pare, E. et al. 2002. ``CELESTE: An atmospheric Cherenkov telescope for high energy gamma astrophysics,'' Nucl. Instr. and Meth. A 490: 71-89. DOI: 10.1016/S0168-9002(02)01005-7.

[Peccei 1977] Peccei, R. D. and Quinn, H. R. 1977. “CP Conservation in the Presence of Pseudoparticles.” Phys. Rev. Lett. 38: 1440–1443. DOI: 10.1103/PhysRevLett.38.1440.

[PICO 2024] The PICO experiment: searching for dark matter with bubble chambers, https://www.picoexperiment.com/

[Pinfold 2017] Pinfold, J. 2017. “The MoEDAL experiment at the LHC.” EPJ Web Conf. 145: 12002. DOI: 10.1051/epjconf/201614512002.

[Plehn 2014] Plehn, T. 2014. “Lectures on LHC Physics.” (Springer). DOI:10.1007/978-3-642-24040-9.

[Rao 2023] Rao, S. K. et al. 2023. “Analog signal processing for large area SiPM in Cherenkov telescope camera.” Nucl. Instr. and Meth. A 1051: 168191. DOI: 10.1016/j.nima.2023.168191.

[Rhodes 2012] Rhodes, R. 2012. “The Making of the Atomic Bomb.” (Simon & Schuster, 25th Anniversary ed.). ISBN: 978-0-671-44133-3.

[Sahoo 2021] Sahoo, S. et al. 2021. “The background study at 555 m deep underground with superheated emulsion detector.” Nucl. Instr. and Meth. A 1008: 165450. DOI: 10.1016/j.nima.2021.165450.

[Schneider 2021] Schneider, A. 2021. “Quantum Sensing Experiments with Superconducting Qubits.” (KIT Scientific Publishing). DOI: 10.5445/KSP/1000118743.

[SeaQuest 2010] The SeaQuest Collaboration 2024. “Drell-Yan measurements by Fermilab E-906/SeaQuest experiment.” http://www.phy.anl.gov/mep/SeaQuest/

[Shiltsev 2023] Shiltsev, V. et al. (Eds.) 2023. “Novel ideas for accelerators, particle detection and data challenges at future colliders.” (Frontiers Media SA Ebook). DOI: 10.3389/fphy.2023.1177534.

[SKA 2024] The Square Kilometre Array Observatory 2024. https://www.skao.int/

[SND 2021] Ahdida, C. et al. 2021. “SND@LHC - Scattering and Neutrino Detector at the LHC”. CERN Report, CERN-LHCC-2021-003. URL: https://cds.cern.ch/record/2750060?ln=en

[Snowmass 2021] Proceedings of the 2021 US Community Study on the Future of Particle Physics, https://www.slac.stanford.edu/econf/C210711/

[thooft 1971] 't Hooft, G. 1971. “Renormalizable Lagrangians for Massive Yang-Mills Fields.'' Nucl. Phys. B 35: 167-188. DOI: 10.1016/0550-3213(71)90139-8

[TMT 2024] The TMT International Observatory 2024. https://www.tmt.org/

[Torii 2011] Torii, S. et al. 2011. “Calorimetric electron telescope mission: Search for dark matter and nearby sources.” Nucl. Instr. and Meth. A 630: 55-57. DOI: 10.1016/j.nima.2010.06.026.

[Tzanankos 2011] Tzanankos, G. et al. (The MINOS+ Collaboration) 2011. “MINOS+: a Proposal to FNAL to run MINOS with the medium energy NuMI beam.'' DOI: 10.2172/1028838.

[Varsi 2024] Varsi, F. et al. 2024. "Evidence of a Hardening in the Cosmic Ray Proton Spectrum at around 166 TeV Observed by the GRAPES-3 Experiment." Phys. Rev. Lett. 132: 051002. DOI: 10.1103/PhysRevLett.132.051002.

[VS 2019] Vigyan Samagam 2019. https://dst.gov.in/vigyan-samagam-exhibition-brings-world-major-mega-science-projects-together.

[Wagner 2021] Wagner, V. et al. 2021. "Exploring CEvNS of reactor neutrinos with the NUCLEUS experiment.". J. Phys. Conf. Ser. 2156: 012118. DOI: 10.1088/1742-6596/2156/1/012118.

[Weekes 2002] Weekes, T. C. et al. 2002. "VERITAS: the Very Energetic Radiation Imaging Telescope Array System." Astropart. Phys. 17: 221-243. DOI: 10.1016/S0927-6505(01)00152-9.

[Yadav 2022] Yadav, K. K. et al. 2022. "Commissioning of the MACE gamma-ray telescope at Hanle, Ladakh, India." Current Science 123: 1428. DOI: 10.18520/cs/v123/i12/1428-1435.

[Zimmerman 2019] Zimmermann, F. et al. 2019. "Future Circular Collider - European Strategy Update Documents, High-Energy LHC (HE-LHC)." Tech. rep., CERN, Geneva. https://cds.cern.ch/record/2653676.

Glossary of Acronyms

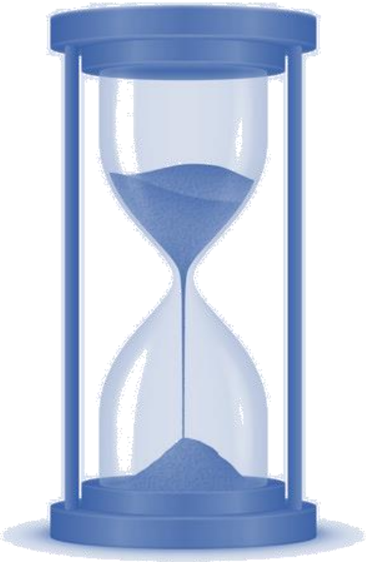
ADMX	Axion Dark Matter eXperiment
AI	Artificial Intelligence
AMS	Alpha Magnetic Spectrometer
ANUBIS	AN Underground Belayed In-Shaft search experiment
APV	Atomic Parity Violation
BSM	Beyond Standard Model
CAST	CERN Axion Solar Telescope
CERN	European Organization for Nuclear Research
CKM	Cabibbo–Kobayashi–Maskawa
CLIC	Compact LInear Collider
CMBR	Cosmic Microwave Background Radiation
CMS	Compact Muon Solenoid
COBE	Cosmic Background Explorer
CODEX-b	COmpact Detector for EXotics at LHCb
CP	Charge Parity
CR	Cosmic Ray
CTA	Cherenkov Telescope Array
DAE	Department of Atomic Energy
DESY	Deutsches Elektronen-SYnchrotron
DLS	Deuterated Liquid Scintillator Detector
DM	Dark Matter
DST	Department of Science and Technology
DUNE	Deep Underground Neutrino Experiment
ECFA	European Committee for Future Accelerators
FASER	ForwArd Search ExpeRiment
FCC	Future Circular Collider
Fermi-LAT	Fermi Large Area Telescope
FLArE	Forward Liquid Argon Experiment
FNAL	Fermi National Accelerator Laboratory (Fermilab)
FORMOSA	FORward MicrOcharge SeArch
FPF	Forward Physics Facility
FTE	Full-time Equivalent
GEM	Gas Electron Multiplier

GMRT	Giant Metrewave Radio Telescope
GNOME	Global Network of Optical Magnetometers for Exotic physics searches
GRAPES-3	Gamma Ray Astronomy PeV EnergieS (Phase-3)
HAGAR	High Altitude GAmma-Ray
HEI	Higher Educational Institutions
HEP	High Energy Physics
HK	Hyper-Kamiokande
HL-LHC	High Luminosity LHC
HPC	High-Performance Computing
HTC	High-Throughput Computation
IAC-HEP	Inter-Agency Committee for HEP MSPs
IACT	Imaging Atmospheric Cherenkov Technique
ICAL	Iron Calorimeter
ICARUS	Imaging Cosmic And Rare Underground Signals
ICNSE	India-based Coherent Neutrino Scattering Experiment
IICHEP	Inter-Institutional Centre for High Energy Physics
ILC	International Linear Collider
INO	India-based Neutrino Observatory
ISMRAN	Indian Scintillator Matrix for Reactor Anti-Neutrinos
ISR	Intersecting Storage Rings
IUPAP	International Union of Pure and Applied Physics
JUSL	Jaduguda Underground Science Laboratory
KATRIN	Karlsruhe Tritium Neutrino
LEP (collider)	Large Electron Positron (collider)
LHC	Large Hadron Collider
LHCb	Large Hadron Collider beauty
LLP	Long-Lived Particle
LST	Large Size Telescope
LUX	Large Underground Xenon
MACE	Major Atmospheric Cherenkov Experiment
MAGIC (telescope)	Major Atmospheric Gamma Imaging Cherenkov (telescope)
MATHUSLA	Massive Timing Hodoscope for Ultra Stable neutraL pArticles
MINER	Mitchell Institute Neutrino Experiment at Reactor
MINERνA	Main Injector Neutrino ExpeRiment

MicroBooNE	Micro Booster Neutrino Experiment
ML	Machine Learning
MoEDAL	Monopole and Exotics Detector At the LHC
MSCU	Mega Science Coordination Unit
MSP	Mega Science Project
MST	Medium Size Telescope
MSV-2035	Mega Science Vision-2035
MUonE	MUon ON Electron elastic scattering
NDBD	Neutrinoless Double Beta Decay
NEP	National Education Policy
NKN	National Knowledge Network
NOνA	Neutrinos at the Main Injector Off-Axis ν_e Appearance
NP	Nuclear Physics
NQM	National Quantum Mission
NUSTEC	Neutrino Experimental-Theory Collaboration
P5	Particle Physics Project Prioritization Panel, USA
PI	Principal Investigator
PICASSO/PICO	Project In CAnada to Search for Supersymmetric Objects
PRL	Physical Research Laboratory, Ahmedabad
PSA	Principal Scientific Advisor to the Government of India
QCD	Quantum Chromodynamics
RPC	Resistive Plate Chamber
SBND	Short Baseline Near Detector at Fermilab
ShiP	Search for Hidden Particles
SLAC	Stanford Linear Accelerator Center
SM	Standard Model
SMEFT	Standard Model Effective Field Theory
SND	Scattering and Neutrino Detector at the LHC
SRC	Scientific Review Committee
SST	Small Size Telescopes
SuperCDMS	Cryogenic Dark Matter Search
SWGO	Southern Wide-field Gamma-ray Observatory
SWOT	Strengths, Weaknesses, Opportunities and Threats
TDR	Technical Design Report

TIFR	Tata Institute of Fundamental Research
TinTin	The INdia-based TIN detector
UCIL	Uranium Corporation of India
WIMP	Weakly Interacting Massive Particle
WMAP	Wilkinson Microwave Anisotropy Probe

ANNEXURES



Annexure A.1
Projected Timelines of Major Projects

Experiment	2020 — 2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
CMS	Data collection				Upgrading			Data Collection				Maintenance		Data
BELLE II	Data	Upgrading	Data		Upgrading		Data collection						Analysis	
NOvA	Data collection													
PICO	Data	Upgrading	Data collection											
MAGIC	Data collection													
GRAPES-3	Data collection and Upgrading										Data Collection & Analysis			
MACE	Data collection and Analysis													
Super-CDMS	Data Collection and Analysis													
ICNSE	Concept and Sanction			Planning and Commissioning					Data Collection and Analysis					
JUSL	Commissioning	Data Collection and Analysis								Upgrading and Data Collection				
INO	Planning and R&D													
FCC-ee	Planning and R&D									Construction & Commissioning				
ILC *	Planning and R&D					Construction & Commissioning								
FCC-pp	Planning and R&D													
MuonC	Concept and Sanction					Planning and R&D								
MATHUSLA	Planning and R&D				Commissioning			Data Collection and Analysis						
DUNE	Construction & Commissioning								Data Collection and Analysis					
HYPER-K	Construction & Commissioning					Data Collection and Analysis								
IceCube Gen2	Planning and R&D				Construction & Commissioning							Data Analysis		
CTA	Planning and R&D					Construction & Commissioning					Data Analysis			
DINO*	Planning and R&D									Construction & Commissioning				
Quantum Sensors *	Concept and Sanction									Planning and R&D				
HEP detector in space *	Concept and Sanction									Planning and R&D				

* Indicates uncertainty

[grey box] indicates discontinuation of the project

Gold *dinara* of Samudragupta, depicting the goddess Saraswati

Annexure A.2

Tentative Assessment of Funding Requirements

	Years →		2020-2025		2025-2030		2030-2035	
Sec-tion	Name / Acronym of Project	Current/last sanctioned annual budget (Rs. Cr)	FTE personnel *	Funding (p.a.) (Rs. Cr)	FTE personnel *	Funding (p.a.) (Rs. Cr)	FTE personnel*	Funding (p.a.) (Rs. Cr)
Section 2. Current Projects and their Upgrades								
2.1.1	CMS	24	100	24	150	40	200	45
2.1.1	CERN Associate Membership (50%) †	50	NA	80	NA	100	NA	120
2.1.2	Belle II	1.5	45	1.5	55	5	45	3
2.1.3	NOνA	2.2	20	2.2	30	4	—	—
2.1.4	Picasso/PICO	0	3	0	5	0	5	0
2.1.5	MAGIC	0.6	6	0.2	10	0.2	—	—
2.2.1	GRAPES-3	3	25	5	40	7.5	50	10
2.2.2	MACE + MACE stereo	5	80	5	50	62	50	42
2.2.3	ICNSE	0	10	2	15	5	20	3
2.2.4	INO	5	35	5	—	—	—	—
Section 3. From Current Expertise to Future Experiments								
3.2.1	FCC-ee / ILC	0	20	0	40	15	70	25
3.2.1	FCC-pp	0	0	0	0	0	15	15
3.2.1	muon collider	0	5	0	5	2	10	5
3.2.2	MATHUSLA/FPF	0	10	2	20	8	30	10
3.2.3	DUNE	0	10	1	25	17	35	15
3.2.4	Hyper-Kamiokande	0	5	0	15	20	25	15
3.2.5	Icecube-Gen2	0.5	5	0.6	10	4	25	20
3.2.6	CTA	0	4	2	40	20	80	15
3.2.7	SWGO	0	0	0	1	0	1	0
3.2.8	Super-CDMS	1	4	0.1	6	1.5	8	1.5
3.2.9	GNOME/ADMX	0	0	0	1	1	3	1.5
3.3.1	JUSL/ InDEx	2	8	1	15	3	30	12

3.3.2	Quantum Sensors	0	2	1	6	3	20	20
Section 4. Building an Ecosystem : Investing and Planning for the Future								
4.3.3	HPC (NP + HEP) ***	0	350	200	450	240	550	300
4.4.1	INFHEP	0	10	2	30	40	40	20
4.4.3	Underground facility	0	2	5	25	100	15	50
Section 5. Possible India-based Projects								
3.3.4	Experiments synergistic with NP***	0	5	50	10	70	15	100
3.3.5	Satellite-based Experiments	0	0	0	5	2	10	5
3.3.3 3.3.4	Other new ideas (including experiments at the underground facility)	0	2	10	10	25	20	50

(The monetary estimates are based on actual figures, where available, and extrapolations otherwise. The figures quoted for future 5-year periods have the inherent inflationary and FE rate uncertainties.)

* Personnel include scientists and engineers, including students and postdocs

† This accounts for the 50% of the CERN Associate Membership; for the rest, please refer to the MSV-2035-Nuclear Physics document [MSV-2035-NP]

*** already included in the MSV-2035 Nuclear Physics report [MSV-2035-NP]

NA indicates ‘Not Applicable’

Prioritised Landscape for 2020 – 2025

MODEST GROWTH SCENARIO	Rs. (Cr) (p.a.)
Total Required Funding (p.a.)	**138.6**
Ongoing projects	**126.0**
Collider Physics	**105.5**
(1) CMS	24.0
(2) CERN Associate Membership	80.0
(3) Belle -II	1.5
Neutrinos	**9.2**
(1) NOνA / MINERνA	2.2
(2) ICNSE	2.0
(3) INO	5.0
Astroparticle Physics	**11.3**
(1) GRAPES-3	5.0
(2) MACE	5.0
(3) JUSL/InDEx	1.0
(4) MAGIC	0.2
(5) Super-CDMS	0.1
New projects / activities	**3.6**
Collider Physics	**0.5**
(1) FCC-ee / ILC	0.0
(2) MATHUSLA/FPF	0.5
(3) FCC-pp	0.0
(4) muon collider	0.0
Neutrinos	**1.6**
(1) DUNE	1.0
(2) HyperKamiokande	0.0
(3) IceCube-Gen2	0.6
Astroparticle Physics	**1.5**
(1) CTA	0.5
(2) Quantum Sensors	1.0
Ecosystem Building Activities	**4.0**
(1) Underground Facility	2.0
(2) Indian National Facility in High Energy Physics (INFHEP)	2.0
(3) HPC-NP&HEP ***	50.0***
Possible India-based Projects	**5.0**
(1) Satellite-based experiment	0.0
(2) Other new ideas (incl. experiments at the underground facility)	5.0
(3) Experiments synergistic with nuclear physics (DLS, ISMRAN, Tin.Tin) ***	15.0***

ASPIRATIONAL GROWTH SCENARIO	Rs. (Cr) (p.a.)
Total Required Funding (p.a.)	**149.6**
Ongoing projects	**126.0**
Collider Physics	**105.5**
(1) CMS	24.0
(2) CERN Associate Membership	80.0
(3) Belle -II	1.5
Neutrinos	**9.2**
(1) NOνA / MINERνA	2.2
(2) ICNSE	2.0
(3) INO	5.0
Astroparticle Physics	**11.3**
(1) GRAPES-3	5.0
(2) MACE + MACE Stereo	5.0
(3) JUSL/InDEx	1.0
(4) MAGIC	0.2
(5) Super-CDMS	0.1
New projects / activities	**6.6**
Collider Physics	**2.0**
(1) FCC-ee / ILC	0.0
(2) MATHUSLA/FPF	2.0
(3) FCC-pp	0.0
(4) muon collider	0.0
Neutrinos	**1.6**
(1) DUNE	1.0
(2) HyperKamiokande	0.0
(3) IceCube-Gen2	0.6
Astroparticle Physics	**3.0**
(1) CTA	2.0
(2) Quantum Sensors	1.0
Ecosystem Building Activities	**7.0**
(1) Underground Facility	5.0
(2) Indian National Facility in High Energy Physics (INFHEP)	2.0
(3) HPC-NP&HEP ***	200.0***
Possible India-based Projects	**10.0**
(1) Satellite-based experiment	0.0
(2) Other new ideas (incl. experiments at the underground facility)	10.0
(3) Experiments synergistic with nuclear physics (DLS, ISMRAN, Tin.Tin) ***	50.0***

*** not added since already included in [MSV-2035-NP]

Prioritised Landscape for 2025 – 2030

MODEST GROWTH SCENARIO	Rs. (Cr) (p.a.)
Total Required Funding (p.a.)	**360.2**
Ongoing projects	**228.2**
Collider Physics	**145.0**
(1) CMS	40.0
(2) CERN Associate Membership	100.0
(3) Belle -II	5.0
Neutrinos	**9.0**
(1) NOνA / MINERνA	4.0
(2) ICNSE	5.0
(3) INO	0.0
Astroparticle Physics	**74.2**
(1) GRAPES-3	7.5
(2) MACE + MACE Stereo	62.0
(3) JUSL/InDEx	3.0
(4) MAGIC	0.2
(5) Super-CDMS	1.5
New projects / activities	**51.0**
Collider Physics	**11.0**
(1) FCC-ee / ILC	5.0
(2) MATHUSLA/FPF	5.0
(3) FCC-pp	0.0
(4) muon collider	1.0
Neutrinos	**22.0**
(1) DUNE	10.0
(2) HyperKamiokande	10.0
(3) IceCube-Gen2	2.0
Astroparticle Physics	**18.0**
(1) CTA	15.0
(2) Quantum Sensors	3.0
Ecosystem Building Activities	**70.0**
(1) Underground Facility	50.0
(2) Indian National Facility in High Energy Physics (INFHEP)	20.0
(3) HPC-NP&HEP ***	120.0***
Possible India-based Projects	**11.0**
(1) Satellite-based experiment	1.0
(2) Other new ideas (incl. experiments at the underground facility)	10.0
(3) Experiments synergistic with nuclear physics (DLS, ISMRAN, Tin.Tin) ***	40.0***

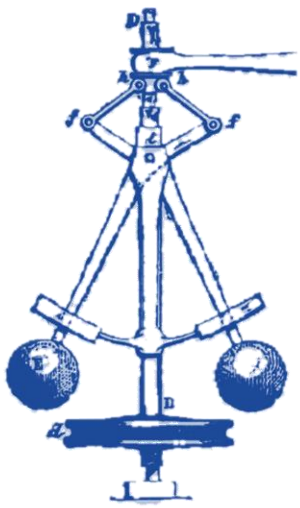
ASPIRATIONAL GROWTH SCENARIO	Rs. (Cr) (p.a.)
Total Required Funding (p.a.)	**484.2**
Ongoing projects	**228.2**
Collider Physics	**145.0**
(1) CMS	40.0
(2) CERN Associate Membership	100.0
(3) Belle -II	5.0
Neutrinos	**9.0**
(1) NOνA / MINERνA	4.0
(2) ICNSE	5.0
(3) INO	0.0
Astroparticle Physics	**74.2**
(1) GRAPES-3	7.5
(2) MACE + MACE Stereo	62.0
(3) JUSL/InDEx	3.0
(4) MAGIC	0.2
(5) Super-CDMS	1.5
New projects / activities	**89.0**
Collider Physics	**25.0**
(1) FCC-ee / ILC	15.0
(2) MATHUSLA/FPF	8.0
(3) FCC-pp	0.0
(4) muon collider	2.0
Neutrinos	**41.0**
(1) DUNE	17.0
(2) HyperKamiokande	20.0
(3) IceCube-Gen2	4.0
Astroparticle Physics	**23.0**
(1) CTA	20.0
(2) Quantum Sensors	3.0
Ecosystem Building Activities	**140.0**
(1) Underground Facility	100.0
(2) Indian National Facility in High Energy Physics (INFHEP)	40.0
(3) HPC-NP&HEP ***	240.0***
Possible India-based Projects	**27.0**
(1) Satellite-based experiment	2.0
(2) Other new ideas (incl. experiments at the underground facility)	25.0
(3) Experiments synergistic with nuclear physics (DLS, ISMRAN, Tin.Tin) ***	70.0***

*** not added since already included in [MSV-2035-NP]

Prioritised Landscape for 2030 – 2035

MODEST GROWTH SCENARIO	Rs. (Cr) (p.a.)	ASPIRATIONAL GROWTH SCENARIO	Rs. (Cr) (p.a.)
Total Required Funding (p.a.)	**364.0**	**Total Required Funding (p.a.)**	**503.0**
Ongoing projects	**231.5**	**Ongoing projects**	**236.5**
Collider Physics	**163.0**	**Collider Physics**	**168.0**
(1) CMS	40.0	(1) CMS	45.0
(2) CERN Associate Membership	120.0	(2) CERN Associate Membership	120.0
(3) Belle -II	3.0	(3) Belle -II	3.0
Neutrinos	**3.0**	**Neutrinos**	**3.0**
(1) NOνA / MINERνA	0.0	(1) NOνA / MINERνA	0.0
(2) ICNSE	3.0	(2) ICNSE	3.0
(3) INO	0.0	(3) INO	0.0
Astroparticle Physics	**65.5**	**Astroparticle Physics**	**65.5**
(1) GRAPES-3	10.0	(1) GRAPES-3	10.0
(2) MACE + MACE Stereo	42.0	(2) MACE + MACE Stereo	42.0
(3) JUSL/InDEx	12.0	(3) JUSL/InDEx	12.0
(4) MAGIC	0.0	(4) MAGIC	0.0
(5) Super-CDMS	1.5	(5) Super-CDMS	1.5
New projects / activities	**72.5**	**New projects / activities**	**141.5**
Collider Physics	**26.5**	**Collider Physics**	**55.0**
(1) FCC-ee / ILC	15.0	(1) FCC-ee / ILC	25.0
(2) MATHUSLA/FPF	5.0	(2) MATHUSLA/FPF	10.0
(3) FCC-pp	5.0	(3) FCC-pp	15.0
(4) muon collider	1.5	(4) muon collider	5.0
Neutrinos	**27.5**	**Neutrinos**	**50.0**
(1) DUNE	10.0	(1) DUNE	15.0
(2) HyperKamiokande	7.5	(2) HyperKamiokande	15.0
(3) IceCube-Gen2	10.0	(3) IceCube-Gen2	20.0
Astroparticle Physics	**18.5**	**Astroparticle Physics**	**36.5**
(1) CTA	12.0	(1) CTA	15.0
(2) GNOME/ADMX	1.5	(2) GNOME/ADMX	1.5
(3) Quantum Sensors	5.0	(3) Quantum Sensors	20.0
Ecosystem Building Activities	**35.0**	**Ecosystem Building Activities**	**70.0**
(1) Underground Facility	25.0	(1) Underground Facility	50.0
(2) Indian National Facility in High Energy Physics (INFHEP)	10.0	(2) Indian National Facility in High Energy Physics (INFHEP)	20.0
(3) HPC-NP&HEP ***	150.0***	(3) HPC-NP&HEP ***	300.0***
Possible India-based Projects	**25.0**	**Possible India-based Projects**	**55.0**
(1) Satellite-based experiment	5.0	(1) Satellite-based experiment	5.0
(2) Other new ideas (incl. experiments at the underground facility)	20.0	(2) Other new ideas (incl. experiments at the underground facility)	50.0
(3) Experiments synergistic with nuclear physics (DLS, ISMRAN, Tin.Tin) ***	50.0***	(3) Experiments synergistic with nuclear physics (DLS, ISMRAN, Tin.Tin) ***	100.0***

*** not added since already included in [MSV-2035-NP]



Textbook sketch of a Watt Governor a key invention of the Industrial Revolution

Annexure A.3:
Collaboration with Industry

Several industries within India have been involved in the hardware projects or product development conducted for MSPs in High Energy Physics both in India and abroad. A selected list of industry participation in such projects are given in the table below.

	Industry name	Nature of contribution	Project name	Remarks / output
1.	Bharat Electronics Ltd	Development of Si microstrip detectors	Belle II	First indigenous Si strip detectors for use in medium-energy nuclear physics and space-based applications.
2.	Reliance Industries Ltd.	Carbon composite frames for the STT detector modules	DUNE	The company is interested in partnering in the development of the STT tracking detector.
3.	Electrowaves Electronics Pvt. Ltd.	SMD-PCB, Endplugs	DUNE	Contacts with this company will be useful for CTA also
4.	L&T and/or Godrej	Mechanical Structure of Telescopes	CTA	Initial contacts made and a very preliminary budget has been discussed.
5.	Bhargab Engineering Works, Howrah	Temperature & pressure-controlled system (TPCS)	SLD-JUSL (no precise name for the project)	It is for the DM search expt at JUSL, Jaduguda. The first TPCS is under development and the preliminary budget has been discussed.
6.	CSIR – Central Scientific Instruments Organization, Chandigarh	R&D for Scintillator Tiles, Grooving	CMS HO Calorimeter	
7.	Central Tool Room, Ludhiana	Grooving of the Scintillator Tiles	CMS HO Calorimeter	
8.	Bharat Electronics Limited, Bengaluru	Silicon milli-strip sensors	CMS Preshower	
9.	Alpha Pneumatics, Mumbai	Gas Mixing System for RPC, PLC Based Gas Mixing Controller, Gas Recirculation system	CMS RPC Detector	
10.	Hi-Q Electronics	Baseplate PCB and hexaboard PCBs	CMS HGCAL	These products are indigenously developed and would likely be our in-kind contributions to the project.
11.	H. Fillunger & Co PVT LTD., Pune	Custom designed stainless steel (SS) manifold system	CRL, Ooty	Used during proportional counter (PRC) fabrication at GRAPES-3
12.	Techno Cables PVT LTD., Hyderabad	Customised Coaxial Cables	CRL, Ooty	In use at GRAPES-3
13.	Kovai CNC Applications PVT LTD., Coimbatore	Sigma grooves for plastic scintillator tiles	L3-C, CERN and CRL, Ooty	Used for Air Shower Array on surface at P2, LHC, CERN, Geneva and CRL, Ooty
14.	Craftsman Automation Limited, Coimbatore	Polishing of SS base plates for plastic scintillator casting mould	CRL, Ooty	Plastic Scintillator casting at CRL, Ooty
15.	Fontech India Welding, Coimbatore	Automation of Welding	CRL, Ooty	Tried out for proportional counter fabrication
16.	EWAC Alloys Limited (A subsidiary of L&T Ltd),	Manual Welding	CRL, Ooty	Tried out for proportional counter fabrication

	Coimbatore			
17.	Micropack, Bengaluru	PCB fabrication	CMS HCAL	CMS HB, HE front-end electronics.
18.	Peninsula Electronics, Bengaluru	Electronics board assembly. Fabrication of prototype boards (ESM, IPMC, ELM)	CMS HCAL	CMS HB, HE front-end electronics. Upgrade of trigger electronics.
19.	Eata Plast Fabrics, Rabale, Mumbai	Fabrication of Aluminium housings	CMS HCAL	CMS HB, HE front-end electronics
20.	Electronics Enterprises, Kota	Back-end electronics, HV/LV systems for detectors	CMS	
21.	PARSRAM & COMPANY PVT. LTD., Mumbai	Scintillators, PMTs, Back-end electronics, HV/LV systems for detectors	CMS	
22.	Silicom Electronics, Delhi	Oscilloscopes, Pulse Generators, LV systems, Digital multimeters, Sourcemeters	CMS	Setting up particle physics detector development facilities
23.	Electronic Enterprises (India) Pvt. Ltd	Power Supply systems and Front-End/Data Acquisition modules (Partnership with CAEN)	CMS	Particle and nuclear physics detector development and indigenous set up of particle physics experiments for training graduate and masters students.
24.	DesignTech Systems India, Hyderabad	Telescope Structure Design and Analysis	MACE	
25.	ECIL, Hyderabad	Telescope Structure Manufacturing	MACE	
26.	MECHVAC, Mumbai	Mirrors	MACE	For the first time in India, the company produced diamond-turned mirrors.

Annexure A.4:
Technology Development, Societal Applications and Spinoffs

Since the early days of cosmic ray research, the Indian HEP community has a long-standing tradition of building particle detectors, gradually evolving into a strong participation in Mega Science Projects in HEP like the L3 experiment at LEP, the DØ experiment at the Tevatron, the CMS and ALICE experiments at LHC, as well as astrophysics experiments like GRAPES at Udhagamandalam (Ooty) and HAGAR/MACE at Hanle. The development of these detectors involves both active-sensing detection elements as well as the associated data acquisition and trigger electronics, which take centre stage, especially in the experiments involving large background rejection in real time to reduce the amount of data to be saved permanently. This process almost always involves the development of new technologies as well as partnerships with industry, and often generates spinoffs that may lead to societal applications. For example, the Artificial Neural Network used in the DØ single top quark search (which had substantial Indian participation) was one of the early developments in modern AI/ML which won the 2024 Nobel Prize in Physics.

The Report already summarizes the technology development, industry involvement and possible spinoffs in individual projects, in Chapters 2 and 3 and in Annexure A.3. A summary/compilation of these important outcomes of the MSPs follows.

Technologies Developed

- **Semiconductor-based detectors:**

  (i) *Silicon-based detectors*: Given their excellent signal-to-noise separation, radiation endurance, industrial ease in fabrication in the form of micropixels and microstrips and developments in integrating the on-detector readout electronics, the silicon-based detectors are heavily used in collider experiments. Such charge-coupled devices (CCDs) are also widely used in astrophysics and cosmology experiments. The Indian community supplied 1,100 silicon-strip modules based on 320 micron-thick 4-inch sensor technology for the pre-shower detector of the CMS experiment, which were fabricated by Bharat Electronics Limited (BEL) at Bengaluru and thoroughly tested in India for their quality and radiation hardness.

  (ii) *Silicon microstrip sensors*: The work on silicon vertex detectors (SVDs) carried out for the Belle-II experiment in Japan has resulted in a successful R&D program with BEL, Bengaluru in developing silicon microstrip sensors.

  (iii) *Solid-state detector modules*: In the near future, the community is committed to deliver silicon-based detector modules for the outer tracker upgrade of the CMS experiment for the high luminosity LHC (HL-LHC), and to develop thin-sensor strip detectors with a finer pitch for the Belle-II experiment.

  (iv) *Silicon photomultiplier camera*: R&D for a prototype SiPM-based camera for a small 4 m class imaging Cherenkov telescope is also well under way. As a part of the second phase of HAGAR, the TIFR group has built a SiPM camera, with 256 pixels of 0.3 deg each, covering the field of view of 5 deg x 5 deg, which is the first of its kind in the country. For the CTA experiment, the calibration box for the camera of a prototype large-scale telescope (LST) was designed at SINP, developed and tested at TIFR and later at SINP. Control and access of the calibration box with OPC/UA interface was developed at TIFR. The CTA-India Consortium wishes to contribute to the development of a SiPM camera for the Small Size Telescopes (SSTs) of CTA.

- **Gas detectors:** India has a legacy of building gaseous detectors for many decades and Indian scientists have successfully installed many large and rugged sealed proportional counters for cosmic ray experiments at Ooty and elsewhere. The community has supplied large-area Resistive Plate Chambers (RPCs) for the CMS experiment, which have good spatial resolution as well as fast timing for triggering on single muons. Based on this experience, the capability for large-scale production of RPCs with a size as large as 2 m x 2 m was developed for the ICAL experiment that was proposed to be carried out as a part of the INO project. The R&D was carried out completely indigenously (including large-size magnets, ASICs and other electronics, gas-mixing units, and monitoring systems), and a prototype mini-ICAL recorded cosmic ray data at Madurai for more than 5 years.
- **GEM detectors:** The Gas Electron Multipliers (GEMs) are advanced detectors to handle the fast-triggering rates and higher backgrounds expected in the CMS experiment during the high-luminosity operations of the HL-LHC. The detectors supplied to CMS as a part of the ongoing detector upgrade, along with associated electronics boards, were fabricated in India in collaboration with the Bengaluru -based industrial partner Micropack Pvt. Ltd.
- **High-end electronics:**
  - (i) *Data acquisition systems*: The groups involved in various experimental setups for cosmic ray and collider-based research have broad experience with CAMAC-and VME-based data acquisition systems, trigger logic, several controller cards and development of a RTC (real time clock) synchronized with GPS. The GRAPES experiment also excels in indigenous development and production of ultra-fast amplifiers, discriminators, fan-in/fan-out modules, time-to-digital converters (TDCs), FPGA-based signal-processing and data-recording electronics at a fraction of the cost of the imported modules.
  - (ii) *Fast triggers*: In collaboration with the Indian industry, the Indian HEP community has supplied a large fraction of SiPM readout boards, control systems and calibration modules for the CMS hadron calorimeter. The group has also developed trigger and readout boards for the new generation data acquisition systems based on micro-TCA protocols, replacing the old VME-based systems for the forward hadron calorimeter upgrades.
  - (iii) *Next-generation trigger readouts*: The India-CMS group is heavily involved in the development of next-generation trigger readout boards to adapt to much larger particle multiplicity at the high luminosity HL-LHC, with technology based on high-speed optical links and fast FPGAs. This includes development of the central trigger system as well as high-granularity calorimeters, which will also be the basis for experiments at the future linear and circular colliders, like the planned ILC and FCC.
- **Scintillator detectors:** Over the years, the GRAPES experiment has succeeded in making high-quality plastic scintillators with high light-output and timing. This expertise has been developed using the industry around Coimbatore. This technology would be invaluable in case India is to contribute in building the surface array at the IceCube-Gen2 detector in Antarctica (see below).
- **Superheated liquid droplets (SLD) technology:** In the InDEx experiment currently at JUSL, the technology of superheated liquid droplets, developed for the PICASSO/PICO detectors, has been

employed for dark matter searches. This technology can be expanded to make a major dark matter experiment in India as explained elsewhere in this report.

- **Straw Tube Tracking (STT) detector:** Indian participants in DUNE, among other things, are already contributing to the development of the Straw Tube Tracking (STT) detector for the SAND detector at the Near Detector complex. There are plans to set up a STT production and testing facility for the production of STT modules for the SAND detector.
- **Deuterated Liquid Scintillator (DLS):** The DLS detector, for which R&D is in progresss, would leverage the existing capacity of the country for generating large amounts of heavy water, and lead to the development of technology for scintillator purification.
- **Quantum Technologies:** For GNOME and the atomic physics-based experiments, there will be development of technologies like ultra-precision atomic clocks. The R&D for the ADMX experiment has an overlap with techniques used in quantum computing, in particular, quantum noise-defeating technologies, which are actively being developed.

Potential applications/spinoffs and technological returns for India

- **Capacity-building in semiconductor-based detector technologies:**
  - (i) *Silicon-based detectors*: In-kind contribution of Si-based detectors to the CMS and Belle-II experiments led BEL, Bengaluru to acquire this technology. The MSPs in HEP thus seeded and helped grow this state-of-the-art technology in India. There will also be opportunities for other Indian industries to take part in the Slicon Vertex Detector upgrade, as well as in the longer-term international and home-grown projects that follow thereafter.
  - (ii) *Silicon photomultiplier camera*: The capacity for building Silicon Photomultiplier Cameras and allied equipment for the second phase of HAGAR and for the CTA experiment has led the CTA-India Consortium to plan for a possible contribution of a SiPM camera for the Small Size Telescopes (SSTs) of CTA.
  - (iii) *Semiconductor photodetectors*: The novel semiconductor photodetectors can also find wide applications in other particle physics and astroparticle physics experiments where high granularity scintillators are used. They can also find significant applications in improving the sensitivity of Positron Emission Tomography (PET) for clinical purposes.
- **Capacity-building in high-end electronics**: The detector technologies developed, or being developed, for HEP experiments involve high-end electronics and communication technologies, which, with their wide dynamic range of signal size, radiation hardness and fast timing, find usage across a variety of societal and cross-disciplinary applications, including safety, security and defence.
- **Capacity-building in high-quality plastic scintillators:** The IceCube-Gen2 experiment needs a huge number of large-area scintillation detectors, which may be developed using the expertise acquired at the GRAPES-3 experiment. Additional muon counters may also be set up, which opens up the possibility of having an air shower detector at the South Pole.
- **Potential for Imaging applications:** Among the detectors for which R&D has been extensively carried out in India, Resistive Plate Chambers (RPCs) and Gas Electron Multipliers (GEMs) have potential to be used in cargo tomography, X-ray imaging, medical imaging (e.g. for cancer treatment), neutron imaging, space sciences and other medical and national security applications.

- **Potential for Muon tomography:** Silicon-strip detectors find potential societal applications in muon tomography and medical imaging. They also have potential uses for carrying out archaeological investigations.
- **Applications in Radiation monitoring**: BARC has developed single-sided silicon strip detectors for the CMS experiment, which it uses to build many variations of radiation-monitoring devices. Work on medical applications of particle detectors has been initiated under the CERN detector R&D programmes. The STT technology, that includes boron-coated straws, can be effectively used for neutron detection, which may have security applications. The technology of superheated liquid droplets (SLD) can also be used as high-accuracy neutron dosimeters for (i) neutron monitoring at various accelerator sites, (ii) environmental radiation monitoring and (iii) cancer radiation therapy, a possibility that the SINP group is already in the process of exploring.
- **Applications for Big data and AI/ML:** Tools used in handling large data volumes and distributed computing over GRID already have widespread applications in finance and banking industries and have the potential to be used in variety of scientific and societal applications. The students graduating in HEP now have a working knowledge of applications invoking machine learning and artificial intelligence techniques, and some of them could easily branch out and develop such technologies.
- **Capacity-building in Magnet development:** The capacity built in the country for developing magnets as part of many HEP projects like the LHC and upcoming DUNE, will become very valuable for building hadron therapy machines for cancer treatment, new-generation synchrotron radiation sources, etc. It would also provide a platform for Indian industry to develop the infrastructure for the manufacture of large-size superconducting magnets.
- **Capacity-building in Segmented Mirror Technology for Atmospheric Cherenkov detection:** The MACE telescope deploys a 21 m diameter tracking light collector made up of about 1400 aluminium mirror facets of 50 cm x 50 cm, which have been developed within the country. The imaging camera is designed to be a compact array of 1088 photomultiplier tubes arranged in a triangular pitch of 55 mm corresponding to a pixel resolution of 0.125 degrees. While ECIL has built the structure, the camera and electronics have been built by the BARC Electronics Division. BARC has collaborated with a government industrial partner, Mechvac, which has built the mirrors and done their coating. Segmented Mirror Technologies for building telescopes is a new beginning for the nation with immense potential for the future of large telescopes in the country.
- **Technology know-how for Dual Mirror Technology:** The SSTs in CTA will be built on the concept of dual mirror technology with SiPM cameras at the foci of the secondary mirrors. In future, there is a strong possibility of technology transfer, especially related to aspheric mirror development for the SSTs. Currently, the technology to build imaging telescopes based on dual mirror technology does not exist in the country.
- **Capacity-building in Quantum Technologies:** The capacity to develop ultra-precision atomic clocks will be useful for better physical standards, navigation, communications, etc. Similarly, the noise-defeating technologies in ADMX will have overlap with quantum computing. These technological developments align quite well with the goals of the National Quantum Mission (NQM) of India, and can be expected to bring rich strategic and commercial dividends in a field that is believed to hold tremendous promise.

Other societal returns

- **Enhancement in India's standing and competitiveness in International HEP:** India has been participating in international HEP projects since the 1950's and her hardware involvement has gradually grown to become increasingly sophisticated over time. This journey has been described in detail in various chapters in this Report. It is globally acknowledged now that Indian institutions and industry can supply technically-reliable and good-quality hardware and software items for detectors and accelerators (see, for example, the MSV-2035-Accelerator S&T and Applications Report [MSV-2035-ASTA]). This has enhanced India's standing and competitiveness in HEP globally and its participation in prestigious global projects is widely solicited.
- **Enhancing India's industrial competitiveness in high-tech areas and entry of Indian industry in global supply chains:** By successively contributing in-kind items of increasing sophistication to important MSPs in HEP, the capacity of Indian industry to produce cutting-edge high-tech items on time, requiring considerable upfront R&D, has been considerably strengthened, and it is globally noticed and acknowledged. In most cases, production in India also has cost advantages for the projects. As a result, with India's CERN Associate Membership and showcasing of such high-tech items in various projects, the Indian industry is slowly getting into the highly-competitive global supply chains for such projects. From the LHC sitting on India-made PMPS jacks to silicon-based detectors and RPC and GEM detectors to computer software, vacuum components and sophisticated power converters, the Indian industrial contributions have come a long way. These aspects have also been covered in great detail in the MSV-2035 Reports in Nuclear Physics, Astronomy & Astrophysics and Accelerator S&T and Applications [MSV-2035-NP, MSV-2035-A&A, MSV-2035-ASTA]. This is a very important societal and economic contribution of such projects as these activities have pushed the overall technological capacity and horizons of our industry.
- **Enhancement in India's capacity to undertake ambitious HEP Projects nationally:** The technical knowhow gained as part of participation in global MSPs in HEP have enabled the Indian scientific community to plan for relatively more ambitious national MSPs in EHEP. The INO Project that was planned by the Indian HEP community as a non-accelerator-based underground neutrino observatory with globally-competitive aims is one such example. The RPC detector technology learnt as part of the India-CMS Collaboration was further improved indigenously to suit our requirements and would have formed the essence of the INO project. As mentioned above, these RPC detectors have already taken data for over 5 years with the prototype mini-ICAL detector at Madurai. Similarly, the technology of superheated liquid droplets (SLD), developed for the PICASSO/PICO detectors, has been employed in the InDEx experiment currently running at JUSL.

  There are several examples described in the MSV-2035-NP, MSV-2035-A&A and MSV-2035-ASTA reports where specific technologies have been (or will be) useful in setting up national MSPs.
- **Feedback of new technologies into important national R&D programmes:** As mentioned above, many of the detector and magnet technologies learnt as part of participation in international projects, have already found important applications in radiation monitoring, accelerator projects, etc. nationally. Manpower trained in AI/ML and overlap with quantum technologies will also feed into our ambitious national programmes in these domains.
- **Enhancing the quality of higher education and scientific human resource:** HEP is a discipline which tries to extend the very frontiers of human knowledge about the nature of matter and the Universe we live

in. While the technological spinoffs of experimental research in this field have been, and continue to be, many (including the World Wide Web), the primary contribution of this field is towards advancing fundamental knowledge. This leads to enhancement in the quality of higher education and scientific human resource. In the Indian context, it can be safely said that R&D in this field continues to attract some of the best science students across the country. Ph.D. students trained in these projects have found post-doctoral positions in prestigious universities and laboratories around the world, and many of them subsequently have also found positions on the faculty of some of the best national HEIs including IISERs, IISc and IITs. They have thus strengthened the overall higher educational ecosystem in the country; something that cannot and should not be disregarded for the long-term scientific as well as technological competitiveness of India.

- **Enhancing public interest in frontiers of knowledge:** It is inherent in human nature to be attracted to the deeper mysteries of Nature and to question how it functions. Curiosity, to quote Albert Einstein, has its own reason for existing. In the ultimate analysis, MSPs in HEP try to address this deep-seated curiosity at the very frontiers and at the most fundamental level.

The central part of the back cover depicts (top to bottom) an artist's view of a gravitational wave in spacetime, a panoramic view of the Hanle experimental site in Ladakh, the GRAPES-3 experiment at Udhagamandalam in Tamil Nadu and the erstwhile proton decay experiment at the Kolar Gold Fields in Karnataka.

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