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Editorial

India at the Large Hadron Collider

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What are the fundamental constituents of the diverse forms of matter present in the universe? This is one of the earliest questions that intrigued the human mind. Of course, the huge expanse of the universe, spanning billions of light years, and its huge matter content were then beyond the wildest human imagination. In Antiquity, this quest remained in the realm of guesswork and 'logical deductions' by philosophers. Several philosophers in India and Greece dealt with the issue. The Renaissance, Enlightenment and Industrial Revolution profoundly impacted the way we seek answers to questions. The empirical roots of the natural sciences were firmly established during this period, and science was established not only as a body of knowledge but also as a methodology of acquiring, verifying and discarding knowledge. A tortuous separation of the natural sciences from theology took place during this period. With the development of sophisticated equipment for experiments, it became possible to systematically test different hypotheses. A number of ground-breaking observations were made regarding the chemical elements, atoms and molecules in the run up to the twentieth century.

The twentieth century saw a quantum jump from 'classical physics' to 'modern physics'. Particle physics, also known as high-energy physics, began its journey at this juncture and developed very rapidly as an independent branch of study, riding the crest of the huge wave generated by quantum mechanics, the special theory of relativity and experimental observations. Along with its theoretical tools, the experimental tools available to particle physicists also evolved very rapidly – fluorescent screens, nuclear emulsion, cloud chambers, bubble chambers, etc. gave way to huge detectors comprising thousands of modules of gaseous, scintillation and silicon detectors; collisions of ultra-relativistic particle beams produced by giant particle accelerators became the hunting grounds for new particles, observation of rare processes and precision measurements. Non-accelerator experiments also evolved rapidly. The way experiments are done also radically changed – large, international collaborations of hundreds of scientists and technologists replaced individual or small groups of scientists.

One recurring feature in the development of the subject since its early days is that the existence of many new particles and their interactions had been predicted before they were experimentally observed – the neutron, positron, pion, neutrino, omega, charm quark, W, Z, and Higgs boson, etc. are the most notable examples. With the advancement of technology, bigger and bigger particle accelerators are constructed for specific purposes. After the Standard Model (SM) took concrete shape in the 1960s, the Super Proton Synchrotron (SPS) was proposed and constructed at CERN to verify its predictions, and the W and Z were discovered in 1983. Similarly, the Large Electron Positron Collider (LEP) was proposed to verify the SM in detail, which it accomplished superbly, although its other goal, discovery of the Higgs boson, was beyond its reach. The Tevatron at Fermilab made a dedicated effort to discover the top quark, observed it in 1985, and came tantalizingly close to observing the Higgs boson. The Large Hadron Collider (LHC) at CERN was designed to exhaustively search for the Higgs particle, where it was finally discovered in 2012. Supersymmetry (SUSY) is one of the most popular theoretical models looking beyond the Standard Model (BSM), and it postulates the existence many new particles. Like its predecessors, LHC experiments are searching for these. Recent non-accelerator experiments such as the Super-Kamiokande, Sudbury Neutrino Observatory, K2K, XENON, etc., have also been designed with specific goals in mind.

One remarkable aspect of this subject is the size and complexity of the experiments and the number of people involved in a single experiment. Particle physics experiments take a long time to construct and have a much longer active lifetime. The LHC was conceived in the early 1980s along with the LEP, and was approved in 1994 [1], proposals for the four big experiments were accepted soon and a number of smaller experiments were approved later. The big four are now 15 years young and will continue through the High Luminosity

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phase of LHC (HL-LHC, 2035–). Hence, ageing of the detector modules owing to radiation and other factors and the obsolescence of technologies are serious concerns for such collider experiments. Hence, the replacement and upgrade of components continue throughout their life cycle. The design, construction, maintenance, operation and upgrade of these experiments require state-of-the-art expertise from diverse fields from electronics, materials science, cryogenics to computing and statistical analysis.

During the 1970s, particle physics experiments typically involved a few institutes and a few tens of researchers. As more and more powerful accelerators were constructed and the collision energy increased, the experiments grew rapidly in both size and the number of collaborators involved. The number of experimentalists involved in a single experiment grew to several hundreds during the Tevatron (Fermilab, 1983–2011), the LEP Collider (CERN, 1989–2002) and HERA (DESY, 1992–2007) era. Currently ATLAS and CMS, the two gigantic general-purpose experiments at the LHC (CERN, 2008–), involve ~ 3000 scientists. Also, the introduction of silicon-based detectors, particularly for tracking of charged particles, increased the number of electronic channels in the experiments by orders of magnitude and, consequently, the amount of information per 'event'. The rate of events also increased rapidly, and the volume of data collected by the experiments grew. Thus, processing and storage of data and their availability to thousands of collaborators spread across the entire globe became crucial in the LHC era, and distributed computing in the form of the GRID provided the solution. Neural networks, multivariate analysis, machine learning and statistical techniques are now indispensable for the analysis of such huge datasets.

The accelerators and these experiments necessitated technological innovations that have enormously benefitted humanity – precision radiation therapy using accelerators, medical imaging, fast and radiation-tolerant electronics, instrumentation, distributed computing, etc.

Compared with colliding beam experiments, non-accelerator experiments typically have to deal with a much smaller volume of data and involve fewer collaborators. The Super-Kamiokande experiment, one of the largest collaborations for studying neutrinos, has ~ 200 collaborators belonging to 50 institutes from 11 countries [2]; in contrast, the CMS has ~ 3400 researchers, belonging to 247 institutes from 57 countries [3].

CERN, The European Organization for Nuclear Research, was established in 1954 as a joint effort of 12 European countries. The framework of collaboration and collective responsibility, which was a necessity after most of Europe was devastated in World War II, became its source of strength and long-term success. Since its inception, it has been an excellent cradle for international scientific collaborations beyond the founding countries. Over the years, more European countries have joined CERN, and several non-European countries have become associate members. India became an associate member in 2017.

A defining aspect of CERN is the long-term planning of its scientific programme and the maximal utilization of the existing resources. The protons are accelerated in a number of stages before they are injected into the LHC – LINAC2 (1978–2018), Proton Synchrotron Booster (1972), Proton Synchrotron (1959) and Super Proton Synchrotron (1976). LINAC2 was replaced by LINC4 only in 2020. Heavy ions follow almost the same chain of accelerators – LINAC3 (1994), Low Energy Ion Ring (1996), Proton Synchrotron and Super Proton Synchrotron, and finally the LHC. It is amazing that the LHC works in perfect harmony with the Proton Synchrotron, which is more than six decades old.

The LHC has a very wide-ranging physics programme. The search for the Higgs boson and precision measurement of its properties are some of its most important goals. Any deviation in the Higgs sector from the SM will hint at new physics. The high statistics dataset made available by the LHC is exploited to extensively and systematically search for new particles predicted by different theoretical models and the enigmatic dark matter that is required to explain astronomical observations. In spite of the multitude of free parameters, SUSY and other BSM theories have been severely constrained. The high statistics dataset also facilitates precision measurements in the strong and electroweak sectors of the SM – the value of the strong coupling constant, understanding quantum chromodynamics over a very wide range of energy, the parton distribution function of the proton, the mass of the W boson, properties of the top quark, rare decays, etc. The physics of the charm and bottom hadrons, including charge conjugation–parity (CP) violation, is another area of intense study at the LHC. Collisions of heavy ions, particularly Pb–Pb collisions, are studied to understand a new state of matter that exists for a very short duration and is marked by extremely high temperature and density, being similar to the state of the universe immediately after the Big Bang.

The experiments at the LHC have been planned to comprehensively scrutinize the LHC data to meet the physics goals. CMS and ATLAS are general-purpose detectors with excellent track finding, calorimetry, and good solid angle coverage, and deal with all the topics mentioned above [4]. ALICE is optimized to study collisions of heavy ions [5], and the focus of LHC-b is to study heavy quarks in proton–proton collisions.

Building these accelerators and carrying out such experiments require funds, technology, infrastructure and human resources at a scale that is prohibitive even for the most developed and rich nations. The model of international collaboration developed at CERN is mutually beneficial – it is essential for the success of the LHC programme and facilitates the participation of non-member countries such as India in front-line research over a prolonged period.

Indian scientists and research groups started participating in the experiments at CERN way back in the 1960s [1]. This participation, in spite of severe constraints, grew with time and became more structured with long-term planning and involvement. The Government of India has made participation in the LHC programme a part of its long-term Mega Science Programme. India's participation includes the accelerator and two experiments – CMS and ALICE. India-CMS is a consortium of the Indian groups participating in the CMS experiment. Similarly, there is India-ALICE. Some of these groups joined CMS and ALICE at the very beginning. It is heartening to see that the Indian LHC community – scientists and institutions participating in the LHC activities – has grown considerably over this period. It is particularly encouraging to see that this expansion has brought many teaching institutes and their younger faculty members into the LHC community, and a few more are keen on joining.

Scientists from India are now involved in all aspects of the experiments. They are contributing to the two detectors in all possible ways – R&D for sophisticated detector components, fabrication, electronics, firmware, installation and commissioning. The fabrication of the detector modules and testing were nothing short of pioneering and made possible by overcoming severe constraints. The development of GEANT, the detector simulation tool, is another area where Indian scientists have contributed significantly [6].

The physics programme at the LHC has inspired a large number of theorists from India to work on diverse issues – precision calculations in the framework of the Standard Model as well as different BSM scenarios, analysis strategies, interpretation of the results from the experiments, etc. [7]. Many of them have been hosted by the Theory Division of CERN, which hosts theorists from all around the world and facilitates intense collaborations.

India contributed to the LHC machine in several crucial areas – superconducting magnets, precision magnet positioning system jacks, quench protection heater power supply, quench detection electronics units, and control electronics for high-current circuit breakers, liquid nitrogen tanks, etc. India also contributed to engineering studies of different components of the LHC machine and its control software, database and web interfaces, and technical personnel for testing the magnets [8]. The hardware contribution to the LHC and the two detectors will have a long-term benefit in terms of the participation of Indian industry in the basic research and development of technologies. Deriving societal benefits through access to sophisticated technologies and capacity building for large indigenous scientific experiments are also important aspects.

This Special Topics issue of the *European Physical Journal* is an attempt to put together an account of the participation of scientists from India in the different aspects of the LHC for posterity. We hope that this will be a useful starting point for persons interested in different aspects of this huge, collaborative science programme.

It should be emphasized that India's participation in the experiments at CERN is only a part of the larger picture of particle physics in India. In the past, researchers from India have taken part in several accelerator-based experiments elsewhere and are continuing to do so.

- The D0 experiment at the proton–anti-proton collider Tevatron, FNAL, which jointly with the CDF experiment, discovered the top quark in 1995
- Belle I and II at the asymmetric electron–positron collider at KEK, Japan, to study the bottom and charm hadrons, particularly CP violation, and rare decays
- STAR at the heavy ion collider at BNL, USA, to study the deconfined state of quarks and gluons
- The DUNE experiment with the neutrino beam from FNAL, to study neutrino oscillation

Scientists from India are also participating in a number of non-accelerator experiments in India and abroad to study cosmic rays, gamma rays and dark matter.

- HAGAR and MACE, at Hanle, Ladakh, India, to study very high-energy gamma rays
- GRAPES-3 at Ooty, Tamilnadu, India, to study very high-energy cosmic rays and ultra-high-energy gamma rays
- PICO/PICASSO at Sudbury Neutrino Observatory, Canada, for direct detection dark matter search
- MAGIC at the Canary Islands, Spain, to study very high-energy gamma rays
- A prototype dark matter search experiment has started data taking in the Jaduguda Underground Science Laboratory, India

A long-term Mega Science Vision Plan is being prepared to cover the activities mentioned above in a comprehensive way, and participation in a number of new collaborations is also under consideration. All these, along with the LHC, will provide comprehensive coverage of the entire subject.

A. Gurtu traced the participation of scientists from India in the experiments at CERN leading up to the LHC. He obtained his PhD from Panjab University, Chandigarh in 1971 and has been involved in scientific collaborations with CERN since 1969—bubble chamber and hybrid bubble chamber (EHS-RCBC) experiments (1969–85), L3 experiment at LEP (1984–2002) and CMS (1993–2011) and is part of the Particle Data Group (1992–). He was deeply involved with the development of the Z Lineshape package and represented the L3 experiment in the LEP Lineshape Combination Group. Later, he held many leading positions in the CMS collaboration and was the spokesperson of India-CMS, the collaboration of Indian groups in CMS. He is a fellow of the Indian Academy of Sciences, Bengaluru.

S. Raychaudhuri reviewed the rich body of theoretical work related to the LHC, with an emphasis on works from India. He obtained his PhD in elementary particle theory from the University of Calcutta in 1994 and is currently in the Department of Theoretical Physics, TIFR, specializing in the physics of electroweak interactions and physics beyond the Standard Model. He was awarded the TAA-B.M.Udgaonkar Award for excellence in teaching by TIFR in 2021. With K. Sridhar he is co-author of the book *Particle Physics of Brane Worlds and Extra Dimensions* (Cambridge University Press, 2016). He has authored another book, *The Roots and Development of Particle Physics in India* (Springer, 2021).

S. Banerjee reviewed the development of tools for detector simulation, particularly GEANT4 and its application in the LHC experiments. He obtained his PhD in high-energy physics from the University of London, London in 1976. He was a member of the High Energy Physics Group of TIFR, Mumbai (1978–2007), FNAL, Chicago (2007–10, 2015–21), and SINP, Kolkata (2010–15) and is presently with the IACS, Kolkata. He is one of the core developers of the detector simulation packages GEANT3 and GEANT4. He has been deeply involved in the detector simulation and event reconstruction packages for the L3 experiment, and later the CMS experiment. He is a fellow of the Indian Academy of Science, Bangalore, and Indian National Science Academy, New Delhi.

S. Sharma reviewed the major physics results from the CMS experiment. She obtained her PhD from TIFR, Mumbai in 2008 and was a postdoctoral research associate at Fermilab, USA; she is currently a faculty member at IISER, Pune. She has been deeply involved in the CMS experiment, especially the calorimeter performance, calibration and simulation as well as object reconstruction. Her physics analysis interests are focused on searches for new physics beyond the Standard Model. She held several leadership positions in CMS and is currently the deputy spokesperson of India-CMS. She is a fellow of the Indian Academy of Sciences, Bengaluru.

S. Chattopadhyay reviewed the contribution to the ALICE experiment from India. He joined VECC, Kolkata, as a scientist in 1988 and obtained his PhD from the University of Calcutta in 1998. He worked on the WA93 experiment for his PhD, followed by WA98, STAR and ALICE, and has contributed to building advanced detector systems for these experiments. His physics interest is to study the deconfined state of strongly interacting matter produced in high-energy heavy-ion collisions. He was spokesperson of the ALICE-India collaboration and is currently deputy spokesperson of the CBM experiment at GSI. He is recipient of the Homi Bhabha Science and Technology award from the Department of Atomic Energy, Government of India and a fellow of the National Academy of Sciences, India.

The editor of this volume has been privileged to participate in experiments at CERN for over three decades. He did his PhD at the L3 experiment at LEP, and later worked in the CMS experiment starting from 1998, with a brief stint at the D0 experiment at FNAL. He has been witness to the changes in the state of experimental particle physics in India in general, and in the context of its participation in the LHC in particular, which emboldened him to get into this venture.

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