How has man’s centuries’-long search for the fundamental particles and energies in nature led to this historic moment in science?

July 4, 2012 marks an important epoch in the history of science as well as of mankind in unraveling nature’s deep secrets. The major experiments at the Large Hadron Collider (LHC) machine at CERN, ATLAS (A Toroidal Lhc ApparatuS) and CMS (Compact Muon Solenoid), announced the discovery of a particle of mass about 125 GeV (Giga electron Volt, roughly the mass of the proton) which is likely to be the hitherto sought after Higgs boson. The discovery marks the beginning of an exciting era in the story of the LHC.

Mankind has always been curious about the fundamental building blocks of matter and the basic forces at work among them. The thirst for this knowledge goes back to the era of the sages in our country and is matched by the Greek philosophers in identifying the so-called constituents of the universe.

In the 19th century, it seemed as if there were too many elements, starting with hydrogen and going beyond lead, uranium and so on, which make up the world around us. By the turn of the 20th century, it was known that there is unity in diversity. We now know that there are only very few fundamental particles that could be classified into different categories in broad ways, albeit, each being unique in terms of its attributes. Our everyday matter is made up of electrons and essentially two types of quarks.

Soon after World War II, it was found that there are heavier cousins of electrons and the quarks which are unstable and hence they can only be created artificially by converting energy according to the famous equation of \( E = mc^2 \). An exception is the case of muon, which is produced naturally in cosmic ray showers and when it carries high energy, the life time gets dilated enough to reach the laboratories on earth.

Computer reconstructed candidate event for the two-photon decay mode of Higgs boson. The large green legos signify energetic photons while the yellow streaks correspond to low energy charged particles produced in the collision along with the Higgs boson.
As of today, four fundamental forces are identified: Gravitation, Electromagnetic, Strong and Weak. The gravitational and electromagnetic forces are more evident in our daily lives being of long range, while the other two are short ranged. It was Einstein who established the universality of the gravitation laws governing massive objects on the earth as well as in the universe.

Similarly, Maxwell put in electricity and magnetism in a single fold through his equations describing electromagnetic interaction. Importantly, it is also realised that there were much fewer number of basic forces when the universe was much younger and hotter. Summarily, the evolution of the universe in the very early stage essentially deals with science of small length scales and hence equivalently with high energies.

Probing the nature of the universe at early stage is possible, within the purview of particle physics, with powerful machines providing high energy density. This requirement is similar to the way one can...
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The meticulous preparation and construction of the accelerator and the experiments took over twenty years. The operation of the LHC machine started in 2008, which unfortunately was cut short following a small accident. Diligent work by accelerator engineers ensured that the machine was operational within a year, following a small accident. Diligent work by accelerator engineers ensured that the machine was operational within a year.

This theory is further developed into a combined theory of electromagnetic, weak and strong interactions, which are the forces operating between the fundamental matter particles at the microscopic level. Each of these forces is described by its own symmetry and has its own mediators. This theory, called the standard model of particle physics, is capable of describing nature down to the scale of 10^{-18} metres.

The biggest puzzle was posed by the mediators of the weak interaction. This interaction, which is responsible for the beta decay and for the burning of the sun, is effective only at small distances, implying that the corresponding mediators must be massive. However, the masses for mediators spoil the symmetry of the theory. Thus, we are faced with two conflicting constraints on the theory: we want it to be symmetric but we also want the force carriers to be massive. This impasse could be cleared if we assume that the symmetry is implicit as in the case of the bar magnet. That is, the equations of the weak interactions are symmetric. When the universe was very hot, this symmetry was explicit and all the particles were massless. The expansion of the universe is accompanied by cooling and in the very early phase of this cooling, the symmetry was lost.

This is similar to the case of the bar magnet, in which all the tiny magnets inside a bar magnet are symmetric under any arbitrary rotation, but the magnetic field changes if the bar magnet is rotated. The search for symmetry also led to the dogma of conserved quantities. As noted early in 20th century, conservation of momentum is a consequence of translational symmetry, i.e., the system remains unchanged if every part in it is shifted by a constant displacement.

The development of several revolutionary ideas during 20th century, from relativity to quantum mechanics to the existence of antiparticle, played the precursory role for a consistent and highly tested quantum theory of electromagnetism, which is based on a simple symmetry. The success is based on the idea that electromagnetic interaction, of infinite range, between two charged particles is mediated by a carrier, the photon. The symmetry of the theory requires the photon to be massless.

Interestingly, the theory can predict result of an experiment if we provide the masses of the particles. The Higgs particle was inferred to have a mass from very small values up to 1000 GeV. Particle physicists have been toiling to pin down the Higgs particle since the last thirty years without losing hope, since the theory is beautiful and successful from the point of view of other aspects.

The previous accelerator at CERN, the Large Electron Positron (LEP) collider, searched for the Higgs boson but could not find it and established that the Higgs boson should be more massive than about 115 GeV. Comparison of all experimental data with standard model led to the prediction that the Higgs boson should be lighter than about 700 GeV. The LHC accelerator is planned to produce the Higgs boson, whatever be its mass in the above range. The production rate is sparse and stochastic, needing a very large number of collisions to take place before a handful are produced.

The Higgs boson, like any other very massive particle, decays almost instantaneously into lighter particles. The experiments at LHC are carefully designed to detect the Higgs boson through different decay modes. Unfortunately, the Higgs boson cannot be detected in the most dominant decay modes, to a pair of quarks, when the mass is less than about 140 GeV. The strong interaction of the constituents of the colliding protons, in general, produce much the same final state. Thus identification of the Higgs boson is achieved via rare decay modes. The sitting of collision data is thus highly crucial as well as recognition of the pattern for the production and subsequent decay of the Higgs boson. The physics mandate of LHC, has driven the machine parameters as well as the features of the experiments.

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Situated hundred metres below the surface, oppositely moving beams consisting of about 1400 bunches are made to collide at few specific points with very high flux. Each bunch, measuring about 5 centimeters in length, 20 microns across and 50 nanosecond apart from the neighbouring ones, contains about 300 trillion protons. Mammoth detectors, positioned around the collision points, act as sleuth detectives and record the “event”: the aftermath of violent collisions through digital image via eighty million electronic channels.

Very careful selections are necessary to reduce the total proton-proton interaction rate of about 100 million Hertz to the permanent archiving rate of information of few hundred Hertz. The data processing, analysis, and storage are achieved via distributed computing, LHC Grid. The backbone of the success of LHC physics programme has been the immaculate computing which involves, for example, petabytes (a million gigabytes) of data moving across the globe within a short time scale and several thousand scientists analysing the data simultaneously from different parts of the world.

The measurement of events in the detector, when the Higgs boson decays to two photons or four charged leptons (e.g., electron or muon) is the most accurate. It is to be noted that there are many other processes occurring in the collisions at LHC, which can produce two photons or four charged leptons and hence mimic a Higgs boson signal. All these possibilities were studied well in advance, using lots of simulated events.

High-resolution measurements and advanced analysis methods developed for the discovery could establish the production of the Higgs boson and its subsequent decays.

A computer reconstructed candidate event for the two-photon decay mode of Higgs boson in CMS experiment is shown in the illustration on page 19. The large green legos signify energetic photons while the yellow streaks correspond to low energy charged particles produced in the collision along with the Higgs boson. At the final stage of analysis an excess of actually observed events over expected backgrounds is the indication of the production and subsequent decay of the Higgs boson in a particular final state.

The illustration on page 20 shows the resonance structure observed in CMS experiment at 125 GeV which can be explained again only in the presence of the Higgs boson. The blue and green contributions in the histogram correspond to the background, which are well reproduced in simulation indicating that the theoretical understanding is sound. Though the discovery was achieved mainly via these channels, other final states were also measured and considered in the final statistical interpretation. The high statistical significance of five standard deviations for the discovery implies that the probability of fluctuations in background events to imitate the events of the Higgs boson decay signal is one in several hundred millions.

The amount of data used to announce the discovery was limited. Since then, the data accumulated has doubled and is likely to increase by threefold when LHC machine stops providing proton-proton collisions by end of 2012. This data is extremely crucial to understand in detail property of the Higgs boson. This data may also bring in additional exciting results, so stay tuned! LHC machine, with a shutdown of about eighteen months will restart in end of 2014 to provide collisions at higher energy with greater flux. That is needed to learn the physics beyond the one described by standard model. The discovery of other new massive particles are not ruled out.

Both ATLAS and CMS collaborations, each consisting of about four thousand scientists as of today, invested wisely to make excellent detectors using cutting edge technology. Each detector has several major subsystems meant for a particular type of job. India has been collaborating in CMS experiment and contributing in all aspects: detector fabrication, simulation studies, data collection, monitor, analyses, computing and so on. With LHC programme chalked out for next twenty years, the future of Indian participation in CMS experiment is very promising. Come and join us!

The success of LHC underlines the power of a cohesive work by a dedicated community over a long time with a vision of a grand goal. Thus, LHC is also a sociological experiment. Most importantly it is defining the way to look at basic research that drives the evolution in technology.