Large Hadron Collider: Higgs hunting gets serious!

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In this article I give a status report of the real exciting prospect that the 'billion dollar question' about the Higgs boson (the 'Holy Grail' of the Standard Model (SM) of particle physics) may be answered in the coming months! To put the excitement in perspective, I begin with a short summary of the century-long journey, by theoretical and experimental particle physicists as well as accelerator physicists, which will find its natural culmination in this event. I will also summarize the story of the Large Hadron Collider: the machine and experiment, from the troubled early steps to the confident strides that are being made now. I will outline why particle physicists believe that, if we are lucky, the SM train may be arriving at the terminus within this year!

Keywords: Higgs boson, Large Hadron Collider, particle physics, Standard Model.

ALMOST about three years ago, the Large Hadron Collider (LHC) came into limelight due to the spectacular show of its start-up, the equally spectacular accident soon after and also for the doomsday stories that circulated around its start-up. The accident put the LHC out of action for a while. The necessary repairs done and the damaged pieces replaced, the machine took the first tentative steps in its life beginning on 23 November 2009. Having set a world record for the proton beam energy, of 1180 GeV (1 GeV = 10^9 eV, 1 eV being the energy that an electron gains when it falls through a potential difference of 1 V) on 30 November 2009, it went back to the lower beam energy of 450 GeV per beam and ran for about two weeks in the mode where the two beams collided. The detectors collected data corresponding to a few hundred thousand proton–proton collision events over this period (see note 1), confirming that their intricate machinery performed as it should and can measure the properties of the myriad of particles produced in these collisions to the desired accuracy. After a winter shutdown the machine started working again on 20 February 2010. After circulating proton beams at the higher energy of 3.5 TeV (1 TeV = 1000 GeV = 10^{12} eV) since 19 March 2010, finally collisions at the total centre of mass energy of 7 TeV happened on 30 March 2010; albeit this was still only half the originally planned energy and with the number of colliding particles in a bunch smaller by a factor of ten than initially foreseen for the restart. Further, at the beginning of this restart, there was only one bunch per beam compared to the currently (July 2011) achieved ~1300 bunches per beam, and the final goal of 2808 bunches per beam. After this successful run, albeit with very low number of collisions in 2010 and a planned shutdown in December, the machine started delivering collision data to experiments again at the end of February 2011. I write these lines from CERN, Geneva, where even in the cafeteria the television screens display information about the operation of the LHC machine. The number of particles per bunch, the number of colliding bunches and the length of time for which the beam circulates continuously (see note 2), all have been growing at a very fast pace in the last months, increasing tremendously the amount of data becoming available to the detectors (see note 3). Particularly after the short planned shutdown in December 2010, the machine has made progress by leaps and bounds in the number of collisions that it could deliver, now delivering in one week the number of collisions equal to that delivered in the entire 2010 run. The giant, extremely intricate detectors which took decades to design and build, are functioning beautifully; the huge amount of data are being analysed using the worldwide computing grid developed for the purpose. The moment of reckoning for the Standard Model (SM) of particle physics is now coming closer, ever faster!

The journey to the 'heart of matter', which started in 1897 with the observation of a new, light, negatively charged object, the electron, by J. J. Thomson in his experiment with vacuum tubes, has now arrived at the endgame of trying to entice the Higgs boson out of the corners where it might be hiding, using the biggest man-made accelerator, the LHC, after passing through the discovery of nucleus of an atom by Lord Rutherford using the energetic α particles being emitted by radioactive nuclei. The energies required started from a few electron

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volts to 3.5 TeV to which the colliding protons are being accelerated today at the LHC. To appreciate the enormity of the importance of the event when the LHC will deliver the proof of *the existence or nonexistence* of a Higgs boson over the entire range of masses allowed in SM, it is necessary to follow two stories which developed side by side in the last century. One is the story of how SM, the theory describing the fundamental constituents of matter and the fundamental forces among them, was put together in its present form, brick by brick (see note 4). This story started from the discovery of the electron by Thompson, but has developed mainly over the past 60–70 years. The other is the story of our quest for particle beams with higher and higher energies and the intimate link of this effort to the quest of what lies at the 'heart of matter'. This partnership between accelerator and particle physicists has continued throughout the past century. The legendary physicist Rutherford had said, dreaming about using high-energy particles to uncover nature's secret, 'It has long been my ambition to have available a copious supply of atoms and electrons which have energies transcending those of the alpha and beta particles from the radioactive bodies'. His dream was fulfilled by Walton and Cockroft in the Cavendish Laboratory. The target of energy, MeV, to which the particles needed to be accelerated, was set by Gamow's theory of α decay. Using this theory one could calculate the height of the Coulomb barrier faced by the proton in nuclear reactions and hence indicated the energy to which it needs to be accelerated for producing artificial radioactivity in a controlled manner: the aim of Rutherford's experiments around 1931 when Cockroft and Walton built their accelerator (see note 5). Since then, the nuclear/particle physicists have been setting the bar higher and higher and accelerator physicists have been clearing it with regularity just like the pole vaulters Sergey Bubka or Yelena Isinbayeva. To appreciate the scope of this gigantic effort, made possible only by big international collaborations which, I am happy to add, include Indian engineers and physicists, we need to follow also the story of the methodology of the 'mega' science projects that the high-energy physicists have developed. However, that can be a subject of separate discussion and is not pursued here.

In this article I will begin with a short summary of SM of particle physics, outlining the importance of the 'hunt' for the Higgs boson. Then I will outline the history of LHC, which has been designed such that it is sure to provide information on the presence or absence of this last missing piece of SM, predicted by the theorists. I will give a short discussion of the accident at the start-up and following repairs and finally of the wonderful performance of the machine in the last six months. I will then describe the expected timeline of the journey to the first stage on the LHC agenda, the quest for the Higgs boson. I will end by outlining the timeline of the expected explorations at LHC of theories of particle physics beyond SM: the BSM physics. The need for the latter is indicated by the inadequacy of SM while addressing various theoretical and experimental puzzles.

Story of Standard Model

Fermions, bosons and interactions between them

The SM of particle physics is the current answer provided by science to the age-old question, 'what is the world around us made up of?'. Even though the question has remained the same through the ages (see note 6), the answers have changed. Starting from the Greeks who thought that everything was made up of four 'elements' (or five if one follows the Indian philosophers who talked about the Panchmahabhootas), our answer to this question has come home to roost in the concept of quarks and leptons, going successively through the idea of chemical elements, molecules, atoms, nuclei and protons/neutrons (p/n) which make the nuclei.

The SM is not just about the 'quarks and leptons' being the fundamental constituents, but also about there being only four fundamental interactions among these elementary particles. It is possible to explain all the observed forces in nature, in principle, in terms of the following four:

- Gravitational force: The force that holds us on the earth and gives rise to planetary motion as well as tides.
- Electromagnetic force: The force that holds electrons inside atoms, and which is responsible for electrostatic effects, electric currents and magnetic fields.
- Strong force: The force that binds together the quarks inside protons and neutrons, and also makes the latter stick to each other to form the atomic nucleus.
- Weak force: The force that causes the decay of radioactive nuclei with emission of electrons, in which a proton changes into a neutron or vice versa.

Out of the four above, the first two are well known to us from everyday experience, the last two are felt only within nuclei. An important discovery of the twentieth century was that the force between two particles (charges) could be understood in terms of the field generated by one of the charges at the position of the other and also in terms of an exchange of a field quantum, i.e. the interactions are 'mediated' by exchange of force carriers, which themselves are elementary particles. Tables 1 and 2 summarize the list of matter particles and force carriers which have been established experimentally. The weak interactions have the lowest strength characterized by a constant $\sim 10^{-5}$, whereas for electromagnetic interactions it is the fine structure constant $\alpha = 1/137.02$ and for the

Table 1. The fundamental constituents of matter and their masses

Quarks (q, $\bar{q}$)	Leptons (l, $\bar{l}$)
$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$ × 3 colours	$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix}$
$\begin{pmatrix} u \\ d \end{pmatrix}_r \begin{pmatrix} u \\ d \end{pmatrix}_g \begin{pmatrix} u \\ d \end{pmatrix}_b$ etc. + anti-quarks	'colourless Leptons' + anti-leptons
$m_u = 0.002$ GeV/c^2, $m_d = 0.005$ GeV/c^2 $m_c = 1.3$ GeV/c^2, $m_s = 0.1$ GeV/c^2 $m_t = 173$ GeV/c^2, $m_b = 4.2$ GeV/c^2	$m_e = 0.000511$ GeV/c^2, $m_{\nu 1} = 0$–0.13×10^{-9} GeV/c^2 $m_\mu = 0.106$ GeV/c^2, $m_{\nu 2} = 0.009$–0.13 GeV/c^2 $m_\tau = 1.777$ GeV/c^2, $m_{\nu 3} = 0.04$–0.14 GeV/c^2

Table 2. Basic forces in nature and their carriers

Interaction	Range	Carrier	Mass	Acts on
Electromagnetic	∞	Photon γ	0	Particles with electrical charge
Weak	$< 10^{-18}$ m	Weak bosons $W^{\pm}/Z$	$M_W c^2 = 80.404$ GeV $M_Z c^2 = 90.1876$ GeV	Quarks q, leptons l and $W^{\pm}/Z$
Strong	q, g confined within 10^{-15} m	Gluons g	0	Quarks q and gluons g

strong interactions it is a constant of order 1. Table 2 does not include the gravitational interaction since we do not have a similar level of theoretical description of this interaction in terms of a force carrier and moreover, it does not play a role in the discussions of SM of particle physics. The properties of all these particles, such as their masses, electromagnetic charges, etc. have been measured to a great degree of precision now and the 'periodic table' of particle physics is almost established. The names up, down, strange, charm, beauty and top are just arbitrary labels and do not mean anything. These labels are generally called 'flavours'. The colour associated with the strong force has nothing to do with real colour, but is like the electromagnetic charge associated with the electromagnetic force. Except there are three different types of these charges and one requires precisely eight kinds of gluons to describe interactions between the quarks carrying these. The quarks u, d (up, down) make the normal matter (which is colourless) like protons/neutrons and these together with the lightest charged lepton, the electron, in fact make up atoms/molecules, etc. The lighter quarks (u, d, s) manifest themselves only as colourless composites like the p/n along with a large number of other unstable particles, such as $\pi^{\pm}$, π^0, Σ^0, K^0, $\bar{K}^0$, etc. which were first found in cosmic rays. The existence of quarks was first inferred through the properties of these composites by Gell Mann and others. All the remaining fundamental particles: the quarks charm (c), beauty (b) and top (t), the charged leptons μ, τ and the neutral leptons: neutrinos (ν's), are produced either in decays of nuclei or unstable particles and/or in high-energy processes. The heavier quarks (c, b, t) and the heavier charged leptons (μ, τ) are all short-lived, with lifetimes of the order of 10^{-6} s or lower. Just like the u, d and s, the c, b quarks also form composites which are short-lived unstable particles. The top quark decays even before it can form such composites. The quarks all carry fractional electromagnetic charges. However, no 'free' quark with fractional charges has ever been seen. The neutrinos have only weak interactions, whereas the charged leptons being colourless have weak and electromagnetic interactions and the quarks being coloured feel all the three interactions. One should also add here that at present SM is not able to answer why the number of quarks and leptons is what it is. However, SM predicts that the number of lepton and quark pairs observed in nature should be the same.

A major difference between the 'matter' particles (quarks and leptons) and the 'force carriers' is the spin angular momenta they have. All the particles can only have spin angular momenta which are multiples of $\hbar$ and if the multiple is n, the particle is said to have spin n. The matter particles all have spin 1/2 and are subject to an exclusion principle first postulated by Pauli in the context of atomic electrons. All the particles for which n is half integral are collectively called 'fermions'. The force carriers all with spin 1 are called bosons, a generic name for all particles for which n is integral, named after S. N. Bose, who made an important observation about the quantum behaviour of such integral spin particles. The fact that all the matter particles are spin 1/2 and all force carriers spin 1, already points towards the possibility of the same framework for a mathematical description of all the three interactions and perhaps even a 'unified' description of all of them.

Mathematical description of fundamental interactions

The logical sequence of steps leading to our current understanding of the structure of matter has been as follows:

- Seek the regularities/patterns in properties such as masses, spins, etc. Very often these reflect possible existence of a more basic fundamental unit which makes the whole.
- Measure the 'size' of the constituents. At the level of atomic distances and smaller, this has meant doing scattering experiments using beams of particles with higher and higher energies so as to probe smaller and smaller distances.
- Develop simultaneously a theory of the dynamics that holds these units together or causes the decays of these composites. One needs then to also check if the observed properties of the composites agree with the predictions of the theory.

Thus establishing SM was not just about organizing the list of fundamental particles and interactions among them, but also about 'understanding' the observed laws of nature in terms of an 'organizing' principle. For example, according to our current understanding, the $1/r$ nature of the Coulomb potential is due to the fact that γ has zero rest mass. Further, the photon rest mass is required to be zero, if the equations of motion for particles with electromagnetic interactions are to remain the same under a change of electromagnetic potentials such that the electromagnetic fields remain unchanged, the so called 'gauge transformations'. Thus the observed $1/r$ behaviour of Coulomb potential then is 'understood' in terms of this 'symmetry' property under 'gauge transformations' displayed by the electromagnetic interactions. As seen from Table 2 even though the mass of the mediating gauge bosons, γ and g is zero in each case, the electromagnetic and strong interactions show somewhat different behaviour, the Coulomb force has infinite range and the strong interactions are confined within a nucleon. This is an interesting feature of SM, which by itself can be a subject of an article (see note 7).

The most significant theoretical achievement while establishing SM was the development of a common theoretical framework to describe the different interactions. Because of the high energies and small distances that are involved in particle physics, any such framework has to be based on the two pillars of theoretical physics of the twentieth century: quantum mechanics and relativity. The common framework is thus a quantum theory of fields, called 'quantum field theory'. Quantum field theories which possess symmetries of the type described above are called gauge field theories. Thus the current paradigm is that all the fundamental interactions are described in terms of gauge theories, with spin 1 gauge bosons being the force carriers among the spin 1/2 matter fermions. The obvious differences in the properties that the three interactions exhibit, indicate that even though the mathematical framework is the same, the particular gauge symmetry operation is different in each case. At the same time, the obvious similarity in the mathematical description also started a quest for a unified description of all of them. For the purposes of this article, more relevant is the unified description of electromagnetic and weak interactions as a gauge theory, called the electroweak (EW) theory. In the next section we will recapitulate some points in this development, which are essential in our understanding of the choice of different parameters of LHC.

Verifications of predictions show the way forward

The idea of unification of electromagnetic and weak interaction started with Fermi when he wrote his theory of β-decay of nuclei, which shared some features of the theoretical description of the electromagnetic interactions. However, rates of processes involving ν, p and n, calculated using this theory had problems with quantum mechanics at high (see note 8) energies. To be specific, these rates increased with energy at rates higher than allowed by quantum mechanics. Schwinger showed that these problems could be solved by postulating a large mass for the carrier of weak interactions, which he called the $W^{\pm}$ (for weak) boson. Glashow, who was his student, in fact realized that if this were the case, the observed large difference between the strengths of the weak and electromagnetic interactions could be attributed to the difference in the mass of the carrier bosons.

However, weak interactions differ from electromagnetic interactions in yet another important way. These seem to treat the left-handed matter particles, quarks and leptons, whose direction of the spin is opposite to the direction of motion, differently, from those which are right-handed, i.e. those for which these two directions are parallel to each other (see note 9). For a particle with a nonzero rest mass, a left-handed state can be seen as a right-handed state by simply going to a frame which is moving faster than the particle. Thus the weak interactions then will depend on the frame of reference. This would be in conflict with Einstein's theory of relativity. The electromagnetic interactions, on the other hand, treat particles with both handedness the same way. In addition, gauge theories with massive vector gauge bosons had their own mathematical problems.

Glashow put forward a proposal for unifying the weak and electromagnetic interactions, reconciling the difference in the way they treat particles with different handedness. However, he succeeded in doing this only by predicting a new massive neutral boson, which he called the Z boson, along with a new class of weak processes which do not change the electromagnetic charge of the particles involved, called neutral current interactions (see note 10). Weinberg and Salam were able to extend this idea further by marrying it with the so-called Higgs mechanism and solve the possible conflict with relativity mentioned above. This thus now achieved EW unification, but needed existence of one more new particle, this time with spin 0; hence a boson named Higgs boson after one of its inventors. With this extension, the Glashow–Weinberg–Salam (GWS) model now predicted unification of electromagnetic and weak interactions and two new particles H and Z. The model further predicted masses of the W, Z bosons, M_W, M_Z in terms of the fine structure constant α_{em}, half-life of muon τ_μ and a single unknown parameter called $\sin^2\theta_W$. The latter could in turn be determined from measurements of rates of different processes initiated by high energy neutrinos. The model is not capable of making any predictions for the mass of the Higgs M_H, but has precise predictions for its interactions with all the fermions and the gauge bosons of SM.

The great success of the GSW model was that it could explain this suppression 'naturally', only if there existed another quark with the same charge as the u quark, viz. $2/3|e|$ (see note 11). Further, one could even predict the mass of this charm quark to be around 1.5 GeV/c^2 using the observed suppression. The observation of charmonium, a bound state of charm quark c and anti-charm quark $\bar{c}$, with a mass of 3.1 GeV/c^2 at the e^+e^- colliders (see note 12) along with that of the ν-induced neutral current processes whose existence was postulated in the GSW model (see note 13), were the first steps in establishing its correctness. The real test of this model came when indeed measurements of a variety of different high-energy ν, μ and e scattering processes led to a unique value of the above-mentioned unknown parameter of the model, $\sin^2\theta_W$. In fact, soon the accuracy of the determination of $\sin^2\theta_W$ was good enough ($\sin^2\theta_W = 0.234 \pm 0.013 \pm 0.009$)[1] to make a prediction for M_W and M_Z: $M_W = 82 \pm 2$ GeV/c^2, $M_Z = 92 \pm 2$ GeV/c^2. This led to the planning of a large project called super proton–antiproton synchrotron: the $Sp\bar{p}S$, set-up by converting the proton–proton collider operating at CERN since 1976, into a proton–antiproton collider, each beam with an energy of 270 GeV (see note 14). The machine started operation in 1983 and indeed discovered W/Z with these masses (see note 15) in the UA-1/UA-2 experiments (UA standing for underground). It should be noted, however, that these experiments did not give any 'direct/indirect' evidence for the existence of the Higgs yet.

Further high-precision experiments at the electron–positron colliders at CERN (Large Electron Positron Collider, LEP) and SLAC (Stanford Linear Collider, SLC) studied properties of 'millions' of Z bosons as well as the thousands of W bosons at the $p\bar{p}$ collider, Tevatron at the Fermi National Accelerator Laboratory (FNAL), USA (see note 16). In fact, these measurements ushered in an area of precision testing of the GSW model (SM) of EW interactions. To get a feel for the level of precision in the experimental measurements and that in the theoretical predictions, I show in Figure 1 (taken from ref. 2), the improvement with LEP/SLC in the accuracy of quantities which determined $\sin^2\theta_W$. Figure 1 shows two quantities g_V, g_A, which are a measure of the interactions of ν with charged leptons and quarks and are predicted in the SM as a known function of $\sin^2\theta_W$, given the electromagnetic, weak charges of the different fermions. The area bounded by intersection of all the curves determines the $\sin^2\theta_W$ of SM. The great improvement in the precision using the data from LEP and SLC, is obvious from the inset. The value of $\sin^2\theta_W$ of 0.23153 ± 0.00016 obtained from these measurements[2] is to be compared with $\sin^2\theta_W = 0.234 \pm 0.013 \pm 0.009$, mentioned earlier[1].

Table 3 lists some of the crucial parameters of the unified theory, comparing the experimental measurements with SM predictions for the best-fit value of $\sin^2\theta_W$ (refs 3, 4). The very precisely measured M_W shown in Table 3, would have in fact disagreed with the one predicted in SM, using the precisely measured value of $\sin^2\theta_W$ extracted from measurements of Figure 1, if the used predictions were obtained using an approximation wherein

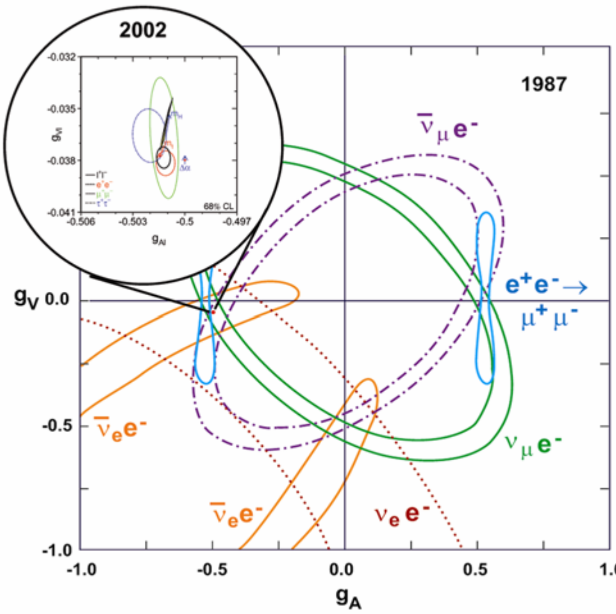

Figure 1. Testing of the SM predictions of the interaction of neutrinos with other fermions carrying electromagnetic charge, from early $\nu_l l'$ scattering processes and the later high-precision measurements at LEP, taken from ref. 2. The figure shows two quantities g_V, g_A, which are a measure of the interactions of ν with charged leptons and quarks, and are predicted in the SM as a known function of $\sin^2\theta_W$, given the electromagnetic, weak charges of the different fermions. The area bounded by intersection of all the curves determines the $\sin^2\theta_W$ of the SM. Note the vast improvement in the measurements, which is obvious by comparing the change in scales of both the axes, by over two orders of magnitude.

Table 3. Precision testing of the SM at the Large Electron Positron Collider (LEP). Few of the observables which have been measured at LEP with high precision and the predictions of the SM fit to the data for the same are also shown. For more details see: http://lepewwg.web.cern.ch. The S_M 'prediction' for the mass of top quark Mt is indirect as contrasted with, e.g. M_W

Observable	Experimentally measured value	SM prediction
Width of the Z boson: Γ_Z	2.4952 ± 0.0023 GeV	2.4959 GeV
Mass of the W boson: M_W	80.404 ± 0.030 GeV/c^2	80.376 GeV/c^2
Mass of the t quark M_t	172.5 ± 2.3 GeV/c^2	172.9 GeV/c^2

some of contributions, majority coming from existence of a t quark, were neglected. Thus the precision of calculation had to match the precision of measurements. The precise calculations of these additional contributions are made possible only due to an extra property called 'renormalisability' that the presence of the Higgs lends to the EW theory. In fact, at the time of these precision measurements at LEP and SLC, there was no convincing 'direct' evidence for the t quark yet and thus these measurements were an 'indirect' indication. The agreement of the t mass in the third column of Table 3 with the one that was measured later at the Tevatron collider in the 'direct' observation, was considered as the first 'indirect' proof for the existence of the Higgs boson (see note 17).

Information available from earlier colliders thus set the goals for LHC, just like Gamow's theory predicted goal posts for energy required for radioactivity. Results at the current series of machines have always driven the physics at the next generation of machines, giving an indication of the required energy/luminosity. The framework of SM was abstracted using results from the fixed-target ν experiments and from the low energy e^+e^- colliders. In that framework one had a prediction for the masses of W/Z bosons. The UA-1 and UA-2 experiments measured the masses of these W/Z bosons producing them directly, thus giving the first 'direct' confirmation of the SM predictions of these masses. The measurements at the LEP and the $p\bar{p}$ collider Tevatron, combined with high-precision theoretical calculations in the framework of SM, then led to a prediction of the top mass. The agreement of this predicted value of M_t with the one directly determined at the Tevatron (Table 3), proved the correctness of SM to a high degree of accuracy. These precision measurements and calculations, now predict the range in which the Higgs mass M_H value must lie in SM. We discuss this next.

Where can the Higgs be?

As already stated, unlike the case of W, Z, the SM has no prediction for the mass of the Higgs M_H. On the other hand, it has precise predictions that the strength of its interactions with all the fermions and gauge bosons will be proportional to their masses. As a result, given the Higgs mass, it predicts precisely how it could be produced at the colliders. All the colliders before LHC have so far looked for the evidence for the production of Higgs boson through its decay products and have found none so far, thus eliminating regions of M_H where a SM Higgs boson, i.e. a Higgs boson with interactions as predicted in SM, could be present. Thus there exist 'direct' experimental lower bounds on M_H from its non observation so far at LEP[5] and Tevatron[6].

A question to be asked is whether the theory has anything to say about the Higgs mass, even though it cannot predict the value it should have in terms of other parameters of the model. Indeed one can predict the range where M_H must lie by demanding that the theory satisfy some simple properties such as boundedness of potential energy for the Higgs field, finiteness of interaction of the Higgs field with itself, etc. This thus gives theoretical bounds on M_H. The range of allowed masses is obtained assuming validity of SM, up to a given energy scale Λ.

The precise measurements of a large variety of observables at the LEP and SLC collider, coupled with the measurement of the W mass in the experiments at the Tevatron collider can be analysed in the framework of SM. In SM, values of the above-mentioned observables can be predicted, in terms of the three parameters, α_{em}, $\sin^2\theta_W$, τ_μ, just like the case of M_W, M_Z. The calculation of additional contributions required for precision predictions adds a dependence of the predictions on M_t, the mass of the heaviest fermion top and on M_H. Since accurate direct measurements of M_t are available from the Tevatron, M_H is the only unknown in the game. Hence SM fit to all the precision observables can then give an 'indirect' information on the mass region for the Higgs that will be favoured by consistency of these measurements with the SM predictions.

In the two panels[7,8] of Figure 2, I summarize the theoretical as well direct and indirect experimental bounds on the Higgs boson mass in SM. A few remarks are in order. The x-axis of Figure 2 *a* stops around 10^{18} GeV, as that is the scale where gravitational effects, which are neglected throughout this discussion as well as all the studies of SM mentioned herein, become important. The SM and the various statements made in its context so far, may not be valid beyond this energy. Results of Figure 2 *a* show that

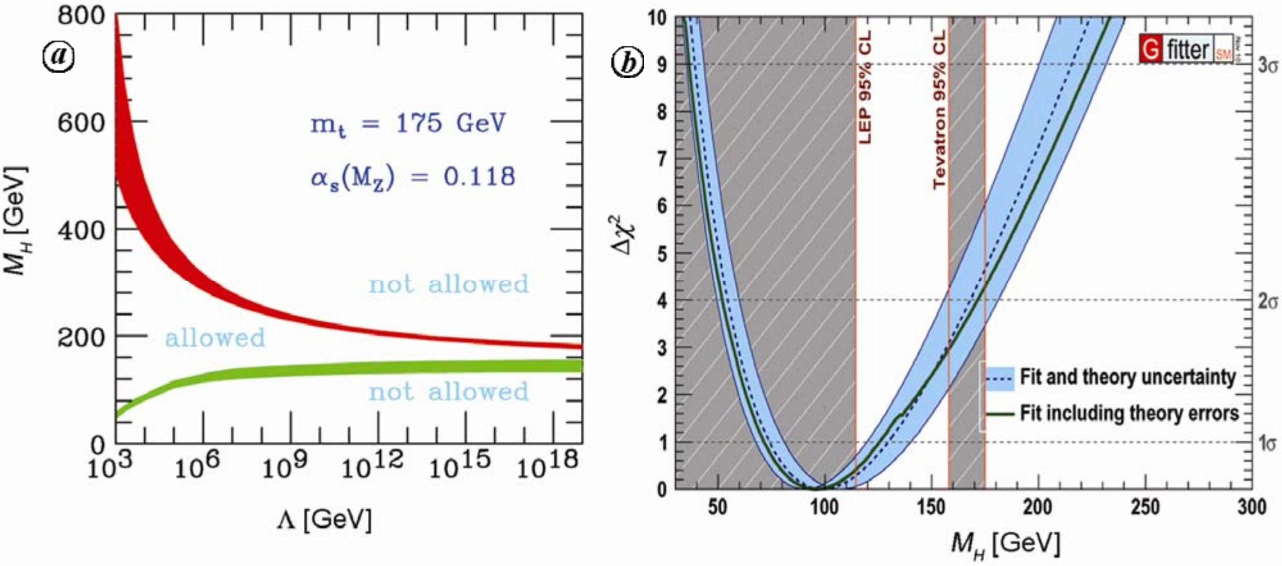

Figure 2. Theoretical upper and lower bounds on the Higgs mass in the SM as a function of the assumed energy scale Λ for the validity of the SM taken from Hambye and Riesselmann[7] are shown in (***a***) along with a summary of the current, direct and indirect experimental constraints on the Higgs mass from the collider experiments in (***b***). The coloured areas show Higgs mass ranges excluded at 95% CL from direct searches. The figure also shows $\Delta\chi^2$ as a function of M_H for a SM fit to a variety of precisely measured EW observables taken from ref. 8.

just the mass of the observed spin 0 boson should be able to give some information about the existence or absence of some particles and interactions beyond those in SM (BSM), up to a given energy. For example, observation of a Higgs with mass in the region of ~160–180 GeV will indicate that SM without any further additions, new particles or interactions, can be valid all the way up to $\sim 10^{18}$ GeV. Clearly, any physics which exists at this scale will not be accessible in direct searches, not just at LHC but at any collider ever. On the other hand, a heavier Higgs (say ~300 GeV) would accommodate new physics around TeV scale. Also, a Higgs lighter than ~125–130 GeV/c^2, while not providing any 'proof' for BSM physics, will indicate possibility of its existence; albeit it would not pin down, with too much accuracy, the energy scale at which this physics should appear. Specific examples of such new physics can be, for example, one extra pair of quarks and/or presence of strong interaction dynamics around TeV scale. The results shown in Figure 2 *b* tell us that in SM, current data prefer a light Higgs and on inclusion of the direct limits from the collider searches, one gets $M_H < 185$ GeV/c^2, at 95% confidence level (CL). The closeness of this upper bound with that seen in the theoretical analysis presented in Figure 2 *a*, in fact raises the prospect that we might find only such a light Higgs with $M_H \sim 160$–185 GeV/c^2 and nothing else at LHC. It should be mentioned here, however, that some of the details of the analyses of the EW observables, are quite sensitively dependent on the way in which the theoretical and experimental errors are accounted for therein. Further, the exclusion of an SM Higgs in the mass range around 160 GeV/c^2, coming from direct searches at the Tevatron, depends crucially on the knowledge of the quark/gluon content of the proton and hence suffers from uncertainties in the same[9,10]. Thus a confirmation or denial of this result from LHC is important. At LHC, search of the Higgs in this mass range would be free of these issues that plague the Higgs search at the Tevatron. Thus this knowledge now sets the stage for the LHC Higgs searches.

Why do we need physics beyond SM

Having thus discussed why the ultimate verification of SM hinges on the (now imminent) direct observation or exclusion of the Higgs boson, we can also ask a question whether such an observation will bring to a conclusion this century-long story of the quest of finding what lies at the heart of matter and how it is put together. The short answer is no. As successful as SM is, there still remain a few puzzles that it has no answers to.

One of these is the presence in the Universe, of matter that does not shine, the so called 'Dark Matter' (DM). Its existence is inferred only from its gravitational effect by measuring velocities of galaxies and galaxy clusters at the present epoch and also by the role such matter seems to play in the formation of galaxies in the early epochs. The astrophysical evidence is pretty convincing. None of the members of the 'periodic table' of SM (Tables 1 and 2) can be a DM candidate. The entire set of SM particles listed earlier, in fact make up only 4% of the total matter in the Universe. This experimental information indicates at least one particle beyond SM (BSM). Note that we can draw this conclusion only because we understand completely the interactions that 'all' the SM particles have. In fact, it is also interesting that almost all the extensions of SM that have been suggested to address some of the theoretical lacunae in the model, have a DM candidate 'naturally', i.e. the DM candidate is not being invented therein to explain the observed DM.

The Universe of today seems to have a matter–antimatter asymmetry. If B denotes number of proton-like particles (baryons) and $\bar{B}$ that of the anti-baryons, measurements show that in today's universe $N_{\bar{B}} \simeq 0$, in spite of the fact that the early universe is expected to have had $N_B = N_{\bar{B}}$. Interestingly, a qualitative explanation of this asymmetry, *in the Universe* in terms of known properties of SM particles, *measured in laboratory*, is possible. A quantitative explanation, however, indicates the need of BSM physics. The ability of SM physics to explain these cosmological issues is no longer in doubt, as one can explain the relative abundance of different elements in the Universe satisfactorily in terms of known physics of SM and reaction rates measured in terrestrial laboratories. Another puzzle is posed by the observation – honoured by the Nobel Prize this year – that the Universe is accelerating as well as expanding. Within the current understanding of Gravity and space time, one seems to require a new source for this acceleration and this is termed 'Dark Energy'. String theorists trying to extend our theory of fundamental interactions to include gravity are attempting to solve this puzzle.

On a different note, since now the properties of all the particles, the constituent matter particles and the force carriers, have been measured to a high degree of accuracy and the periodic table for particle physics is *almost* complete, it is time to see if there is an underlying theory which explains the patterns in these properties. It is now firmly established that neutrinos have tiny, nonzero masses (see note 18). This means that the masses of the different fermions vary over a wide range. For example, the mass of neutrinos is smaller than 1 eV/c^2 and the mass of the top quark is $\sim 175 \times 10^9$ eV/c^2. In SM all these masses are just arbitrary parameters. A natural question that has been asked by particle theorists is whether we can have a fundamental understanding of why they have the values they have? Such questions might sound esoteric, but a lot of progress in science actually has come from asking such questions. To answer such questions, one has to go beyond SM.

In all this I have not yet talked about the one reason for BSM that is closest to a theorist's heart. As mentioned before, a lot of progress in particle physics (and in fact theoretical physics) has come from looking for elegant explanation of observed physical phenomena and properties in terms of some underlying organizing principle. The precision testing of SM implies that a particle, elementary or otherwise, with interactions very close to that predicted in SM must exist. Further, the data tell us it must be light and have mass comparable to the W, Z bosons. Just like gauge invariance gave an explanation of the power of r in Coulomb's law, one would like to 'understand' why the Higgs is light. Supersymmetry is one of the leading candidates for such a theory, predicting among other things, a DM candidate which can be hunted for at LHC[11].

It is to be noted that the plot such as shown in Figure 2 *a*, will change due to the existence of a particular type of BSM physics at a particular energy scale. Hence observation or non-observation of a Higgs with a particular mass, can give indirect information/clue to the existence and character of BSM physics at a particular scale, even in the case that LHC may not have enough energy to probe the new physics at that scale. In some BSM scenarios we expect more than one neutral Higgs boson state to exist and some others predict existence of charged Higgs boson which do not exist in SM at all. In the case of BSM scenarios which predict more than one neutral Higgs bosons, all that the precision tests are able to tell us is that one state out of these will have to resemble the SM Higgs boson in its properties. The theoretical limits on the mass of this state can be different in different BSM scenarios: in the case of supersymmetry, which has more than one Higgs boson, the mass of the lightest among them is bounded from above by ~ 135 GeV/c^2 in the simplest version of the model. Thus a failure to find any Higgs below this mass range will severely restrict the supersymmetric models. This discussion thus tells us that after finding the Higgs boson at LHC, even approximate information on its mass can already give us hints of the presence of BSM and/or information on the energy scale at which BSM physics, i.e. particles outside the three generation SM framework can exist.

LHC machine

LHC design

If SM is correct, a light Higgs (i.e. with mass comparable to that of the W/Z) **must** be found experimentally. There is strong evidence that SM is a good approximation to reality. Right now LHC is the only collider which will be able to find a 'light' Higgs boson (see note 19). It should also be said that since the existence of BSM physics can in principle change the bounds on the Higgs mass shown in Figure 2, it is imperative that LHC hunts for the Higgs over the entire range of the Higgs mass of Figure 2 *a*. Even if SM is not the entire story and hence the Higgs is not in the low-mass range predicted by SM, or is not present at all, the agreement of the SM predictions with the precision measurements (cf. Table 3) tells us that something like a Higgs boson must be present. The general theoretical bounds on M_H mentioned earlier, encompass those that one computes for such look-alikes as well.

Hence, observation of the Higgs, measurement of its mass or even the non-observation in a given mass range, will shed light on the puzzle of the formulation of a unified theory of electromagnetic and weak interaction (EW theory) mentioned before.

It was clear while planning LHC that one has to design the machine such that it should be able to probe the issue of unified EW theory in a completely model-independent fashion. A general theoretical upper limit on the Higgs mass is about 900 GeV/c^2 (see note 20). Hence, even though in SM, due to the information obtained from precision measurements, we expect the Higgs to be light, the LHC design should be such that one will have a measurable signal even in this worst case scenario, at the highest mass of $M_H \sim 1$ TeV. Even if SM is not the complete reality, hence no light Higgs boson is found, it should still be possible to unravel the mystery of EW unification if one can study effective *WW* scattering up to a total energy of 1 TeV $\sim M_H^{\max}$. The choice of energy and luminosity of LHC was made by demanding that LHC should be able to cover this eventuality (see note 21).

The choice can be understood somewhat simply as follows. The available knowledge of the quark/gluon content of the proton indicated that unlike the case of the earlier CERN and FNAL colliders, the physics potential of a higher energy hadronic machine would be independent of whether one has a pp machine or a $p\bar{p}$ machine. Hence a decision to make, the cheaper and the easier-to-build, pp machine was taken. Thus the LHC collides protons on protons. As mentioned earlier, the protons are made of quarks and gluons. Hence collisions at LHC are effectively collisions among these quarks and gluons. They carry only a fraction of the energy of the proton.

Figure 3 shows a possible process of producing a Higgs boson, which then decays to two Z bosons. The production is via the process $qq \to qqWW$ ($q = u$, d, s, etc.); the two W-bosons fusing to produce a Higgs boson, which then decays into a pair of Z bosons via $WW \to H \to ZZ$. The presence of the two Z bosons is then detected through the decays of the each Z boson into a pair of a lepton and anti-lepton $\ell^+\ell^-$, where $\ell = e$, μ. For the two W bosons (whose fusion produces the Higgs boson) to have a total energy of 1 TeV, the most energy-efficient configuration is when each of them has an energy of 0.5 TeV. This means that each parent quark in the figure must have an energy of 1 TeV. From the measured distribution of the momenta of a proton among its quarks, one knows that on the average, the quarks carry about one-sixth energy of the proton. This means that the protons must have an energy of 6 TeV. Hence, one planned on a pp collision energy of 7 TeV on 7 TeV. The total number of pp collisions was decided using the theoretical estimate for the rate of production of the events $pp \to WW \to ZZ \to \ell^+\ell^-\ell'^+\ell'^-$, and demanding that at least ten events per year be produced. Note how our theoretical knowledge about SM has set the bar for the new machine energy and intensity.

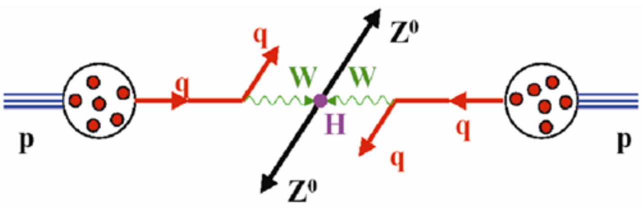

Figure 3. How the LHC parameters were decided.

LHC machine: start-up and current status

Even by the standards of HEP laboratories designing and building LHC was a challenging exercise. The LHC was conceived in 1980s and the planning began in 1989. The tunnel which houses LHC now, was built between 1983 and 1988, and was home to the LEP experiment till 2000. CERN Council approved the construction of LHC in 1994. Limiting oneself to the use of the LEP tunnel meant that there was an upper limit of 7 TeV energy to which the protons could be accelerated (see note 22). Hence LHC had to plan on larger luminosity. This meant narrower bunches, higher magnetic fields and packing more particles per bunch. The LHC builders then decided to use new methods for acceleration. They also decided to use an innovative idea where the beams would circulate in two separate rings just above one another. For e^+e^- or $p\bar{p}$, the same magnetic field automatically suffices to steer the two bunches with opposite electromagnetic charge in opposite directions. That is not the case when both colliding particles have the same charge as they do for LHC. All this was not just technologically challenging, but also expensive. The decision was then taken by the CERN Council to build it in two stages, starting with lower energy and lower luminosity first and then enhancing both. In the meanwhile, plans for SSC were abandoned. From 1995 onwards, countries which were not members of CERN, viz. Japan, USA, Canada, India and Russia, promised support to the LHC machine and a decision was taken to build it in one go. While the Indian HEP community had participated in building detectors and doing experiments at the earlier fixed target and collider facilities, this was the first instance where India had participated in the building of the machine itself.

Given the ring size, the energy to which particles need to be accelerated implied that one needed to have higher magnetic fields of about 8 T. This in turn meant that the magnets had to be cooled down to 1.9 K. Contrast this with the other superconducting collider Tevatron, where the temperature is about 5.2 K and the magnetic fields required about a factor of two smaller. The magnetic fields required at LHC are also higher than the one used

Figure 4. The quadrupole–dipole connection: undamaged (left panel) and damaged (right panel).

at the old SPS, by about a factor of 5. Not just that, 10–12 T is about the upper limit at which these niobium–titanium accelerator magnets can function, still remaining superconducting. All this should give a flavour of the engineering and technological improvements that were required for LHC. The most crucial piece of machinery for LHC are the 1232 dipole magnets, each weighing 34,000 tonnes and costing about 0.5 M Swiss Francs each.

Before the start-up of September 2008, the goal for energy per beam was already lowered from the initial 7 TeV to 5 TeV, with plans to raise the energy afterwards. Its start-up in September 2008 came to an abrupt end during a test of the one sector which had not been tested before for the full current corresponding to an energy of 5 TeV. Most likely, an electrical arc developed and it punctured the helium enclosure. Large amounts of helium gas were released into the insulating vacuum of the cryostat and a large pressure wave travelled along the accelerator both ways. The pressure was too large to handle for the pressure release systems which had been put in place. One of the quadrupole–dipole connection, before and after the incident is shown in Figure 4. The severity of the accident becomes obvious when one recalls how heavy these magnets are. Thirty-nine of the 1232 dipole magnets and 16 of the quadrupole magnets had to be replaced, vacuum tubes had to be cleaned, new pressure release systems as well more diagnostic methods to avoid a similar accident again had to be installed. All these repairs were completed by fall 2009. A large amount of time is required to cool the machine to the low temperatures, which has to be done gradually. Finally, by the end of November 2009, the machine was ready to go again and as mentioned in the introduction the collisions at high energies are now happening routinely. However, it has been noticed that the superconducting magnets need to be ‘trained’ to carry higher currents and hence the ramping of the energy will now be gradual. The machine has been running now only with beams of 3.5 TeV each (exactly half the design energy and less than the 5 TeV, which was planned for the 2009 run). It is now proposed that the machine will run at this energy till end of 2011/2012 and then again there will be a major shutdown to ramp the energy up to 6.5–7 TeV per beam (7 TeV seems a bit difficult to reach according to the present studies), as well as an increase towards the ultimate design luminosity, total number of collisions per unit area per unit time of 10^{34} cm^{-2} s^{-1}. (This is the number for the luminosity that I had used in explaining how the LHC design energy was decided.) According to the current plan, the design energy and luminosity, will now be reached only a little later.

In the initial running of the machine in 2010, only a luminosity of few times 10^{30} cm^{-2} s^{-1} had been achieved. This is partially because these big machines are like a delicate musical instrument which needs to be finely tuned. For example, when larger number of bunches are injected, to increase the luminosity, the bunch–bunch interactions can destabilize the beam. These interactions are understood, in principle, and included in the designs; still fine adjustments to the beam parameters are required to get rid of these effects while the machine is running. During the last year the accelerator physicists worked hard, alternating their work with making available the beams for actual physics run to the experimental physicists. The bunches with the LHC design intensity (i.e. 1.15×10^{11} particles per bunch (ppb)), were successfully injected in the early stages in 2010 itself. To increase the luminosity, the number of bunches had to be increased. After beginning in 2009 with one bunch with $\sim 10^{10}$ ppb, by the end of 2010, the machine physicists managed to inject about 318 bunches, with $\sim 10^{12}$ ppb, reaching peak luminosity of about 10^{32} cm^{-2} s^{-1}.

After the planned shutdown in December 2010 and the retuning in early 2011, LHC started delivering beams for physics explorations in February. Now the number of bunches has reached ~ 1300, with a peak luminosity of

~ 10^{33} cm^{-2} s^{-1}. One full year at this luminosity would mean that there will be 10 events per year (~ 10^7 s = 150 running days in a year), per fb cross-section. This is termed as luminosity of 10 fb^{-1} per year. Thus now the machine is beginning to deliver more collisions in a single fill, than was delivered in the entire early running in 2010.

It is the enormous success of the accelerator physicists in delivering the higher luminosity that has brought the prospects of getting, *within this year*, an answer to the 'billion dollar question' about the existence and mass of the Higgs. It is amazing that even with the reduced energy and still short of the design luminosity by an order of magnitude, LHC has begun making inroads into this all-important question. In June 2011, LHC achieved a total luminosity of 1 fb^{-1}, which corresponds to 70 million million (10^{12}) collisions. This was initially the target set for the end of 2011. The fact that it has been achieved only within three months of operation, has raised the possibility that the Higgs will run out of space to hide within the next few months, should LHC continue to operate on the same high note.

Current results and timeline

How do we look for things at LHC?

As already mentioned, an evaluation of how well the mammoth detectors can achieve their goals, is possible only with precise theoretical predictions for the various possible production processes. There are two general-purpose detectors called CMS and ATLAS, whose main mandate is to search for the Higgs boson and new particles beyond those present in SM (see note 23). A large number of detailed studies, with the combined participation of the theorists and experimentalists, were done to evaluate the physics prospects of LHC[12]. Most of the detailed analyses had used the nominal LHC energy of 14 TeV and the nominal luminosity of 10^{33}–10^{34} cm^{-2} s^{-1} in the first year. Figure 5 shows the expected cross-sections for different processes for different values of centre of mass energy. The vertical line labelled LHC corresponds to the original energy of 14 TeV. The number on the right-hand side of Figure 5 indicates the number of events expected per second for a particular process, for the lower value of the nominal luminosity of 10^{33} cm^{-2} s^{-1} (this corresponds to 10 fb^{-1} over one year). One can see from Figure 5 that even at high energy and luminosity, finding a Higgs with the lowest mass that is allowed for it by experimental constraints is not easy. For example, for a Higgs with $M_H c^2$ = 120 GeV, one expects only a few hundred events where a Higgs boson is produced. The rates for other processes are higher by many orders of magnitude. When one multiplies the (small) expected number of events with the probability that the Higgs will give rise to a final state that will make it easier to distinguish the Higgs signal from the background, the number of expected events goes further down. To be specific, for a Higgs of mass 120 GeV/c^2, decaying into $b\bar{b}$, the relevant background would be the one denoted by two curves labelled σ_b and E_{jet} > 100 GeV. Note that the curve labelled σ_b shows that the production cross-section of $b\bar{b}$ production from processes other than the Higgs production lies 8–9 orders of magnitude higher than that for the Higgs production, which is even less than that shown by the curve σ_{Higgs} (M_H = 150 GeV) in Figure 5. Therefore, the only promising channel for such a light Higgs is when the H decays into the $\gamma\gamma$ final state. Such events will happen only at a rate 1000 times smaller than that with a $b\bar{b}$ in the final state. Figure 6 shows the signal significance that one expected to achieve at the originally planned 14 TeV LHC, for an integrated luminosity of 100 fb^{-1}, with most conservative estimates of the production cross-sections. This corresponds to the assertion that used to be made that a single experiment can discover the Higgs over the entire mass range allowed by theoretical considerations with a significance of 5σ at the 14 TeV LHC. This is a more technical description of the analysis I presented to explain how the design luminosity and energy were arrived at. Clever strategies to use final states with b, $\bar{b}$ quarks in them have been suggested[13]. However, the

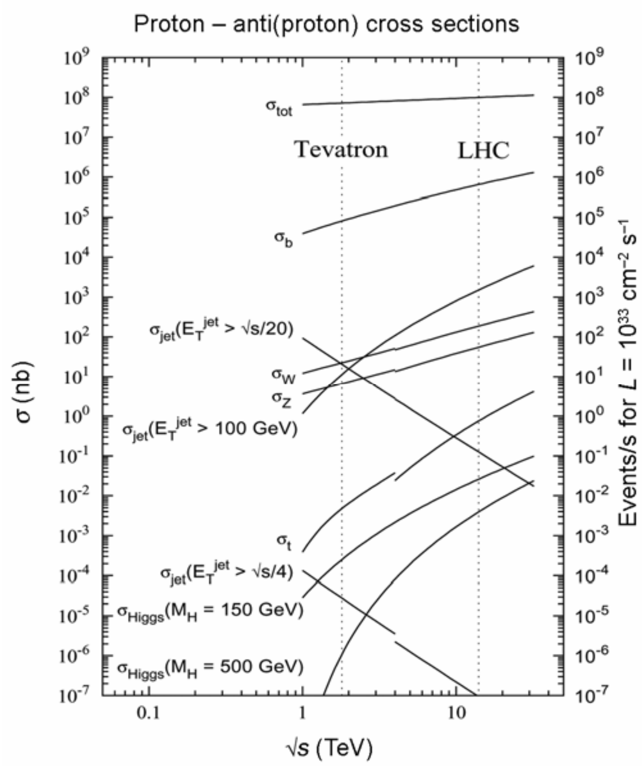

Figure 5. The cross-sections for various processes expected at the LHC taken from ATLAS TDR[12]. The right-hand side scale indicates the expected number of events per second for the indicated class of processes for a luminosity of 10 fb^{-1} over one year.

general expectation was that these improvements will be possible only after a good understanding of the detector has been achieved. Further, the lowering of energy to 7 TeV causes a reduction in the expected cross-sections. This had led to expectations that some minor inroads in the Higgs territory would be made when the machine delivers at least 1 fb^{-1} luminosity and we would need to wait till the end of 2012 (perhaps even longer if the Higgs is really light ~ 120 GeV) to get a clear answer to this most urgent question[14].

To the great surprise and delight of everyone involved, the detectors performed exceptionally well in the run of LHC in 2010. In fact, within a few weeks the entire SM was rediscovered at LHC. Figure 7 shows the rediscovery of various resonances at LHC in the process $pp \to \mu^+\mu^- + X$ as a function of total energy of the $\mu^+\mu^-$ pair in a frame where the total momentum carried by the pair is zero. These resonances were first discovered in the process $e^+e^- \to \mu^+\mu^-$ at a series of e^+e^- colliders, beginning from the first one ADONE at Frascati in 1969 to the LEP collider in 1989. The plot brings home clearly how LHC is a broad sweep machine and is able to give us, in one go, a glimpse of the physics which had been discovered over these three decades and over a large energy range (see note 24). I have taken this plot from the talk by CMS collaboration given at the end of 2010 in the LHC Jamboree held at CERN; it corresponds to the luminosity of only 40 pb^{-1}, with detectors whose performance in real operating conditions was just being understood. Normally, particularly at a hadronic collider, it takes some time before the experimentalists can extract from the data information which uses the full design ability of the detectors. For LHC, the long preparation time and the rather long wait imposed due to repairs to the machine, meant that the experimentalist already had time to understand the giant detectors and tune their analysis tools, *before* they started collecting data in the high luminosity operating conditions.

Emboldened by this excellent early performance, in October 2010, the ATLAS and CMS detectors gave the projected abilities to entice the Higgs out of the nooks and crannies where it could be hiding, where already the full use of all the new search strategies was envisaged[15,16]. The left panel of Figure 8 shows the luminosity required for Higgs discovery at 5σ and 3σ significance as well as for Higgs exclusion at 95% CL at two values of the centre of mass energy $(\sqrt{s})$ of 7 and 8 TeV respectively, according to the ATLAS projection. The right panel, on the other hand, shows the CMS version of Figure 6 but now for $\sqrt{s} = 7$ and 8 TeV. It gives the expected level of significance of observation of the Higgs, combining information from different possible final states into which the Higgs can decay, for a few selected values of integrated luminosities. The figures are extremely complicated and contain a lot of information, but the main lesson to take home is that with an integrated luminosity of about 8–10 fb^{-1}, a single detector should be able to discover a Higgs with better than 5σ significance over almost the entire range of theoretically allowed values of M_H, if the mass is above 130 GeV/c^2. This thus meant that depending on the luminosity the LHC machine manages to deliver, one would have significant information on the SM Higgs mass by the end of 2011/2012. For more details, I refer the readers to information available on the web pages in refs 15 and 16 respectively. Based on this information, in January 2011, the LHC council took a decision to continue running at

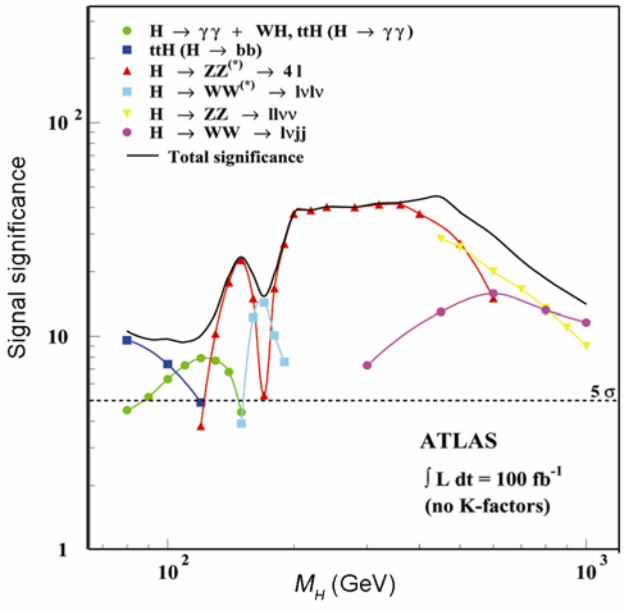

Figure 6. The expected signal significance in different search channels for the Higgs boson as a function of the Higgs boson mass, for the 14 TeV LHC, taking very conservative predictions for the production cross-sections, for 100 fb^{-1} luminosity, taken from ATLAS TDR[12].

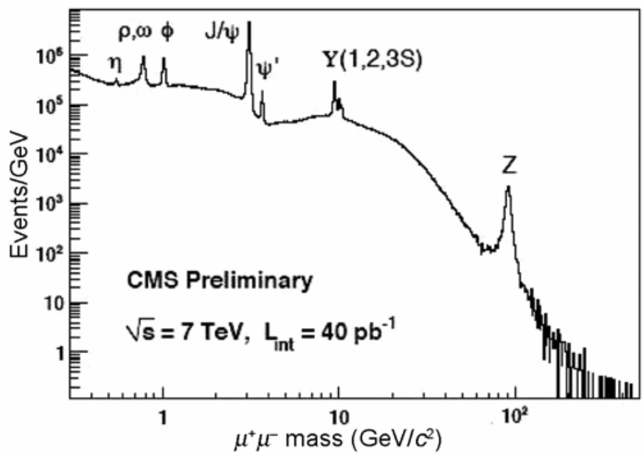

Figure 7. SM rediscovered at LHC: the plot shows a series of resonances seen at the LHC in $pp \to \mu^+\mu^-$. These resonances were initially found at various e^+e^- colliders starting from ADONE in 1969 to LEP in 1989.

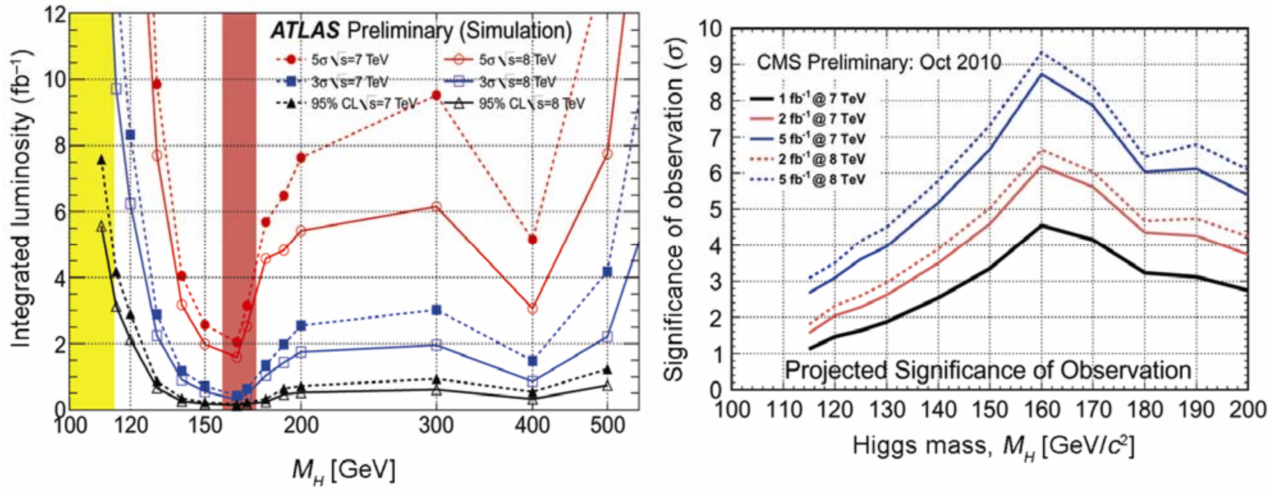

Figure 8. ATLAS simulation for the required integrated luminosity for exclusion at 95% CL and discovery at 3 and 5σ level (left panel)[15], and the expected level of significance of observation at different integrated luminosities from CMS simulation (right panel)[16], as a function of M_H. Results are shown for both $\sqrt{s} = 7$ and 8 TeV.

7 TeV with an aim to collect 1 fb^{-1} luminosity (still a factor of 10 smaller than the one envisaged during the decades long planning) by the end of 2011. As described earlier, the machine delivered this already in three months from the restart in February 2011, by end of June 2011. This combined with the better than expected understanding and performance of the detectors, the LHC experiments have already yielded significant information about the Higgs. I will turn to a description of this information in the next section.

What do the current results say?

As mentioned earlier, majority of the data were collected in June and already at the meeting of the European Physical Society in the last week of July 2011, the collaborations were able to present the result of the analyses, combining all the complicated analyses strategies. This requires efficient and quick analyses of the data. This small gap between collecting the data and presenting the results, in fact illustrates the success of all the work put in by all the experimental groups, in developing efficient software to simulate the response of the detectors beforehand. The contribution of the Indian groups both in the construction of the parts of the LHC detectors and in setting up these analyses software has been impressive.

The results of the ATLAS and CMS detectors are summarized in the two panels[17] of Figure 9. The plots show the 95% CL upper limit on σ^{obs}/σ_{SM} as a function of M_H. This is in fact an envelope obtained using all the different possible final states which the produced Higgs can give rise to. In general, for different masses, different final states are produced at different rates and thus the sensitivity to a Higgs does not depend on M_H monotonically, even though production cross-section for the Higgs decreases monotonically with increasing M_H. The plot is rather complicated, but the lesson is clear. The regions of M_H for which the thick solid line goes below 1 are thus excluded at 95% CL. The two detectors differ in their sensitivities to individual channels, but the overall reach is similar. The plots show that a Higgs boson with interactions as predicted in SM (the SM Higgs) is ruled out at 95% CL, over mass ranges $155 < M_H < 206$ GeV/c^2 and $270 < M_H < 450$ GeV/c^2. In all the other three mass windows that are still allowed: $113 < M_H < 155$, $206 < M_H < 270$ and $450 < M_H < \sim 700$–800 GeV/c^2; (cf. Figure 2) the upper limit on the observed ratio lies quite a bit above 1, for one or both of the experiments. Hence it clearly does not allow to rule out the Higgs in that mass range yet. In fact, the large value of the upper limit on the observed cross-section in units of SM expectation in some of these regions is tantalizing indeed and might really be indicating the existence of a Higgs in this mass range. Indeed this is the place to watch the development with increasing luminosity. A combination of the results by both the experiments, over all the channels was expected to at the International Symposium on High Energy Lepton Photon Interactions, held in Mumbai at the end of August 2011. However, that did not happen. In any case, as shown in Figure 8, by the time LHC collects 10–20 fb^{-1} data, even the most stubborn SM Higgs (in the mass range 115–120 GeV/c^2) will have to show its face.

What are the implications for SM/BSM?

As already mentioned, even the mass of the Higgs when (and if) it is discovered, will in fact already answer quite a few questions about SM and BSM. The mass

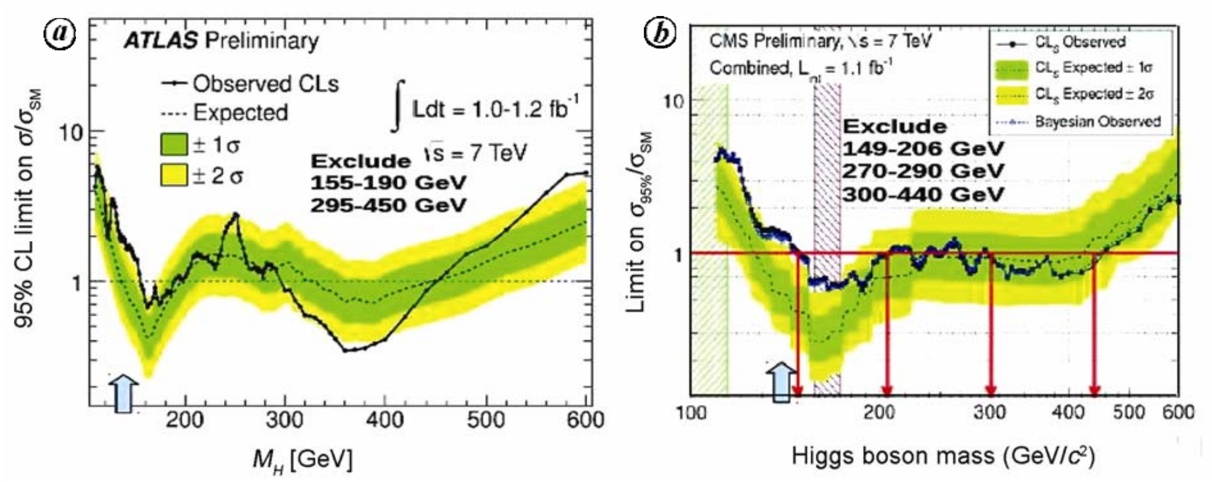

Figure 9. A summary of current results on the SM Higgs from ATLAS and CMS[17].

regions between $155 < M_H < 206$ GeV/c^2 and $270 < M_H < 450$ GeV/c^2 have now been ruled out at 95% CL, for a SM Higgs. If we now take a relook at Figure 2 *a*, we see that if the Higgs mass in the mass range $160 < M_H < 180$ GeV/c^2 had been allowed, it would have meant that there need be no new particles/interactions beyond those in SM, all the way to 10^{18} GeV. Thus exclusion of a Higgs in this mass range is an indirect indication that SM need not describe the particles and their interactions in their **entirety** all the way up to the energies where gravitation starts playing an important role. Should we find the Higgs in the lower mass range that is still allowed for it, $M_H < 130$ GeV/c^2 (and where in fact the experiments see a possible excess above expectations from the background processes), it would mean that there is 'indirect' indication for the BSM physics around the ~ TeV scale. Note the ~ in front of the TeV scale. The pre-factor may be a factor 10, in which case the energy of LHC will not be enough to produce this BSM physics 'directly'. Precision measurements of the observed Higgs state will then be the way to go ahead and the International Linear Collider being planned may be the ideal machine for that[18].

If (one) or more Higgs states should be lurking in the higher mass range of ~ 200–250 GeV/c^2 that seems to be allowed, then that is likely to be a BSM Higgs in view of the 'indirect' limits of Figure 2 *b*. However, depending on its type the BSM physics can affect the expected signal rates of the Higgs bosons, and thus the exclusions of Figure 9 have to be then reinterpreted. Let us take an example of the simple BSM physics; a 4-generation version of SM with just one extra pair of quarks and leptons. It has been shown that, in principle, in this case the indirect limit on the Higgs mass to be much higher than the 185 GeV/c^2 expected in the case of the 3-generation SM. The presence of such a fourth generation, however, will raise the expected level of signal for the Higgs at the LHC by about a factor of 9. Thus then one should have seen evidence for it in the current data, since they are already sensitive to a Higgs boson with cross-section equal to or a few times that expected in SM. In fact, one can reinterpret the results of Figure 9 using the expected enhancement of the signal cross-section due to the existence of the fourth generation and see that these data rule out the existence of a Higgs with a mass in the range $150 < M_H < 600$ GeV/c^2, independent of the mass of the heavier fermions. Even more interestingly, the counterpart of 'theoretical' limits of Figure 2 *a* in such models, implies that only up to a Higgs mass of 700 GeV/c^2, can such an additional quark pair be 'elementary'.

For the really heavy Higgs, with a mass above 700 GeV/c^2, right now the machine does not have enough luminosity to make any statement.

All in all exciting days and months ahead for the Higgs hunting!

In search of answers to puzzles and further

It should be clear from all these discussions that the job of LHC is not finished when it gives us information on the Higgs boson. If the indications of a light Higgs boson are confirmed, the next item on the LHC phenomenology agenda is to look for direct/indirect evidence for the new particles, new interactions that theorists have introduced to 'explain' and 'understand' the 'lightness' of the Higgs boson. The next question is: what if the LHC excludes the existence of the Higgs over the entire mass range of Figure 2? It would mean that there is an alternate to EW unification, which passes the challenge posed by the precision tests as comprehensively as the SM does. Then the LHC agenda item would be to check which one of these alternates, if any, is correct. One of the big areas of phenomenological research has been how to delineate different BSM ideas from each other at LHC[19].

Hunt for most of these BSM scenarios may in fact help us explore further at the heart of matter and probe the structure of space–time. Most of the time due to the very nature of these BSM ideas, they have implications for the early universe and hence this is an opportunity to test some of the ideas of SM of cosmology at LHC.

I reproduce below a list of objectives that have been set out in a road map of particle physics for the next decades by the world community.

- Are there undiscovered principles of nature: new symmetries, new physical laws?
- Are there extra dimensions of space?
- Do all the forces become one?
- Why are there so many kinds of particles?
- What is dark matter? How can we make it in the laboratory?
- What are neutrinos telling us?
- How did the universe come to be?
- What happened to the antimatter?
- What is dark energy?

We expect LHC to shed light on almost all these points. That is the reason why LHC is considered as the watershed experiment.

Apart from the Higgs hunting, the hunt for the 'direct' signatures for the BSM physics also has benefitted from the jump in energy by a factor of about 3 from the Tevatron to LHC, as well as from the successful functioning of the detectors. Unfortunately, the benefit has translated only into an increase by a factor two in the lower limits of many of the new particles expected, for example, in supersymmetric models. In the framework of the minimal supersymmetric extension of SM (MSSM)[11], the masses of supersymmetric particles ((s)particles) predicted by the theory are mainly controlled by two parameters, m_0, $m_{1/2}$. The current searches rule out a region in this parameter space. For example, for $m_0 < 0.5$ TeV/c^2, masses of spin 1/2 partners of gluons (gluinos) and spin 0 partners of quarks (squarks) which are predicted in this model, up to about 1.1 TeV/c^2 are ruled out[20]. They are at the edge of theoretical expectations for the values of these parameters and masses. However, it needs to be noted that the indications for these masses from theoretical considerations can be trusted only up to an order of magnitude. Again, as mentioned before, the mass of the Higgs boson, when discovered will have implications for what the masses of these (s)particles have to be. A combined analysis of the 'direct' search for supersymmetric particles and indirect information from the Higgs mass will then propel us forward in this BSM search.

The LHC at present is supposed to run with the lower energy and with this high luminosity till the end of 2012. One expects by then that the experiments will tell us something definitive about the Higgs mass, over the entire mass range allowed theoretically. As I have tried to explain, this will also point the way for the BSM searches.

The LHC engineers have sorted out how to increase safely the luminosity to its design value. After a planned shutdown and a year of work to be able to raise safely the beam energy as well, the experiments will begin treading 'terra incognita' once again. In all probability it will throw up some unexpected results, which in fact will point the way ahead in this journey towards truth.

Note added in proof: The plots indicating current information on the Higgs searches in the article were taken from the talk by W. Murray at the EPS conference in July 2011. Those on the cover include compilation of information from October 2011, taken from refs 21–23. This shows clearly how the available information is fast evolving with the accumulating data.

Notes

1. At full throttle LHC detectors will have to deal with over 600 million proton–proton collisions per second.
2. The beam once ramped up to full energy keeps on circulating for up to 12–13 hours before it is necessary to dump the beam and start all over again.
3. One can see the information updated continuously on the LHC dashboard at the url: http://op-webtools.web.cern.ch/op-webtools/vistar/vistars.php?usr=LHC1.
4. In fact, about 16 of the Nobel Prizes in Physics since 1936 have gone for discoveries which have had direct connection in establishing different aspects of the SM.
5. Cockroft and Walton were awarded the Nobel Prize in 1951, 'for their pioneer work on the transmutation of atomic nuclei by artificially accelerated atomic particles'.
6. One could say that trying to answer this question has led to the development of science as we know it today, in a big way.
7. In fact, elucidation of this special property of quantum chromo dynamics, the gauge theory description of strong interactions led to a Nobel Prize for D. Gross, H. Politzer and F. Wilczek in 2004.
8. ~GeV, whereas β-decay involved particles with ~ MeV energies.
9. Theoretical work by C. N. Yang and T. D. Lee (Nobel Prize for Physics in 1957), experimental work by Madam C.S. Wu in the context of β-decay, and theoretical work by E. C. G. Sudarshan and R. E. Marshak in the context of other processes caused by weak interactions were crucial in establishing that this was indeed the case.
10. At that time there was also a competitor model put forward by Glashow and Georgi together, which addressed the same issue of unification, but not by postulating a new spin 1 particle, but a spin 1/2 heavy counterpart of electron and without any neutral current processes.
11. Glashow–Illiopoulos–Maini (GIM), who did this work were awarded a prize by the European Physical Society (EPS) this year during the Biannual High Energy Physics Conference of the Society.
12. The discovery of charmonium which gave S. Ting and B. Richter their Nobel Prize in 1974.
13. Sheldon L. Glashow, Abdus Salam, Steven Weinberg were awarded the Nobel Prize for their contribution to the theory of this unified description in 1979.
14. This was later increased to 315 GeV.
15. C. Rubbia and S. Van Der Meer, were awarded the Nobel Prize in 1984 for their contribution to realizing this project and making the experimental discovery of W/Z a possibility.
16. These can be put in perspective by realizing that the UA-1/UA-2 experiments had detected only a handful of these particles.

17. After the agreement of the value of m_t predicted using LEP data with that measured at the Tevatron, G. 't Hooft and M. Veltman were awarded the Nobel Prize in 1999 for their work done in 1974, which demonstrated that the presence of the Higgs gives the special property of 'renormalizability' to the EW theory.
18. This won the Nobel Prize for R. Davis and M. Koshiba in 2002.
19. The Tevatron collider at Fermi National Accelerator Laboratory, which has stopped functioning as this article goes to press, also did hunt for the Higgs boson, but was not so effective for a 'light' Higgs range mentioned above.
20. Look, for example, at Figure 2 *a*. For $\Lambda = 1$ TeV, the upper bound on M_H is around this value.
21. This choice could be made even before the results of the precision measurements at LEP were available to us, because of the general nature of the argument.
22. To reach the same physics goal of being able to hunt for the Higgs up to the general upper limit of about 900 GeV, the then under planning and later cancelled, Superconducting Super Collider (SSC) project in USA, was supposed to accelerate the beams to an energy of 20 TeV in a much bigger tunnel.
23. The Indian team has participated in the design and construction of the CMS detector, and is now participating in physics studies with it. A large Indian team is also participating in exploring heavy ion collisions at the LHC using a special purpose detector called ALICE.
24. This one plot encompasses many Nobel Prize winning discoveries made during the period from 1969 to 1989.

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