While the Higgs boson continues to be elusive so far, scientists are quite confident of detecting it by the end of the year 2012.

Has it been seen? Some say faint evidences of its presence have been recorded. Others are not so sure. While still others downright ridicule any such finding. The mystery of the elusive particle, which is supposed to have imparted mass to matter immediately after the Big Bang, gets curiouser and curiouser by the day. It was in 1964 that Prof Peter Higgs predicted the presence of the particle, later called the Higgs boson. While Prof Higgs has patiently waited 48 years for confirmation of its presence, scientists at the European Council for Nuclear Research (CERN) are now feverishly working to snare the particle.

Researchers are poring over data obtained from the world’s largest particle collider – the Large Hadron Collider (LHC) – a 17-mile ring based deep underneath the Swiss-French border, trying to ascertain whether or not the Higgs boson exists. The Higgs boson is a hypothetical massive elementary particle whose mass is expected to be in the GeV range. When evaluating results in particle physics, the scale of certainty used by researchers is the sigma scale.
GeV=10^9 electron Volt (eV), a unit of mass and/or energy. It is predicted by the Standard Model (SM) theory of particle physics to explain how the spontaneous breaking of electroweak symmetry mechanism, known as the Higgs mechanism, occurs in nature. This understanding will in turn explain why other elementary particles have mass.

The Higgs boson is regarded as one of the keys to understanding the universe around us. This is because it is assumed to be the agent that imparts mass and energy to matter after the Big Bang about 13.7 billion years ago. Without mass, the particles would have moved into the cosmos at the speed of light, unstable to bind together to form the atoms that make up everything we see around us.

It is hoped that LHC will produce the elusive Higgs boson, the observation of which would confirm the predictions and missing links in the SM theory. The Higgs boson is the only elementary particle predicted by SM theory that has not yet been observed in particle physics experiments. According to the SM theory, there exists a field called Higgs field, which prevails in the entire space. In empty space, the Higgs field has a non-zero amplitude, i.e. a non-zero vacuum expectation value. This non-zero vacuum expectation spontaneously breaks electroweak gauge symmetry, which in turn gives rise to the Higgs mechanism.

The verification of the existence of the Higgs boson would be a significant step in the search for the ‘grand unified theory’ which intends to unify three of the four fundamental forces (weak force,
Electroweak Interaction & Spontaneous Symmetry Breaking

An overarching goal of particle physics is to build a unified description of all inter-particle forces. The four known fundamental interactions are electromagnetism, strong interaction, weak interaction and gravitational force. Incidentally, this unification also ties up to questions of how the universe was created as the Big Bang explosion provides some of the unique conditions for unification to occur.

Higgs mechanism plays a salient role in a smaller unification involving electroweak interaction, or the integration of the electromagnetism and the weak interaction. Electromagnetism and the weak interaction appear as distinct phenomena at low energies of the everyday world. Physicists think that during the Big Bang explosion, the universe was hot enough (with energy greater than 100 GeV) for these forces to exist as a single force.

However, the Higgs mechanism caused a spontaneous (without external intervention) breakdown of the electroweak force into two W and Z bosons, and the photon. While the W and Z bosons have a mass of 80 and 90 Gev respectively, the photon is mass-less. How did the breaking of a field yield these particles with mass? The Higgs boson is thus a missing piece of the puzzle to explain why the W and Z bosons acquired mass during spontaneous symmetry breaking.

While physicists express these concepts in mathematical terms, Trefil provides an analogy of a snowflake to understand spontaneous symmetry breaking. While hydrogen and oxygen atoms are symmetrical atoms, they lose their original symmetry, without any external intervention, when they form a water molecule or freeze into a snowflake. In the same way, electromagnetism and the weak interaction have different symmetry in unified and distinct manifestations.

The vacuum expectation value is the expected energy of a field in vacuum. Physical fields have zero vacuum expectation value, but in the quantum theories some abstract fields are said to have a value in order to explain physical phenomena at the quantum level. The Higgs field has a vacuum expectation value of 246 GeV, and its energy facilitates the Higgs mechanism to work.

The Higgs boson has long been a focus of great scientific speculation. If it does exist, it can account for why everything in the universe has weight/mass, and forms a key component of everything from humans to star and planets.
The Higgs boson may also help to explain why the fourth force, gravitational force, is so weak ($10^{40}$ times weaker than the strong force, $10^{38}$ times weaker than the electromagnetic force and $10^{14}$ times weaker than the weak force). Experiments to verify the existence of the Higgs boson were also being performed by Fermilab’s Tevatron until its closure on 22 December 2011, but these experiments have not yielded any definite conclusions.

**Higgs Field**

There was great ferment in particle physics in the 1960s and 1970s when it was realized that there were close ties between the two of the four fundamental forces – the weak force and the electromagnetic force. These two forces can be described within the same theory, which (along with Quantum chromo dynamics) forms the basis of the Standard Model. This unification implies that electricity, magnetism and some types of radioactivity are all manifestations of a single underlying force called electroweak force.

For this unification to work mathematically, the force carrying particles had to be mass-less. It was known from experiments that this is not true. In 1964, Peter Higgs and fellow physicists came up with a solution to this puzzle. They proposed the existence of a field – the Higgs field – which pervades the entire universe and interacts with some particles; and this interaction gives elementary particles mass. Higgs field is a scalar field and the Higgs boson is a scalar boson.
It is hoped that LHC will produce the elusive Higgs boson, the observation of which would confirm the predictions and missing links in the SM theory.

**What if Neutrinos Exceed the Speed of Light in Vacuum?**

This is an exciting, even provocative question. The answer is: there is no harm, save for sacrificing Einstein’s special theory of relativity to save causality. Contrary to the concept of causality that says “causes precede effects”, showers of neutrinos may arrive here on the earth before a supernova actually explodes on the other side of the galaxy. Or light will reach the observer before photons are present at the source point if neutrinos, supposed to be moving faster than the photons, could create a sense of vision in the observer!

The speed of light is the cornerstone in Einstein’s theory of special relativity. Special relativity deals only with frames having no acceleration i.e. inertial frames (general relativity deals with accelerated frames), which is what gives us the concept of causality. The neutrino beams would then reveal a ‘new aspect’ of cosmos. In this event, it would be a tremendously fascinating time for physics, but a daunting one for physicists. Einstein may not have been wrong if we concede that there are extra dimensions of space (at least more than the currently accepted three) that particles can nip into and out of. Some theories have already been around for a while that suggest as much.

Now, what is a neutrino? A neutrino is an electrically neutral, weakly interacting elementary subatomic particle with a half-integer spin, chirality (left-handed helicity) and a small non-zero mass (this is disputed). Neutrinos are created as a result of certain types of radioactive decay, nuclear reactions such as those that take place in the Sun and in nuclear reactors and when cosmic rays hit atoms. The neutrino (meaning ‘small neutral one’ in Italian) is not affected by the electromagnetic forces, but only by the weak forces (10^14 times weaker than the strong nuclear force). Neutrinos are therefore able to travel large distances through matter without being affected by that matter.

There are three types or flavors of neutrinos: electron neutrino, muon neutrino and tau neutrino. Each type also has a corresponding anti-particle (having same physical properties but equal and opposite electromagnetic properties), called anti-neutrino with an opposite chirality (right-handed helicity). About 65,000,000,000 neutrinos emanate from the Sun every second and pass through every square centimeter of Earth perpendicular to the direction of the Sun.

Neutrinos are the tiniest quantity of matter ever imagined and never cease to puzzle physicists. Wolfgang Pauli introduced the massless neutrino in 1930 as a desperate measure to save the laws of conservation of energy, linear momentum and angular momentum (spin) in radioactive beta decay. Pauli did this by adding a then-undetected particle that he termed a ‘neutron’. In 1933, Enrico Fermi, while developing the theory of beta decay in radioactivity, renamed the neutron as “neutrino”.

Proton and electron were already known to be the products of beta decay. Fermi theorized that an undetected particle (neutrino) was carrying away the observed difference between energy, momentum and angular momentum of the initial and final particles. However, it then took twenty-seven years to find the first experimental evidence for its existence.

The three types of neutrinos in the Standard Model (SM) are actually named after their partner leptons (electron, muon and tau). The correspondence between the six quarks (up (u), down (d), charm (c), strange (s), top (t) and bottom (b)) in the SM and the six leptons (among them the three neutrinos), suggests to physicists’ intuition that there should be exactly three types of neutrino.
In December 2011, the search for Higgs boson mass narrowed to the approximate region 115-130 GeV with a specific focus around 125 GeV, where both the ATLAS and CMS experiments independently reported an excess of events.

It is very interesting to note that neutrinos can change flavor or oscillate from one flavor to another. Neutrino oscillations suggest that the neutrinos must have a non-zero mass. Electron neutrinos have mass around 2.2 eV (electron Volt=10^-3 eV) and for muon neutrino it is of the order of 170 KeV (killo electron Volt=10^3 eV) and for the tau neutrinos the mass is approximately 15.5 Mev (Mega electron Volt=10^6 eV). However, neutrino is an oddity in the family of elementary particles: it hardly interacts with the matter and can easily travel through the Earth without being stopped.

How can neutrinos be detected? Neutrinos cannot be detected directly, because they being electrically neutral, they do not ionize the matter they are passing through. All detection methods therefore require the neutrinos to carry a minimum threshold energy. Neutrino detectors are often built underground to isolate the detector from the cosmic rays and other background radiations.

As neutrinos interact with the other particles and fields only through the gravitational and weak forces, it is very difficult to detect them experimentally. Some physicists think that just like the cosmic microwave background radiation left over from the Big Bang, there is a background of low energy neutrinos in our universe. In the 1980s it was proposed that these neutrinos might explain the existence of dark matter in the universe. The dark matter made from neutrino is termed as ‘hot dark matter’. Neutrinos have an important advantage over most other dark matter candidates: we know they exist.

Neutrino velocity is defined as the ratio of the precisely measured distance from the source in the European Council for Nuclear Research in Geneva to the detector at Gran Sasso laboratory in Italy (which is 732 km away) to the time of flight of neutrinos through the Earth’s crust (which is measured to be 2.43 milliseconds). The neutrinos appear to have outraced the speed of light by 0.00000006 seconds. Now scientists have to investigate all the possible explanations for this exciting result before confirming that some new physics exists on the horizon. At the very least pretty well synchronized clocks are needed!

**The Intriguing OPERA experiment**

If the rest mass of the neutrinos is different from zero, transition among different flavors can take place when they propagate through space (neutrino oscillation). OPERA (Oscillation Project with Emulsion-Racking Apparatus) is a collaboration between CERN in Geneva, Switzerland and the Gran Sasso laboratory in Italy. OPERA is trying to identify uniquely the appearance of tau neutrino from a pure muon neutrino beam propagating from Geneva to Gran Sasso.

In September and November 2011, the OPERA collaboration released calculations from their data showing velocities of 17-GeV and 28-GeV neutrinos exceeding the speed of light. Scientists at CERN claimed that the neutrinos arrived 60 nanoseconds (1 nanosecond=10^-9 second) earlier than the time that would have been taken by light to traverse that distance. One implication of this data was that a postulate of Einstein's over 100-year-old theory of special relativity was definitely wrong. Only on February 22 this year, a new report questioning the early arrival time of neutrinos was announced; the superluminal neutrinos appeared to be due to a loose connection in the GPS system.

Another blow to the excitement came at the end of March 2012, when a similar detector in Gran Sasso, ICARUS, found that their (neutrinos') speed was well within the light speed limit. Two of these repeated experiments, ICARUS and LVD using a new finely pulsed beam, have recently reported results confirming that neutrinos cannot travel faster than light. Although in the coming months other neutrino detectors will repeat the controversial OPERA experiment, most of the scientific world seemingly considers the case of superluminal neutrinos as a closed one.
The “God” Particle

Higgs boson is often referred to as the “God particle” by the media. This name was bestowed by the Nobel Prize winning Physicist Dr. Leon Lederman in his book “The God Particle: If the Universe Is the Answer, What is the Question?” written with Dick Teresi.

Dr. Lederman chose this name as he felt the particle was “so central to the state of physics today, so crucial to our final understanding of the structure of matter, yet so elusive.” He jokingly adds “the publisher wouldn’t let us call it the Goddamn Particle, though that might be a more appropriate title, given its villainous nature and the expense it is causing.”

The book provides a popular history of particle physics leading upto the Standard Model. Most physicists, including Peter Higgs himself, do not like this name as it is grandiose and overstates the implications of the research.

These beams (known as the proton and anti-proton beam) collide on their circular journey and simulate the Big Bang (and creation and decay of the Higgs boson). This series of events is measured by detectors that capture various characteristics of this collision (e.g. path and energy of the beams and mass of particles created). After extensive processing to remove the background noise in the data, the ‘footprint’ of the Higgs boson shows up as a bump in the graphs in which the particle mass data is plotted.

Higgs bosons, if they exist, are very short lived and can decay in many ways. LHC experiments rely on observing the particles that the Higgs bosons decay into, rather than the Higgs boson itself. Physicists have to look for these particles through an expansive range of mass possibilities. While the hope amongst the array of subatomic particles generated from the proton-antiproton collision would be the Higgs boson itself, it would almost instantly decay into different combinations of other particles. Finding the Higgs bosons would then involve looking for statistically significant ‘excess’ of those particles.

Evidence that the Higgs boson exists would definitely help solve a big puzzle: why some objects in the universe such as the quarks (the constituents of protons, neutrons and many other subatomic particles) have mass while others like photons and gravitons (hypothetical elementary particles that mediate the force of gravitation in the framework of quantum field theory) possess only energy but zero rest mass.

Its discovery may help explain why anything in our universe has mass, and it could thus rank as one of the biggest scientific discoveries of all time. On the other hand, if it cannot be found, then the field will be left open for physicists to develop a completely new theory to explain the origin of particle mass, rubbing what theorists have been talking about for more than forty years. It is because of such high stakes that the CERN experiments continue diligently despite significant challenges.

Current Status of Higgs Boson

A promising sign is that a modest significant excess of elementary particles has been found in the data from the latest experiments at LHC. One of the experiments performed on the detector known as ATLAS (A Toroidal LHC ApparatuS) suggests that Higgs boson could have a mass in the range of 116 to 130 GeV, with other masses excluded at 95% confidence level. The other experiment performed on the detector known as CMS (Compact Muon Solenoid) pegged the particle’s mass at 115 to 127 GeV with 95% certainty.

When evaluating results in particle physics, the scale of certainty used by researchers is the sigma scale. Researchers actually need a five-sigma level of certainty to make a bona-fide formal discovery, which means there is only a one in a million chance that the result is a statistical error.

The sigma probabilities for the Higgs hunt in the ATLAS experiment is 2.8 sigma and in the case of CMS experiment 1.9 sigma (where three sigma level of certainty means nearly 99% accurate result). In December 2011, the search for Higgs boson mass narrowed to the approximate region 115-130 GeV with a specific focus around 125 GeV, where both the ATLAS and CMS experiments independently reported an excess of events higher than expected number of particle patterns compatible with the decay of a Higgs boson were detected in this energy range).

The data are not yet sufficient to show whether or not these excess events are due to background fluctuations and statistical significance is not large enough to draw conclusions yet, but the fact that the two independent experiments have shown excesses at around the same mass (125 GeV) has led to considerable excitement in the particle physics community.

Although the signal for existence for Higgs boson does not yet meet the strict scientific standards for a scientific discovery, it is still enough for the CERN scientists to predict a discovery by the end of 2012. Without this cornerstone of physics, many of the theories that serve as the underpinnings of the scientific understanding of the universe will be without foundation.

The Higgs boson has long been a focus of great scientific speculation. If it does exist, it can account for why everything in the universe has weight/mass, and forms a key component of everything from humans to star and planets. Its discovery would also shed light on the vast majority (96%) of the universe that is invisible. Twenty-three per cent of this includes dark matter (ordinary matter that does not interact even with photons and is thus not seen) and 73% is dark energy (repulsive force that acts against the gravitational force and tends to accelerate the rate of expansion of the universe).

The year 2012 is going to be an eventful year in the field of particle physics, we will have to wait and watch whether scientists out there will rewrite history by the end of the year!

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