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CERN announces that the highly elusive Higgs boson had in all probability been discovered.

FABRICE COFFRINI/AFP

**Peter Higgs, the British physicist whose prediction of the existence of the boson launched the decades-long search for the subatomic particle.**

The new particle whose discovery was announced on July 4 at the European Organisation for Nuclear Research (CERN) in Geneva is in all probability the highly elusive Higgs boson, which was being desperately sought by theoretical high-energy physicists for nearly four decades. While technical considerations prevented the scientists from actually saying, at the end of the seminar where the announcement was made, that it was the Higgs boson, Rolf Heuer, the CERN Director General, remarked, "As a layman, we have it."

Experimental high-energy physicists around the world began the hunt for the particle in the 1990s when high-energy accelerators came on the scene, beginning with the Large Electron Positron Collider (LEP) at CERN, but were unsuccessful so far. Now a new particle has shown up at the Large Hadron Collider (LHC), which took the place of the LEP in the underground tunnel 27 km in circumference after it was dismantled in 2000. If it is really the Higgs boson, an important chapter in high-energy physics, hitherto incomplete and unsatisfactory due to that important missing piece, will stand completed.

What is the Higgs particle and why was it so important to find it? The existence of the Higgs boson is predicted by a highly successful theoretical framework called the Standard Model of particle physics, which describes the subatomic world of elementary particles and the fundamental forces of interaction among them, except gravity. But the particles of the theory cannot have mass without the Higgs boson. The Higgs boson is the particle manifestation of a force-field that is included in the theory as a quantum mechanical agent to provide mass to the particles. So if the theory is to describe the real universe, the Higgs boson had to be found. The particle is a boson because it has zero value for the quantum attribute of particles called 'spin'.

The Higgs field and its mass-generating mechanism can be likened to an ether-like all-pervading force-field in the universe, which endows particles with mass (or inertia) because of the drag that the field exerts on all particles by sticking to them as they move through space. The Higgs particle, too, gets its mass in this way through self-interaction. More technically speaking, the mass arises through a mechanism known as "spontaneous symmetry breaking" by the Higgs field of a certain universal symmetry that prevailed at the time of Big Bang. The aim of particle physicists in the last few decades has been to find evidence for its existence even as experiments have verified all the theory's predictions to great precision with the assumption of the existence of Higgs.

It is important to know that the model itself does not predict a value for the mass of Higgs. But there are indirect constraints on the Higgs mass from other theoretical and phenomenological considerations based on other processes such as particle decay properties governed by the Standard Model. These constrain its mass to be less than 160-180 giga (or billion) electron Volt (GeV) of energy. (At relativistic energies, mass and energy are interchangeable in accordance with Einstein's relation $E = mc^2$. So masses of particles are measured in units of energy.) A proton has a mass-energy of about 1 GeV and the weak force carriers W and Z bosons have about 100 GeV. Such a Higgs is called "low mass Higgs" because there are other theoretical models that allow Higgs to be much heavier, up to 600 GeV. This "low mass Higgs" is, therefore, referred to as the "Standard Model Higgs Boson".

DENIS BALIBOUSE/AP

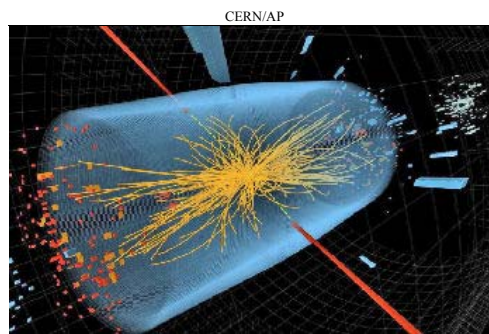
**Atlas experiment spokes person Fabiola Gianotti (centre), CERN Director General Rolf-Dieter Heuer, and CERN spokesman Joe Incandela look at a screen on July 4 during the seminar in Geneva where the discovery of the Higgs boson was announced.**

The LEP accelerated beams of electrons and positrons (the antiparticle counterpart of electrons) up to energies of over 100 GeV each and brought them to collide head-on. With the combined data from four of its experiments, the LEP had ruled out the existence of a Higgs with a mass less than 114.4 GeV when it shut down in 2000. The search was followed up by the next-generation accelerator at Fermilab in the United States, called the Tevatron proton-antiproton collider. The accelerator is so named because it accelerated proton and antiproton beams to tera energy scale. Both proton and antiproton beams were accelerated to 1 tera or trillion (10 followed by 12 zeros or 10^{12}) electron Volt (TeV), which meant a collision energy of 2 TeV (see separate story on the Higgs search at the Tevatron). On the other hand, the LHC, a next-generation accelerator and the most powerful in the world, which went into operation in March 2010, is designed to give a maximum of 7 TeV to each of its colliding proton beams. The LHC, by virtue of its higher energy of operation well into the tera scale, has thus succeeded where others did not.

How much is a TeV? An electron Volt is the energy gained by an electron as it is accelerated across 1 Volt potential difference. In spite of several zeros that the prefixes such as giga and tera imply, these energy scales are much smaller than the energy scales that we experience in our daily lives. The energy of 1 TeV is just as much as the energy of a mosquito flying at its usual speed of about 1.5 km/h. But it is the fact that this energy is squeezed into the tiny size of a proton (10^{-17} cm), which means very high energy density, results in such particle collisions in accelerators producing myriads of particles as final products.

To gain a perspective of what these particle search experiments at the accelerators mean, it is important to mention that particle discovery in particle physics is often a long and painstaking process requiring sifting through huge amounts of data to isolate the signal of a rare process, such as a Higgs signal, that is statistically significant. The lifetime of Higgs itself is very short (10^{-22} second). So one cannot actually detect a Higgs boson itself. It is only by measuring the characteristics of its decay via various final states (decay channels) into other subatomic particles according to the Standard Model that the Higgs boson will be identified.

For example, the following channels are available for the Higgs to decay into: $H \rightarrow$ two photons; $H \rightarrow$ two tau leptons; $H \rightarrow WW$; $H \rightarrow ZZ$ and others. But the task is made really tough by particle processes not involving the Higgs that mimic the Higgs decay and form a large background to data from the Higgs decay channels. A Higgs signal would appear as an excess number of events over the large background. It is like trying to capture the photograph of snowflakes against the backdrop of a snowfield. The effort is to pick such excess which is statistically significant. Statistical significance is measured in terms of what is called standard deviation (called sigma). For any discovery in particle physics, the signal should be at least at '5 sigma level' over the background. This is equivalent to the chance of explaining the bump of excess events by a statistical fluctuation of the background events being only 3-in-10 million. For improving the statistics of event data, the scientists obviously need to look at a lot more collision events so that events producing the signal we are looking for stack up and give a statistically significant peak of excess events.



An undated handout distributed by CERN showing a representation of traces of a proton-proton collision measured in the Compact Muon Solenoid experiment.

A higher-energy machine requires much higher luminosity (or beam intensity) to yield a far greater number of candidate events because of the much larger number of channels available at the higher energy resulting in a much larger background. The speed with which the LHC experiments have been analysing data has also been unprecedented. The Worldwide LHC Computing Grid (WLCG), which links up computer centres around the world (including India), was routinely processing up to 200,000 physics analysis jobs concurrently. Two of the six international experimental collaborations – ATLAS and CMS – at the LHC are designed with the search for the Higgs as one of their key objectives. After commissioning, the accelerator was operating at a total energy of 7 TeV (3.5 TeV/beam) until end 2011. On April 5, the beam energy was ramped up to 4 TeV, which means a total of 8 TeV of collision energy. This increase in energy, along with unprecedented performance of the accelerator and the detectors, improved techniques of analysis and the intense computation on the WLCG, enabled this landmark finding within a short time of two and a quarter years since the LHC went into operation.

Consider the following to get an idea of the intensity of work and the unprecedented effort that went into the discovery. Until end-2011, the experiments took data from about 400 trillion proton-proton collisions at 7 TeV of total energy, when there were already tantalising hints of a Higgs signal at around a mass of 125 GeV (*Frontline*, January 13, 2012). But it was not statistically significant to be called a discovery. The statistical significance of the bump in the data around 125 GeV at end-2011 was only at the level of about 3 sigma, which means one-in-750 chance of being due to statistical fluctuation, which is far from the "gold standard" of 5 sigma for a discovery.

But the data taken in just three months (from April 5 to June 18 when the experiments stopped collecting data) at 8 GeV of collision energy – from about 500 trillion proton-proton collisions – surpassed the data taken in all of 2011 at 7 TeV. By combining the data of 2011 and 2012, scientists now analysed data from over 900 trillion collisions. Moreover, according to Alejandro Nisati, a member of the ATLAS collaboration from the National Institute for Nuclear Physics (INFN), Rome, the Standard Model predicts an enhancement of Higgs boson production at 8 TeV by a factor of 1.27. So if you do the arithmetic of combining the effect of increased energy and that of a higher proton-proton collision rate because of better accelerator performance, scientists now have 2.6 more Higgs-like events at 8 TeV compared to 2011.

Vivek Sharma of the CMS collaboration from the University of California at San Diego (UCSD) pointed out that this increased chance of Higgs production also implied a larger number of characteristic Higgs events that they could capture. According to him, analysis was improved significantly (by as much as 20-30 per cent in some cases compared to last year). "A major improvement has been in the way Higgs decay daughters like photons, electrons, muons, tau particle, etc., are selected. We also use advanced and more efficient multivariate techniques for picking out interesting Higgs-like events," Sharma added in his email response. All these have contributed to the improved statistics in the data gathered, in particular for two of the five important Higgs decay channels: $H \rightarrow$ two photons and $H \rightarrow$ 4 leptons (electrons/muons). These channels allow the Higgs mass to be measured with greater precision and are hence regarded as important. The latter channel is, in fact, called the Golden Channel because it is much cleaner than the others. The analysis had also been particularly optimised to pick Higgs-like events

decaying into these final states, according to Nisati. Nisati also added in his email response that ATLAS was finalising the results of studies based on the other important channel of $H \rightarrow WW$. While ATLAS presented data only from these two channels, CMS presented data from all the five channels for probing for Higgs around 125 GeV – $H \rightarrow$ two photons, $H \rightarrow ZZ$, $H \rightarrow WW$, $H \rightarrow$ tau tau and $H \rightarrow$ b (anti) quarks. Besides $H \rightarrow WW$, the last one is also being intensely analysed by ATLAS as well.

But for ascertaining the Higgs mass value, both the experiments have used predominantly data from the two important channels of 2 photon and 4 lepton final states. According to the presentations made on July 4 by Joe Incandela and Fabiola Gianotti, the spokespersons of CMS and ATLAS respectively, both the experiments, which have worked entirely independently of each other, observed a “new particle” in the mass region around 125-126 GeV at 5-sigma level. That the experiments would reach the 5-sigma level so quickly was not really expected by physicists. This only points to the remarkable achievement of the global enterprise that these experiments truly are. India is an important collaborator in CMS.

Consistent results

Specifically, the mass value given by CMS to this Higgs-like particle is 125.6 GeV with an error window of 0.6 GeV, and that given by ATLAS is 125.3 GeV with an error bar of 0.6 GeV. It is clear that both the results are consistent with each other within experimental errors. The immediate next step for these experiments is first to analyze data from the remaining three channels of Higgs decay and the check for consistency before the LHC shuts down for maintenance. The larger task in the months ahead is to ascertain whether the other properties of this new Higgs-like particle fit the predicted properties of the Higgs boson or whether it is something entirely different. In particular, for example, the couplings of this Higgs-like particle to other particles have to be measured carefully. And also its decay properties, in particular whether it is a scalar or a pseudoscalar, as Incandela pointed out at the post-seminar press conference on July 4. If it is a pseudoscalar, its decay channels would violate the symmetry of mirror inversion or parity; that is, in a mirror-reflected world, the decay channels of the Higgs boson should have the same characteristics as the world we live in. Establishing this is important because the Standard Model requires the Higgs boson to be a scalar.

Many such experiments are required to be carried out over the next many months to establish the true identity of the new particle. If it is the real Higgs, then while the chapter of the Standard Model may be closed, the next chapter, on its consequences in higher energy scales, where the Standard Model is bound to break down, have to be looked at – for example, whether it is a single boson or part of a family of Higgs-like bosons required by theories of supersymmetry and other theories beyond the Standard Model.

If it is not the Higgs boson, the chapter remains unfinished. Since then almost the entire energy domain up to 250 GeV would have been excluded for Higgs, some variants of the Standard Model will have to be looked at by theorists, and experimenters will have to begin their search at higher energy scales. But from the data presented it appears to be the Higgs that scientists so critically needed to have a complete understanding of the universe at below tera energy scales.



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