

The discovery of the Higgs particle

On 4 July 2012, two experimental collaborations at the Large Hadron Collider (LHC) in CERN Geneva, CMS (Compact Muon Solenoid) and ATLAS (A Toroidal LHC Apparatus) announced a 5 sigma signal for the presence of a spinless particle at a mass of about $125 \text{ GeV}/c^2$ (in these units the proton mass is roughly $1 \text{ GeV}/c^2$). This signal amounts to the discovery of the Higgs particle, whose existence was predicted by the theorist Peter Higgs in 1964, long before the rise of the so-called Standard Model of elementary particle interactions that describe the electroweak and strong interactions. This came from the analysis of data gathered over several years in the collision of protons on protons circulating in the 27 km rings with each of the beams of the protons reaching energies of 4 TeV each, where a TeV is an energy unit corresponding to 1000 times the energy obtained when a proton is converted into energy. Such high energies are required since the proton itself is a composite particle and in actual collisions only a certain fraction of the energy is available for conversion into the immense fireballs of energy from which very heavy and unstable particles can be born. These heavy particles live fleetingly and decay into other well-known particles such as photons, the quanta of the electromagnetic field. In such fireballs large numbers of known and unknown particles are produced, in accordance with the laws of quantum physics and relativity that allows energy and mass to be interconverted, at rates that can be calculated in theoretical models that assume what the couplings of particles to each other and the force carriers are. It is due to this that there are enormous 'backgrounds' to the 'signal' that is being looked for. It is the task of experimentalists to figure out what is the best signal to look for and how to see it above the background noise. It is the task of theorists to help compute the signal and the background and to separate the wheat from the chaff. In order to produce a sufficiently large signal, huge number of particles in bunches need to be collided after being accelerated by magnetic fields and after keeping them in carefully calibrated orbits, for which superconducting magnets are required. The most

compelling signals for the Higgs are associated with its formation and subsequent decay into a pair of photons, the force carriers of the electromagnetic

force. Other signals are associated with its heavy counterpart, the Z boson (which weighs about $91 \text{ GeV}/c^2$) responsible for part of the weak force: one of the signals

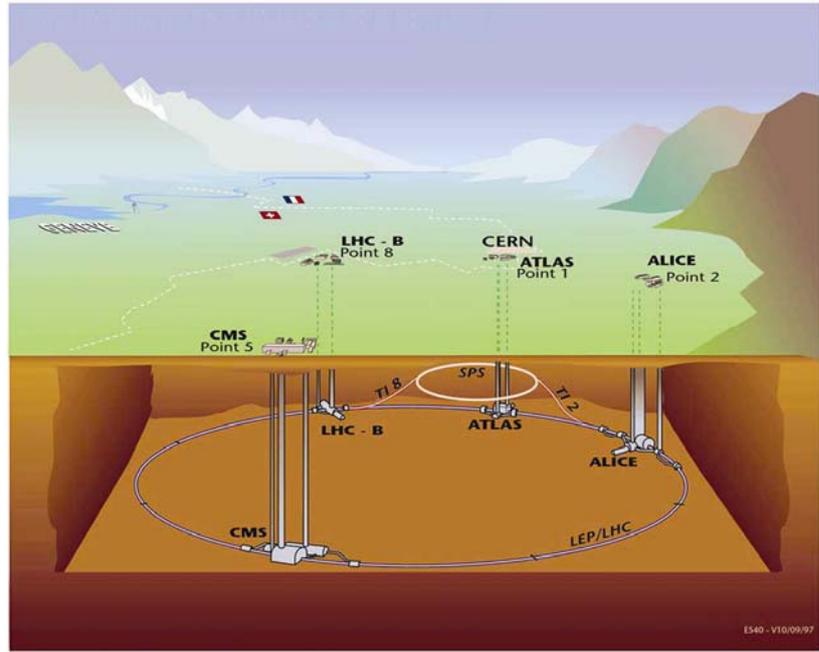


Figure 1. Scheme of the Large Hadron Collider.

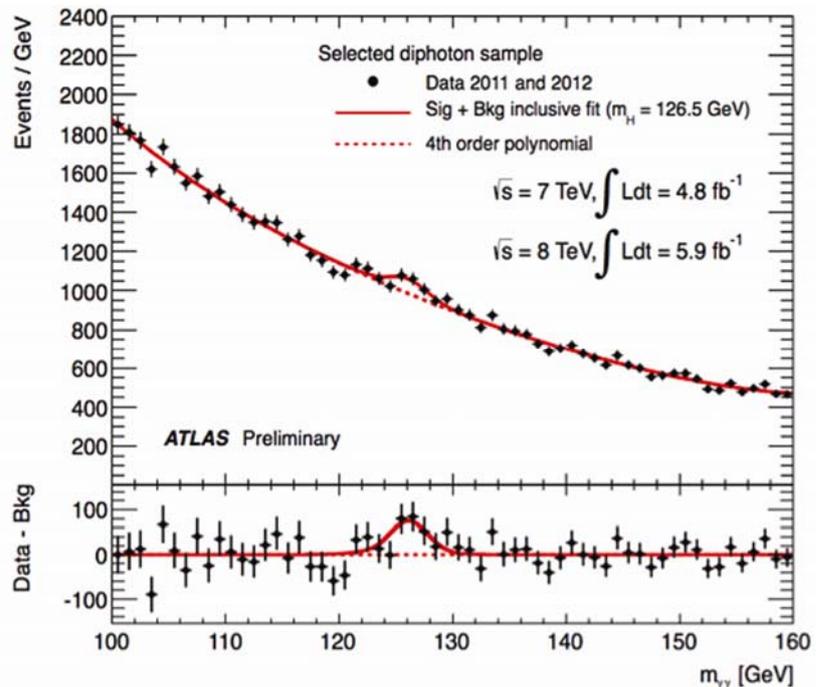


Figure 2. Mass distribution for the two-photon channel from A Toroidal LHC Apparatus (ATLAS).

is the Higgs decaying into (virtual) Z bosons that subsequently decay into a electron–positron pair or a muon–anti-muon pair.

The neutral Z boson has charged cousins known as the W bosons, weighing roughly $80 \text{ GeV}/c^2$. These W bosons are responsible for such well-known phenomena as the disintegration of free neutrons and for the beta decay of radioactive isotopes such as 14-carbon used in archaeology and radioactive iodine used in cancer treatment. It is clear that in day-to-day experience, the weak interactions operate at the sub-

nuclear scale, which is the result of the extremely high masses of the W and Z bosons. Today, we no longer talk about the electromagnetic and weak interactions as separate phenomena but as a unified electroweak theory, not quite unlike the situation with the electromagnetic interaction towards the end of the 19th century, when James Clerk Maxwell unified the seemingly disparate phenomena of electricity and magnetism. The work of Maxwell which was further developed by others including Hermann Weyl, who demonstrated that the electromagnetic interaction could be derived by assuming

the laws of nature to have a certain (continuous) symmetry. Such theories based on symmetries are known as gauge theories, associated with a ‘gauge transformation’ that leave the laws of physics unchanged.

What gives masses to the Z and W bosons, while their electromagnetic counterpart, the photon is massless (which is why the force is infinite ranged)? The answer to the question of how a force carrier can become massive was provided by Higgs and the mechanism is named in his honour as the Higgs mechanism. The Higgs mechanism was also discovered in the context of condensed matter physics earlier by Philip Anderson, and in relativistic quantum field theory by the late Robert Brout and Francois Englert, and by Gerald Guranlik, Thomas Kibble and Carl Hagen. The Higgs mechanism is equivalent to the ‘spontaneous breaking’ of the gauge symmetry of the underlying theory. The mechanism is predicated on the introduction of a field (now known as the Higgs field) that interacts with the force carriers and through the dynamics of the interaction, renders the force carrier into a massive object. Remnants of the original field may survive and become the elusive Higgs particle, whose mass remained a free parameter in the theory which only experiment could unveil. It may be fair to say that it was Peter Higgs who emphasized that a physical particle would be left behind in spontaneous symmetry breaking.

The application of this mechanism to the electroweak theory was due to the Nobel prize winning trio of Sheldon Glashow, Abdus Salam and Steven Weinberg. The full electroweak theory is based on a more complex gauge theory whose structure was established through trial and error by these authors. Such complex gauge theories had been studied by Chen Ning Yang and Robert Mills as an extension of electromagnetism in a mathematically well-defined sense. However, problems persisted regarding the use of such gauge theories with spontaneous symmetry breaking. That these theories stay sensible was proved by Gerard ‘t Hooft and Martinus Veltman in the early 1970s, who were themselves awarded the Nobel prize in 1999.

Despite all the celebrated successes of the theory in what is now historic and also what are recent explorations of elementary particle physics at the frontier,

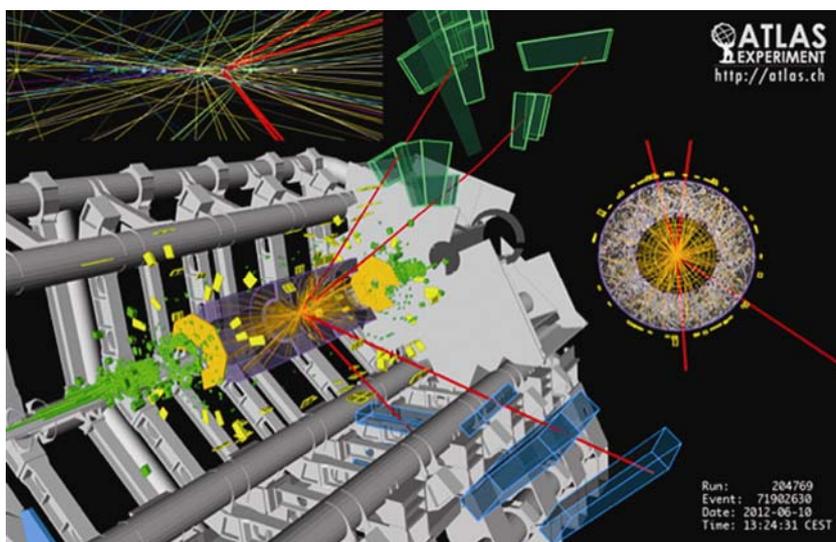


Figure 3. Candidate Higgs decay to four muons recorded by ATLAS in 2012.

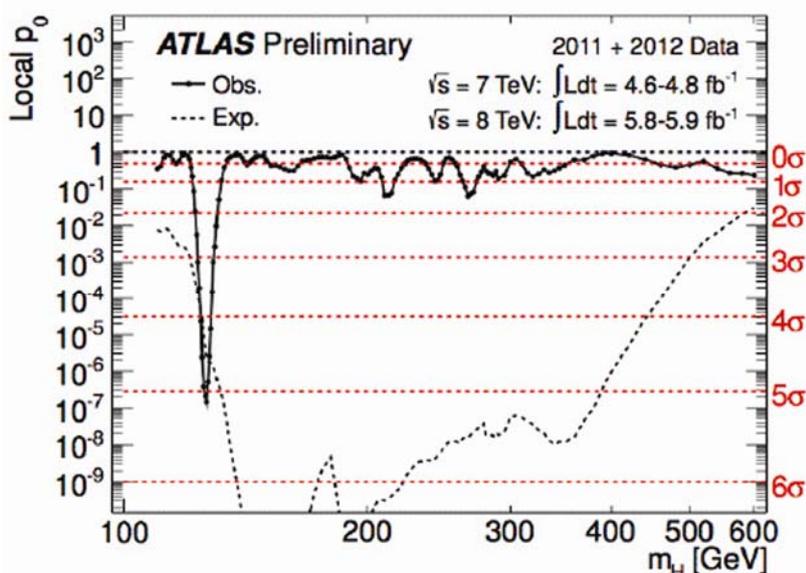


Figure 4. The probability of background to produce a signal-like excess, for all masses tested. (Note that the data shows 5 sigma!)

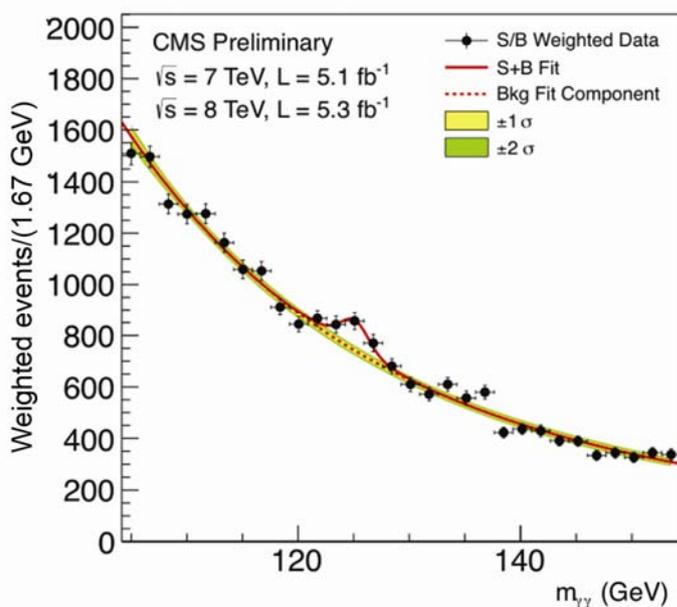


Figure 5. Di-photon invariant mass distribution for Compact Muon Solenoid for 2011 and 2012 data. Solid red line shows fit for signal plus background.

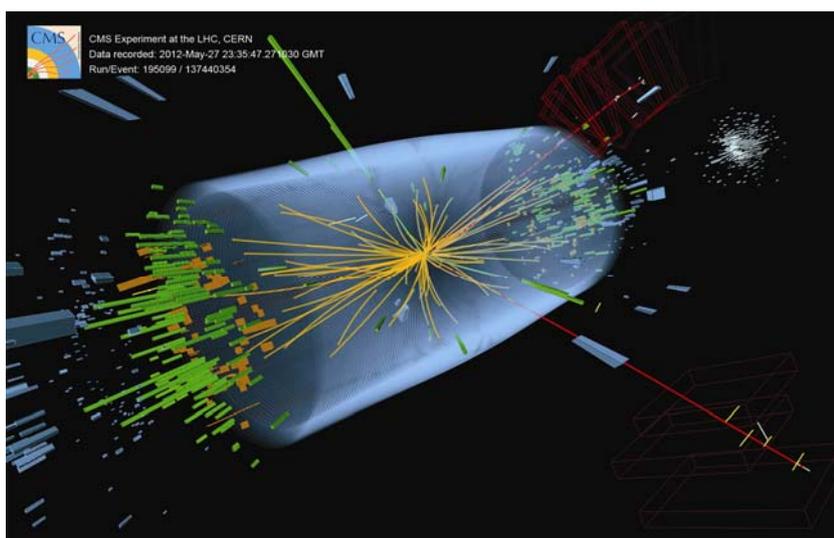


Figure 6. Event recorded with the Compact Muon Solenoid detector in 2012 showing characteristic expected from the decay of Higgs to a pair of Z bosons which then decay to a pair of electrons and muons.

the will-o'-the-wisp continued to be the missing Higgs particle. All the paper and pencil calculations could not say what its mass was. Searches took place at various

collider experiments in the 20th century and the first decade of the 21st century. The Tevatron experiment in the USA which collided protons on anti-protons

with the energy of each beam around 1 TeV saw some tantalizing hints for the production of the Higgs particle in the gigantic fireballs, but no conclusive proof. The Large Electron Positron experiment, the precursor to the LHC, would have been able to produce the Higgs if it had weighed less than $114 \text{ GeV}/c^2$, but that was not to be.

At the LHC, the two gigantic experiments, the CMS and ATLAS have dedicated their efforts to search for the signal of the Higgs. They have announced, based on their data assuming that they now have clinching evidence for a signal from Higgs production via its two-photon decay mode corresponding to a Higgs mass of about $125 \text{ GeV}/c^2$. In Figures 1–6, we capture some of the exciting information that was made available on the CERN website after the momentous announcements of 4 July 2012.

The Higgs mechanism in the electroweak has another side benefit: due to some properties of the weak interaction known as parity violation, all known elementary particles such as the electron or the quarks which constitute protons and neutrons remain massless unless they have interactions with the same Higgs field that was introduced into the theory.

Tribute must be paid to the dedication of the CERN staff and the thousands of participating scientists from all over the world in this breathtaking effort. The contributions of Indian participants from the country's leading institutes, universities, laboratories and industry that won global tenders must be commended.

In the coming months and years, the properties of the putative Higgs boson will be studied in great detail and the validity of the Standard Model will be studied. Many extensions of the Standard Model will be tested, some will fail and others will pass. The times are truly exciting.

B. Ananthanarayan, Centre for High Energy Physics, Indian Institute of Science, Bangalore 560 012, India.
e-mail: anant@cts.iisc.ernet.in