

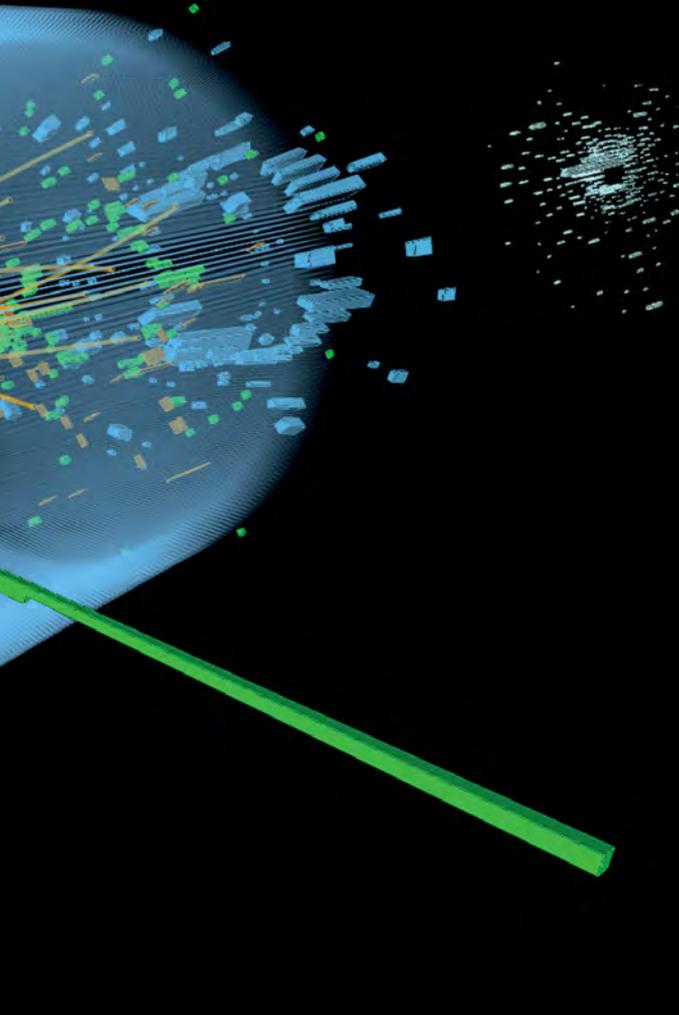
# The seven months that changed physics

The discovery of the Higgs Boson and its implications for High Energy Physics

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**Researchers of the ATLAS and CMS experiments at CERN, have announced the discovery of a new particle whose characteristics seem to be consistent with the ones expected for the long sought Higgs boson. Are we there at last? And what could be the implications of this historical discovery?**

**T**he Higgs boson is an unstable particle, living for only the tiniest fraction of a second. But it plays a major role in particle physics and in shaping the cosmos. The particle can be seen as a manifestation of an invisible field that fills every corner of our universe, assigning a distinctive mass to each elementary particle through its interaction with the field. Heavy particles, like super-massive top quarks, experience strong couplings with the Higgs field, while massless particles, like photons, can fly through it unaffected. As a consequence of the mechanism, the chaotic ingredients of the early universe at a certain moment started eventually



to attract one another and clump into atoms, gas, galaxies, planets and people. It is not simply a new elementary particle, it is the real cornerstone of the Standard Model (SM), a highly successful theory that provides an accurate description of matter and of its interactions.

### The Standard Model and the Higgs Boson

The SM considers matter as composed by quarks and leptons and describes their interactions through the exchange of force carriers: the photon for electromagnetic interactions, the W and Z bosons for weak interactions, and the gluons for strong interactions. The SM is a simple and elegant theory that brings together quantum mechanics and special relativity, the two major pillars of 20<sup>th</sup> century physics. It explains a huge amount of data using only 19 parameters and yielded an incredibly precise set of predictions. A key component of the SM is the Higgs particle. Back in 1964, Robert Brout and Francois Englert in Brussels and, independently, Peter Higgs in Edinburgh (Fig.1)

proposed a mechanism called spontaneous symmetry breaking. It allowed to generate large masses for the W and Z bosons carrying the weak interactions, while the photon remained massless [1,2,]. The absolutely innovative approach consisted in getting these results into a framework in which the elegant symmetry of the underlying gauge equations was fully preserved. The mechanism was based on a new scalar field, later named *H* after Peter Higgs, whose excitations can manifest themselves in a real spin 0 particle. The field can also provide mass to the fundamental fermions, quarks and leptons, through the so-called Yukawa interaction<sup>1</sup>.

### The Longest and Toughest Hunt Ever in Particle Physics

Physicists have been hunting the Higgs boson ever since the mid-1970s, when the SM gained widespread acceptance. The discovery of the elusive particle was among the highest priorities for several generations of experiments. The exact mass  $m_H$ , of the Higgs is not predicted by theory. General considerations suggest only that  $m_H$  should be smaller than  $\sim 1$  TeV. Since the production cross-section, width and branching fractions in the various decay modes do depend strongly on the mass, the search in itself becomes extremely challenging. To make things even more complicated, the most promising decay modes are heavily contaminated by many sources of reducible and irreducible backgrounds due to known SM processes.

Since it was not observed in data, even the most sophisticated experiments preceding LHC were only able to produce limits on its mass. Over the past twenty years, direct searches for the Higgs boson have been carried out at the Large Electron Positron (LEP) collider, leading to a lower bound of  $m_H > 114.4$  GeV at 95% confidence level (CL), and at the Tevatron proton-antiproton collider, excluding the mass range between 162 and 166 GeV [3,4]. Precision electroweak measurements, not taking into account the results from direct searches, indirectly constrain the SM Higgs boson mass to be less than 158 GeV.

### The Large Hadron Collider (LHC) and its General-Purpose Detectors: ATLAS and CMS

The project of building the Large Hadron Collider (LHC) and its large general-purpose detectors was mostly driven by the goal of discovering the SM Higgs boson or alternative mechanisms for the electroweak symmetry breaking. The LHC (Fig.2) is the most powerful collider ever built. It is a gigantic accelerator equipped with thousand of superconducting magnets and accelerating cavities distributed in a 27 km tunnel, 100 m underground, close to Geneva.

◀ The Higgs boson at last? Event recorded by the CMS detector in 2012

<sup>1</sup> The Yukawa interaction was introduced to describe the strong nuclear force between nucleons, which are fermions, mediated by pseudoscalar pions. The same formalism has been used to describe the interaction between the massless fermions, quarks and leptons, and the Higgs scalar field.

In normal operation it accelerates about 1400 packets of particles, each one containing roughly  $1.5 \times 10^{11}$  protons, up to an energy of 3.5 (later 4.0) TeV per beam corresponding to a center-of-mass energy of 7 (8) TeV<sup>2</sup>. Squeezed packets of protons are brought to collisions every 50 ns in the interaction regions surrounded by the large detectors. ATLAS and CMS are modern, general-purpose detectors based on sophisticated tracking systems embedded in strong magnetic fields. State-of-the-art calorimeters cover a large fraction of the solid angle and are complemented by huge sets of muon detectors [5,6]. A complex system of trigger and data acquisition selects the most interesting events that are permanently recorded for offline analysis. A distributed system of computing, based on GRID technologies, has been developed to reconstruct, store and analyse the data. Thousands of physicists and engineers worked feverishly for many years to build these cathedrals of modern technologies. The efforts continue nowadays to maintain, operate and improve detectors and computing infrastructures, while physics results are continuously extracted from the analysis of the data. LHC started 7 TeV operations in spring 2010, at very low intensity, but the progress in the last two years have been such that, nowadays, the machine is capable to deliver, in a few hours, the same amount of data yielded in the whole first year of operation.

### December 2011-July 1012: from the First Evidence to the Discovery

Thanks to the excellent performance of LHC, at the end of 2011 the experiments reached a key milestone. For the first time, the amount of data was large enough to perform a complete and exhaustive search of the SM Higgs in the full mass range. The preliminary analysis of these data yielded important results that were presented in a special seminar held at CERN on December 13<sup>th</sup>, 2011 [7,8]. Since the Higgs boson decays immediately into other particles, experiments can observe it only by measuring the products of its decays. ATLAS and CMS reported a complex set of studies using all major decay modes: pairs of W or Z bosons, pairs of b quarks,  $\tau$ -leptons and photons. New exclusion limits, at 95% CL, were reported by each experiment between 600 and about 130 GeV. The

striking news was that both experiments were not able to exclude the SM Higgs boson in the low mass region due to the presence of a narrow bump around 125 GeV. The excess was driven by the high-resolution channels,  $H \rightarrow \gamma\gamma$  and  $H \rightarrow ZZ \rightarrow 4$  leptons, and the two independent observations were fully consistent each other. Although the statistical significance of the observed excesses, 3.5 and 3.1  $\sigma$  respectively for ATLAS and CMS, was not large enough to claim a discovery, this 'coincidence of signals' was un-precedented. Many physicists started thinking that something real was happening at around a mass of 125 GeV. New data would have allowed understanding fully the origin of the excess.

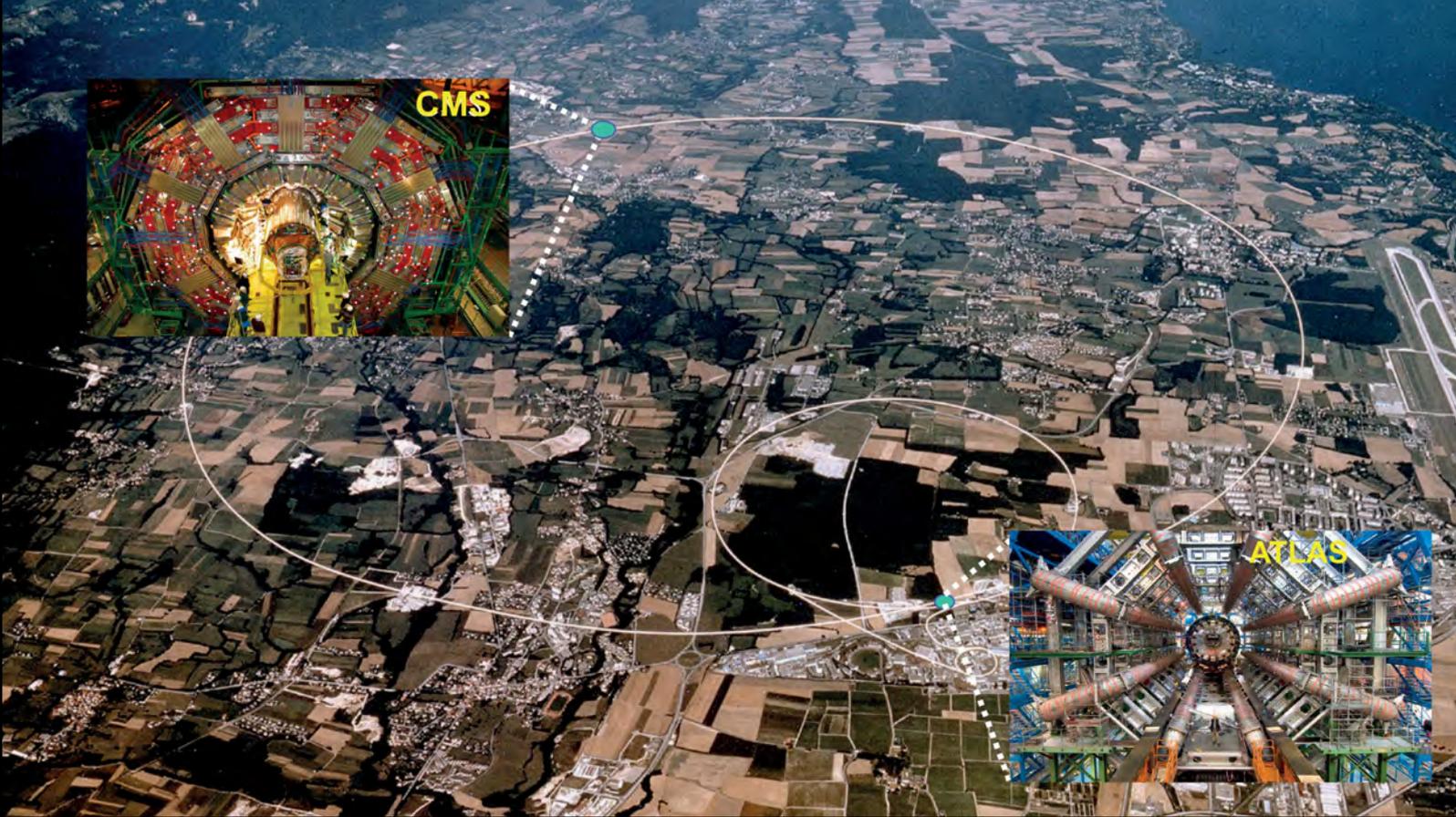
Since then, researchers launched a frantic activity in preparation of the new data taking. With LHC providing collisions at 8 TeV, all studies performed at 7 TeV had to be carefully re-done. In addition, in the effort of raising the instantaneous luminosity, LHC operators increased significantly the number of protons per bunch. As a consequence, the average number of interactions per crossing roughly doubled with respect to 2011 conditions, forcing analysts to review and sharpen further their analysis tools. Lastly, to avoid any kind of bias in looking at the new data, the collaborations decided to perform a so-called "blind analysis", meaning that nobody was allowed to look at the signal region before a certain date that was fixed to be mid-June. By then, after only 11 weeks of running in 2012, the accelerator had delivered an amount of data equivalent to the full 2011 data set. As soon as the "signal box" with new data was opened, the signals from 2012 data were appearing again, exactly in the same region, around 125 GeV, that had created so much excitement at the end of 2011. Now even the most prudent scientists within the collaborations started believing that they were witnessing the discovery of a new particle.

A second special seminar was called at CERN, on July 4<sup>th</sup>, 2012, the opening day of the ICHEP conference held this year in Melbourne (Australia). This time, by combining the 2011 and 2012 data, both collaborations presented striking peaks with statistical significance at or above 5.0  $\sigma$ , the golden standard for any major finding in particle physics. It was definitely time to announce the long-awaited discovery of a Higgs-like boson with a mass near 125 GeV [9,10]. Although both collaborations reported excess in the  $H \rightarrow WW$  channel, the evidence was strongest in the final states with the best mass resolution,  $H \rightarrow \gamma\gamma$  and  $H \rightarrow ZZ \rightarrow 4$  l. For these channels we can clearly distinguish narrow bumps showing up in the invariant mass distributions in the vicinity of 125 GeV [Fig. 3, 4]. A fit to these signals allows measuring the mass of the new particle. The result is  $125.3 \pm 0.4$  (stat.)  $\pm 0.5$  (syst.) GeV for CMS, fully compatible with the ATLAS result  $126.0 \pm 0.4$  (stat.)

► FIG. 1: Francois Englert (left) and Peter Higgs (right) at the CERN discovery seminar, July 4<sup>th</sup>, 2012.



<sup>2</sup> LHC operated at 3.5 TeV per beam (7 TeV collision energy) in 2010 and 2011 and at 4 TeV (8 TeV collision energy) in 2012.



▲ FIG. 2: The Large Hadron Collider and its two general-purpose detectors: ATLAS and CMS.

$\pm 0.4(\text{syst.})$  GeV. The strong signals detected in the decay of the new particle to two photons indicate that the new particle is a boson with spin different from one.

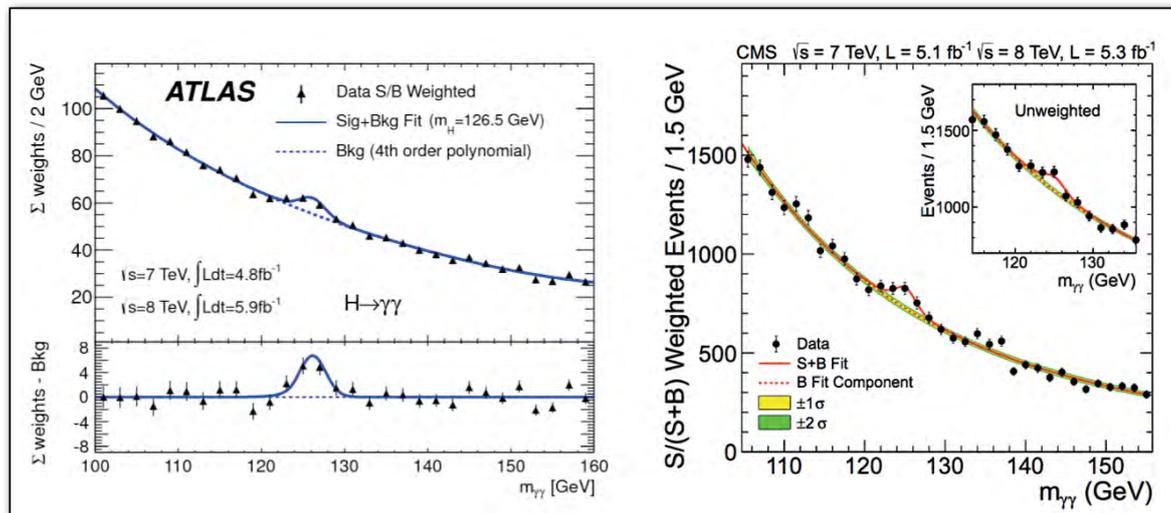
### Implications of a New Boson with a Mass of 125 GeV

Meanwhile we celebrate a historical achievement; the work is definitely not over. Many questions are still on the table. First of all is the new particle really "the" SM Higgs boson? Are the strengths of its interactions with all other particles and with itself precisely the ones predicted by the SM? Is it alone or accompanied? Is it "elementary" or "composite"?

All these questions are still absolutely open. Measuring the quantum number of the new particle will be among the first priorities. There are good prospects to soon measure spin and parity of the new state of matter. Preliminary results show that this will be possible by carefully studying

the angular distribution of the decay products in the two high-resolution channels,  $H \rightarrow \gamma\gamma$  and  $H \rightarrow ZZ \rightarrow 4l$ . The two decay modes are quite sensitive and clean, but statistics is absolutely needed. The recent decision to extend the current pp run of LHC up to the middle of December is therefore excellent news. There are therefore realistic hopes to reach integrated luminosities for 2012 in the range of 25-30  $\text{fb}^{-1}$ .

The most challenging task will be to measure the couplings well. Being so sensitive to any new particle, the freshly discovered Higgs-like boson could act as a portal for new physics beyond the SM. Both ATLAS and CMS have produced results on the signal strength, expressed as a ratio with respect to the SM expectations,  $\sigma/\sigma_{\text{SM}}$ , in different decay modes. ATLAS and CMS results on this quantity ( $1.4 \pm 0.3$  and  $0.87 \pm 0.23$  respectively) are fully compatible with the SM prediction (Fig. 5). Still they are very preliminary results and for some modes, like decays



◀ FIG. 3: Di-photon invariant mass distributions for ATLAS and CMS. A narrow bump is clearly showing-up around 125 GeV.

to t-leptons or b-quarks, the current data are not yet able to distinguish a SM signal from background. So far, we can only conclude that the Yukawa coupling of the new particle to fermions has not been firmly established by the LHC experiments. By looking instead to the couplings to bosons, the ratio of the couplings to W and Z, which is protected by the custodial symmetry, seems to be consistent with expectations in both experiments. The only possible hint of an anomaly comes from some intriguing difference, with respect to the SM prediction, reported in  $H \rightarrow \gamma\gamma$  by both experiments. ATLAS measured  $1.8 \pm 0.5$ , and CMS  $1.6 \pm 0.4$ . Still too early to draw any conclusion, but it will be worth to closely follow this issue. The Higgs boson cannot couple directly to photons, therefore the coupling proceeds through loops of virtual particles involving heavy bosons or fermions. For the known objects in the SM, loops of W and of top quarks dominate the mechanism. New, heavy particles, like the ones predicted in Supersymmetry (SUSY) models, or some of the massive objects predicted by Extra-Dimensions models could enter into the game and modify the rates. If experimental data will definitely show an anomaly here this could be the first un-ambiguous evidence of physics beyond the SM. From careful measurements we could even indirectly infer its energy scale. Only additional data will tell us if these preliminary hints will fade away or if there is something happening there.

A Higgs-like particle of mass 125 GeV puts strong constraints on many SUSY models. SUSY could be consistent with a Higgs-like boson but it would prefer it to be lighter. There is room still to accommodate this relatively heavy object but a precision measurement of the couplings will add important additional constraints. The combination of direct and indirect searches for SUSY, and the implications for SUSY coming from the measurement of mass and couplings of the new boson, will relatively soon lead either to a discovery of super-symmetry or to a drastic revision of some of its paradigms.

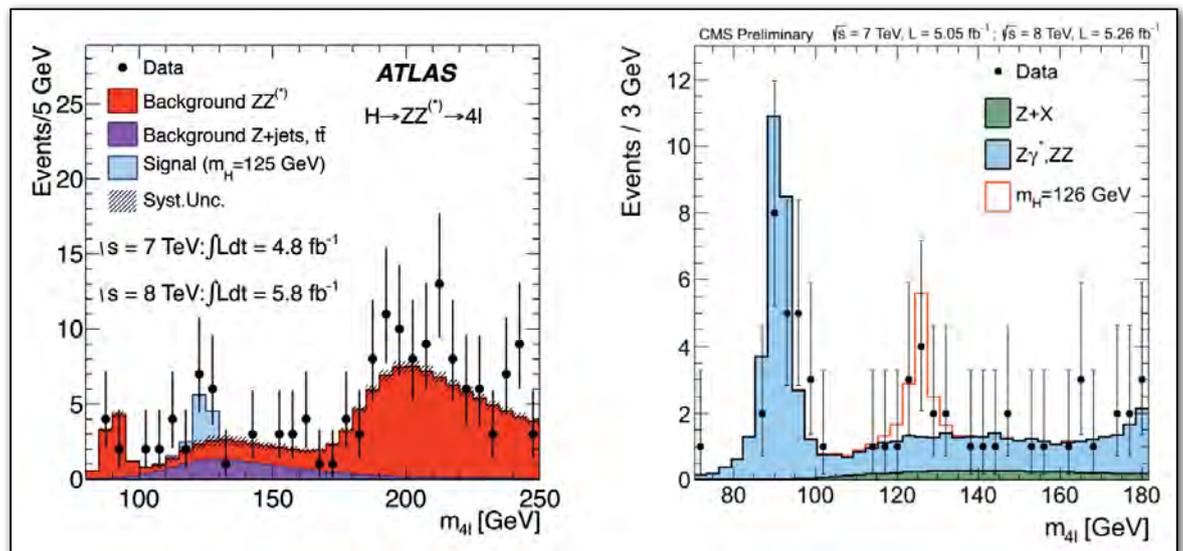
### The Problematic Triumph of the Standard Model

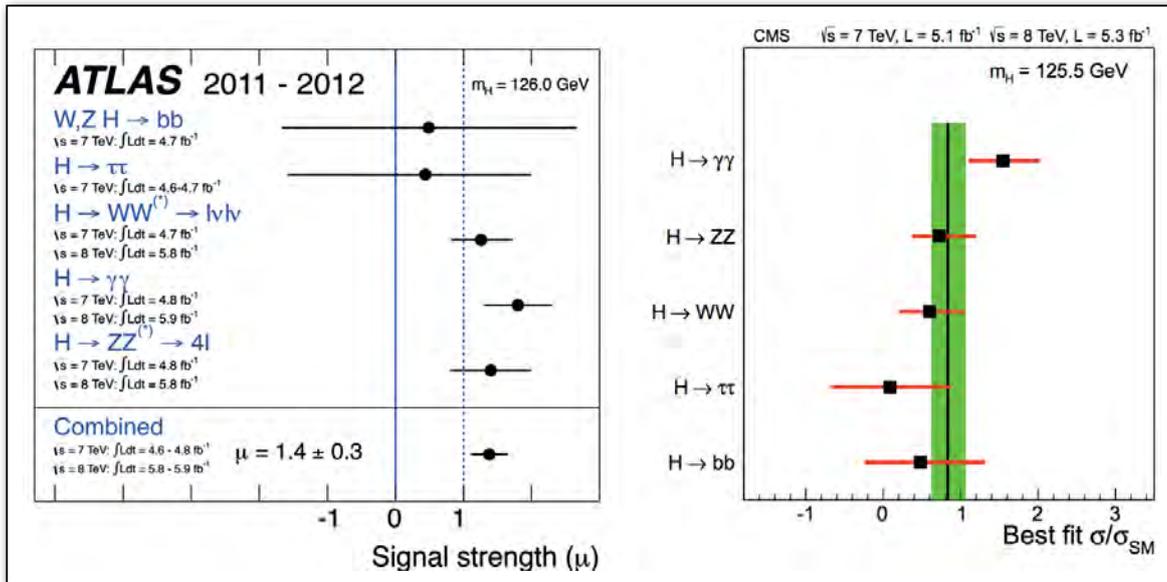
If it will come out that no anomaly will survive the scrutiny of additional data, we will be forced to conclude that the newly discovered particle is precisely the SM Higgs. At that moment we could say that we have understood what happened at about  $10^{-11}$ s after the big bang. When the average temperature of the universe was about 100 GeV, the electroweak symmetry-breaking mechanism entered suddenly in action. The weak force was separated from the electromagnetic one, and leptons and quarks acquired a mass giving shape to the evolution of the universe that lastly produced everything we know including us. Still, in the exact moment in which we celebrate another triumph of the Standard Model, we know that, even including the Higgs, the SM remains an incomplete theory. We know it does not account for the many phenomena that play big roles in the evolution of our universe. What is the mechanism responsible for the inflation? What is the origin of dark matter and dark energy? Why is gravity so weak? What is the source of the large asymmetry between matter and anti-matter? And so on.

We do not know at which energy scale we shall be able to find answers to some of these fundamental questions. Today we have in hand another sensitive tool to explore some of them. The newly discovered particle must be studied in detail. We are doing it already with LHC running at 7(8) TeV. A much better job will be possible in 2014 as soon as the machine will upgrade its energy to 13.5 or 14 TeV. But we are also aware that a hadron collider is not the best environment to perform precision studies. Colliding leptons is by far the right choice. The European High Energy Physics community is facing important discussions already. While LHC is producing new data and CERN experiments continue to yield new information, it is a very appropriate moment to address a few compelling questions.

Would it be technically possible to build a new lepton collider to study in detail the new boson and measure precisely all its properties? And if the answer is yes, what would be

► FIG. 4: Four-lepton invariant mass distributions for ATLAS and CMS. Higgs candidate events clusters in the narrow bump around 125 GeV. The large peak around 90 GeV seen in CMS is due to a rare decay of the Z particle recorded for calibration purposes.





◀ FIG. 5: Preliminary measurements of  $\mu$ , the ratio of the signals strengths in different decay modes with respect to the SM expectation for ATLAS and CMS.

the best investment: a challenging new Linear Collider producing collisions at 250 or 400 GeV and/or a less ambitious LEP III machine running beyond the Z-H threshold? And if we'll be so lucky, sometime in the future, to collect evidence for additional physics in the 10 TeV region, would it be realistic to consider doubling the energy of LHC? As it happened already several times in the past, with a new discovery an era comes to an end, and we already might have entered a new era whose contours, to be really well defined, will need the active contribution of the whole community.

## Conclusion

By analyzing the 2011 and 2012 data, the ATLAS and CMS experiments have discovered a new boson around a mass of 125 GeV. The result is consistent, within uncertainties, with expectations for a standard model Higgs boson. The collection of further data will enable a more rigorous test of this conclusion and an investigation of whether the properties of the new particle imply physics beyond the standard model. ■

## Acknowledgements

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## About the Author



**Guido Tonelli** is a full professor in general physics at the University of Pisa (Italy) and a researcher at the Italian Institute for Nuclear Physics (INFN). He has pursued high-energy physics research in several CERN and Fermilab experiments. The last two decades of his career have been devoted to the search for the Higgs boson and for

signatures of new physics beyond the Standard Model. He has been working on the CMS experiment at CERN since 1993, having served as its spokesperson in 2010 and 2011. In that capacity, in December 2011, he delivered one of the two CERN presentations showing the initial evidence for a Higgs boson at 125 GeV. He is author of about 450 scientific publications.

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