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CERN, the LHC, the Higgs boson and the rest

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Abstract. The Higgs field was proposed in 1964 as a new kind of field that fills the entire Universe and gives mass to all elementary particles. The Higgs boson, a wave in that field, was discovered at CERN in 2012 by the two international collaborations ATLAS and CMS which operate the two eponymous detectors installed at the Large Hadron Collider. This achievement was the result of several decades of scientific developments and constructions by hundreds of teams, thousands of scientists and staff all over the globe. None of this would have been possible without the vision and dedication of a few individuals who set up the scene in the years post-World War II.

1. Foreword

With these few words this paper will attempt to tell the story of the human adventure which led to the discovery of the Higgs boson, announced at CERN on 4th July 2012. It will present an abridged version of the story which lasted about half a century. I took part in the adventure from 1990 when I joined what would later become the ATLAS collaboration. My vision mainly stems from twenty years of intense R&D, instrumentation and construction for the ATLAS detector. This vision carries a more global view that just mine.

2. CERN is magic

The European Organisation for Nuclear Research, known as CERN (from the French *Conseil Européen pour la Recherche Nucléaire*) was conceived in the beginning of the 1950s. The wish to create a scientific community in Europe after the destructions of World War II was followed by a group of very inspired men who pursued the aim of gathering scientists from Europe and further afield. CERN which was formally created in July 1953 at a meeting in Paris would be located on the French-Swiss border near Geneva.

The document stating that “*The Organization shall provide for collaboration among European States in nuclear research of a pure scientific and fundamental character, and in research essentially related thereto. The Organization shall have no concern with work for military requirements and the results of its experimental and theoretical work shall be published or otherwise made generally available*." was signed by representatives of twelve European countries: Belgium, Czechoslovakia, Denmark, France, Germany, Greece, Italy, Netherland, Norway, Sweden Switzerland and the United Kingdom. Today twenty three states are members of CERN.

The work at CERN rests on the following pillars:

- A simple but strong Convention excluding military applications.
- An organisation for the domain of high energy physics and not for a project.

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- Researchers come from everywhere including from non-Member States.
- A global budget (payment proportional to the member state GDP) and not "I want my money back".
- No national or other quota for employment of personnel.
- International experimental collaborations where CERN is minority.

CERN builds and operates facilities and coordinates exploitation with high technical competence. Users come from universities, national laboratories etc., bringing scientific competence and also rejuvenation. The concept of Open Access for data technologies is an essential aspect of the work at CERN.

CERN has the ambition to be at the frontier of world excellence in spite of high risks.

Figure 1. (1954) Excavating the CERN site. Geneva was selected as the site for the CERN Laboratory in 1952. On 17th May 1954 the first shovel of earth was dug on the Meyrin site under the eyes of Geneva officials and members of CERN staff.

Working at CERN is fantastic with the possibility of collaborating with scientists and people from many other domains such as administration and innovative companies from all over the world. At CERN all languages can be heard and the spirit of collaboration with this exceptional organisation makes CERN a particularly inspiring place.

One of CERN's highest technical strengths is its tradition of large beam infrastructures for high energy physics. Since the beginning of its installation in 1954 progress has grown around particle accelerators such that the next infrastructure is fed from the former.

As an illustration the photograph in figure 1 can be compared to the current version of the CERN acceleration complex shown in figure 2, which includes the Large Hadron Collider that will be described in the next section.

Halfway between the creation of CERN and the discovery of the Higgs boson, in 1983 the two collaborations running the two experiments UA1 and UA2 discovered the $W^{\pm}$ and Z^0 bosons. This double discovery was the fruit of the innovative ideas of Simon van der Meer and Carlo Rubbia. Simon van der Meer invented the technique of stochastic cooling of particle beams, which allowed the accumulation of intense beams of antiprotons for head-on collision with counter-rotating proton beams at 540 GeV centre-of-mass energy or 270 GeV per beam in the Super Proton Synchrotron at CERN. Carlo Rubbia proposed the construction of the detectors which would allow the detection of the $W^{\pm}$ and

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Z^0 bosons. They together received the Nobel Prize in Physics in 1984. This success opened the door for the preparation of the Large Hadron Collider.

CERN then built the Large Electron Positron Collider (known as LEP) in order to measure the Z^0 boson and possibly discover new physics. LEP operated from 1989 until 2000. The four collaborations which ran the four experiments at LEP set a lower limit on the Higgs boson mass at 114.6 GeV.

The Fermi Laboratory in USA, located close to Chicago, operated the Tevatron between 1983 until 2011. The Tevatron was a high energy proton-antiproton collider with a centre of mass energy of 2 TeV. The top quark with a mass of 175 GeV was discovered there in 1995.

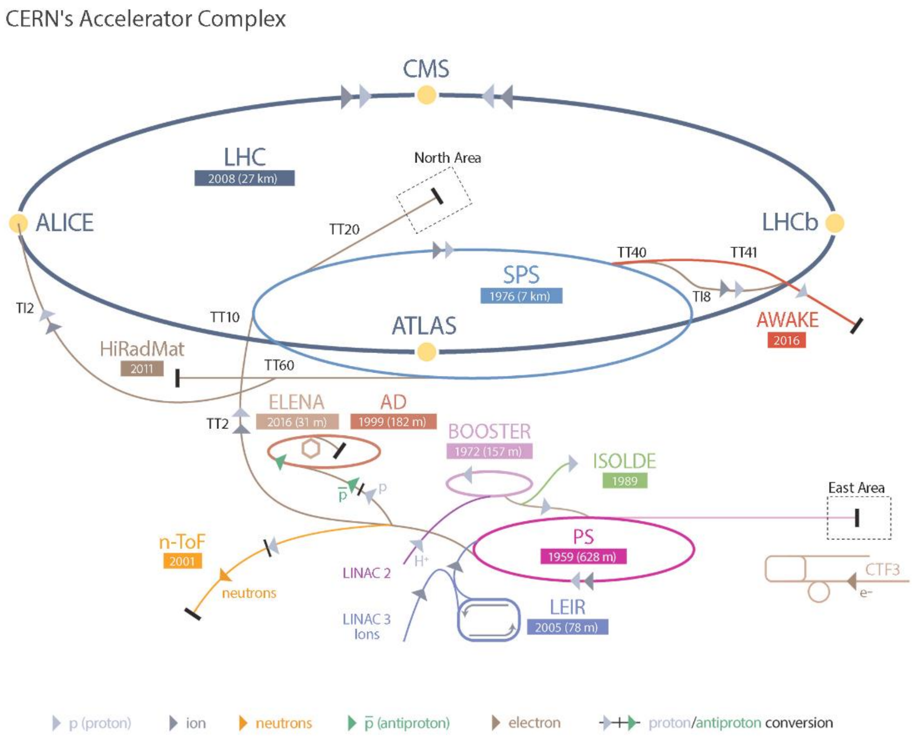

Figure 2. The CERN accelerator complex (2023). Dates of start of operations of each accelerator are given: 1959 for the PS to AWAKE and ELENA in 2016, the largest being the LHC which started operation in 2008.

3. The Large Hadron Collider

After the success of the operation of head-on proton-antiprotons collisions at CERN the idea to build its giant successor emerged; the motivation was to pursue the quest for the Higgs boson and any new type of matter still unknown. This next collider would collide protons against protons for the following reasons which had implications on its design:

- Choose protons rather than electrons as protons lose less energy than electrons when accelerated, the mass of the proton being two thousand times larger than that of the electron.
- Choose to collide protons against protons instead of protons against anti-protons for two main reasons:
  - The collision of the quarks and gluons, the components of the protons, are enhanced with protons rather than anti-proton at high energy.
  - Accumulating anti-protons is very delicate and much more difficult than with protons.
- Being able to reach very high intensity to search for rare phenomena requires having many protons to generate many collisions: 10^9/s.

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- Bending the protons inside the 27 km LEP tunnel requires a high magnetic field for high energy protons (√s=14 TeV). This led to the development of:
    - Powerful magnets providing a magnetic field of 8.4 Tesla and
    - Superconductors operating at 1.9 degrees Kelvin, colder than the Universe.

The LHC project was approved in 1997 and the construction then started. The key elements for the accelerators are:

- Magnets of 8.3 Tesla in order to bend protons of 7 TeV.
- Super-fluid Helium at 1.9 K to provide superconductivity for the magnets.
- 9,300 magnets: 1,232 dipoles, 858 quadrupoles and 6,208 correctives magnets
- Eight radio-frequency cavities.
- The necessary electrical power is 120 MW.

When operated at full power the protons would carry 300MJ of energy per beam.

The definition of the characteristics of the LHC was guided by its physics goal: to be able to detect the Higgs boson and be sensitive to very rare events. Figure 3 presents the expected cross-sections for various productions. The key point of this figure, which led to the design of the accelerator and of the detectors, is the scarcity of Higgs production: high intensity and precision measurements were essential for the designs.

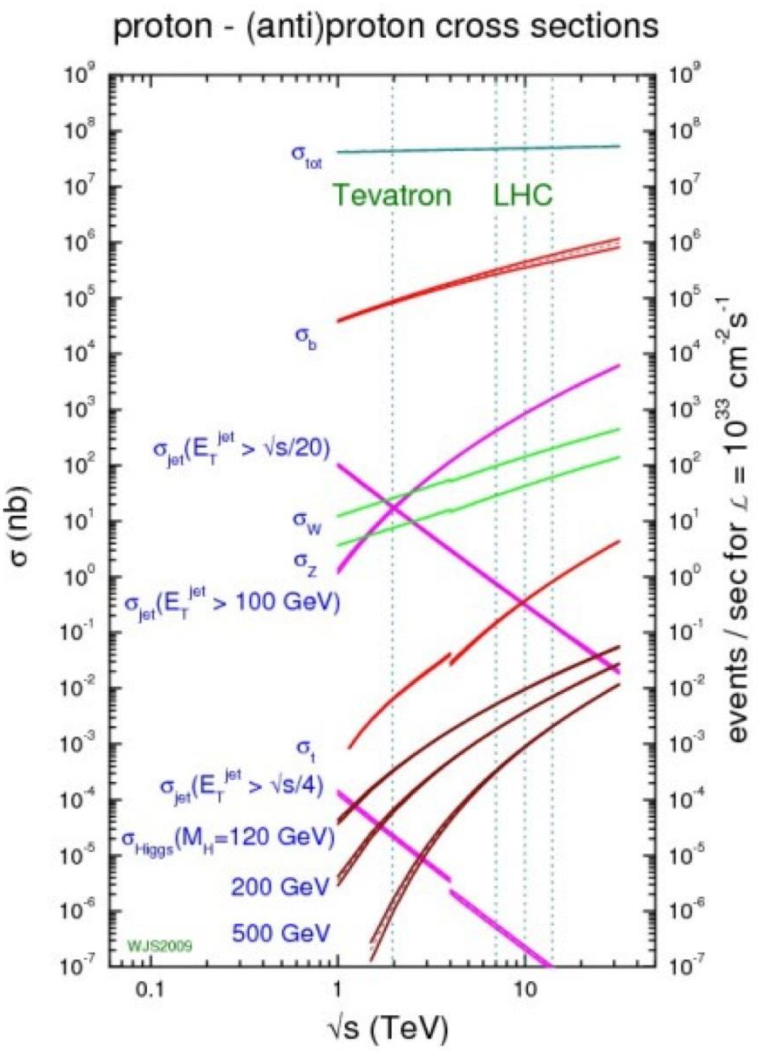

Figure 3. Predicted cross-sections for production of known and possible physics processes in proton-(anti)proton collisions as a function of the centre of mass energy (2009). The expected LHC centre of mass energy was 14 TeV. There is a factor of 10^{-9} between the cross-section for the production of a Higgs boson with mass of 120 GeV and the total proton-proton collisional cross-section.

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4. Higgs boson and detector design

At the end of the 1990s the Higgs boson mass was essentially unknown. The LHC therefore had to cover a very wide mass range, from 0 to 1000 GeV. The Higgs boson mass determines its coupling to elementary particles and consequently the nature of the particles produced when the Higgs boson decays. The question was: if the Higgs boson can be produced, can it be detected?

The Higgs boson is unstable and decays instantly, so observers can only detect the decay products. If the Higgs boson exists and its mass was not too large, it would be produced in proton-proton collisions at the LHC; it would decay to a pair of Z bosons, a pair of W bosons, a pair of bottom quarks, a pair of top quarks, a pair of photons (with a dependency on the mass) and more.

As shown in figure 3 the Higgs boson production cross-section is minuscule compared to other phenomena. In addition proton-proton collisions produce phenomena with similar final states to Higgs boson decays. The highest precision in particle identification is therefore required.

The experimental physicists had to design and build a detector like a giant microscope to measure particles produced by proton-proton collisions. In actual fact they would build two detectors, the ATLAS and CMS, to analyse proton-proton collisions in order to cross check each other.

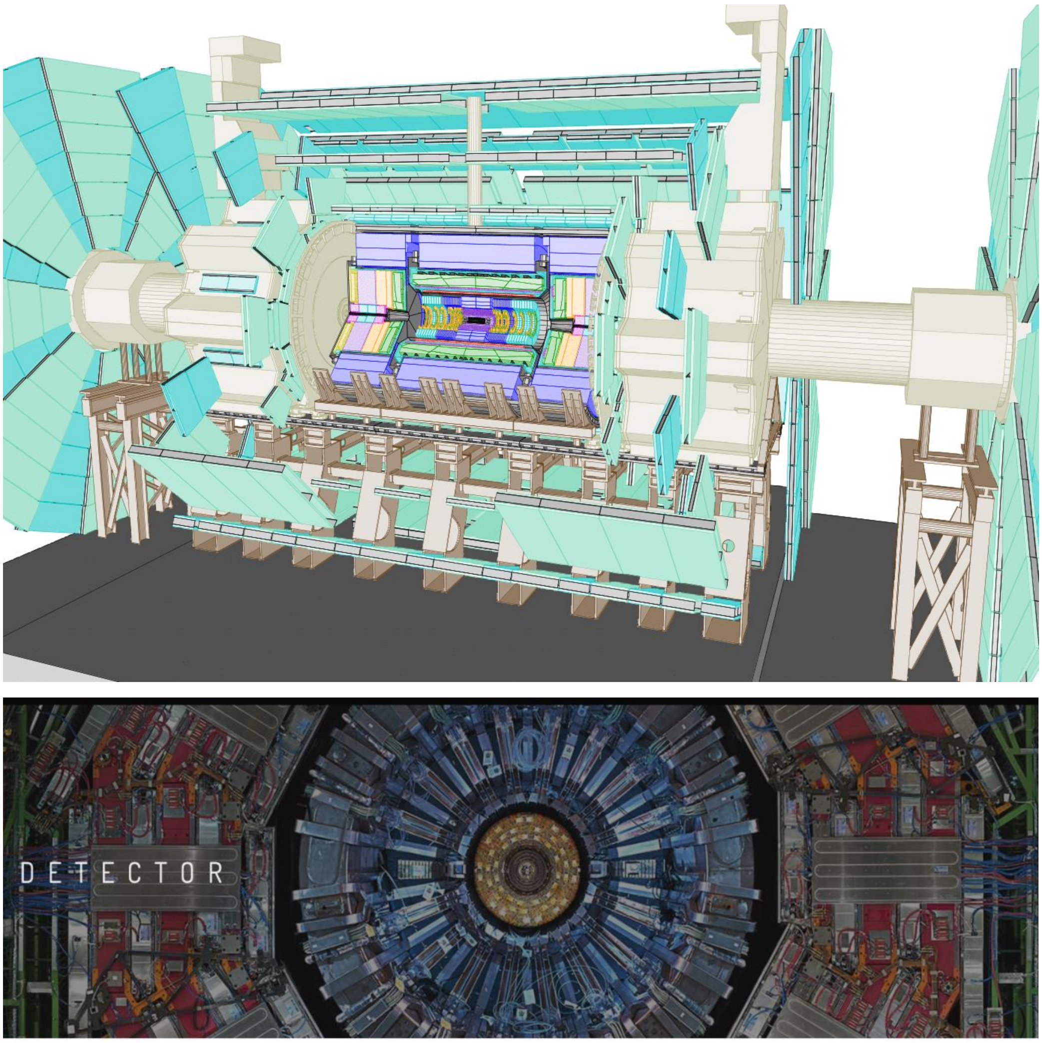

Figure 4. Top: Schematic representation of the ATLAS detector (2010). Bottom: Photograph of the CMS detector. Both apparatuses are installed on the LHC ring and can collect data from proton-proton collisions.

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The constraints on the detectors were numerous. Looking back thirty years it must be remembered that technology has greatly advanced. The same detectors would not be built today, although both ATLAS and CMS are still operational today with a very high performance. For instance, the fraction of operational channels among a hundred million is above 95%.

The challenges to surmount were many:

- The detector components had to be highly radiation resistant: in order to produce very rare events (expected at the level of 10^{-9}) many proton-proton collisions which create radiation have to be produced.
- The beam collision rate was defined at 40 MHz. The detector technology and the associated electronics had to perform at this frequency.
- Thousands of particles are produced in a strong proton-proton collision; the detector has to detect them individually and therefore needs to be highly segmented.
- The particles emitted are of different natures (lepton or hadron, stable or unstable, charged or neutral…) which need to be identified; the detector has to be able to distinguish between the interactions.

Both the ATLAS and CMS detector were designed, constructed and installed with the required characteristics. In summary each one is a giant microscope with a hundred million channels, installed 100 metres underground, about 50 m long and 25 m high with a weight of one to two Eiffel Towers. They both measure particle trajectory with a precision of 0.0002 m (20 μm) and the energy at 1%.
In figure 4 are shown two representations of the detectors: a schematic representation of ATLAS and a photograph of CMS.

5. The Higgs boson discovery

The two detectors were installed inside their respective caverns in the course of the first eight years of the 21st century and were ready in 2008 when the LHC was about to start. In September 2008 an incident damaged several LHC magnets. The repair took place and the accelerator started to operate in December 2009. The fist high energy collisions at a centre of mass energy of 7 TeV took place in Spring 2010. The first precise physics measurements were published in 2010. In 2011 and 2012 the LHC centre of mass energy was pushed to 8 TeV. Later on in 2015 it was increased to 13 TeV and the collider is currently running at 13.6 TeV.

The two collaborations accumulated each about 10/fb of data by end of June 2012. Both were analysing data, checking for biases and unforeseen backgrounds. All possible final states with Higgs boson signatures, such as pairs of photons, pairs of Z bosons, pairs of tau leptons and pairs of W bosons, were carefully studied.

On 4th July 2012, Fabiola Gianotti and Joseph Incandela, on behalf of the ATLAS and CMS collaborations respectively, presented the status of the search for the Higgs boson; both showed the discovery of a particle which had the properties of the Higgs boson [1], [2]. In figures 5 and 6 are shown the mass distributions which revealed the existence of a new particle; in other words, the description of the measured data requires the introduction of a new object, which is not a background and which turns out to follow the characteristics of the Higgs boson particle as predicted by theory.

The results presented by the two collaborations agreed to a high precision. The compatibilities of the predictions, summing background and Higgs boson calculations with the data were at the level of 5σ for each data set, meaning that the probability that the observed excess would be coming from a statistical fluctuation is below 0.00006%. Both collaborations measured the Higgs boson mass at ~125 GeV with an uncertainty of order 1 GeV.

The fact that all channels showed an excess above background compatible with the expectations from the decays of Higgs boson carried a strong meaning: the coupling of the Higgs bosons are precisely predicted. The observed new particle was most probably the Higgs boson.

Since 2012 more precise measurements have been published and the decay of the Higgs bosons in other channels such as b bar, which were thought to be impossible to measure because of the very low signal over background ratio, have been completed.

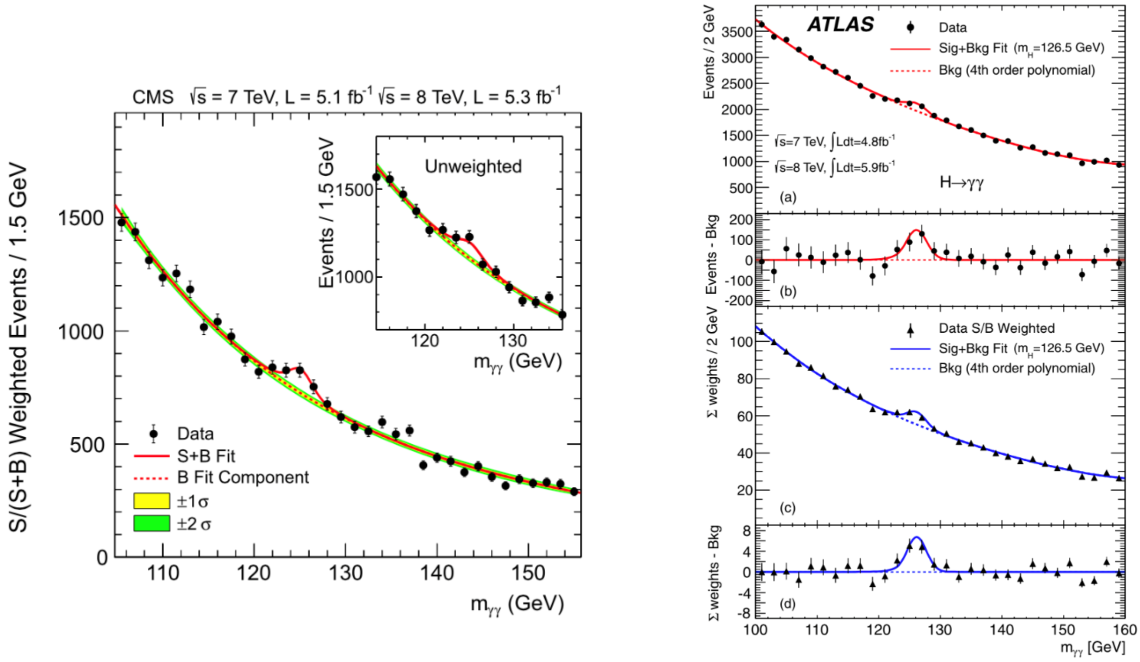

Figure 5. Mass distribution of pairs of photons measured with the CMS detector (left) (2012) and with the ATLAS detector (right).

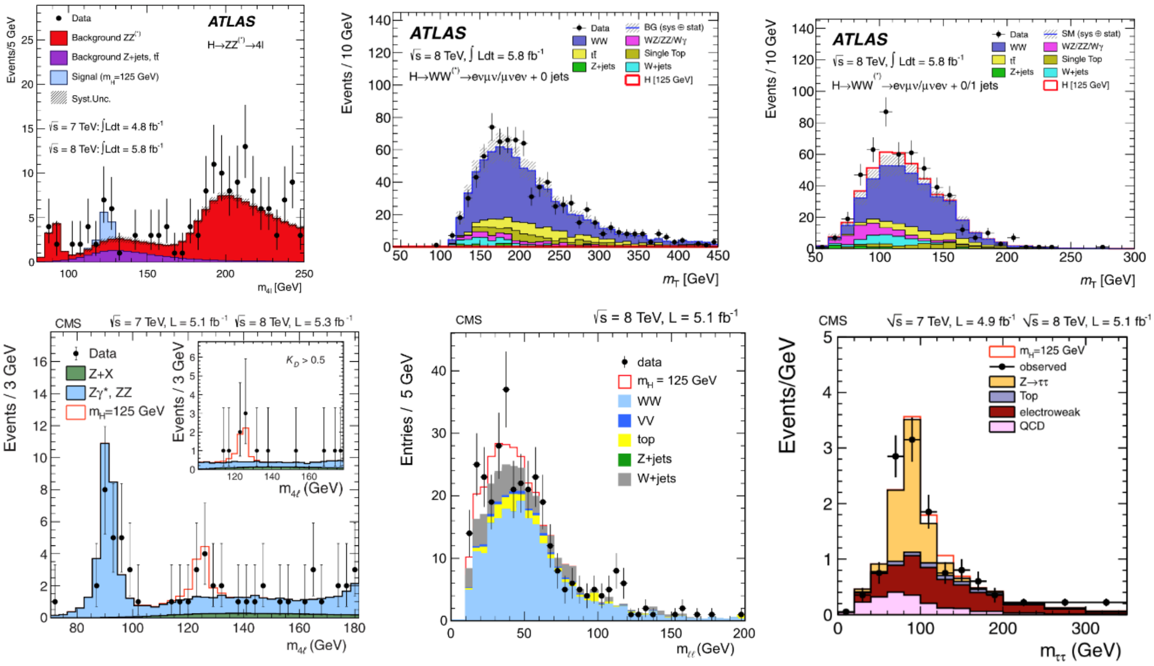

Figure 6. Mass distribution of pairs of Z bosons (left), pairs of W bosons (middle) and pairs of τ leptons (right) measured with the ATLAS detector (top) and with the CMS detector (bottom) (2012).

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6. The rest

The LHC was designed and constructed to study high energy proton-proton collisions with two main goals: the first was to search for the Higgs boson, the second to search for other rare phenomena of any type which would reveal new aspects of physics. The search for the Higgs boson has been fruitful and the particle so far carries the properties that were described in 1964.As of today no deviation from the Standard Model of particle physics has been observed either in the Higgs boson description or in any other domain. The LHC is expected to produce at least as many collisions as already produced and the High Luminosity LHC, scheduled to start in 2028, is foreseen to produce ten times more data: will anything surprising be revealed in the course of the next decade?

Acknowledgements

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References

[1] CMS Collaboration *et al* 2012 Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC *Phys. Lett. B* **716**(1) pp 30–61

[2] ATLAS Collaboration *et al* 2012 Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC *Phys. Lett. B* **716**(1) pp 1–29