PLENARY SESSION

THE LHC AND THE DISCOVERY OF THE HIGGS BOSON: 50 YEARS OF HIGGS MECHANISM

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ABSTRACT. We describe briefly the ATLAS detector and some of the physics results on QCD, top physics and.the Higgs boson discovery that lead to the Nobel Prize of Physics in 2013. We finish the short report by a new method to look for extra-dimensions in the universe.

Keywords: LHC, ATLAS, Higgs boson

1. The Large Hadron Collider and the ATLAS experiment

1.1. The Large Hadron Collider

The Large Hadron Collider is now the most energetic collider that has ever been built. It collides proton with a center-of-mass energy of 7 TeV (2011), 8 TeV (2012) and will restart next year with an energy of 13 TeV. It allows studying the internal structure of nuclei in terms of quarks and gluons. In relation with cosmology, the LHC proton proton collider reproduces the conditions in the universe less than 10^{-10} seconds after the big-bang or a temperature higher than 10^{15} degrees which could lead to a sign of dark matter candidates. For comparison, the heavy ion mode of the LHC probes a time of about 10^{-9} seconds after the big-bang or a temperature above 10^{12} Kelvin.

Before the start of the LHC, the standard model of particle physics was almost complete with the discovery of the six quarks (up, down, charm, strange, top and bottom) and leptons (electron, muon and tau with their associated neutrinos) and the photon, gluon, and Z/W bosons responsible for the electromagnetic, strong and weak interactions. But the Higgs boson responsible for the existence of mass in the standard model of particle physics was still elusive despite the active searches at LEP and at the Tevatron.

The LHC as we mentioned already is now the largest accelerator on earth with a circonference of 27 km, located underground at a depth varying between 50 to 100 m. The weight is of the order of 38,000 tons, and the typical magnetic field of the order of 8.3 T. The typical energy per beam stands at 400 MJ (let us recall that 1 MJ melts 2 kg of copper), and the power consumption of the LHC is about 120 MW (as a comparison, a city such Ann Arbor in the US consumed 190 MW in 2008).

As many accelerators, the LHC is composed of dipole magnets that keep the beam in circular orbits, quadrupole and sextupole magnets that focus the beams and radiofrequency cavities that accelerate the beams. The LHC is one of the hottest spot in the universe: when two proton beams collide, they reach a temperature of about 10^{17} degrees over a minuscule area (for comparison the temperature in the sun's core is about 10^7 degrees) and it creates a condition similar to that 10^{-13} second after the big-bang., It is one of the hottest spots in the universe today. Ironically, the LHC is at the same time one of the coolest places on earth. LHC beams are kept in orbit by superconducting electromagnets operating at a temperature of 1.9 K. It takes about one month to cool down and needs about 10,000 tons of liquid nitrogen and 100 tons of liquid helium to cool and to keep it cold. The LHC is also one of the largest instrument on earth in order to track particles with micron precision over a lenth of 50 m with about 100 million electronic readout channels. These detectors are analogous to digital cameras but taking pictures at a rate of 40,000,000 per second and they are sensitive to light and other radiations.

1.2. The ATLAS and CMS detectors

Many experiments coexist in the LHC: Alice, ATLAS, CMS, TOTEM, LHCb, Moedal, LHCf. We will concentrate in this report of the two generic ones namely ATLAS and CMS. As an example, a sketch of the ATLAS detector is shown in Fig. 1. It is made of different subdetectors: the pixel, semiconductor and transition radiation detectors that allow to reconstruct the point of interaction and the tracks of charged particles, the calorimeters that allow to measure the position and energy of leptons and hadrons, and the largest one, the muon chambers that allow to detect and measure muons. In comparison, the CMS is more compact and weights more than the Eiffel tower in Paris. The

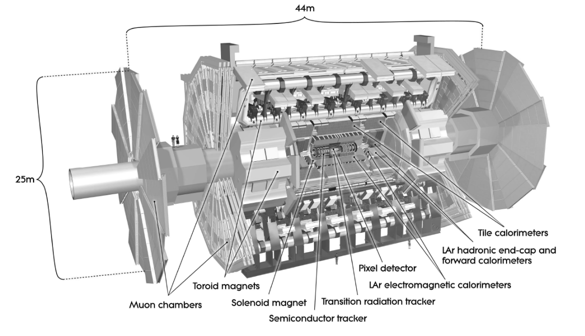

Figure 1: Sketch of the ATLAS detector

ATLAS collaboration is composed of about 3000 scientists from 174 institutes and 38 countries. The ATLAS inner detector alows precise tracking and vertexing with a resolution of $\sigma_{p_T}/p_T \sim 3.8\ 10^{-4} p_T(GeV) \oplus 0.05$. The ATLAS calorimeter is composed of two parts, the electromagnetic Pb-Lar one, with a resolution of $\sigma_E/E = 10\%/\sqrt{(E)} \oplus 0.7\%$ and the central hadronic Fe/Scintillator Tiles one, and the forward Cu/W-Lar one with a resolution of $\sigma_E/E \sim 50\%/\sqrt{E} \oplus 3\%$. The muon detector is made of an air-core toroid system with a bending power of 1 to 7.5 Tm instrumented with gas chambers which leads to a resolution σ_{p_T}/p_T of 2-3% below 200 GeV and 10% at 1 TeV.

In addition, special care was put on the trigger in ATLAS. Protons collide at a rate of 40 MHz and among these, a tiny fraction ($5\ 10^{-6}$) is recorded since not all collisions are interesting and it is not practical to record all of them. The event selection is performed through a multi-level trigger system: the level 1 (hardware) rate is 75 kHz, level 2 (firmware) 3 kHz, and level 3 (software) 200 Hz. This leads to a huge data volume of 320 MB per second or 3PB a year. To give some feeling, the data recorded by each LHC experiment would fill 2,000,000 DVDs per year. In order to analyse this huge volume of data, hundreds of thousands of computers through over the world are connected as a world-wide computing grid.

2. LHC physics

2.1. Rediscovering the standard model: jet measurements

Before looking for discoveries such as the Higgs boson or physics beyond the standard model, it is fundamental to be able to recheck the standard model predictions (what has been discovered in previous experiments) in order to show that the detector is well understood. When a proton collides with another proton at the LHC, the actual collision occurs between quarks and gluons inside the nuclei, and the cross section of produced objects in the final state will be sensitive to the internal structure of the proton.

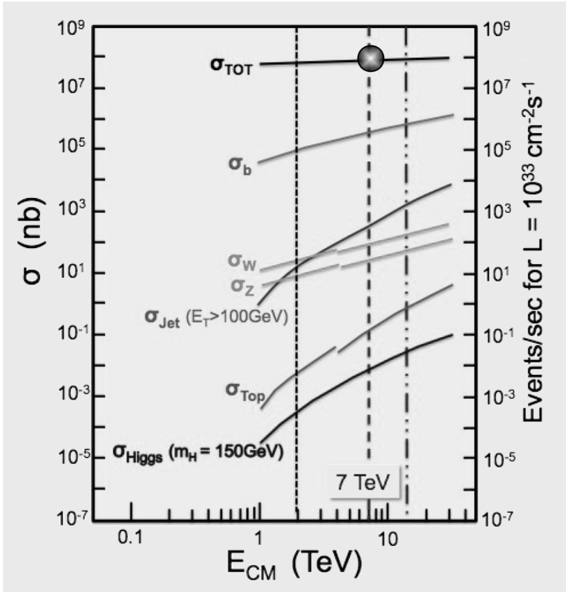

Figure 2: Different physics topics at the LHC

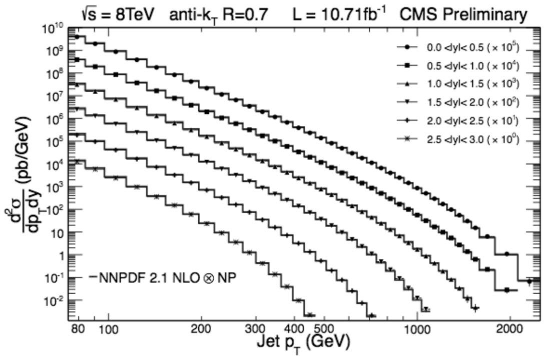

Figure 3: Jet cross section measurements as a function of jet p_T in different rapidity bins

The cross section values for different processes at the LHC are shown in Fig. 2. The largest cross section is the total cross section whereas the W/Z, top quark, and Higgs cross sections are respectively about 6, 8 and 10 orders of magnitude below. We already understand the difficulty to look for the Higgs boson since backgrounds will stand orders of magnitude above our signal.

The jet cross section as a function of jet p_T in different domains of rapidity corresponding to different angular regions in the CMS detector is shown in Fig. 3. This measurement is sensitive the proton structure in terms of quarks and gluons. The measurement is in good agreement with NLO order QCD calculations

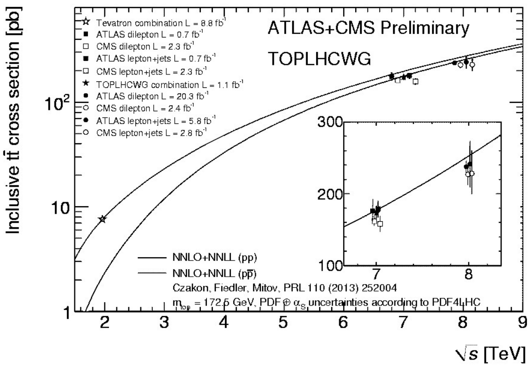

Figure 4: $t\bar{t}$ production cross section measured by the ATLAS and CMS collaborations as a function of the center-of-mass energy compared to NNLO calculations displayed as a full line [1], and allows constraining further the proton structure in terms of quarks and gluons.

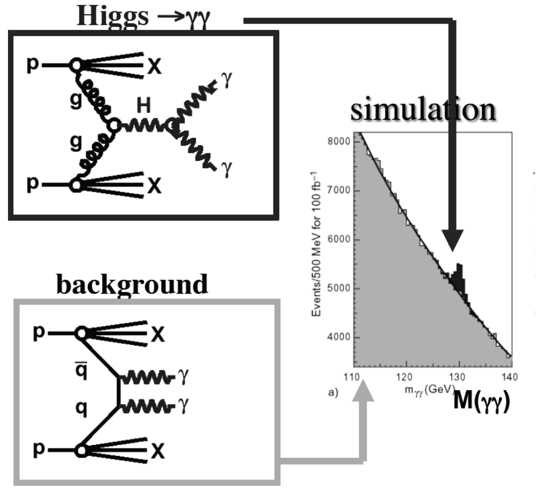

Figure 5: Scheme to look for the Higgs boson in the $\gamma\gamma$ decay channel at the LHC

2.2. Top quark physics

The second standard model measurement that we mention is related to the top qaurk production that was recently discovered at the Tevatron [2]. In about 85% of events, the $t\bar{t}$ events are gluon-induced processes at the LHC. The selection of $t\bar{t}$ events can be performed in different ways. The top quark decays in a bottom quark and a W boson, that itself can decay into two jets or one lepton (electron, muon or tau) and a neutrino. Typically, the signature of a $t\bar{t}$ will be two b-jets originating from the top quark decays, and two Ws that can lead to two leptons (one electron and one muon or two electrons or two muons as an example) and missing transverse energy due to the undetected neutrinos. The $t\bar{t}$ production cross section measured by the ATLAS and CMS collaborations [3] is found to be in good agreement with NNLO cross section calculation as shown in Fig. 4.

3. The discovery of the Higgs boson

Before discussing the processes that lead to the discovery of the Higgs boson at the LHC by the ATLAS and CMS experiments, let us describe the ideas of the Higgs mechanism. Let us imagine a room full of journalists quietly chattering, it is analogous to the space filled only with the Higgs field. A well-known person (the President, Albert Einstein...) enters in the room. This creates a disturbance as he moves through the room and attracts a group of journalist with each step. This increases the resistance to movement of that famous person. In other words, that person acquires mass just like a particle moving through the Higgs field. Something different might happen in the same room full of journalists: a rumor crosses the room, "the Higgs boson has been discovered", for instance. In that case, it creates the same kind of clustering but this time between the journalists themselves. In this analogy, these clusters are the Higgs particles. Of course, this is just an image to illustrate the Higgs mechanism and the real field theory explanation how particles acquire mass was proposed separately by Higgs, Englert and Brount about fifty years ago [4].

At the LHC, the Higgs boson is mainly produced by two gluons originating from the protons. Depending on its mass, the Higgs boson can decay into $b\bar{b}$ (mainly at low masses), WW and ZZ (at higher masses), in $\gamma\gamma$, $t\bar{t}$, $\tau\tau$... At the LHC, all channels were obviously considered while looking for the Higgs boson. We will restrict ourselves to two golden channels of the Higgs boson decay, namely the $\gamma\gamma$ and ZZ ones. The $\gamma\gamma$ channel has a low branching ratio (typically 0.2% for a Higgs boson mass of 126 GeV) but leads to a clean signal of two photons in the ATLAS detectors. In the case of the ZZ decay, this channel is even cleaner when each of the Z boson decays leptonically into electrons or muons. It corresponds only to a branching ratio of 0.014% but leads to a very clean signal with very low background of 4 leptons in the final state (2 muons and 2 electrons, or 4 muons or 4 electrons).

The method to observe the Higgs boson in the $\gamma\gamma$ decay channel is illustrated in Fig 5. The background is due to the standard model production of two photons which is a steeply falling distribution as a function of the diphoton mass. If the Higgs boson decaying into two photons exists, it should appear as a small bump in this distribution provided the production cross section is high enough. This is indeed what was observed in the ATLAS and CMS experiments [5] as shown in Fig. 6. Both ATLAS and CMS collaborations discovered a peak at about 126 GeV in the steeply falling diphoton mass distribution. It is necessary to look in other channels to know if this peak is really due to the existence of the Higgs boson and not to another particle. As an example, the results in the ZZ channel is shown in Fig. 7 and leads to the same conclusion, namely an object compatible with the Higgs boson has been observed in the 4 lepton channel at about the same mass as in the diphoton one. This important result lead to the discovery papers of a Higgs boson-like particle [5] which received more than 3200 citations in about 2 years and lead to the Nobel Prize of Physics to Higgs and Englert (Brout sadly passed away about 1 year before the anouncement of the discovery).

More recent results show that this Higgs boson-like particle has all characteristics (spin, couplings...) so far of the standard model Higgs boson, with a mass of $M_H = 125.35 \pm 0.37$ (stat) ± 0.18 (syst) GeV (ATLAS) and $M_H = 125.03^{+0.26}_{-0.27}$ (stat) $^{+0.13}_{-0.15}$ (syst) (CMS) [6]. More data at a higher center-of-mass energy of 13 TeV and also more statistical precision in the rarest decay channels with more integrated luminosity will confirm this result or show some interesting differences with respect to the standard model in a near future when the LHC restarts next year. It is worth mentioning that many decay channels have been looked at now such as $\gamma\gamma$, ZZ, WW, $\tau\tau$, $b\bar{b}$, $Z\gamma$... as well as different Higgs boson production mechanism (gluon-gluon as already mentioned, or vector bosn fusion, associate production with a vector boson, and associate production with $t\bar{t}$).

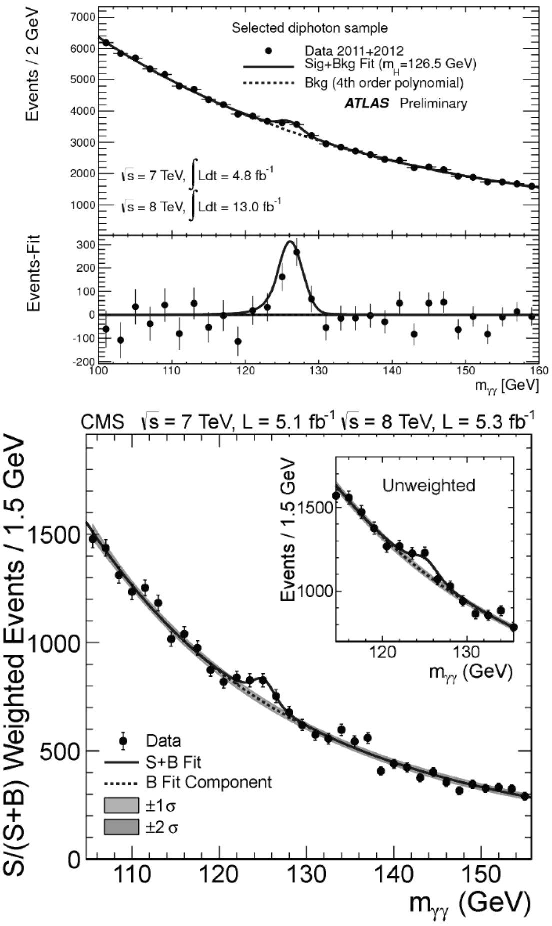

Figure 6: Higgs boson discovery in the diphoton channel at the LHC

4. The future: looking for extra-dimension in the universe

We will finish this short report by mentioning a recent proposal to look for the existence of extra-dimensions in the universe by looking especially at the 4 photon couplings at the LHC [7]. We live in a four dimension of space time but gravity might live in extradimensions, and we aim to probe this idea predicted especially by string theories at the LHC. If extra-dimensions are discovered at the LHC, this might lead to major changes in the way we see the world.

The process that we want to study is shown in Fig. 8. It corresponds to $\gamma\gamma$ productions via photon exchanges. Two photons are produced in the final state that can be detected in the ATLAS and CMS detectors and two intact protons are also produced. They can be measured in dedicated detectors located far away from the interaction point (220 m) from the CT-PPS and AFP projects in the CMS/TOTEM and ATLAS collaborations respectively. The two photons in the final state

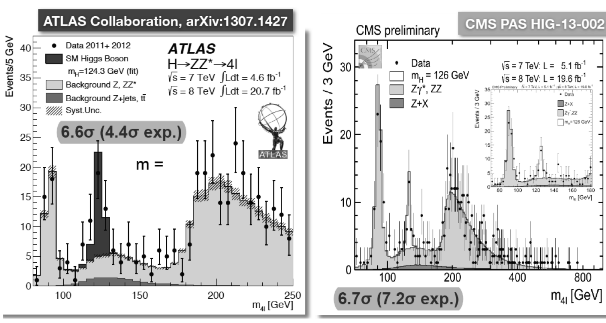

Figure 7: Higgs boson discovery in the ZZ channel at the LHC

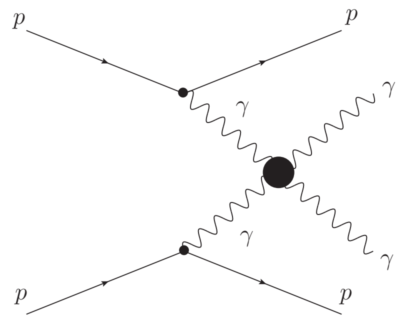

Figure 8: Diphoton production via photon exchange processes at the LHC

appear at high momentum transverse and high masses. The $\gamma\gamma\gamma\gamma$ couplings are predicted by extra-dimension and composite Higgs models. The anomalous couplings was predicted to be of the order of 10^{-14}-10^{-13} for a large range of models. The fact that the event is exclusive, namely that we observe two high mass photons in ATLAS/CMS and two intact protons in AFP or CT-PPS allows suppressing completely the background, including all pile up background up to a pile up of 100. This is due to the fact that the system is completely constrained: the mass and the rapidity of the photon system computed using the photons or the intact protons must be the same within resolution as shown in Fig. 9. After these requirements, the typical sensitivity was found to be $\sim 10^{-14}$ reaching the values expected from generic extra-dimension models [7]. Without tagging the protons and without benefitting from the exclusive requirements, such a reach would not be feasible at the LHC High luminosity and energy at the LHC will thus lead especially to unprecedented sensitivity on quartic $\gamma\gamma\gamma\gamma$ anomalous couplings that, if discovered, might be the sign of the existence of extra-dimensions in the universe, which would be a major discovery.

To conclude, after a brief description of the LHC machine and the ATLAS detector, we described two important SM measurements, namet the jet and $t\bar{t}$ production cross sections that are in agreement with SM expectations. The discovery of the Higgs boson by the ATLAS and CMS experiments was definitely one of the main results at the LHC, that might lead to additional fundamental discoveries such as the existence of extra-dimensions in the universe in a near future.

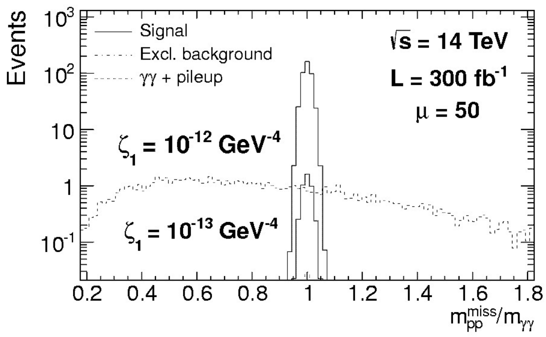

Figure 9: Ratio of the diphoton masses computed from the two photons measured in ATLAS/CMS or from the intact proton information as measured by CT-PPS or AFP. For the signal the ratio is close to 1 whereas it is flatter for the pile up background.

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