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Latest results on the Higgs boson discovery and investigation at the ATLAS-LHC

Nguyễn Anh Kỳ[1,2] **and Nguyễn Thi Hồng Vân**[1]

[1] Institute of physics, Vietnam academy of science and technology, 10 Dao Tan, Ba Dinh, Hanoi, Vietnam

[2] Laboratory for high energy physics and cosmology, Faculty of physics, College of science (VNU university of science), Vietnam national university, 334 Nguyen Trai, Thanh Xuan, Hanoi, Vietnam

E-mail: `anhky@iop.vast.ac.vn, nhvan@iop.vast.ac.vn`

Abstract. On 04 July 2012, ATLAS and CMS, the two biggest LHC collaborations, announced the discovery of a new boson with a mass around 125 GeV. With the preliminarily delivered information, this particle resembles the Higgs boson (of the standard model) playing a key role in the symmetry breaking mechanism generating particle masses in the standard model. To confirm if the newly discovered particle is really the Higgs boson it is necessary to do further and detailed investigations to precisely determine its nature and properties. Here we will summarize some of the latest results of these investigations. If the new particle is the Higgs boson, the standard model will get the full recognition as a very successful model, otherwise, another model may be needed to replace the standard model in order to explain all the observed phenomena. The results obtained by ATLAS (and CMS) for last two years have almost shown that this new particle can be identified with the Higgs boson.

1. Introduction

The Brout-Englert-Higgs boson of the standard model (SM), or just, the Higgs boson, for short, plays a central role in the symmetry breaking scheme giving masses to particles (in the SM)[1]–[5]. Until recently, however, the Higgs boson had been the only particle in the SM not found yet experimentally. It is why searching for the Higgs boson has been an important mission of experimental particle physics. Searching for the Higgs boson was also one of the main goals of building the LHC (*Large Hadron Collider*), the ever most expensive, most powerful and largest particle accelerator. The LHC has four main collaborations, namely, ATLAS, CMS, LHCb and ALICE among which ATLAS (*A Toroidal LHC Apparatus*) and CMS (*Compact Muon Solenoid*) are the two biggest ones. In the summer of 2012 a breaking scientific news was spreading around the world when the collaborations ATLAS and CMS announced the discovery of a new boson of mass of around 125 GeV which might be (identified with) the Higgs boson of the standard model [6, 7]. If the newly discovered boson is identified with the Higgs boson, the SM becomes a fully confirmed model with all its particle content found experimentally. Since its discovery this particle has been intensively investigated so that its properties can be precisely determined, and, thus, its exact nature can be established. Here we will briefly review some of the latest results on investigating the new boson. After the first observations [6, 7] of the new boson via its decays to gauge boson pairs ($\gamma\gamma$, WW and ZZ), its mass, spin-parity and other properties have been more precisely measured and investigated by different collaborations, ATLAS, CMS and Tevatron. One of the important investigations to confirm if the new particle is really the Higgs boson is to investigate if it also couples to fermions and if these couplings are compatible with the SM in which the couplings between the Higgs boson and the fermions give masses to the latter. Recently, both ATLAS and CMS gave a positive answer of this question but below we will concentrate our discussions on the ATLAS experiment.

With the results obtained so far it can be almost sure that the newly discovered particle is the long sought Higgs boson. It has a mass of about 125 GeV, spin-parity $J^P = 0^+$ and couplings to gauge bosons and fermions as predicted by the SM. The discovery of this particle showing that an elementary scalar particle exists in the Nature, is very meaningful for particle physics as, besides that it generates particle masses, all scalar particles found so far are not elementary but composite. This discovery may have cosmological and other consequences as well but they are beyond the scope of our report. Before going to more physical discussions in section 3, let us make in the next section a technical overview on the LHC and the ATLAS detector.

2. Brief information of the LHC and the ATLAS

Here we will present a brief introduction to the LHC and the ATLAS detector. More information about these facilities can be found from their official websites [8, 9].

The LHC, located at CERN (*European organization for nuclear research*), the world's leading laboratory for particle physics, is the biggest (in size, cost and collision energy) particle accelerator ever built by human. It is installed in a tunnel of 27 km long and at a depth of $50 - 100$ m under the French-Swiss border near Geneva. It was designed to accelerate and collide two proton beams at the maximal center-of-mass energy of 14 TeV ($\sqrt{s} = 14$ TeV). The collision energy reached in the first run (2009 – 2012) of the LHC was 8 TeV ($\sqrt{s} = 8$ TeV). The designed maximal energy (14 TeV) is expected to be reached in the second run which will start in 2015. Besides the record particle collision energies, the LHC has achieved many technological records such as a superstrong magnetic field (8.4 T, or about 200 000 times stronger than the Earth's magnetic field), the highest vacuum ($10^{-10} - 10^{-11}$ mbar, in the order of that on the Moon surface), the lowest temperature (1.9 K, or lower than that in the outer interplanetary space, 2.7 K), the highest temperature (5.5 trillion degrees Celsius, or near 350 000 times higher than the temperature in the center of the Sun), etc.

The LHC has four main detectors among which ATLAS and CMS are the two biggest and general-purpose ones (see Fig. 1 for a scheme of how the detectors are located on the LHC ring). The ATLAS and CMS detectors are based on the same operation principle and have similar general structures and purposes. The detailed differences are their sizes, masses, magnetic fields used, sensitivities of sub-detectors, etc.. These detectors are huge and complex high-technological facilities, for example, the ATLAS detector has four sub-detectors which in turn consist of many layers with a total mass of about 7000 tones and an overall size of about 25m (diameter) × 46m (length), while the CMS detector is heavier (13000 tones) but smaller (15m × 22m), thus, the name *"compact"*. Because of materials used, the ATLAS detector, compared with the CMS detector, has a more sensitive hadron calorimeter (thus, a better jet resolution) but a less sensitive electromagnetic calorimeter (thus, a worse e/γ resolution). The ATLAS inner detector is surrounded by a 2T magnetic field, while the CMS one - by 4 T magnetic field. That means the CMS inner detector has a better momentum resolution but restricts the design of

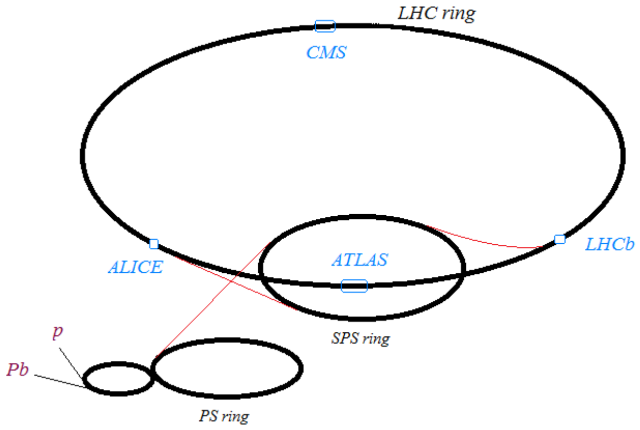

Figure 1: LHC ring and detectors .

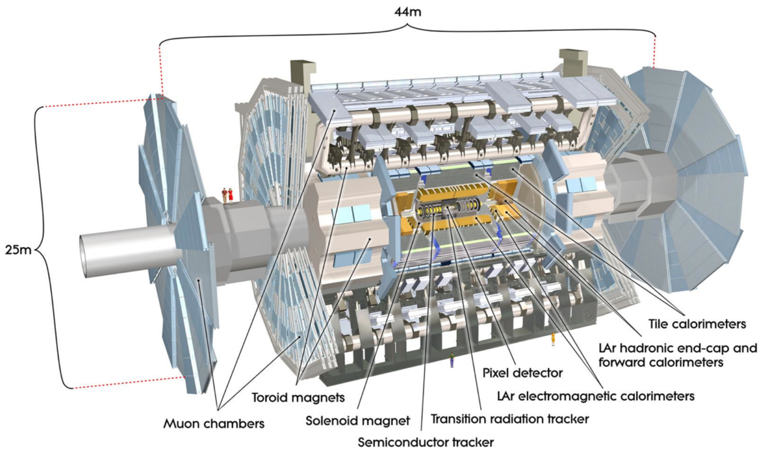

Figure 2: ATLAS detector layout [9].

other components. The research scopes of the ATLAS and the CMS spread on the test of the SM and searching for new physics (beyond the SM): precision measurements of particle parameters and properties, search for the Higgs boson, extra dimensions, supersymmetry, dark matter, etc. Each of these collaborations is participated by more than 3000 scientists and engineers from more than 170 institutions in about 40 countries. Here, as an example, we will make a description of the ATLAS detector. More information of the ATLAS and the CMS detectors and a detailed comparison between them can be got from [10].

As an LHC detector, the ATLAS detector is a complex research facility containing many parts with different functions (see its layout in Fig. 2). This detector has four main components which are ever-larger concentric cylinders, namely, the inner detector (ID), the calorimeters (CM's), the muon spectrometer (MSM) and the magnet systems (MS), surrounding the proton beam axis. Without going to physical and technical details, let us recall general structures and functions of these components.

The ID consisting of three high-resolution parts (the pixel detector, the semi-conductor tracker and the transition radiation tracker (TRT)) used to track and identify charged particles, is the innermost component of the ATLAS detector, surrounded by a solenoidal superconducting magnet system and surrounding the interacting point at the centre where collisions of proton beams take place. The ID measures positions and momenta of charged particles at the pseudo-rapidity range $|\eta| < 2.5$ (in which the TRT covers the range $|\eta| < 2.0$).

The function of the CM's surrounding the ID is to measure energies of (easily stopped) particles by absorbing these energies. This component of the ATLAS detector is divided into two parts: the electromagnetic calorimeter (EC) and the hadronic calorimeter (HC). The EC measures with high precision energies and locations (including trajectories) of particles sensitive to electromagnetic interaction such as photons and charged particles. The HC is designed to measure the energies of those particles sensitive to the strong interaction. It has no high precision as the EC but it can measure the particles at the range $|\eta| < 4.9$, primarily hadrons, which the EC cannot catch.

The MSM is the outermost layer of the ATLAS detector. It is a very large system surrounding the CM's and tracking outgoing muons which are the only detectable particles not stopped by the CM's. The MSM measures the paths of muons and their momenta with a very high precision. It is composed from three parts: a set of large superconducting toroidal magnets, a set of chambers tracking with high spatial precision the outgoing muons, and a set of chambers triggering particles with high time-resolution. The MSM tracks muons at the range $|\eta| < 2.4$ (triggering chambers) and $|\eta| < 2.7$ (tracking chambers).

The MS around the ID and the MSM are used to produce appropriate magnetic fields to bend trajectories of (charged) particles so that their momenta and charges can be determined. The solenoidal magnets, surrounding the ID, can produce 2 Tesla magnetic fields with a peak at 2.6 T, while the magnetic fields produced by the toroidal magnets around the MSM are 0.5 T (by the barrel coils) and 1 T (by the end-cap coils).

For a summary and a general imagination, a simplified view on the structure of the ATLAS detector and how a particle can be detected in the ATLAS detector is shown in Fig. 3 (see more in [8, 9, 10]).

With its very large and extremely fine structure, the ATLAS (along with the CMS) could detect for the first time a new boson which now, after a number of more precise investigations of its masses, spin-parity (J^P) and other production and decay information, can be almost identified with the long-sought standard model Higgs boson. It is a scalar particle having a mass of about 125 GeV, $J^P = 0^+$ and coupling to gauge bosons and fermions (quarks and leptons) as expected by the SM. These investigations have been done on the base of the analysis of the data collected in 2011 (for $\sqrt{s} = 7$ keV) and 2012 ($\sqrt{s} = 8$ keV). Now, with high confidence and for convenience we can call hereafter the new boson the Higgs boson.

3. Searching for the Higgs boson: Why and How ?

As mentioned above, one of the missions of ATLAS and CMS is to search for the Higgs boson which can be treated as the heart of the symmetry breaking mechanism giving masses to particles. It is very important because, for example, the fact that the gauge bosons (W and Z) get masses makes the weak interaction short-ranged, otherwise, the structures like atoms, thus the Universe, could not be formed, and many processes in the Nature such as the reactions

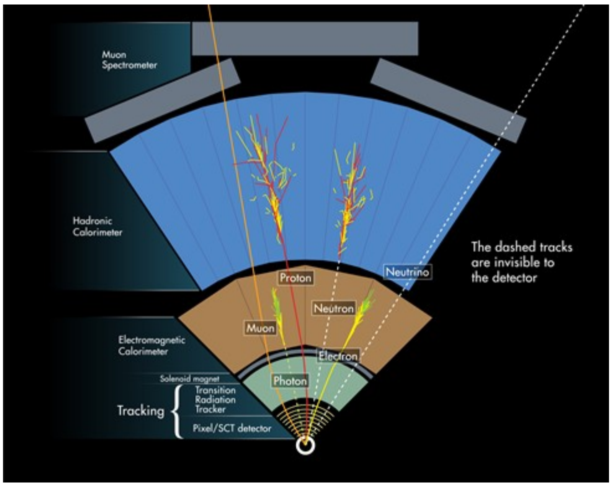

Figure 3: General structure of the ATLAS detector and particle traces [9].

on the Sun, making, in particular, the life on the Earth possible, could not occur. If the Higgs boson does not exist one must work out another symmetry breaking scheme or to deal with another mechanism to generate masses of particles (there have been such attempts but we do not discuss them here). The new boson is also the first real example of an existing fundamental scalar and it is believed to play an important role in particle physics and cosmology. Therefore, the existence or the nonexistence of the Higgs boson may decide the fate of the SM and other theories and models. All that explains why the Higgs boson has been one of the most sought particles for nearly 50 years and its discovery could be classified by some people as one of the most remarkable and important scientific discoveries in the last 100 years. Until the discovery of the Higgs boson the belief in its existence has increased over time as more and more predictions of the SM have been experimentally confirmed. This belief gave a strong motivation for searching for the Higgs boson and, therefore, for building the LHC.

To identify a particle it is important to determine all its basic characteristics including its mass which may be a priori estimated by a theory or constrained by some conditions. For the Higgs boson (H) until its discovery, different theoretical constraints and experimental results (precision measurements) had established several possible ranges of its mass (m_H). In the framework of this short report we do not discuss (because of a limited space) Higgs-type bosons in physics beyond the SM as our topic here is to see if the new boson discovered two years ago by ATLAS and CMS is the Higgs boson of the SM.

Theoretically, the Higgs boson mass, or simply, the Higgs mass, which is one of the fundamental parameters of the SM to be determined (experimentally), cannot be directly predicted by the SM but it can be constrained by, for example, the known SM parameters including masses of other particles such as the top quark and the gauge boson W (or Z). The validity of the SM up to the Planck scale requires the Higgs mass $m_H \leq 180$ GeV (triviality bound) [11], while the unitarity constraints [12, 13, 14] put an upper bound of the Higgs mass at around 1 TeV. The Higgs mass is also bounded from below at about 130 GeV (stability bound) [15] when the stability of the Higgs potential is required. If a metastable electroweak vacuum is allowed the lower bound may become smaller, at about 115 GeV [16]. Taking all said above into account, the Higgs mass 125 GeV is far from the triviality bound (that means there is no need of beyond SM physics until the Planck scale) but on the edge of the vacuum stability-instability.

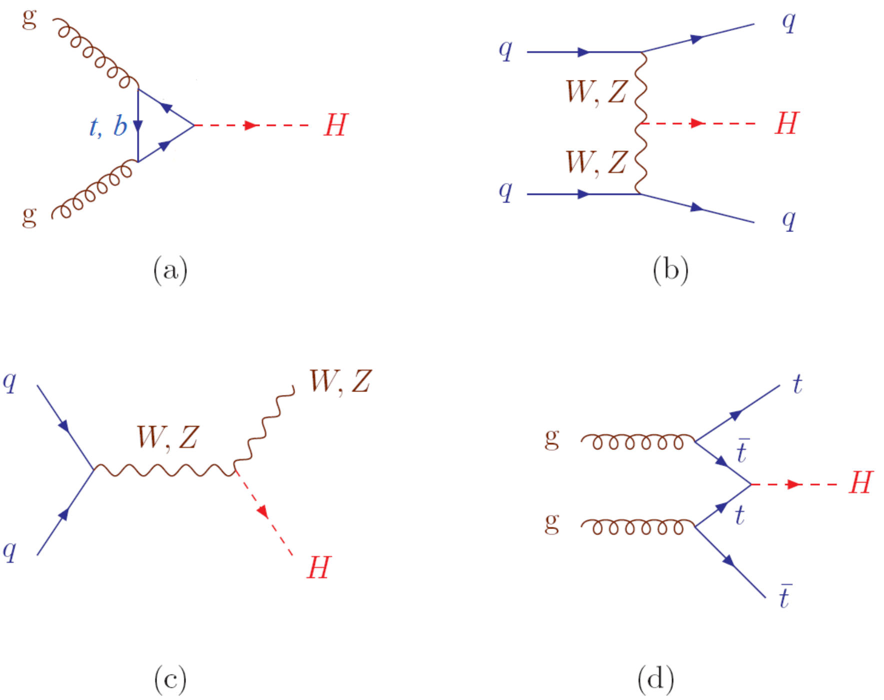

Figure 4: Higgs production diagrams: (a) *gluon fusion*, (b) *W/Z fusion*, (c) *Higgs strahlung*, (d) *top fusion*.

Experimentally, the Higgs mass can be determined indirectly by precision measurements, or "measurements" for short, of electroweak parameters such as the masses of gauge bosons, the top quark mass, Fermi constant, etc., or directly via reconstructing the Higgs mass from its decays. Different collaborations have made measurements to estimate the limits of the Higgs mass which in general have been so far consistent with each other and with the SM. Here we will briefly recall only some results before 4 July 2012 when the Higgs boson's discovery was announced (see more precise information in, for example, [17]). The measurements establish or exclude ranges for the mass of a possible Higgs boson. The lower bound of the Higgs mass established after LEP2 was at about 114.4 GeV [18], while its upper bound given by measurements at LEP, Tevatron and SLC was 152 GeV [19]. The D0 and CDF collaborations at the Tevatron derived the possible Higgs mass range 115 GeV $< m_H <$ 140 GeV [20]. The combined results [21] from LEP, D0 and CDF put the possible Higgs mass between the range 115 GeV $< m_H <$ 135 GeV. Results obtained shortly before 04 July 2012 by the ATLAS and the CMS gave a Higgs mass range around 115 GeV $< m_H <$ 130 GeV [22, 23]. The measurements done have given a more and more narrow range of a possible Higgs mass until reaching the final value around 125 GeV which is slightly below the stability bound.

At the LHC the Higgs boson could emerge from a gluon fusion or a weak-gauge-boson (W/Z) fusion or as a production associated with a gauge boson (*Higgs strahlung*) or with top quarks (*top fusion*) among which the gluon fusion followed by the gauge-boson fusion, is the dominant process [17, 24, 25, 26] (see Fig. 4 for Feynman diagrams of these processes). The Higgs boson with a very short life time (of the order $10^{-22}s$ for a mass around 125 GeV) will decay imme-

***H* decay channel**	**Branching ratio**	**Relative uncertainty** (%)	**Mass resolution** (%)
$H \to \gamma\gamma$	2.28×10^{-3}	+5.0 −4.9	1-2
$H \to ZZ\ (\to 4l)$	2.64×10^{-2}	+4.3 −4.1	(1-2)
$H \to WW\ (\to l\nu l\nu)$	2.15×10^{-1}	+4.3 −4.2	(20)
$H \to \tau\tau$	6.32×10^{-2}	+5.7 −5.7	15
$H \to bb$	5.77×10^{-1}	+3.2 −3.3	10

Table 1: Sensitive Higgs decay channels at the LHC for $m_H = 125$ GeV [17].

diately into lighter particles. According to the SM its possible decays could include [1] $H \to \gamma\gamma$, $H \to ZZ \to 4l$, $H \to WW \to l\nu l\nu$, $H \to \tau\tau$, $H \to bb$, etc., with branching ratios (BR's), relative uncertainties and mass resolutions given in Table 1 for the Higgs mass $m_H = 125$ GeV [17, 24, 25, 26]. A choice of an optimal channel for the Higgs boson search depends on its sensitivity which in turn depends on several factors such as the cross section of the Higgs production, the branching ratio of the Higgs decay, the resolution of the reconstructed mass, the selection efficiency and the signal-to-background ratio (S/B). All these factors strongly depend on a Higgs mass (or mass range) chosen. Thus, for a given Higgs mass (or mass range), there is/are some channels more preferable for the Higgs search.

The Higgs mass measurements by ATLAS and CMS have been done on the base of the invariant mass reconstruction from the decay channels $H \to \gamma\gamma$ and $H \to ZZ \to 4l$, where $l = e$ or μ. The channels $H \to \gamma\gamma$ and $H \to ZZ \to 4l$ have no large cross sections but they are preferred because their reconstructed final states have high mass resolutions (1-2%) and clean signals (due to the construction of the electromagnetic calorimeter and the muon spectrometer). The use of the other three channels is not excluded but it has the following difficulties. The channel $H \to WW \to l\nu l\nu$ has a relatively large branching ratio but the Higgs mass resolution is very low (20%) because of neutrinos present in the final states (see Table 1). The channels $H \to \tau\tau$ and $H \to bb$, because of a low mass resolution (15% and 10%, resp.) and large backgrounds, have no clean signals. These channels, however, are important in investigating the couplings of the Higgs boson to fermions (see below).

For every measurement, a key problem is to separate the true signal events from the fake, or the background, ones. It can be solved by an estimation of the expected background composition

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[1] Hereafter, for short, formal notations like $H \to ZZ$, $H \to WW$, $H \to \tau\tau$ and $H \to bb$ are used but they could be replaced by $H \to ZZ^*$, $H \to W^+W^-$, $H \to \tau^+\tau^-$ and $H \to b\bar{b}$, resp.

and yield in the process measured via a Monte Carlo simulation normalized to the SM theoretical predictions (usually for electroweak-related processes) or by using data (usually for QCD-related processes). A background can be irreducible or reducible (see, for example, [6, 27], for more details). The first type of backgrounds consists of those events with the same final states as those of the signals, while the second one consists of those events with final states misunderstood as the true ones of the signals. As said above, the decays $H \to \gamma\gamma$ and $H \to ZZ \to 4l$ are the "golden" channels for hunting the Higgs boson [6, 7]. Here we briefly count the background (see Fig. 5 and Fig. 6 for a quantitative imagination) in these two Higgs decay channels (while for other channels, see, for example, [27]).

For the channel $H \to \gamma\gamma$, the irreducible background represents the genuine photon pairs produced in Born- ($qq \to \gamma\gamma$), box- ($gg \to \gamma\gamma$) and quark bremsstrahlung ($qg \to q\gamma \to \gamma\gamma$, $gg \to jj\gamma\gamma$) processes, where j denotes a jet. The reducible background for this channel represents γ-jet and jet-jet events in which one or two jets are misidentified as photons, or appear in the decay $Z \to ee$ where the electrons are misidentified as photons. For the channel $H \to ZZ \to 4l$, the irreducible backgrounds come from ZZ^* and $Z\gamma^*$ continuum productions including those in which one of the Z decays into a pair of τ leptons which subsequently decay into lighter leptons. The reducible backgrounds for this channel consist of $4l$ productions from tt and Z+jets (mainly Zbb for the final states $ll + \mu\mu$). More detailed description of the backgrounds for these channels and their estimation can be found in [6] for ATLAS (and similarly, for CMS [7]).

Using the data collected in 2011 and 2012 from proton-proton collisions at the center-of-mass energy $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV with an integrated luminosity of 4.5 fb^{-1} and 20.3 fb^{-1}, respectively, ATLAS found the following values of the Higgs mass (see Fig. 5 and Fig. 6):

$$m_H = 125.98 \pm 0.42(\text{stat.}) \pm 0.28(\text{sys.})\ \text{GeV} = 125.98 \pm 0.50\ \text{GeV}, \tag{1}$$

for the channel $H \to \gamma\gamma$ [28, 29] and

$$m_H = 124.51 \pm 0.52(\text{stat.}) \pm 0.06(\text{sys.})\ \text{GeV} = 124.51 \pm 0.52\ \text{GeV}, \tag{2}$$

for the channel $H \to ZZ \to 4l$ [28, 30]. The difference between the mass measurements at the two channels has about 2σ significance or about 4.8% probability. The combined result [28] obtained at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV with an integrated luminosity of 25 fb^{-1} is

$$m_H = 125.36 \pm 0.37(\text{stat.}) \pm 0.18(\text{sys.})\ \text{GeV} = 125.36 \pm 0.41\ \text{GeV}. \tag{3}$$

For the signal strengths, the measurements by ATLAS for the above discussed Higgs decays are in good agreement with the SM: $\mu = 1.17 \pm 0.27$ (for $H \to \gamma\gamma$) [29], $\mu = 1.44^{+0.40}_{-0.33}$ (for $H \to ZZ$) [30] and $\mu = 1.08^{+0.22}_{-0.20}$ (for $H \to WW$) [31]. It is expected to have more precise measurements in the coming time [31], specially, after the start of the second run of the LHC in the beginning of 2015 [32].

The next step in comparing the new boson with the Higgs boson is to check if it also couples to fermions, as predicted by the SM. If the coupling Htt of the Higgs boson to the top quarks can be studied via the top fusion mentioned above, the couplings of the Higgs boson to other, specially, down-type, fermions can be studied via the Higgs decays into these fermions. The ATLAS (also CMS) has made this study on the potential decay channels $H \to \tau\tau$ and $H \to bb$ for $\sqrt{s} = 7$ TeV (4.5 fb^{-1} and 4.7 fb^{-1}, resp.) and $\sqrt{s} = 8$ TeV (20.3 fb^{-1}) [33, 34]. Other its decay channels into fermions are either low ranked because of small BR's (e.g., $H \to \mu\mu$) or kinematically impossible ($H \to tt$). For the channel $H \to bb$ and $m_H = 125.36$ GeV, it

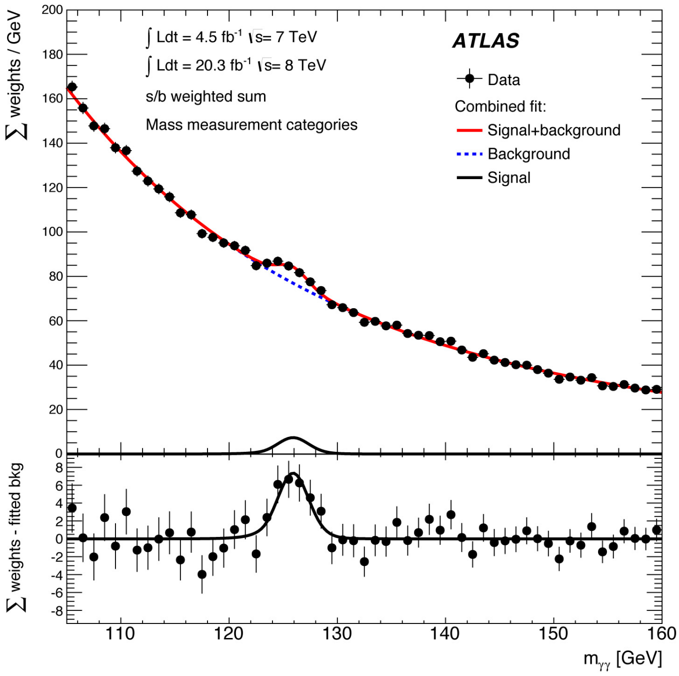

Figure 5: An invariant mass ($m_{\gamma\gamma}$) spectrum in decay $H \to \gamma\gamma$ for the combined $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data and the mass range $105 - 160$ GeV [28, 29].

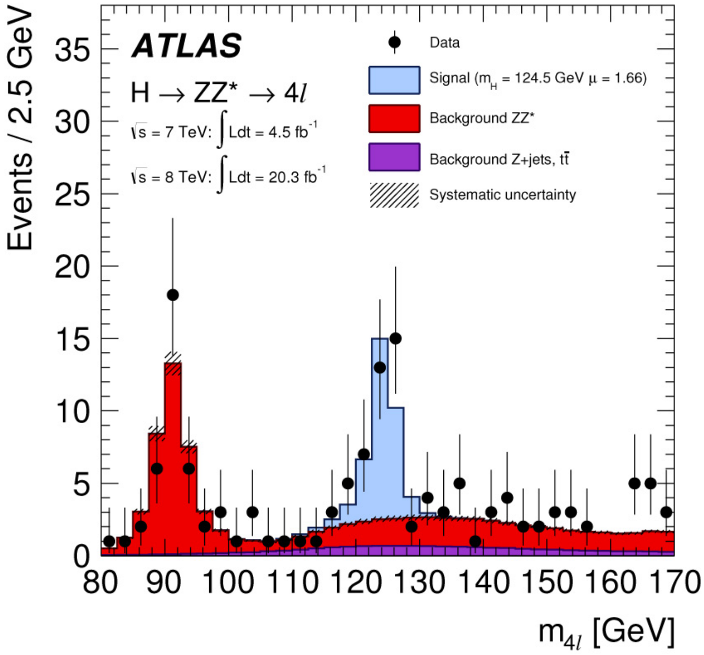

Figure 6: An invariant mass (m_{4l}) distribution in decay $H \to ZZ^* \to 4l$ for the combined $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data and the mass range $80 - 170$ GeV [28, 30].

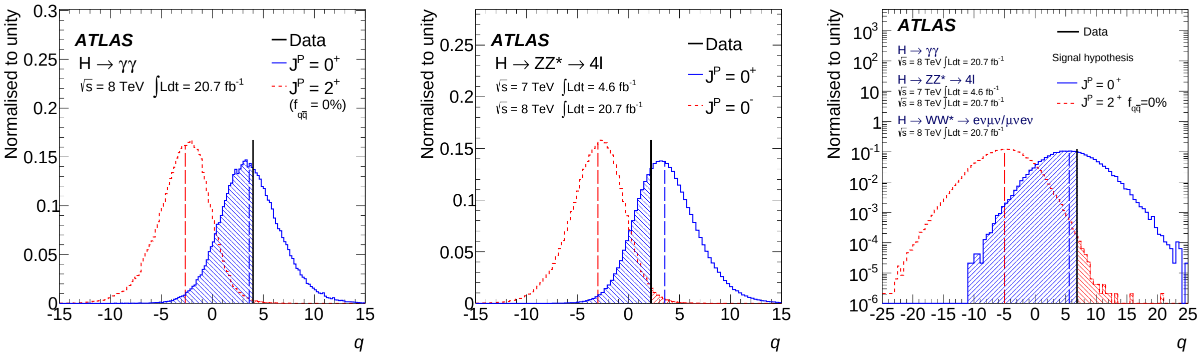

Figure 7: Examples for expected distributions of the logarithm of the ratio of profiled likelihoods (q), under the $J^P = 0^+$ hypothesis in comparison with other spin-parity hypotheses (the observed values are shown by the vertical solid lines) [35, 36].

has been found that the observed deviation from the background is only 1.4σ (compared with the expected 2.6σ) and the signal strength is $\mu = 0.52 \pm 0.32(\text{stat.}) \pm 0.24(\text{syst.})$ [33]. For the channel $H \to \tau\tau$ the results are more convincing as the observed significance of an excess of events over the background is 4.5σ (compared with the expected 3.5σ) and the signal strength is $\mu = 1.42^{+0:44}_{-0.38}$ [34]. The combined results $\mu = 1.30 \pm 0.12 \pm 0.10 \pm 0.009$ for all channels is in quite good and in agreement with those from CMS [32].

To check if the newly discovered particle is really the Higgs boson it is also necessary to investigate its spin and parity (spin-parity, J^P). First of all, decaying into a neutral pairs of gauge bosons, e.g., two γ's, this particle must be a neutral boson with a spin different from 1. It remains to see if it has a spin-0 or spin-2. This problem has been investigated by ATLAS via the decay channels $H \to \gamma\gamma$, $H \to ZZ \to 4l$ and $H \to WW \to l\nu l\nu$ at $\sqrt{s} = 8$ TeV (20.7 fb^{-1}) and the channel $H \to ZZ \to 4l$ at $\sqrt{s} = 7$ TeV (4.6 fb^{-1}). These investigations (see, for example, Fig. 7) have shown a strong evidence for the scalar (spin-0 and positive-parity) nature, $J^P = 0^+$, of the new boson, as expected for the Higgs boson [35, 36].

Conclusions

We have made a brief review on the progress of searching for the Higgs boson and on the main achievements of the ATLAS collaboration in investigating the boson they discovered with the CMS collaboration over two years ago. It has been shown that the newly discovered boson has a mass about 125 GeV and a spin-parity 0^+. Couplings of the new boson to other bosons and fermions have been also checked in high precision and consistence with the standard model (in combination with the results from CMS). These couplings are very important as they give rise to particle masses. The results obtained allow the new boson to be almost identified with the Higgs boson of the standard model. More discussions on spontaneous symmetry breaking and searching for the Higgs boson can be found in, for example, [37] and references therein.

The CMS collaboration has done similar investigations and has obtained results consistent with those by the ATLAS collaboration but in the framework of this short report we constrain ourselves mainly to the ATLAS investigations. By the same reason, we cannot either discuss physics beyond the standard model in which there may be no or more than one Higgs fields, thus, Higgs bosons, with different masses and properties.

Acknowledgments

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