HIGGS BOSON IN THE STANDARD MODEL AND OTHER HIGHLIGHTS OF SM MEASUREMENTS WITH THE LHC*

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In July 2012 the discovery of a new boson with a mass of about 125 GeV and properties in agreement with those expected for the Higgs boson in the Standard Model was announced. In this note, we review the results of the search for the Higgs boson and the study of its properties performed with the proton–proton collision data recorded by the ATLAS and CMS detectors at the LHC in 2011 and 2012, corresponding to an integrated luminosity of 5 fb^{-1} and 20 fb^{-1} per experiment at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, respectively. The presented study confirms the Higgs-like nature of the new boson, with a signal rate consistent with the expectation of the Standard Model, and with the scalar nature of the new boson clearly favoured. In addition, we present studies of the diboson production as an example of a precise electroweak measurement at the LHC. The result, being in agreement with standard model predictions, is interpreted in terms of constraints on anomalous triple-gauge boson couplings.

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1. Introduction: A new boson

After the discovery of a new standard-model-like Higgs boson announced by the ATLAS and CMS collaborations in July 2012 [1, 2], it became essential to establish the nature of this new boson, *i.e.* observe its decay modes, measure its mass and couplings, and finally probe its spin-parity. This goal is achieved by combining information from exclusive analyses sensitive to different production processes and decay modes of the Higgs boson. A study

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of the Higgs boson is one of the main goals of the physics program of the ATLAS and CMS collaborations, and constitutes the main subject of this report. However, it is only a portion of a wide set of analyses performed by LHC collaborations in order to probe the Standard Model (SM). Therefore, we decided to report here, as a selected highlight of SM studies, results of a measurement of the diboson production and its interpretation in terms of constraints on anomalous triple-gauge boson couplings.

2. LHC and experimental challenges

The rich physics program of the ATLAS and CMS experiments, in particular, the discovery of the Higgs boson, was possible thanks to an excellent performance of the LHC collider, and both ATLAS [3] and CMS [4] detec-

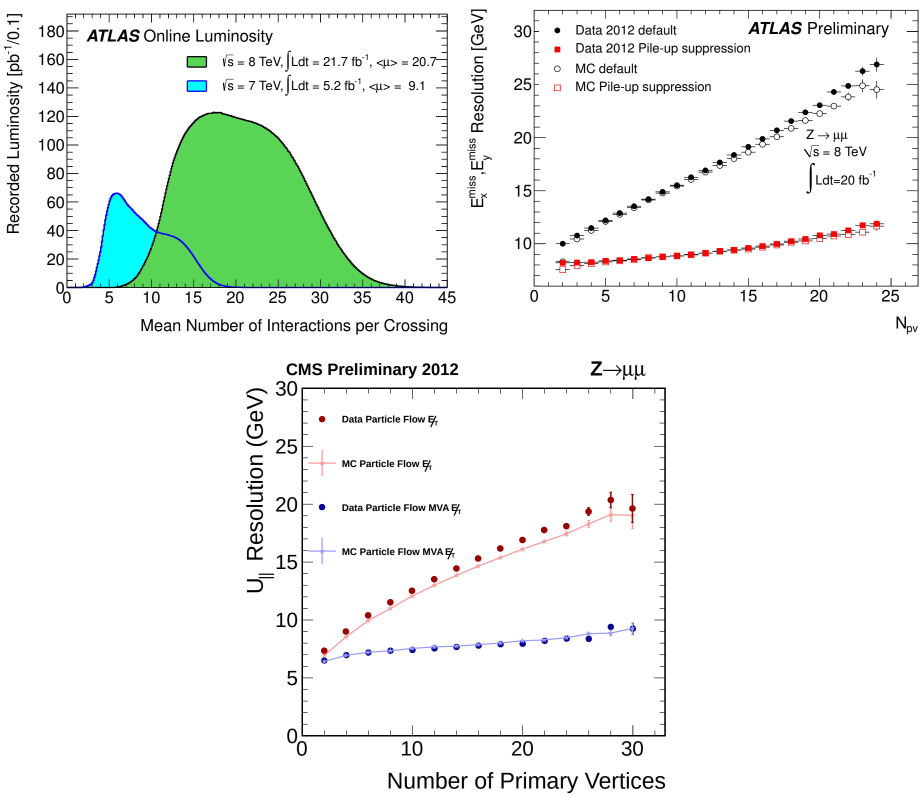


Fig. 1. Luminosity-weighted distribution of the mean number of interactions per crossing for the 2011 and 2012 data (top left); Resolution of x, y (parallel, $U_{||}$) components of $E_{\mathrm{T}}^{\mathrm{miss}}$ before and after pileup suppression as a function of the number of primary vertices in real and simulated $Z \to \mu\mu$ events in ATLAS (top right) and CMS (bottom).

tors. The detectors recorded about 95% of delivered collision data, among which about 90% were certified and used to obtain results reported here. The resulting data sample corresponds to an integrated luminosity of about $5\,\mathrm{fb}^{-1}$ and $20\,\mathrm{fb}^{-1}$ per experiment at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, respectively. Along the way, the experiments had to establish methods to cope with a high number of multiple collisions per beam crossing (pileup), which occurs at high luminosity. An average number of pileup amounted to about 9 and 21 interactions in 2011 and 2012, respectively, as shown in Fig. 1 (top left). Resolution of missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$ as a function of the number of primary vertices is presented in Fig. 1 (top right for ATLAS and bottom for CMS) as an example of a successful pileup mitigation.

3. Higgs boson production and decay

The SM Higgs boson can be produced at the LHC in various processes, among which the most important is the gluon fusion process with cross section of about 19(15) pb, followed by the vector boson fusion (VBF) and associated production VH ($V = W, Z$) modes with cross section of about 1.6(1.2) pb and 1.1(0.9) pb, respectively, for a 125 GeV Higgs boson at $\sqrt{s} = 8(7)$ TeV [5–7]. The two latter processes, despite of being of the order of magnitude weaker than gluon fusion, are important in the Higgs boson analyses thanks to distinct signatures: forward jets in the case of VBF or leptons and $E_{\mathrm{T}}^{\mathrm{miss}}$ from V decays in the case of VH, which allow to improve a signal-to-background ratio (S/B). The structure of decay modes of the SM Higgs boson with mass $m_H = 125$ GeV is very rich with branching fraction for dominating modes of 58%, 22%, 6.3%, 2.6%, 0.23%, respectively, for $b\bar{b}$, WW, $\tau\tau$, ZZ, $\gamma\gamma$. Depending on the specific production process and decay mode, the resulting signal-to-background ratio (and thus, sensitivity) can vary dramatically. Therefore, one can order Higgs analyses basing on their importance on high, medium and low sensitive ones as discussed in the following sections.

3.1. Clearly-seen Higgs: High-sensitivity channels

The most sensitive channel for a Higgs boson discovery and then first measurements of its properties is $H \to ZZ \to 4\ell$ ($\ell = e, \mu$). Four isolated leptons from the Higgs boson decay show up as a narrow mass peak, with the resolution of 1–2%, on top of a locally flat background dominated by the nonresonant ZZ production, Fig. 2 (top left). Kinematics of this channel are fully reconstructed which allows to express the full matrix element of the process in terms of three decay angles and the masses of two lepton pairs. In addition, the single-resonant four-lepton production at 91 GeV ($Z \to 4\ell$) serves as a standard candle. A signal of the Higgs boson is observed by both the ATLAS and CMS experiments for a mass of about 126 GeV with a significance yielding 6.6 standard deviations, σ, (4.4σ expected) in ATLAS [8] and 6.7σ (7.2σ expected) in CMS [9]. A higher sensitivity of the CMS analysis was obtained thanks to higher efficiency for low-$p_{\rm T}$ leptons, exploiting angular distributions distinguishing between the signal and background, and better muon momentum resolution due to high magnetic field. The signal strength defined as a ratio of the measured cross section of the Higgs boson to the SM one, $\mu = \sigma/\sigma_{\rm SM}$, amounts to $\mu = 1.43^{+0.40}_{-0.35}$ (ATLAS) and $\mu = 0.91^{+0.30}_{-0.24}$ (CMS).

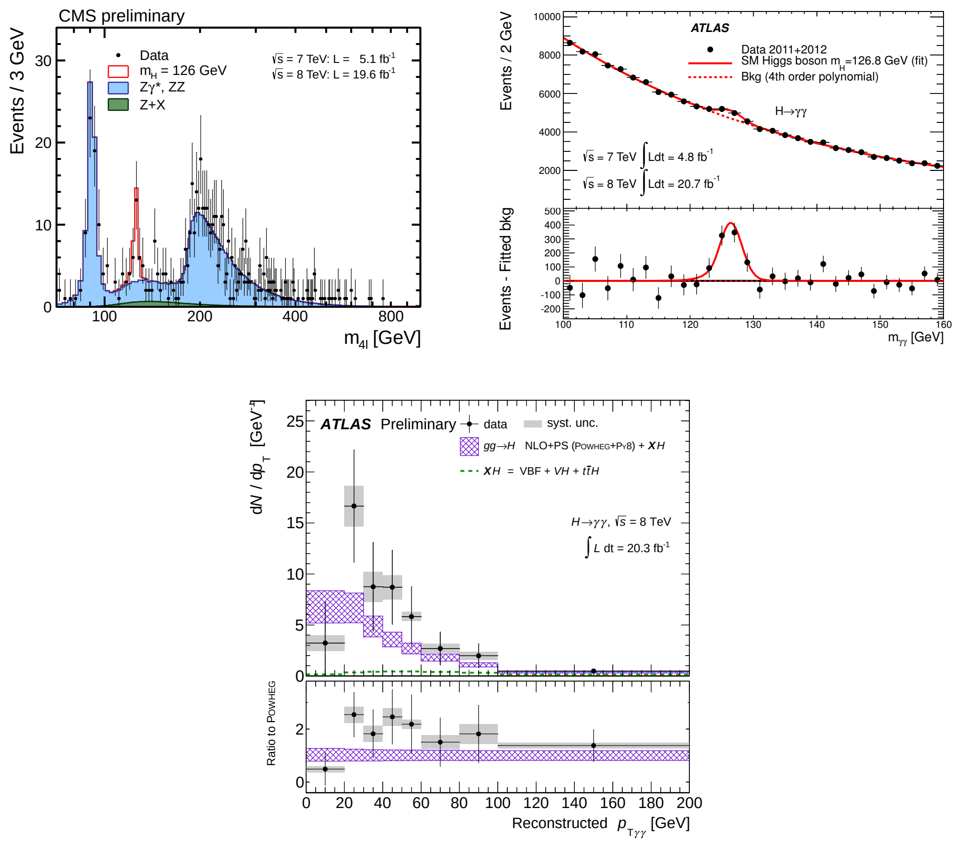


Fig. 2. Distribution of the four-lepton mass in CMS (top left); Distribution of the diphoton mass in ATLAS (top right); $p_{\rm T}$ spectrum of the Higgs boson in the $H \to \gamma\gamma$ process in ATLAS (bottom).

The second sensitive channel is $H \to \gamma\gamma$ characterised by two high-$p_{\rm T}$ isolated photons with a narrow mass distribution. On the contrary, the diphoton mass distribution for the background is steeply falling, Fig. 2 (top right).

It allows to evaluate the background from data without reference to simulation. In this channel, the Higgs boson signal is observed with a significance of 7.4σ (4.1σ expected) by ATLAS [10], and 3.2σ (4.2σ expected) by CMS in the main multivariate analysis and 3.9σ (3.5σ expected) in a cross-check analysis with simpler cut-based selection (the two being consistent within 1.6σ) [11]. The signal strengths are $\mu = 1.55^{+0.33}_{-0.28}$ and $\mu = 0.78^{+0.28}_{-0.26}$, respectively, for ATLAS and CMS.

In addition, ATLAS measured several differential cross sections in the $H \to \gamma\gamma$ channel that are in a good agreement, within still large experimental and theory uncertainties, with predictions of the Standard Model [12]. The p_{T}-spectrum of the Higgs boson is presented in Fig. 2 (bottom) as an example.

The last of the high-sensitivity channels at the LHC is $H \to WW \to \ell\nu\ell\nu$ with two high-p_{T} leptons and significant $E_{\mathrm{T}}^{\mathrm{miss}}$. Due to undetected neutrinos, the Higgs mass cannot be reconstructed in this channel, leading to rather poor sensitivity on its exact value. However, thanks to its high branching fraction, the channel provides an excellent confirmation of the observation in the high-resolution channels. The dilepton mass and the transverse mass of dilepton-plus-$E_{\mathrm{T}}^{\mathrm{miss}}$ system are two of the most powerful variables to distinguish between the signal and background. They also present some sensitivity on the Higgs mass with resolution of about 25%. Both LHC experiments observe a significant excess of events above background expectation consistent with the Higgs boson. The observed significance is 3.8σ (3.8σ expected) in ATLAS [13] and 4.0σ (5.1σ expected) in CMS [14], corresponding with the signal strength of $\mu = 0.99^{+0.31}_{-0.28}$ and $\mu = 0.76 \pm 0.21$ for ATLAS and CMS, respectively.

3.2. Almost-seen Higgs: Medium-sensitivity channels

Other channels showing already some sensitivity on the Higgs boson are fermonic ones: $H \to b\bar{b}$ and $H \to \tau\tau$. Both of them are characterised by a relatively high branching fraction, allow to reconstruct the Higgs boson mass with resolution of 10–20% and suffer from quite high background. Therefore, a special strategy is employed in searches for the fermionic decay modes. The $H \to b\bar{b}$ search explores the VH associated production, while the $H \to \tau\tau$ one uses a complex event classification to enhance the impact of events produced in the VBF and VH processes, but also in the gluon fusion process with additional jets, which increases the signal-to-background ratio. In the $H \to \tau\tau$ analyses, both experiments use an estimate of a full $\tau\tau$ invariant mass calculated using a likelihood based method taking as input the kinematics of visible decay products and $E_{\mathrm{T}}^{\mathrm{miss}}$. It gives better separation between H and Z than the mass of the visible $\tau\tau$ system.

The ATLAS experiment reports only an insignificant excess of events above background expectation in the $VH(b\bar{b})$ channel, which corresponds to the signal strength of $\mu = 0.2^{+0.7}_{-0.6}$ and an exclusion limit at 95% confidence level (C.L.) of $\mu < 1.4$ (1.3 expected) at $m_H = 125\,\mathrm{GeV}$ [15]. This result is compatible with both the background only and signal+background hypotheses. The $VZ(b\bar{b})$ production is clearly visible with a significance of 4.8σ, Fig. 3 (top left).

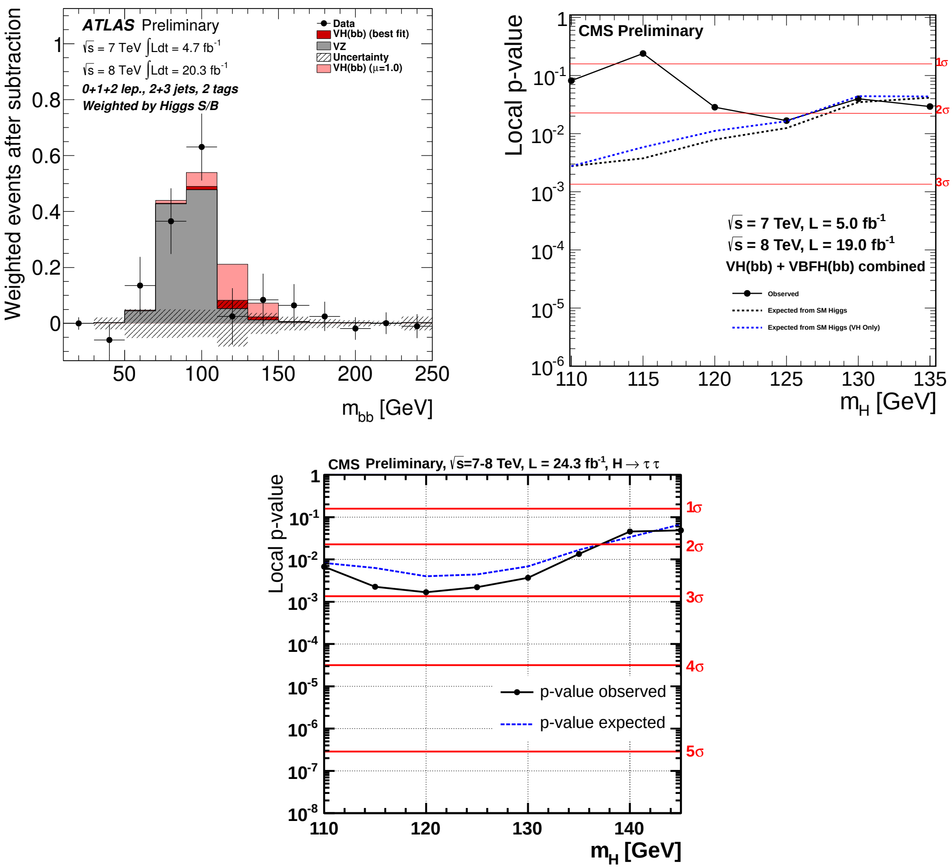


Fig. 3. Background-subtracted distribution of the $b\bar{b}$ mass in ATLAS (top left); The expected (dashed line) and observed (solid line) significance of the combined $VH(b\bar{b})$ and VBF $H \to b\bar{b}$ signal in CMS (top right); The expected (dashed line) and observed (solid line) significance of the $H \to tt$ signal in CMS (bottom).

The corresponding analysis performed by CMS sees an excess of events over expected background with a significance of 2.1σ (2.1σ expected) giving the signal strength $\mu = 1.0 \pm 0.49$ [16]. For reference, the $VZ(b\bar{b})$ process is observed with a significance of 5.7σ.

The CMS experiment has also performed a separate search for $H \to b\bar{b}$ produced via VBF [17]. This search reached sensitivity of about three times the cross section of the 125 GeV SM Higgs boson. It improves the expected sensitivity of the $H \to b\bar{b}$ decay by about 10% when combined with $VH(b\bar{b})$, while observed sensitivity stays unchanged, Fig. 3 (top right).

The ATLAS $H \to \tau\tau$ search has not been recently updated and is still based on 4.6 fb^{-1} and 13.0 fb^{-1} of data collected at 7 TeV and 8 TeV, respectively [18]. The significance observed in this analysis amounts to 1.1σ (1.7σ expected) with the measured signal strength $\mu = 0.7 \pm 0.7$.

The CMS experiment performed the $H \to \tau\tau$ analysis with the full 2011+2012 dataset [19]. An excess of events is observed which allows to report an indication of the $H \to \tau\tau$ decay with a significance of 2.9σ (2.6σ expected) and a signal strength $\mu = 1.1 \pm 0.4$, Fig. 3 (bottom).

A combined result of the $VH(b\bar{b})$ and $H \to \tau\tau$ analyses leads to an evidence that the Higgs boson couples to down-type, third generation fermions with a significance of 3.4σ (3.4σ expected) [28].

3.3. To-be-seen Higgs: Rare decays

There is a list of other less sensitive channels which will play an important role in exploration of the Higgs sector when more data is collected. Studies on some of the channels are already started with current data.

One among such channels is a rare decay of $H \to \mu\mu$ providing an unique way to probe the coupling of the Higgs boson to the second generation of fermions. Despite an expected small branching fraction of this decay of 0.02% for $m_H = 125$ GeV limiting sensitivity in this channel with current dataset, first analyses were launched by the ATLAS [20] and CMS [21] collaborations. In a result, limits at 95% C.L. on the signal strength in this channel were set $\mu < 9.8$ ($\mu < 8.9$ expected) and $\mu < 7.4$ ($\mu < 5.1$ expected) in ATLAS and CMS, respectively.

Another interesting rare decay is $H \to \gamma Z$, $Z \to \ell\ell$ with branching fraction of 0.15% at 125 GeV, subsequently suppressed by branching fraction of $Z \to \ell\ell$. This decay, occurring through a loop, provides a complementary way of probing new physics in the Higgs boson decay compared to the $H \to \gamma\gamma$ decay. Both ATLAS and CMS have set limits at 95% C.L. on the signal strength in this channel, which amount to $\mu < 18.2$ ($\mu < 13.5$ expected) in ATLAS [22] and $\mu < 10$ ($\mu < 10$ expected) in CMS [23].

Finally, the $t\bar{t}H$ production mode is intensively searched for. It is a complicated search in a multiobject final state, requiring good understanding of $t\bar{t} + X$ backgrounds, which are not always predicted precisely. Both the ATLAS and CMS collaborations have performed analyses in the $t\bar{t}H(\gamma\gamma)$ channel setting 95% C.L. upper limits on the signal strength of 5.3 (6.4 expected) in ATLAS [24] and 5.4 (5.3 expected) in CMS [25]. In addition, the CMS Collaboration has explored $t\bar{t}H(b\bar{b},\tau\tau)$ channels [26] setting an upper limit on μ of 5.2 (5.3 expected) which combined with $t\bar{t}H(\gamma\gamma)$ gives $\mu < 3.4$ ($\mu < 2.7$ expected).

4. Properties of the Higgs boson

4.1. Mass measurement

The mass of the observed boson, m_H, is measured in two channels with a high mass resolution, $H \to ZZ \to 4\ell$ and $H \to \gamma\gamma$. The combined mass equals $m_H = 125.5 \pm 0.2(\mathrm{stat.}) \pm 0.6(\mathrm{syst.})$ GeV in ATLAS [27] and $m_H = 125.7 \pm 0.3(\mathrm{stat.}) \pm 0.3(\mathrm{syst.})$ GeV in CMS [28]. The CMS mass measurements in both channels are perfectly consistent with each other, while in the ATLAS case there is a 2.4σ tension between them, as shown in Fig. 4.

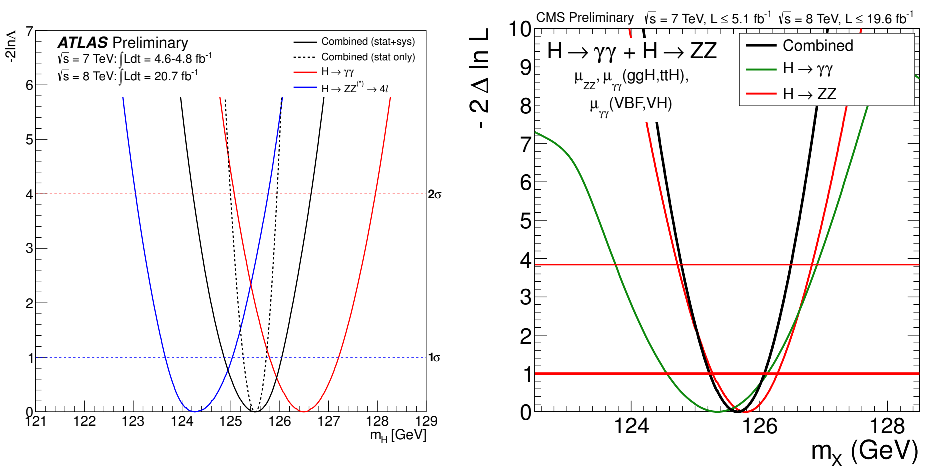


Fig. 4. The profile likelihood ratio $-2\ln L$ as a function of m_H for the $H \to \gamma\gamma$ and $H \to ZZ \to 4\ell$ channels and their combination in ATLAS (left) and CMS (right).

4.2. Couplings

The rate in any combination of production and decay modes of the Higgs boson can be related to the production cross section, and the partial and total widths

$$\sigma \times \mathrm{Br}(ii \to H \to ff) = \frac{\sigma_{ii} \times \Gamma_{ff}}{\Gamma_{\mathrm{tot}}}\,,$$

where ii represents the production mechanism, Γ_{ff} is the partial width into the final state ff and Γ_{tot} is the total width of the Higgs boson. It allows to parametrise measured signal strengths in terms of coupling strength scaling factors $\kappa = g/g_{\rm SM}$, *e.g.* for the $ZH \to b\bar{b}$ process, one can write

$$\begin{aligned}\mu_{ZH\to b\bar{b}} &= \left[\sigma_{ZH} \times {\rm Br}\left(H \to b\bar{b}\right)\right]_{\rm obs} / \left[\sigma_{ZH} \times {\rm Br}\left(H \to b\bar{b}\right)\right]_{\rm SM} \\ &= \left(\kappa_Z^2 \times \kappa_b^2\right) / \kappa_H^2 \,.\end{aligned}$$

By construction, all parameters μ, κ, and $\lambda_{xy} = \kappa_x/\kappa_y$ are equal 1 for the SM Higgs boson. The parameters can be constrained by a simultaneous analysis of the data selected in all exclusive channels accounting for statistical and systematic uncertainties and their correlations. However, as the size of the current dataset is too small to quantify all these parameters, some relation between them are assumed defining specific benchmark models [29]. Both the ATLAS [30] and CMS [28] collaborations performed coupling measurements in this frame. Results summarised in Fig. 5 are in all cases consistent with the SM Higgs boson.

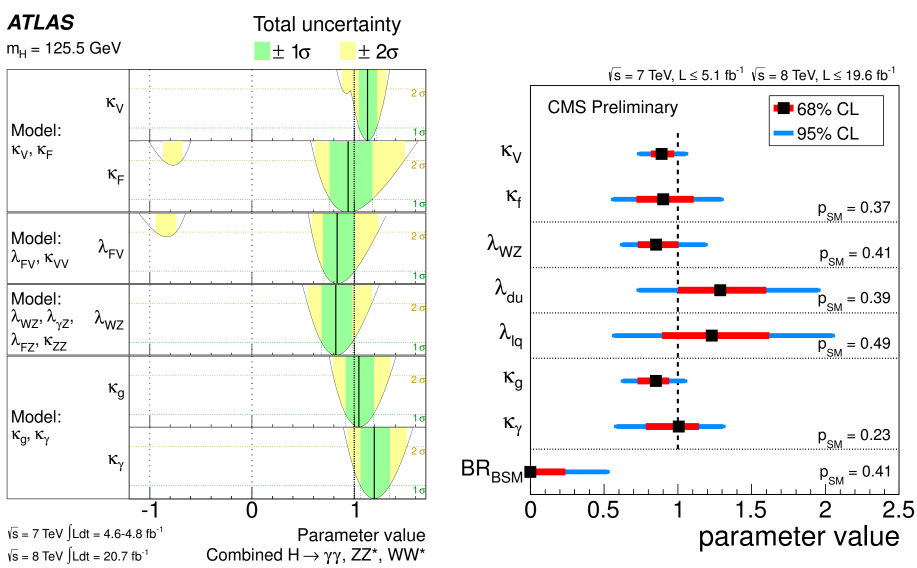


Fig. 5. Summary of the measurements of the coupling scaling factors for a Higgs boson with mass $m_H = 125.5$ GeV for ATLAS (left) and CMS (right). The measurements in the various benchmark models are strongly correlated.

4.3. Spin-parity

In the SM, the Higgs boson is a spin-0 and CP-even particle ($J^{\rm P} = 0^+$). The measurement of spin properties are based on kinematic properties of the three final states $H \to \gamma\gamma$, $H \to ZZ \to 4\ell$ and $H \to WW \to \ell\nu\ell\nu$ independently on the signal (coupling) strengths. Several alternative hypotheses

($J^{\mathrm{P}} = 0^-,\ 1^+,\ 1^-,\ 2^+$) were tested against the SM Higgs boson by the ATLAS [31] and CMS [9, 28] experiments. Summarised results of ATLAS spin-parity tests are shown in Fig. 6 (left). In Fig. 6 (right) there is also presented, as an example, a separation between the 0^- (pseudoscalar) and the 0^+ (scalar) hypotheses with the $H \to ZZ \to 4\ell$ channel in CMS.

All preformed tests of spin-parity favour the SM scalar nature of the new state compared to alternative hypotheses.

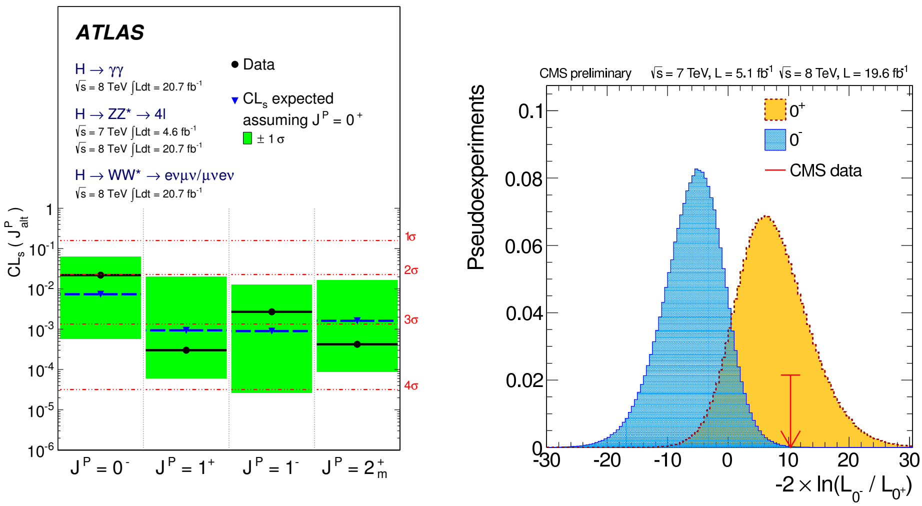


Fig. 6. Expected and observed confidence level for various alternative spin-parity hypotheses with respect to a 0^+ signal with ATLAS (left); Expected and observed test statistic distributions corresponding to 0^- hypothesis compared the 0^+ signal in the $H \to ZZ \to 4\ell$ channel in CMS (right).

5. Diboson production

In the Standard Model, measurements of diboson final states are an excellent test of the electroweak sector at the TeV scale. Any deviation of the diboson cross sections or kinematic distributions from the SM predictions is an indication of anomalous triple-gauge boson couplings (aTGC) and of the existence of new particles. A summary of such cross section measurements performed by the ATLAS and CMS collaborations is shown in Fig. 7. The total diboson production cross sections were found in agreement with the SM predictions within the uncertainties.

The ATLAS and CMS experiments have searched for anomalous triple-gauge boson couplings and found no deviation from the SM values. A set of constraints at 95% confidence level on the aTGCs obtained by ATLAS and CMS compared with those set by LEP and Tevatron experiments are shown in Fig. 8.

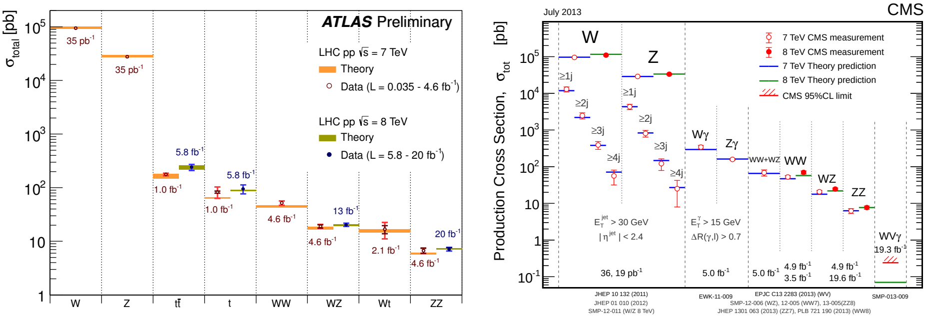
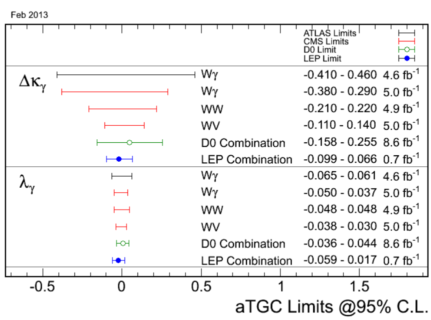
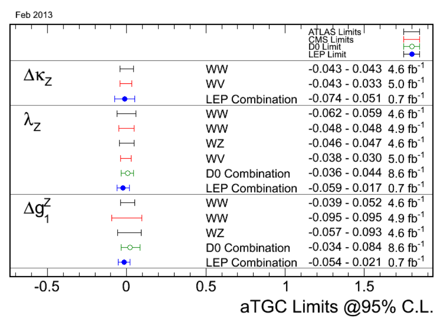


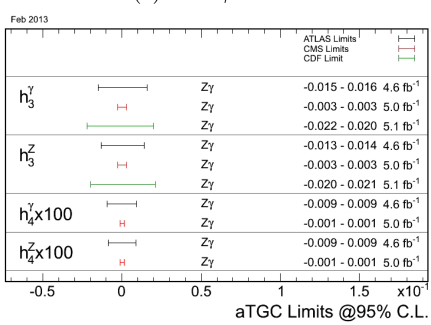
Fig. 7. The diboson cross sections (among other SM production cross sections) compared to their theoretical predictions in ATLAS [32] (left) and CMS [33] (right).



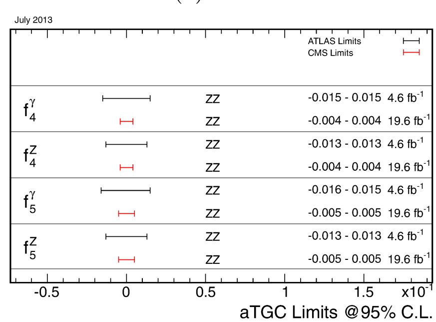
(a) $WW\gamma$ aTGC



(b) WWZ aTGC



(c) $Z\gamma\gamma$ and $ZZ\gamma$ aTGC



(d) $ZZ\gamma$ and ZZZ aTGC

Fig. 8. A summary of limits on anomalous triple-gauge boson couplings (aTSG) at 95% confidence level [34].

6. Summary

An impressive progress in understanding the observed Higgs boson has been made since its discovery just a year ago: it is observed in three bosonic decay modes with a high significance, there is an evidence that it couples to fermions, its mass is known with high precision, and its spin-parity assignment has been tested. All performed tests favour the Standard Model Higgs boson hypothesis, with a signal rate consistent with expectation of the Standard Model, and with the expected scalar nature clearly favoured.

The Standard Model is complete after the Higgs boson discovery and, to date, all measurements agree with its predictions with current, sometimes low, precision. However, it is clear that there are still questions which deserve answers, *e.g.* if the observed Higgs boson is responsible for the $V_{\mathrm{L}}V_{\mathrm{L}}$ scattering unitarisation, what is the nature of the Higgs potential, *etc.*, which will be pursued vigorously in future LHC runs.

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