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Measurements of the Higgs boson by ATLAS and CMS

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Abstract. Recent results on Higgs boson production and decays in the ATLAS and CMS experiments at the LHC are reviewed. They are mostly based on the analyses of 13 TeV LHC proton-proton collision data accumulated during 2015–2016 or 2015–2017 year exposures. Production cross sections in five main decay channels are measured. These channels are combined to extract the Higgs boson signal strength, mass and couplings. All experimental results are found to be compatible with the Standard Model predictions. Upper limits on non-standard Higgs boson production in different decay modes are also derived.

1. Introduction

The Large Hadron Collider (LHC) [1] at CERN provides proton-proton (pp) collisions at the center-of-mass energy of 13 TeV since 2015. Two huge multi-purpose experiments, ATLAS [2] and CMS [3] operate at the LHC. In total, the ATLAS and CMS detectors each accumulated large amount of data corresponding to an integrated luminosity of more than 150 fb^{-1} at 13 TeV, 23 fb^{-1} at 8 TeV and 5 fb^{-1} at 7 TeV pp-collisions.

The main aims of the ATLAS and CMS experiments are to test the Standard Model of interactions (SM) in the new energy range, to study the properties of the recently discovered Higgs boson (h), as well as to search for new physics beyond the Standard Model (BSM).

The note is organized as follows. Section 2 is devoted to the SM-like Higgs boson. A brief summary of its expected production cross sections in different mechanisms as well as branching ratios (BR) is given in Section 2.1; in Section 2.2, the most sensitive bosonic decay modes, namely the $h \to ZZ^\star \to 4\ell$, $h \to \gamma\gamma$ and $h \to WW^\star \to \ell\nu\ell\nu$ are considered; Section 2.3 is devoted to the fermionic decay modes $h \to \tau\tau$ and $h \to b\bar{b}$; in Section 2.4 the $t\bar{t}h$ production is discussed. At last, the result of the combination of all mentioned decay channels is given in Section 2.5. In Section 3, results from searches for BSM Higgs bosons searches are summarized. Conclusions are drawn in Section 4.

2. SM Higgs boson measurements

2.1. SM Higgs boson production and decays

The Higgs boson in the SM provides all fundamental particles with masses. Before 2012 the h boson mass was the last unknown parameter. From theoretical considerations (perturbative

unitarity) $m_h \leq 1$ TeV is expected. The Higgs boson should have vacuum quantum numbers, i.e. zero spin and even parity ($J^P = 0^+$). In 2003, LEP experiments put the lower bound on its mass, $m_h \geq 114.4$ GeV at the 95% confidence level (CL); smaller masses were excluded at much higher CL [4]. Theoretical analyses of electroweak precision data predicted $m_h = 94^{+29}_{-24}$ GeV, i.e. $m_h \leq 152$ GeV at the 95% CL [5]. Indeed, a new boson with a mass of 125 GeV, i.e. in-between the mentioned limits, was discovered by the ATLAS [6] and CMS [7] Collaborations at the Large Hadron Collider (LHC) six years ago.[2] This discovery was a great success of the SM as all measured properties of this particle were found to be compatible with the predictions for the h boson.

A search for the SM Higgs boson at the LHC is a complicated task because the expected production cross section is $\sigma_h = \mathrm{O}(10)$ pb while the rate of background processes are much higher. The predicted production cross section for $m_h = 125$ GeV increases with the pp center-of-mass energy from ≈ 20 pb at 8 TeV to ≈ 50 pb at 13 TeV [9]. There are four main mechanisms of the SM Higgs boson production at the LHC energies: gluon fusion (ggF) via heavy-quark (mostly top) triangular loop, vector-boson fusion (VBF) where the Higgs boson is accompanied by two jets going at small polar angles, associated production with one vector boson (Vh, where V stands for W or Z) and top-antitop fusion. The first and the last mechanisms as well as the second and the third ones have common couplings ($t\bar{t}h$ and VVh, respectively). At 13 TeV the ggF mechanism dominates while rates via VBF (Vh, $t\bar{t}h$) mechanisms are ten (a few dozen) times smaller, respectively [9].

The expected branching ratios (BR) of the experimentally favourable decay modes are given in Table 1. Despite of 58% probability, the $h \to b\bar{b}$ channel is very difficult experimentally due to a huge background and it is not possible to see it via the ggF mechanism. However, one can try to extract the signal in the associated production of the h with a vector boson or a pair of top quarks. The $h \to WW^\star \to \ell\nu\ell\nu$ channel (throughout this paper ℓ stands for electron or muon) is easier to observe even if the branching ratio is only $\approx 1\%$. However, it does not allow to reconstruct a Higgs boson mass. The cleanest decay channels where this is possible are the $h \to ZZ^\star \to 4\ell$ (BR $\approx 1.3 \times 10^{-4}$) and the $h \to \gamma\gamma$ (BR $\approx 2.3 \times 10^{-3}$). In the last case a signal is searched above large background. The $h \to \tau\tau$ channel is observable experimentally in the VBF production mode or using boosted τ-leptons. The yield of events expected in 36 fb^{-1} pp collisions at 13 TeV, under the assumption of 100% efficiency and acceptance is also reported in Table 1.

Decay mode	BR, %	Observability in the experiment	Event yield in 36 fb^{-1}
$h \to bb$	57.5 ± 1.9	Mainly in Vh and tth production	≥ 24000
$h \to WW^\star$	21.6 ± 0.9	Leptonic decays of both W	≈ 17000
$h \to gg$	8.56 ± 0.86	no good experimental signature	
$h \to \tau\tau$	6.30 ± 0.36	Mainly in VBF production	≈ 10000
$h \to c\bar{c}$	2.90 ± 0.35	Very big continuum background	
$h \to ZZ^\star$	2.67 ± 0.11	Leptonic decays of both Z	≈ 250
$h \to \gamma\gamma$	0.228 ± 0.011	Excellent photon resolution	≈ 5000
$h \to Z\gamma$	0.155 ± 0.014	Leptonic decays of Z	≈ 250
$h \to \mu\mu$	0.022 ± 0.001	Excellent muon resolution	≈ 500

Table 1. Expected branching ratios for a SM Higgs boson h with mass $m_h = 125.1$ GeV and event yield in 36 fb^{-1} of pp collisions at 13 TeV (corresponding to the data set recorded by the LHC experiments in 2015–2016) assuming full acceptance and ideal efficiency.

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[2] The CDF and D0 experiments at the FNAL Tevatron $p\bar{p}$-collider were able to find only an evidence for the Higgs boson production at 3σ level [8].

2.2. The $h \to ZZ^\star \to 4\ell$, $h \to \gamma\gamma$ and $h \to WW^\star \to \ell\nu\ell\nu$ decay channels

2.2.1. The $h \to ZZ^\star \to 4\ell$ mode [10]–[11] The $h \to ZZ^\star \to 4\ell$ signature is two pairs of isolated, opposite-sign leptons. The invariant-mass distributions, $m_{4\ell}$, measured by the ATLAS and CMS experiments after the combination of all lepton cases are shown in Fig. 1. Clear peaks above a background are seen in the region around 125 GeV. Based on a dataset of 80 fb^{-1}, the ATLAS experiment observes 195 events in the mass window 115–130 GeV with an estimated background 59 ± 4 events and an expected signal 112 ± 5 events. The signal strength μ, defined as the ratio of the measured yield to the number of events expected according to the SM prediction, is measured to be 1.19 ± 0.16. The fiducial cross section, measured within a phase space close to the geometrical accceptance of the detector, is found to be 4.0 ± 0.5 fb, in agreement with the SM prediction of 3.35 ± 0.15 fb.

In the CMS experiment 126 events are observed in the mass window 117–130 GeV with an estimated background 39 ± 3 events and an expected signal 69 ± 6 events in the subsample based on 41.5 fb^{-1}. The value of μ is measured to be 1.06 ± 0.14 in a larger dataset corresponding to 77.4 fb^{-1}. The experimental fiducial cross section of 2.9 ± 0.6 fb agrees well with the SM prediction of 2.76 ± 0.14 fb.

The measured cross sections in the ATLAS experiment in the main production modes multiplied by the $h \to ZZ^\star \to 4\ell$ branching ratio are shown in Fig. 2(a). No deviation from the SM is observed. Similar conclusion can be drawn from the values of μ, measured by the CMS experiment in the same production modes (Fig. 2(b)).

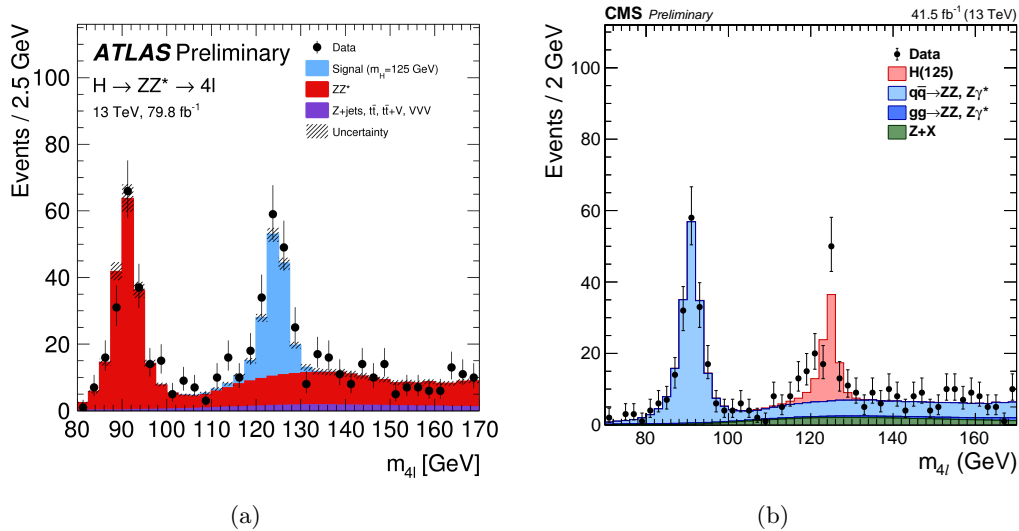(a)   (b)

Figure 1. Measured four-lepton ($m_{4\ell}$) invariant-mass distribution at 13 TeV. (a) Result of the ATLAS experiment [10]. (b) Result of the CMS experiment [11].

2.2.2. The $h \to \gamma\gamma$ mode [12]–[14] The signature of the $h \to \gamma\gamma$ decay channel is two isolated photons with an invariant mass close to m_h. To increase the discovery potential, the ATLAS and CMS experiments subdivided events into independent categories having different expected $m_{\gamma\gamma}$ resolution and signal-to-background (S/B) ratio and optimized for the best separation of the Higgs boson production processes. The value of the signal strength is found to be 1.06 ± 0.13 in the ATLAS dataset of 80 fb^{-1}. The corresponding value measured by the CMS experiment in the 80 fb^{-1} sample is $1.18^{+0.17}_{-0.14}$. Both numbers are in agreement with the SM prediction.
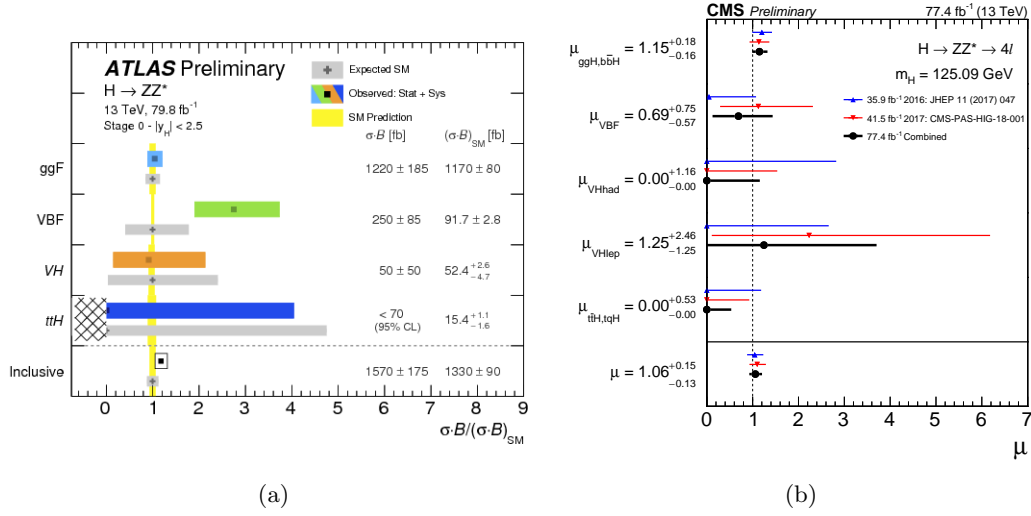
(a)   (b)

Figure 2. Results of the $h \to ZZ^\star \to 4\ell$ study at 13 TeV in the ATLAS and CMS experiments. (a) The measured ATLAS cross sections in the main production modes multiplied by the $h \to ZZ^\star \to 4\ell$ branching ratio [10]. (b) The measured values of signal strengths, μ, in the main production modes, by the CMS experiment [11]. They are normalized to the SM predictions.

The fiducial cross section of the Higgs boson production measured by the ATLAS experiment is found to be 60.4 ± 8.5 pb while the expected value is 63.5 ± 3.3 pb. The corresponding values from the CMS experiment are 84 ± 13 pb and 73 ± 4 pb, respectively. No deviation from the SM is found.

Fig. 3 shows the measured cross sections in the ATLAS and CMS experiments in the main production modes multiplied by the $h \to \gamma\gamma$ branching ratio. The numbers are normalized to the SM predictions. There is nice agreement between the measurements and the theory.
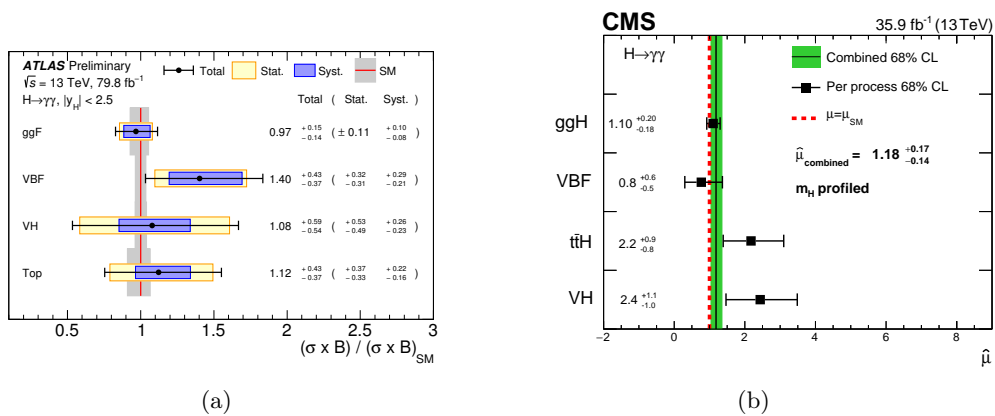

(a)   (b)

Figure 3. The measured cross sections in the ATLAS and CMS experiments in the main production modes multiplied by the $h \to \gamma\gamma$ branching ratio. The numbers are normalized to the SM predictions. (a) The result of the ATLAS experiment [12]. (b) The result of the CMS experiment [13].

2.2.3. The $h \rightarrow WW^\star \rightarrow \ell\nu\ell\nu$ mode [15]–[16]　　The signature in the $h \rightarrow WW^\star \rightarrow \ell\nu\ell\nu$ decay channel is two isolated opposite-sign leptons (electrons or muons) and sizeable E_T^{miss} due to neutrinos so one cannot reconstruct the Higgs boson mass due to the neutrinos. In these events the Higgs boson mass cannot be directly measured. However, the transverse mass, measured with the momenta of the two leptons is indicative of m_h. The event samples are subdivided in accordance with the number of jets (0, 1 or ≥ 2). For the 0 and 1 jet cases the ggF mechanism is expected to be dominant while for ≥ 2 jets case signal events are mostly due to the VBF mechanism. Both the ATLAS and CMS results are based on the 36 fb^{-1} datasets; in the ATLAS case only the $e\mu$ final state is considered and the Vh-production mode is not included. The observed (expected) signal significance at 125 GeV in the ATLAS experiment for the ggF h production is 6.0σ (5.3σ), respectively. The corresponding signal strength in the SM units is 1.10 $\pm$ 0.20, and the ggF cross section multiplied by BR($h \rightarrow WW^\star$) is measured to be 11.4 $\pm$ 2.1 pb, in agreement with the theoretical prediction 10.4 $\pm$ 0.6 pb. The observed (expected) signal significance in the VBF production mode is 1.9σ (2.6σ), $\mu = 0.62 \pm 0.36$ and the measured cross section is 0.50 ± 0.28 pb being compatible with the expected value of 0.81 ± 0.02 pb. The correlation between the ggF and VBF cross sections measured by the ATLAS experiment is shown in Fig. 4(a). No significant deviation from the SM is observed.

The combined value of μ measured by the CMS experiment is found to be 1.28 $\pm$ 0.18, being $1.38^{+0.21}_{-0.24}$ ($0.29^{+0.66}_{-0.29}$) for the ggF (VBF) production modes. The observed signal significance is 9.1σ, while the expected one is 7.1σ. The fiducial cross section is also measured by the CMS. Based on these measurements, the cross sections in different Higgs boson production modes are obtained (Fig. 4(b)). They are normalized to the SM predictions; no significant deviation from the SM is observed.
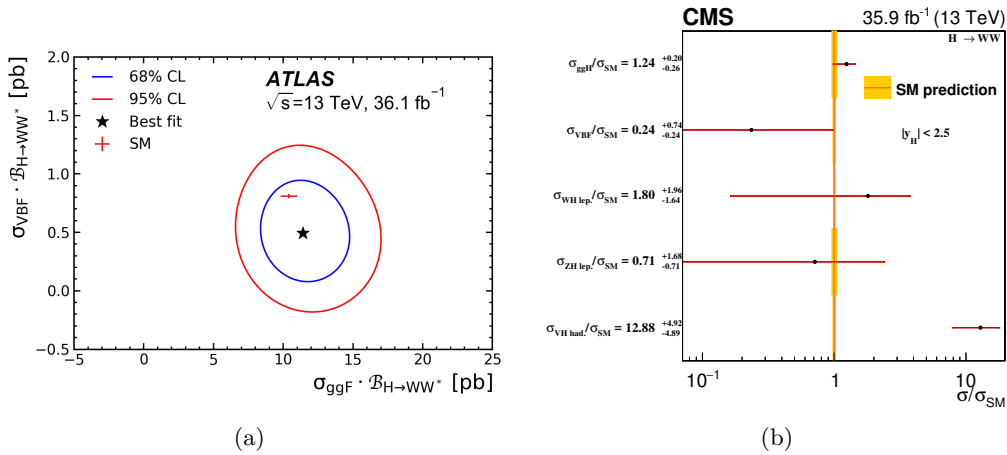

(a)　　　　　　　　　　　　　　　　　　　　　(b)

Figure 4. The results of the $h \rightarrow WW^\star \rightarrow \ell\nu\ell\nu$ studies at 13 TeV in the ATLAS and CMS experiments. (a) The correlation between the ggF and VBF cross sections measured by the ATLAS experiment [15]. (b) Cross sections, normalized to the SM predictions, measured for different Higgs boson production modes by the CMS experiment [16]. They are normalized to the SM predictions.

2.3. The $h \rightarrow \tau\tau$ and $h \rightarrow b\bar{b} + X$ decay channels

2.3.1. The $h \rightarrow \tau\tau$ decay channel [17]–[18]　　The $h \rightarrow \tau\tau$ signature is two well reconstructed opposite-sign τ-leptons with $m_{\tau\tau}$ around m_h. They decay each leptonically or hadronically.

Events are categorized to improve signal significance; the VBF and boosted-τ categories play a major role. A dataset of 36 fb^{-1} is used by both ATLAS and CMS for this analysis.

The observed (expected) signal significance in the ATLAS experiment in the $\tau\tau$ channel is 4.4σ (4.1σ). It rises to 6.4σ (5.4σ) if one combines 13 TeV results with those obtained earlier at 7–8 TeV. The signal strength is measured to be $\mu = 1.09^{+0.36}_{-0.30}$ at 13 TeV. No deviation from the SM is observed. Fig. 5(a) shows the experimental cross sections for the VBF and boosted-τ categories. They are compatible with the SM predictions.

The observed (expected) signal significance in the CMS experiment is 4.9σ (4.7σ). It increases to 5.9σ (5.9σ) if one combines results at 13 TeV with those obtained earlier at 7 and 8 TeV. The signal strength is measured to be 1.09 ± 0.26 at 13 TeV; the values of μ for separate categories are given in Fig. 5(b). No deviation from the SM is observed.
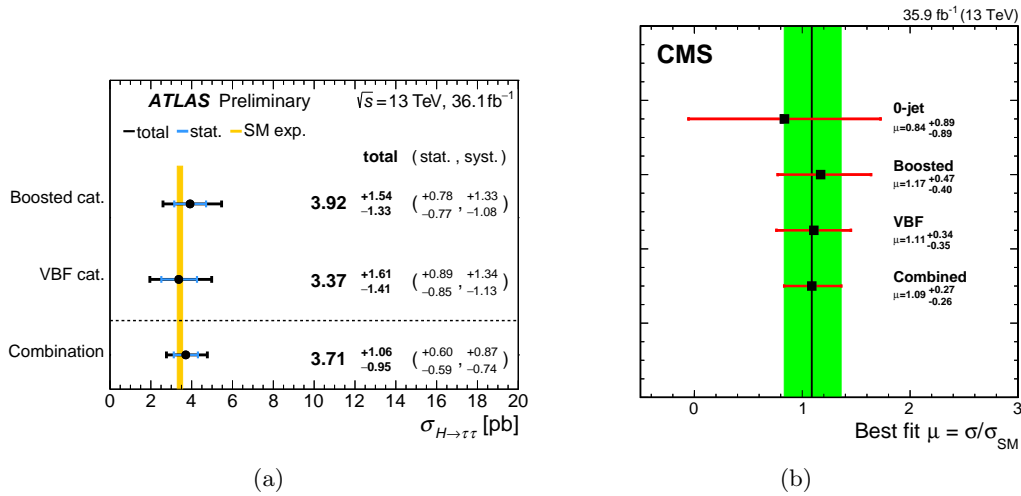

Figure 5. The results of the $h \to \tau\tau$ studies in the ATLAS and CMS experiments. (a) The measured h production cross section multiplied by the $\tau\tau$ branching ratio in the ATLAS experiment at 13 TeV [17]. (b) The measured $h \to \tau\tau$ signal strength in the CMS experiment at 13 TeV [18].

2.3.2. The $h \to b\bar{b} + X$ decay channel [19]–[20] The $h \to b\bar{b} + X$ signature includes two jets originating from b-quarks with an invariant mass close to m_h. In addition, only events with tight lepton(s) and/or high E_T^{miss} depending on the Z/W final state: $Z \to \nu\nu$ (0 leptons), $W \to \ell\nu$ (one lepton) and $Z \to \ell\ell$ (two leptons) are considered. Multivariate analyses are performed to discriminate the signal from the background. The procedures are successfully tested on the $(W/Z)Z$ process with subsequent $Z \to b\bar{b}$ decay. A statistics of 80 fb^{-1} is used for these analyses in both experiments.

The observed (expected) signal significance in the ATLAS experiment in the Vh production mode is 4.9σ (4.4σ). It increases to 5.4σ (5.5σ) if one combines 13 TeV results with earlier measurements at 7 and 8 TeV. This corresponds to the signal strength $\mu = 0.98^{+0.22}_{-0.21}$. Fig. 6(a) shows the measured μ separately in the Wh and Zh production modes. No deviation from the SM is found.

The observed (expected) signal significance in the CMS experiment in the Vh production mode is 4.8σ (4.9σ). It increases to 5.6σ (5.5σ) if one combines results for all possible production modes. The signal strength is measured to be 1.04 ± 0.20; the values for separate production modes are given in Fig. 6(b).
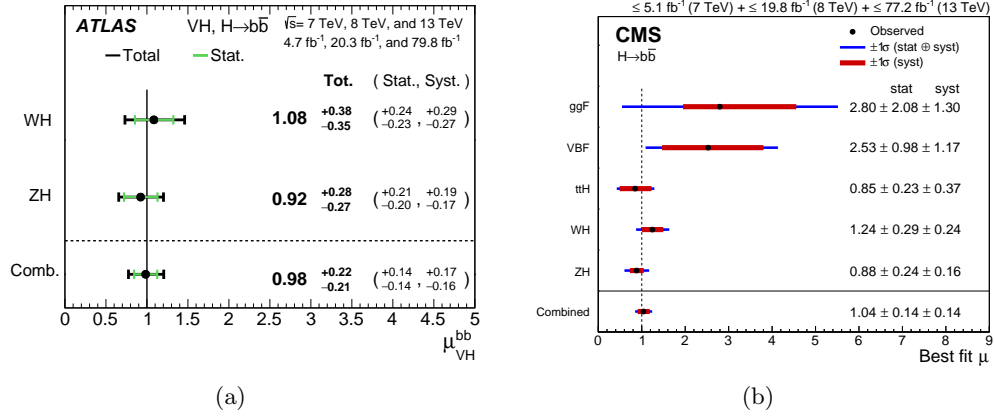
Figure 6. The observed $h \to b\bar{b} + X$ signal strength in the ATLAS and CMS experiments. (a) The result of the ATLAS experiment in the Vh production mode at 13 TeV before and after the combination with older 7 and 8 TeV results [19]. (b) The result of the CMS experiment at 13 TeV in different production modes after the combination with older 7 and 8 TeV results [20].

2.4. The $t\bar{t}h$-production [21]–[22]

The $t\bar{t}h$-production mechanism is studied using a variety of multi-lepton final states as well as $b\bar{b}$ and $\gamma\gamma$ ones. A multivariate technique to discriminate the signal from a background is used by both experiments.

The measured μ is $1.32^{+0.28}_{-0.26}$ in the ATLAS experiment which corresponds to observed (expected) signal significance 5.8σ (4.9σ). It increases to 6.3σ (5.1σ) if one combines 13 TeV results (based on $36 - 80$ fb^{-1} datasets) with older 7–8 TeV ones. The values of signal strengths in the different production modes are shown in Fig. 7(a). No deviation from the SM is found.

The observed (expected) signal significance in the CMS experiment is 5.2σ (4.2σ) in the combined data taken at 13 TeV (36 fb^{-1}) and at 7–8 TeV. The value of μ is measured to be $1.26^{+0.31}_{-0.26}$. It is shown in Fig. 7(b) together with the ones for separate final states. The result agrees well with the SM prediction.

2.5. Preliminary combinations of different Higgs boson decay channels [23]–[24]

The results obtained for the mentioned individual channels are combined to extract a Higgs boson signal strength at 13 TeV in different production mechanisms (Fig. 8) and in different decay modes (Fig. 9). The global signal strength measured in the ATLAS (CMS) experiment is found to be $1.13^{+0.09}_{-0.08}$ ($1.17^{+0.10}_{-0.10}$), in agreement with the SM prediction. All four main production modes as well as five main decay channels are observed with more than 5 σ significance in each experiment. The measured signal strengths in different production mechanisms under the assumption of the SM branching ratios are also in agreement with the SM predictions. The same is true for the experimental values of the branching ratios under the assumption of the SM production cross sections. More data are needed to reduce the current error of 8% on the global Higgs boson signal strength in each experiment.

3. Search for the Higgs boson beyond the SM at 13 TeV

The discovery of the Higgs boson (h) more than six years ago was the great success of the SM. However it does not explain many things. Different extensions of the SM proposed by theorists were rejected after this discovery, but some of them have not yet been excluded. One of the simplest extensions of the SM is the electroweak singlet model which includes extra (heavy)
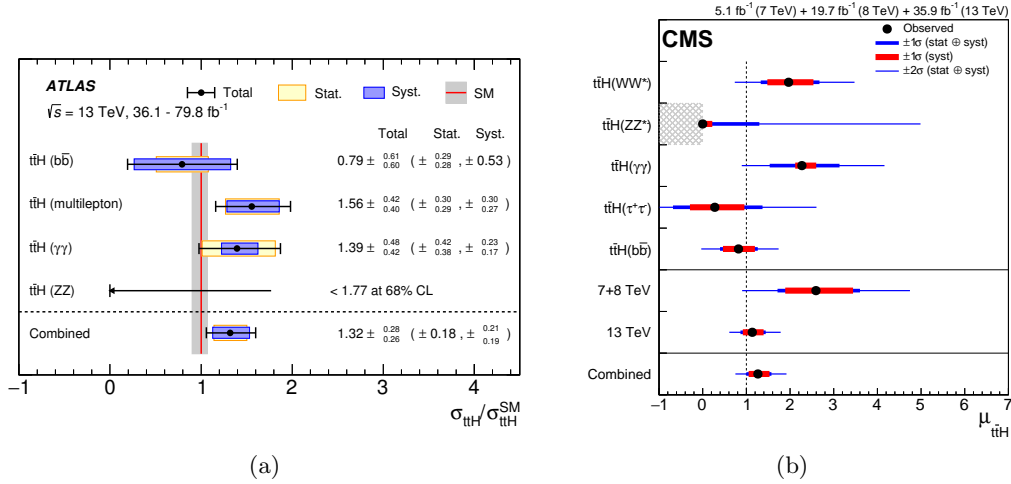
Figure 7. The observed signal strengths in the $t\bar{t}h$ production mode in the ATLAS and CMS experiments. (a) The ATLAS results based on $36 - 80$ fb^{-1} datasets at 13 TeV [21]. (b) The CMS results based on 36 fb^{-1} dataset at 13 TeV before and after the combination with older 7 and 8 TeV results [22].
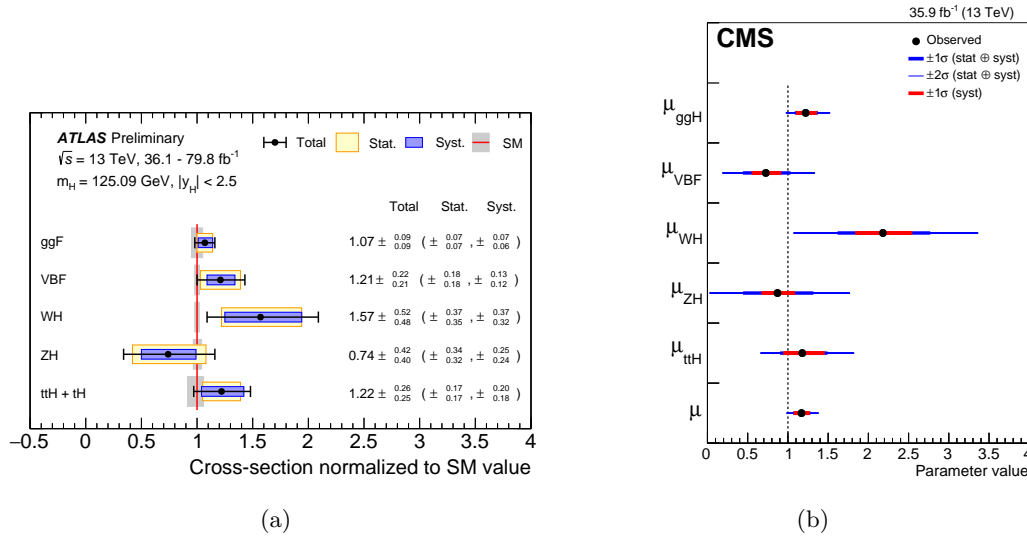

Figure 8. Results of the preliminary combination of Higgs boson production at 13 TeV in the ATLAS and CMS experiments under the assumption of the SM branching ratios. (a) Result of the ATLAS experiment [23]. (b) Result of the CMS experiment [24].

scalar Higgs boson. Other models contain five Higgs bosons (neutral light and neutral heavy CP-even states, h and H, one CP-odd neutral state A and two charged states, H^+ and H^-). Four masses m_h, m_H, m_A, m_{H^+}, a mixing angle α between the light and the heavy neutral Higgs boson, and the ratio $\tan\beta$ of two vacuum expectation values are the free parameters. The Minimal Super Symmetric Model (MSSM) represents a specific implementation of the models with two higgs doublets.
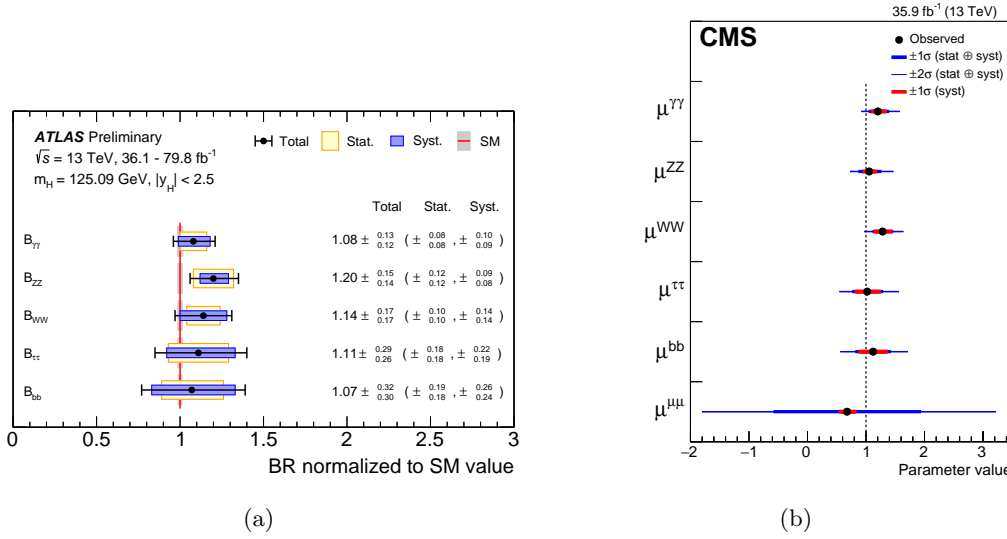
Figure 9. Higgs boson branching ratios measured with *pp* collisions at 13 TeV by the ATLAS [23] (a) and CMS experiments [24] (b) under the assumption of the SM production cross sections.

3.1. Searches for $H \to hh$-production at 13 TeV [25]–[26]
The cross section of non-resonant *hh*-production via gluon fusion is expected to be only 33.4 fb at 13 TeV *pp*-collisions in the SM. Hovewer, in some BSM models resonant $H \to hh$ production is possible with (much) higher cross section. For this reason, both ATLAS and CMS have performed searches for this process combining the $hh \to bbbb$, $hh \to bb\gamma\gamma$ and $hh \to bb\tau\tau$ decay channels[3]. The 95% CL upper limits obtained by the ATLAS experiment vary from 1 pb at $m_H = 300$ GeV to 20 fb at $m_H = 1$ TeV [25]. In the CMS case these limits lie between O(1 pb) at $m_H = 300$ GeV and 3.5 fb at $m_H = 3$ TeV [26]. The corresponding observed limits on the non-resonant *hh*-production are 6.7 (22.2) times higher than the expected SM cross section in the ATLAS (CMS) case. The expected limits are 10.4 (12.8) in the SM units, respectively.

3.2. Charged Higgs boson searches at 13 TeV [27]–[28]
In the MSSM a relation between top quark mass m_{top} and $m_{H^\pm}$ dictates both the production mode and decay channels of $H^\pm$. If $m_{H^\pm} \geq m_{top}$, the H^+ is produced together with *t*- and *b*-quarks. The charged Higgs boson can decay to *tb* or $\tau\nu$. The search mass ranges for the $\tau\nu$ decay are 90–2000 GeV (80–3000 GeV) in the ATLAS (CMS) case. Final states with one τ-lepton and one *W* decaying hadronically are considered. The hMSSM model is used to interpret the results. The 95% CL upper limits on the $\sigma_H \times BR(H \to \tau\nu)$, obtained by ATLAS, vary from 4 pb at $m_H = 90$ GeV to 2.5 fb at $m_H = 2000$ GeV [27]. The corresponding CMS numbers are 6 pb at $m_H = 80$ GeV and 4.5 fb at $m_H = 3000$ GeV [28].

3.3. MSSM Higgs boson searches at 13 TeV [29]–[30]
In the MSSM, mechanisms for the production of neutral heavy Higgs bosons A/H are the gluon fusion or the associated production with one or two b-quarks. The search mass ranges in the analyses of the $A/H \to \tau\tau$ decay channel are 200–2250 GeV (90–3200 GeV) in the ATLAS (CMS) experiment, respectively. Among the possible final states with two τ-leptons only those with hadrons (*hh*) and with a lepton and hadrons (*ℓh*) are considered. Results are interpreted in

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[3] The CMS also includes $hh \to bbVV$ channels, where *V* stands for the *W*- or *Z*-boson.

the MSSM benchmark scenarios. The 95% CL upper limits obtained on $\sigma_{A/H} \times \mathrm{BR}(A/H \to \tau\tau)$ in the ATLAS experiment lie between 5.8 fb and 780 fb (3.7 fb and 700 fb) in the case of the ggF (associated) production [29]. The corresponding CMS numbers vary from 3.5 fb to 18 pb for the gluon fusion and from 2.5 fb to 15 pb for the associated production [30].

4. Conclusion

With 7–13 TeV LHC data, the ATLAS and CMS collaborations observed four main production mechanisms and five main decays of the Higgs boson. Their cross sections and branching ratios were measured. They all agree with the SM predictions.

With the same datasets, some differential cross sections for the SM-like Higgs boson and compared with the most recent theoretical calculations.

ATLAS and CMS also performed searches for non-standard Higgs bosons in many final states. No deviations with respect to the SM background have been observed. Severe constraints on the production cross section of new scalar particles have been derived.

We continue to improve existing measurements and to search for deviations from the SM with new 13 TeV data and, in the future, will use 14 TeV data.

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