Review of Higgs Results from the ATLAS Experiment at the LHC

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Abstract. The LHC has now delivered a large amount of data at 13 TeV center of
mass energy. The experimental sensitivity is equivalent to that of Run-1 for the
Higgs boson (125 GeV), and surpasses it for searches of higher masses Higgs-
like particles. This paper will review recent ATLAS results on both of these
topics.

Introduction

A new boson with a mass of 125 GeV was discovered by the ATLAS [1] and
CMS [2] Collaborations at the Large Hadron Collider [3] (LHC) more than four
years ago. Studies of the Higgs boson properties were based on full dataset
accumulated at proton-proton (pp) collision at 7 TeV center of mass energy (∼5
fb⁻¹) and on partial of 8 TeV data (∼5 fb⁻¹). Since that time both experiments
recorded another 20 fb⁻¹ of 8 TeV data in 2012 and about 40 fb⁻¹ taken at 13
analyzed the full statistics at 7 and 8 TeV as well as about 40% of the 13 TeV
statistics. All measured properties of the new boson are found to be compatible
with the Standard Model (SM) predictions for the Higgs boson (H). It was a
great success of the SM. However, the SM does not explain particle mass
hierarchy, dark matter, dark energy, baryon asymmetry of the Universe and has
problems with the unification of fundamental interactions [5]. Different
extensions of the SM were proposed by theorists to solve these problems. These
extensions contain different amount of extra Higgs bosons. The ATLAS
Collaboration performed neutral and charged Higgs boson searches in different
decay modes. This report contains a short summary of these searches and is
organized as follows. Section 1 briefly describes SM Higgs boson decay modes.
In Section 2, results on some bosonic and fermionic decay modes obtained at 13
TeV are given. Beyond-the-Standard-Model (BSM) Higgs boson searches are
reviewed in Section 3 together with a pair production of Higgs bosons. Section 4
contains summary of results for the SM H obtained at 7–8 TeV pp-collision
energy; the conclusion is drawn in Section 5.

1 SM Higgs boson decay channels

The main production mechanisms of the SM Higgs boson at hadron colliders
at LHC energies are gluon fusion (ggF), vector boson fusion (VBF), associated
production with a W- or a Z-boson (VH) or with a pair of top quarks (ttH);
expected cross sections σ_H at the mass 125 GeV [6] are shown in Fig. 1(a) in the
$pp$ energy range 6–15 TeV. The total $\sigma_H$ is $O(10 \text{ pb})$. The ggF mechanism provides main, about 90%, contribution to the $H$ production cross section. In $\approx$5% cases, the Higgs boson is produced through the vector boson fusion; the signature of such process is a presence of two hadron jets with high transverse momenta going mostly at small polar angles. The $WH$, $ZH$ and $ttH$ processes have even smaller cross sections; another production mechanisms like $bbH$ and $tH$ are not considered here.

Calculated branching ratios (BR) of the main Higgs boson decay channels at a mass 125 GeV \cite{7} are shown in Table 1. Despite of 58% probability, the $H \rightarrow bb$ 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 $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ channel (here and further $\ell$ stands for an electron/positron or a muon) is better for searches, despite having branching ratio of only $\approx$1%. However, it does not allow to reconstruct a Higgs boson mass. The cleanest decay channels where this is possible are the $H \rightarrow ZZ^* \rightarrow 4\ell$ (BR $\approx$1.3$\times$10$^{-4}$) and the $H \rightarrow \gamma\gamma$ (BR $\approx$2.3$\times$10$^{-3}$). In the last case a signal is searched above strongly overwhelming background. Expected signal event rates normalized to 15 fb$^{-1}$ data sample collected at 13 TeV are also shown in Table 1. Here 100% detection efficiency is assumed.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>BR, %</th>
<th>Observability</th>
<th>Event rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow bb$</td>
<td>57.5 ± 1.9</td>
<td>Mainly in VH and $ttH$ production</td>
<td>$\geq 10000$</td>
</tr>
<tr>
<td>$H \rightarrow WW$</td>
<td>21.6 ± 0.9</td>
<td>Leptonic decays of both $W'$</td>
<td>$\approx 7000$</td>
</tr>
<tr>
<td>$H \rightarrow gg$</td>
<td>8.56 ± 0.86</td>
<td>No good experimental signature</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>6.30 ± 0.36</td>
<td>Mainly in VBF production</td>
<td>$\approx 4000$</td>
</tr>
<tr>
<td>$H \rightarrow cc$</td>
<td>2.90 ± 0.35</td>
<td>No good experimental signature</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow ZZ$</td>
<td>2.67 ± 0.11</td>
<td>Leptonic decays of both $Z'$</td>
<td>$\approx 100$</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>.228 ± .011</td>
<td>Big continuum background</td>
<td>$\approx 2000$</td>
</tr>
<tr>
<td>$H \rightarrow \mu\mu$</td>
<td>.155 ± .014</td>
<td>Leptonic decays of $Z$</td>
<td>$\approx 100$</td>
</tr>
<tr>
<td>$H \rightarrow \mu\mu$</td>
<td>.022 ± .001</td>
<td>Big continuum background</td>
<td>$\approx 200$</td>
</tr>
</tbody>
</table>

2 The SM Higgs boson searches at 13 TeV

The $H \rightarrow ZZ^* \rightarrow 4\ell$ signature is two pairs of isolated, opposite-sign leptons. The invariant-mass distribution, $m_4\ell$, measured by the ATLAS experiment after the combination of all lepton cases \cite{8} is shown in Fig. 1(b). Clear peak above a background is seen in the region around 125 GeV. The ATLAS experiment
observes 44 events in the mass window 118–129 GeV with an estimated background $9.7 \pm 0.8$ events and an expected signal 22.3 events. Based on these numbers, the fiducial cross section measurement is performed and the extracted total cross section is found to be $\sigma_{\text{meas}}^{H} = 81^{+18}_{-16}$ pb. It agrees with the SM within $1.6\sigma$ ($\sigma_{\text{SM}}^{H} = 55.5^{+3.8}_{-4.4}$) pb. So the 13 TeV result is compatible with the previous one obtained at 8 TeV.

Figure 1. (a) Predicted total $\sigma_{H}$ in $pp$-collisions at different $\sqrt{s}$ together with separate contributions from different production mechanisms [6]. (b) The measured four-lepton invariant-mass distribution in the $H \rightarrow ZZ^{*} \rightarrow 4\ell$ decay mode in the ATLAS experiment [8].

The $H \rightarrow \gamma\gamma$ signature is two isolated photons with invariant mass equal to $m_{H}$. To increase the discovery potential, the ATLAS experiment subdivided events into independent categories having different expected $m_{\gamma\gamma}$ resolution and signal-to-background ratio and optimized for the best separation of the Higgs boson production processes. The $m_{\gamma\gamma}$-distribution after the corresponding re-weighting is given in Fig. 2 together with the spectra after a background subtraction [9]. The excess of events with $4.7\sigma$ significance is seen around 125 GeV. The value of the signal strength in the SM units is measured to be $\mu = \sigma_{\text{meas}}/\sigma_{\text{SM}} = 0.85 \pm 0.21$.

The results obtained for the individual channels $H \rightarrow ZZ^{*} \rightarrow 4\ell$ [8] and $H \rightarrow \gamma\gamma$ [9] are combined to extract a Higgs boson signal strength in different production mechanisms (Fig. 3(a)) and its production cross section at 13 TeV $pp$ energy (Fig. 3(b)) [10]. The average signal strength is measured to be $\mu = 1.13 \pm 0.18$, in good agreement with the SM prediction. The measured cross section is also compatible with the SM expectations.

The $VH \rightarrow bb + X$ 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 missing transverse energy $E_{T}^{\text{miss}}$ depending on
Figure 2. The measured two-photon invariant-mass distribution in the $H \rightarrow \gamma\gamma$ decay mode in the ATLAS experiment [9].

Figure 3. (a) Cross sections for the ggF, VBF, VH and top production mechanisms measured as a result of the combination of the $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ decay modes [10], (b) total $pp \rightarrow H + X$ cross sections measured at different center of mass energies compared to the Standard Model predictions, in the ATLAS experiment [10].
Z/W final state: $Z \rightarrow \nu\nu$ (0 leptons), $W \rightarrow \ell\nu$ (one lepton) and $Z \rightarrow \ell\ell$ (two leptons) are considered. A multivariate analysis is performed to discriminate the signal from a background. The procedure is successfully tested on the $(W/Z)Z$ process with subsequent $Z \rightarrow bb$ decay. The measured $\mu$ is $0.2 \pm 0.5$ [11], compatible both with the background-only and the SM hypotheses.

The $ttH$-production mechanism is studied using three signatures. With the first signature, where events with at least one top decaying leptonically are selected, one can search for the $H \rightarrow bb$ decay mode. The event categorization is performed according to the jet multiplicity and a number of $b$-jets. A multivariate technique to discriminate the signal from the dominant $tt +$ jets background is used. The measured $\mu$ is $2.1 \pm 1.0$ [12] which is compatible with the SM $ttH$ hypothesis. The second signature contains multiple leptons mostly from the $H \rightarrow WW^*$ and $H \rightarrow \tau\tau$ decays. The corresponding value of the signal strength is measured to be $-0.3 \pm 1.1$ [9], compatible both with the SM and the background-only hypotheses. The combined result is $\sigma_{\text{meas}}/\sigma_{\text{SM}} = 1.8 \pm 0.7 [14]$, so the $ttH$-production is established at the $2.8\sigma$ level in the ATLAS experiment.

The $H \rightarrow \mu\mu$ signature is a small peak at the value of $m_H$ in the invariant-mass distribution of isolated, opposite-sign muons above strongly overwhelming Drell-Yan background. To increase the signal sensitivity events are categorized. The ATLAS experiment is able to exclude $\sigma_{\text{meas}}/\sigma_{\text{SM}} \leq 4.4$ at 95% CL [15]; in the combination with the related Run-1 results this number is reduced down to 3.5.

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

The simplest extension of the SM is the so-called Narrow Width Approximation (NWA) where additional high-mass Higgs boson ($H$) behaves as the SM Higgs boson $h$, except the width is fixed to be equal to 4 MeV, which is the expected width of the SM Higgs boson at $m_h = 125$ GeV. This simplified model allows to produce MC samples easily. In addition, the interference of the signal with background processes can be neglected simplifying the analysis. The predictions for the Higgs boson production cross section at 13 TeV in different mechanisms are shown in Fig.4 as a function of $m_H$. It is interesting to note that above 1.5 TeV mass the VBF mechanism starts to dominate. Another extensions of the SM 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 $m_h$, $m_H$, $m_A$, $m_{H^\pm}$, mixing angle $\alpha$ between the light and the heavy neutral Higgs boson, and the ratio $\tan \beta$ of two vacuum expectation values are usual free parameters.
3.1 High mass Higgs boson searches in the bosonic decay modes

The searches for a high mass Higgs boson in the bosonic decay modes are performed in the following channels: \( H \rightarrow \gamma\gamma \) [16], \( H \rightarrow WW \rightarrow \ell\ell\nu\nu \) [17], \( H \rightarrow \ell\nuqq \) [18], \( H \rightarrow ZZ \rightarrow 4\ell \) [8], \( H \rightarrow ZZ \rightarrow \ell\ell\nu\nu \) [19], \( H \rightarrow ZZ \rightarrow \ell\ellqq \) [20], \( H \rightarrow ZZ \rightarrow \nu\nuqq \) [20], and \( H \rightarrow Z\gamma \) [21].

![Figure 4. Expected Higgs boson production cross section at 13 TeV pp-collisions in different mechanisms as a function of \( m_H \) in the NWA model [6].](image)

The \( H \rightarrow \gamma\gamma \) decay mode has a special interest because of the observation of an excess at around 750 GeV in the di-photon invariant-mass distribution both by the ATLAS and CMS collaborations in the 2015 data sample [22]–[23]. In the ATLAS case, the deviation from the SM was at 3.4\( \sigma \) level (local significance). The ATLAS Collaboration performed a new analysis based on five times larger dataset mostly obtained in 2016. The search mass range is 200–2500 GeV. Some 35891 events with hard photons were selected and the resulting \( m_{\gamma\gamma} \)-distribution is shown in Fig. 5. No significant excess is observed. The resulting 95% CL upper limit on the fiducial cross section multiplied by the \( BR(H \rightarrow \gamma\gamma) \) lies between 0.2 fb and 13 fb depending on the value of \( m_{\gamma\gamma} \).

The mass range between 300–3000 GeV is covered by the \( H \rightarrow WW \rightarrow e\nu\mu\nu \) decay channel. Selection criteria are specially optimized for the high-mass case and a multivariate analysis is performed. Events are subdivided into ggF- and two VBF-enriched categories. No significant excess above a background is found in the search mass range (Fig. 6). 95% CL upper limits on \( \sigma_H \times BR(H \rightarrow WW) \) are established separately in the ggF and VBF production mechanisms in the framework of the NWA model [17]. They are 4.3 pb (51 fb) at \( m_H = 300 \) GeV (\( m_H = 3000 \) GeV) in the ggF case and 1.1 pb (30 fb) at \( m_H = 300 \) GeV (\( m_H = 3000 \) GeV) in the VBF case.
Figure 5. The measured two-photon invariant-mass distribution in the $H \rightarrow \gamma \gamma$ decay mode in the ATLAS experiment [22].

Figure 6. The measured 95% CL upper limits as a function of $m_H$ on $\sigma_H \times BR(H \rightarrow WW)$ for the ggF (a) and VBF (b) production mechanisms in the framework of the NWA model in the ATLAS experiment [17].

A similar study is performed for the $H \rightarrow ZZ \rightarrow 4\ell$ channel. No significant excess is observed in the search mass range 200–1000 GeV (Fig. 7). The resulting upper limits on $\sigma_H \times BR(H \rightarrow 4\ell)$ in the NWA model lie between 4.6 fb
(m_H = 244 GeV) and 0.22 fb (m_H = 1000 GeV) for the ggF production mechanism. They are as large as 1.9 fb (0.2 fb) for the VBF case.

Figure 7. The measured 95% CL upper limits as a function of m_S on \( \sigma_S \times BR(S \rightarrow ZZ \rightarrow 4\ell) \) for the ggF (left) and VBF (right) production mechanisms in the framework of the NWA model in the ATLAS experiment [17].

Upper limits on the \( \sigma_H \times BR(H \rightarrow ZZ) \) are also put using the \( H \rightarrow ZZ \rightarrow \ell\ell vv \) [19], \( H \rightarrow ZZ \rightarrow \ell\ell qq \) [20] and \( H \rightarrow ZZ \rightarrow \nu\nu qq \) [20] decay modes. In the second case both the ggF and VBF cases are considered while in the first and in the third ones only the ggF mechanism is tried. Again, no significant deviation from the SM is observed (Fig. 8). Analyzing the \( X \rightarrow Z\gamma \) decay channel, where \( X \) is a hypothetic scalar state, it is concluded that the 95% CL upper limit on the \( \sigma_X \times BR(X \rightarrow \tau\tau) \) is as large as 215 fb (5 fb) at \( m_H = 270 \) (2400) GeV, respectively in the NWA approach [18] (Fig. 9(a)). Similar limits are obtained for the \( \sigma_X \times BR(X \rightarrow WW) \) (Fig. 9(b)). They are 1 pb (2.5 fb) at \( m_H = 500 \) (3000) GeV [21].

3.2 MSSM Higgs boson searches at 13 TeV

In the Minimal Super Symmetric Model (MSSM), the main A/H production mechanisms are the gluon fusion or the associated production with one or two b-quarks. The mass range between 200–1200 GeV is covered by the \( A/H \rightarrow \tau\tau \) decay channel. Among possible final states with two \( \tau \)-leptons only those with hadrons (hh) and with a lepton and hadrons (lh) are considered. Results are interpreted in the MSSM benchmark scenarios. The 95% CL upper limits on \( \sigma_{A/H} \times BR(A/H \rightarrow \tau\tau) \) lie between 25 fb and 1.3 pb in the case of the ggF [24]. They are changed to 30 fb and 1.5 pb for the associated production.
Figure 8. The measured 95% CL upper limits as a function of $m_H$ on $\sigma_H \times \text{BR}(H \rightarrow ZZ)$ for the ggF production in the $\ell\ell\nu\nu$ channel (top left), ggF production in the $\ell\ell qq$ channel (top right), ggF production in the $v\nu qq$ channel (bottom left) and VBF production in the $\ell\ell qq$ channel (bottom right), in the framework of the NWA model in the ATLAS experiment [19, 20].

Figure 9. The measured 95% CL upper limits as a function of $m_X$ on $\sigma_X \times \text{BR}(X \rightarrow Z\gamma)$ (a) and on $\sigma_X \times \text{BR}(X \rightarrow WW)$ (b) in the framework of the NWA model in the ATLAS experiment [18, 21].
In the MSSM a relation between top quark mass $m_{\text{top}}$ and $m_{H^+}$ dictates both
the production mode and decay channels of $H^+$. If $m_{H^+} \geq m_{\text{top}}$, the $H^+$ is produced
together with $t$- and $b$-quarks. The charged Higgs boson can decay into a $tb$ or
into a $\tau\nu$ final state.

The mass range for the $H \rightarrow tb$ searches is between 300–1000 GeV [25].
Multi-jet final states with one lepton from top decay are studied. A multivariate
analysis is performed; its result is interpreted within benchmark scenarios of the
MSSM models. 95% CL upper limits on the $\sigma_{H} \times \text{BR}(H \rightarrow tb)$ are established
(Fig. 11(a)). They are as large as 1.09 pb (0.18 pb) at $m_{H} = 300$ (1000) GeV,
respectively. This results to exclusion of very small and very large values of $\tan \beta$
mostly for low $m_{H}$ if interpreted in the MSSM $m_{\text{mod}}^{h}$ scenario (Fig. 11 (b)).

Figure 10. 95% CL upper limits as a function of $m_{H/A}$ on the $\sigma_{H} \times \text{BR}(H/A \rightarrow \tau\tau)$
in the ggF (a) and in the associated production (b) in the ATLAS experiment
[24].

Figure 11. 95% CL upper limits as a function of $m_{H^+}$ on the $\sigma_{H^+} \times \text{BR}(H^+ \rightarrow tb)$ (a)
and on $\tan \beta$ in the MSSM $m_{\text{mod}}^{h}$ scenario (b) in the ATLAS experiment [25].
The mass range for the $\tau\nu$ decay searches is between 300–2000 GeV [26]. Final states with one $\tau$-lepton and one $W$ decaying hadronically are considered. The hMSSM model is used to interpret the results. The obtained 95% CL upper limits on the $\sigma_H \times \text{BR}(H \rightarrow \tau\nu)$ vary from 2 pb at $m_H =$200 GeV to 8 fb at $m_H =$2000 GeV. Very large values of $\tan \beta$ are excluded in the hMSSM scenario in the mass range between 300 and 600 GeV.

Figure 12. 95% CL upper limits as a function of $m_{H^+}$ on the $\sigma_H \times \text{BR}(H^+ \rightarrow \tau\nu)$ (a) and on $\tan \beta$ in the hMSSM scenario (b) in the ATLAS experiment [26].

In the SM, the cross section of Higgs bosons pair production ($hh$) is too small to be observed at the LHC with the current dataset. However, in some BSM models, the $hh$-rates could be much higher. The ATLAS experiment searches for non-resonant and resonant $hh$-production in the $hh \rightarrow WW\gamma\gamma$ [27] and $hh \rightarrow bbb$ [28] decay channels; in the first case $\ell\nu\ell\nu$ and $\ell\nuqq$ final states of two $W$’s are considered. No significant excess above a background is found in the search range 250–500 GeV in the first case and in the 300–3000 GeV range in the second one. The observed 95% CL exclusion limit for the $\sigma_{gg} \rightarrow X \times \text{BR}(H \rightarrow hh)$ is 25 pb in the non-resonant case [27]. This number is changed to 47.7 pb (44.7 pb) in the resonant case for $m_X =$260 GeV (500 GeV), respectively. For the $\sigma_{gg} \rightarrow H \times \text{BR}(H \rightarrow hh \rightarrow bbb)$ the 95% CL exclusion limit is 330 fb while the SM prediction is 11.3 ± 1.0 fb [28].

4 Brief summary of the SM $H$ measurements at 7–8 TeV $pp$-collision energy

Using the 7 TeV and 8 TeV collision data produced at the LHC, the ATLAS experiment measured properties of the Higgs boson such as its couplings, mass, spin and parity. The results of these measurements are summarized in Table 2. The Higgs boson mass is found to be $125.36 \pm 0.41$ GeV [29], based on the studies of the $H \rightarrow ZZ \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ channels. This number becomes $125.09 \pm 0.24$ GeV when combined with the CMS measurements [30]. The signal strength $\mu$ in the SM is measured to be $1.18 \pm 0.15$ [31]. This result is obtained from the analysis of the $H \rightarrow ZZ^* \rightarrow 4\ell, H \rightarrow \gamma\gamma, H \rightarrow WW^* \rightarrow \ell\nu\ell\nu, H \rightarrow \tau\tau$ and
$H \rightarrow bb$ decay channels. Note that the first three channels are seen in the ATLAS experiment.

Table 2. Brief summary of the results related to the SM Higgs boson obtained at 7 and 8 TeV collision energy in the ATLAS experiment.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Ref.</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass, GeV</td>
<td>125.36 ± 0.41</td>
<td>[29]</td>
<td>125.09 ± 0.24 with the CMS</td>
</tr>
<tr>
<td>Average $\mu$</td>
<td>1.18 ± 0.15</td>
<td>[31]</td>
<td>1.09 ± 0.10 with the CMS</td>
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<tr>
<td>$\mu$ for $H \rightarrow \gamma\gamma$</td>
<td>$1.17^{+0.28}_{-0.26}$</td>
<td>[31]</td>
<td>5.2$\sigma$ (discovery)</td>
</tr>
<tr>
<td>$\mu$ for $H \rightarrow 4\ell$</td>
<td>$1.46^{+0.40}_{-0.34}$</td>
<td>[31]</td>
<td>8.1$\sigma$ (discovery)</td>
</tr>
<tr>
<td>$\mu$ for $H \rightarrow $ℓνℓν</td>
<td>$1.18^{+0.24}_{-0.21}$</td>
<td>[31]</td>
<td>6.5$\sigma$ (discovery)</td>
</tr>
<tr>
<td>$\mu$ for $H \rightarrow $ℓνℓν</td>
<td>$1.44^{+0.42}_{-0.37}$</td>
<td>[31]</td>
<td>4.5$\sigma$ (evidence)</td>
</tr>
<tr>
<td>$\mu$ for $H \rightarrow $bb</td>
<td>$0.63^{+0.39}_{-0.37}$</td>
<td>[31]</td>
<td>1.4$\sigma$ (no evidence)</td>
</tr>
<tr>
<td>$\mu$ for ggF</td>
<td>$1.23^{+0.23}_{-0.20}$</td>
<td>[31]</td>
<td>1.03$^{+0.17}_{-0.15}$ with the CMS</td>
</tr>
<tr>
<td>$\mu$ for VBF</td>
<td>$1.23^{+0.32}_{-0.32}$</td>
<td>[31]</td>
<td>1.18$^{+0.25}_{-0.23}$ with the CMS</td>
</tr>
<tr>
<td>$\mu$ for VH</td>
<td>$0.80 \pm 0.36$</td>
<td>[31]</td>
<td>0.84$^{+0.40}_{-0.38}$ with the CMS</td>
</tr>
<tr>
<td>$\mu$ for ttH</td>
<td>$1.81 \pm 0.80$</td>
<td>[31]</td>
<td>2.3$^{+0.3}_{-0.6}$ with the CMS</td>
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<tr>
<td>Spin/parity</td>
<td>0$^+$</td>
<td>[32]</td>
<td>4$\ell$, $\ell$ν$\ell$ν and $\gamma\gamma$ modes</td>
</tr>
<tr>
<td>Width, MeV</td>
<td>$\leq 22.7$ (95% CL)</td>
<td>[33]</td>
<td>Off-shell $H \rightarrow ZZ/WW$</td>
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<tr>
<td>BR($H \rightarrow$ inv.)</td>
<td>$\leq 0.28$ (95% CL)</td>
<td>[34]</td>
<td>Important for WIMP searches</td>
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</table>

with $\geq 5\sigma$ significance. The resulting signal strength from two LHC experiments is found to be $1.09 \pm 0.10$ [7]. Analyzing the $H \rightarrow ZZ^* \rightarrow 4\ell$, $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ and $H \rightarrow \gamma\gamma$ decay modes, we conclude with very high confidence level that a spin-parity of the Higgs boson is $0^+$, as predicted by the SM [32]. From the off-shell measurements of the $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow WW^* \rightarrow \ell\ell\ell\ell$ channels the upper limit is put to the $H$ width as 22.7 MeV at 95% CL [33]. The ATLAS experiment also looks for invisible decay of the Higgs boson, $H \rightarrow$ inv., which is interesting for WIMP searches. The upper limit on BR($H \rightarrow$ inv.) $\leq 0.28$ is established at 95% CL [34].

In summary, no significant deviation from the SM is observed in the ATLAS studies of the Higgs boson at 7–8 TeV.

5 Conclusion

With the 7 and 8 TeV LHC data the ATLAS experiment measured properties of the Higgs boson such as its couplings, mass, spin and parity. No significant deviation from the SM is found. Using 13-15 fb$^{-1}$ of the 13 TeV LHC data, the ATLAS obtained preliminary results reconfirming the Higgs boson discovery in the $4\ell$ and $\gamma\gamma$ modes. With the same dataset, the ATLAS performed searches for neutral and charge Higgs bosons predicted by some extensions of the SM. No evidence for new physics was found yet. Limits on the $H$ boson production cross sections in different models were put. The ATLAS Collaboration continues to
study properties of the SM-like $H$ boson improving precision of their measurements and to search for exotic Higgs bosons with new 13 TeV data.

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References

[34] ATLAS Collaboration, JHEP 01 (2016) 172