Standard Model Higgs boson searches in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

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Abstract. We report on searches for the Standard Model Higgs boson with the ATLAS detector at the LHC. Several production mechanisms and decay channels are considered and a wide range of hypothetical Higgs boson masses explored. The datasets correspond to integrated luminosities ranging from $4.6 \text{ fb}^{-1}$ to $4.9 \text{ fb}^{-1}$ of proton-proton collisions collected at $\sqrt{s} = 7$ TeV in 2011. At the 95% confidence level the excluded Higgs boson mass ranges are 111.4 GeV to 116.6 GeV, 119.4 GeV to 122.1 GeV, and 129.2 GeV to 541 GeV, while the mass range from 120 GeV to 560 GeV is expected to be excluded in the absence of a signal. An excess of events is observed at a Higgs boson mass around 126 GeV with a local significance of 2.9 $\sigma$. The global probability for the background to produce an excess at least as significant anywhere in the mass range explored corresponds to a significance of approximately 1 $\sigma$.

1. Introduction

The Lagrangian density of electroweak interactions in the Standard Model (SM) [1]-[3] is based on $SU(2)_L \times U(1)_Y$ symmetry. To preserve gauge invariance and renormalization, fermions and gauge bosons need to have zero mass. The Higgs mechanism[4]-[9] consists of introducing a complex doublet of scalar fields which breaks spontaneously the symmetry. Mass is then generated for the weak bosons, leaving the photon massless. Fermions acquire their mass via Yukawa interactions with the Higgs field. A massive scalar particle is then predicted, namely the Higgs boson ($H$). The mass of the Higgs is a free parameter in the SM, which means that Higgs mass hypotheses over a wide range must be considered. However, for a given mass, production cross sections and decay modes branching fractions are well predicted.

Extensive searches have been conducted at $e^+e^-$ and $p\bar{p}$ colliders for many years. From the LEP experiments a Higgs with a mass below 114.4 GeV is excluded at 95% confidence level (CL) [10], while from the Tevatron experiments the mass range excluded is between 147 GeV and 179 GeV [11].

One of the primary goals of the Large Hadron Collider (LHC) is to search for the SM Higgs boson and probe other mechanisms of electroweak symmetry breaking (EWSB). The expected SM Higgs properties and observables at the LHC are compiled in Ref. [12]. In the following sections we are presenting searches for the Standard Model Higgs boson made with the ATLAS detector [13] on the full pp collisions datasets collected at $\sqrt{s} = 7$ TeV in 2011.

2. Search channels and combination

The Higgs boson can decay into several channels. The ones considered are $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^{(*)}$, $H \rightarrow WW^{(*)}$, $H \rightarrow \tau^+\tau^-$ and $H \rightarrow b\bar{b}$. The $ZZ^{(*)}$ and $WW^{(*)}$ channels can be used to explore
the entire mass range while the other channels are more sensitive to the lower mass region due to their higher branching fraction. Moreover, a different analysis strategy is adopted depending on the decay modes of the $W$, $Z$, and $\tau$. The $H \to \gamma\gamma$ and $H \to ZZ^{(*)}$ provide the highest mass resolution. Table 1 summarizes the individual channels and the Higgs mass range considered for each. In order to enhance the signal sensitivity, each channel is treated and optimized separately. Some channels are also broken down into sub-categories as they have different signal and background compositions and are subject to different systematic uncertainties. The observables used in the combination are either the reconstructed invariant mass or the transverse mass depending on the channel considered.

For each Higgs mass hypothesis, the signal strength, $\mu$, is defined as the ratio of a given Higgs boson production cross section ($\sigma$) to its SM value ($\sigma_{SM}$), $\mu = \sigma / \sigma_{SM}$. A value of $\mu = 0$ corresponds to a background-only model and $\mu = 1$ to a SM Higgs. The combination procedure described in details in [16] is based on the profile likelihood ratio test statistic $\lambda(\mu)$ [15], which extracts the information on the signal strength from the full likelihood including all the parameters describing the systematic uncertainties and their correlations. Exclusion limits are based on the modified frequentist approach (CLs prescription) [14]; a value of $\mu$ is regarded as excluded at the 95% (99%) CL when CLs takes on the corresponding value. The analysis corresponding to each channel is summarized below:

### Table 1. Summary of the individual Higgs channels considered. The integrated luminosity and targeted mass range for each decay channel is also listed. $\ell$ is either an electron or a muon.

| Higgs Channel | $m_H$ Range [GeV] | $L$[fb$^{-1}$] | Ref. |
|---------------|-------------------|----------------|------|
| $H \to \gamma\gamma$ | 110-150 | 4.9 | [17] |
| $H \to ZZ^{(*)} \to \ell^+\ell^-\ell^+\ell^-$ | 110-600 | 4.8 | [18] |
| $H \to ZZ^{(*)} \to \ell^+\ell^-\nu\bar{\nu}$ | 200-280-600 | 4.7 | [20] |
| $H \to ZZ^{(*)} \to \ell^+\ell^-q\bar{q}$ | 200-300-600 | 4.7 | [21] |
| $H \to WW^{(*)} \to \ell^+\nu\ell^-\bar{\nu}$ | 100-200-300-600 | 4.7 | [22] |
| $H \to WW^{(*)} \to \ell\nuqq'$ | 300-600 | 4.7 | [23] |
| $H \to \tau^+\tau^- \to \ell\nuqq'$ | 110-150 | 4.7 | [24] |
| $H \to \tau^+\tau^- \to \tau_{lep}\tau_{lep}$ | 110-150 | 4.7 | [24] |
| $H \to \tau^+\tau^- \to \tau_{lep}\tau_{had}$ | 110-150 | 4.7 | [24] |
| $W H \to \ell\nu\bar{b}\bar{b}$ | 110-130 | 4.7 | [25] |
| $ZH \to \ell^+\ell^-b\bar{b}$ | 110-130 | 4.6 | [25] |
| $ZH \to \nu\nu\bar{b}\bar{b}$ | 110-130 | 4.6 | [25] |

- $H \to \gamma\gamma$: the search consists in selecting two isolated photons with high transverse energy. The background contributions come for the irreducible diphoton continuum, and the reducible photon+jet and jet+jet, where a jet passes the photon selection. The analysis is conducted using nine independent event classifications of varying signal and background compositions and mass resolution. The classification is based on the pseudo-rapidity of each photon, whether reconstructed as a converted or unconverted photon, and the kinematics of the diphoton system. The diphoton invariant mass distribution is fitted using a Crystal Ball and Gaussian functions to estimate the background and is used as a discriminating variable to distinguish signal and background. The mass resolution is approximately 1.7% for a Higgs mass of 120 GeV. In Figure 1 (left) the invariant mass distribution of the diphoton system is shown for the selected candidate events, the fitted background shape and the
expected Higgs signal for $m_H = 125$ GeV. The observed and expected 95% CL limits on the SM Higgs boson production normalized to the predicted cross section as a function of $m_H$ is shown on Figure 1 (right). The largest excess is observed at 126.5 GeV with a local significance of 2.8σ. The excluded mass ranges at 95% CL are from 113 GeV to 115 GeV and from 134.5 GeV to 136 GeV.

- $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^−\ell^+\ell^−$: this channel provides a clean signature with a very small background. The analysis consists in selecting two pairs of oppositely-charged same-flavor leptons with high transverse energy for two of the leading leptons. The invariant mass of one lepton-pair is required to be consistent with the $Z$ mass, while for the second pair the constraint applied is $m_H$ dependent. The main irreducible $ZZ^{(*)}$ background is estimated using Monte Carlo simulation. The reducible $Z$+jets background, which has an impact mostly for low four-lepton invariant masses, is estimated from control regions in the data. The top quark ($t\bar{t}$) background normalization is validated using a dedicated control sample. The events are categorized according to the lepton flavour combinations. The mass resolutions are approximately 1.5% in the four-muon channel and 2% in the four-electron channel for $m_H = 120$ GeV. The invariant mass of the four-lepton system is used as a discriminating variable and the distributions are shown in Figure 2 (left) for the lower mass region. The observed and expected 95% CL limits on the SM Higgs boson production normalized to the predicted cross section as a function of $m_H$ is shown on Figure 2 (right). In this channel, the largest excess is observed at 125 GeV, 244 GeV and 500 GeV, with a local significance of 2.1σ, 2.2σ and 2.1σ respectively. This excess is comparable to the $H \rightarrow \gamma\gamma$ channel. The range of Higgs masses excluded at 95% CL are from 134 GeV to 156 GeV, 182 GeV to 233 GeV, 256 GeV to 265 GeV and 268 GeV to 415 GeV.

- $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^−\nu\bar{\nu}$: the search consists in selecting a pair of oppositely-charged electrons or muons with a high transverse energy and a large missing transverse energy due to the neutrinos. The invariant mass of the electrons or muons should be consistent with the $Z$ mass. To increase the sensitivity, the analysis is further optimized for separate Higgs mass regions below and above 280 GeV, lepton flavour categories, and different data
taking conditions. For instance the average number of interactions per bunch crossing during collisions in the latter part of 2011 was 12. The transverse mass of the dilepton and missing transverse energy system is used as a discriminating variable. No significant excess is observed in this channel and a Higgs mass range from 320 GeV to 560 GeV is excluded at 95% CL. The 95% CL limits are shown in Figure 4.

- $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^- q\bar{q}$: the candidate events are selected by requiring a pair of oppositely-charged electrons or muons and a pair of jets with high transverse energy, and each pair invariant mass should be consistent with a $Z$ boson. The analysis is separated and optimized into Higgs mass regions above and below 300 GeV. The dominant background arises from $Z$+jets production. A sizable fraction of $Z$'s decay into a pair of b-quarks. The analysis is divided into two categories, the first containing events where the two jets are b-tagged and the second using events with less than two b-tags. Using the $Z$ boson mass constraint improves the mass resolution of the $\ell^+\ell^- q\bar{q}$ system by approximately 10% which is used as a discriminating variable. No significant excess is observed in this channel and Higgs mass ranges from 300 GeV to 310 GeV and from 360 GeV to 400 GeV are excluded at 95% CL. The 95% CL limits are shown in Figure 4.

- $H \rightarrow WW^{(*)} \rightarrow \ell^+\nu\ell^-\bar{\nu}$: the search consists in selecting a pair of electrons, muons, or electron-muon with opposite charges and high transverse energy. The lepton pair must not be consistent with a $Z$. Missing transverse energy is also required to be present. The search is optimized for $m_H < 200$ GeV, $200$ GeV $\leq m_H \leq 300$ GeV and $m_H > 300$ GeV due to spin correlations in the $WW^{(*)}$ and kinematic features of the two leptons. The events are classified into jet multiplicities of 0, 1, or 2. The 2-jet category selection targets vector boson fusion (VBF) production process by requiring events to have two jets with a large difference in pseudo-rapidity, a large reconstructed invariant mass and no additional energetic jet in
Figure 3. The observed (full line) and expected (dashed line) 95% CL limits on the SM Higgs boson production normalized to the predicted cross section as a function of $m_H$ are shown for the entire mass range (left) and the low mass region (right) [22]. The dotted curves show the median expected limit in the absence of a signal and the green and yellow bands indicate the corresponding $\pm 1\sigma$ and $\pm 2\sigma$ intervals.

between. The transverse mass of the $WW$ system distribution is used as a discriminating variable. No significant excess is found in this channel and a Higgs mass range from 130 GeV to 260 GeV is excluded at 95% CL. The 95% CL limits are shown in Figure 3.

- $H \to WW^{(*)} \to \ell\nu qq'$: the analysis requires an isolated electron or muon, two jets and missing transverse energy. Additional jets are used to further classify the events as in the previous channel. The invariant mass of the two jets must be consistent with a $W$. The reconstructed $\ell\nu qq'$ mass distribution is used as a discriminating variable. It is estimated using the $W$ boson mass constraint to reconstruct the mass of the $\ell\nu$ system. Events with at least one $b$-tagged jet are rejected to reduce backgrounds from $t\bar{t}$ production. No significant excess is found in this channel and no Higgs mass range excluded from this channel alone. The 95% CL limits are shown in Figure 4.

- $H \to bb'$: this is an important channel to explore in the low mass region because of the high branching fraction, however the multijet background is very large. One has to leverage on the associated Higgs production with a $W$ or $Z$ boson. All three channels below require the events to have exactly two $b$-tagged jets with high transverse energy. The invariant mass of the $b$ jets $m_{bb}$ is used as a discriminating variable. Additional requirements are the following depending on the associated vector boson and its decay:
  - $WH \to \ell\nu bb'$: an isolated electron or muon and missing transverse energy,
  - $ZH \to \ell^+\ell^- bb'$: a pair of electrons or muons with opposite charges consistent with a $Z$ and no significant missing transverse energy present to reduce background from $t\bar{t}$.
  - $ZH \to \nu\bar{\nu} bb'$: a large missing transverse energy and missing transverse momentum using tracks associated with the primary vertex.

The Higgs will recoil against the $W$ or $Z$. This feature is exploited to increase the sensitivity further by looking at four separate regions of $W$, or $Z$ transverse momentum when decaying into charged leptons. For $Z \to \nu\bar{\nu}$ process, the channel is separated into three missing transverse energy regions. These regions have different signal and background compositions. No significant excess is observed in this channel and no Higgs mass region is excluded from this channel alone. The 95% CL limits are shown in Figure 4.
• $H \to \tau^+\tau^-$: although less sensitive due to a small branching fraction and presence of a dominant background from $Z \to \tau^+\tau^-$, it is nevertheless an important channel to look at. The search is split into three different channels depending on the $\tau$ decay mode either leptonic ($\tau_{\text{lep}}$) or hadronic ($\tau_{\text{had}}$). The invariant mass of the $\tau^+\tau^-$ system $m_{\tau\tau}$ is used as a discriminating variable and is calculated using different techniques depending on the event topology. A hadronic tau decay candidates is identified as a narrow jet with a low track multiplicity. The requirements for each channel considered are listed below:

- $H \to \tau^+\tau^- \to \tau_{\text{lep}}\tau_{\text{lep}}$: two isolated and oppositely-charged leptons (either electrons or muons) are required along with a large missing transverse energy present in the event. The separation is done into different jet multiplicities. For the 0-jet category only an electron-muon pair is considered, while for the 1-jet and 2-jet categories all flavour combinations are used. The 2-jet category aims for the VBF contribution as described previously and for the associated production with process with a $Z$, or $W$ decaying hadronically with specific requirements on the two jets selected. For the 0-jet category the invariant mass between the missing transverse energy and four-momenta of the two selected leptons is used as a discriminating variable. For the other categories the mass reconstructed in the collinear approximation is used.

- $H \to \tau^+\tau^- \to \tau_{\text{lep}}\tau_{\text{had}}$: an isolated electron or muon along with a $\tau$ jet having opposite charges are required, and missing transverse energy. No additional electron or muon should be present to suppress background from $Z$ and top quark production. The new Missing Mass Calculator technique is used [26] for the discriminating variable.

- $H \to \tau^+\tau^- \to \tau_{\text{had}}\tau_{\text{had}}$: missing transverse energy, two oppositely-charged $\tau$ jets are required and in order to reduce the large multijet background an additional jet with high transverse energy is required. No electrons or muons should be present in the event. The collinear approximation is used when estimating $m_{\tau\tau}$.

No significant excess is observed in this channel and no Higgs mass region is excluded from this channel alone. The 95% CL limits are shown in Figure 4.

3. Combination and Results

All the channels described in the previous section have been combined into a global likelihood fit. A detailed description of the combination of all the channels can found in Ref. [16], including the treatment of statistical, systematic and theoretical uncertainties. The expected and observed 95% CL limits are shown in Figure 5 for the entire Higgs mass range considered in this search. At the 95% confidence level the excluded Higgs boson mass ranges are 111.4 GeV to 116.6 GeV, 119.4 GeV to 122.1 GeV, and 129.2 GeV to 541 GeV, while the mass range from 120 GeV to 560 GeV is expected to be excluded in the absence of a SM Higgs signal. An excess of events is observed at a Higgs boson mass around 126 GeV with a local significance of 2.9$\sigma$. This excess is observed in the $H \to \gamma\gamma$ and $H \to ZZ^{(*)} \to \ell^+\ell^-\ell^+\ell^-$ channels. The global probability for the background to produce an excess at least as significant anywhere in the mass range explored corresponds to a significance of approximately 1$\sigma$. The local $p_0$ probabilities are shown in Figure 6 (left). The combined best-fit of the signal strength as a function of the Higgs boson mass hypothesis in the low mass range is shown in Figure 6 (right). The signal strength $\hat{\mu}$ at 126 GeV is $1.1 \pm 0.4$, which is compatible with a SM Higgs boson at that mass ($\mu = 1$).

4. Conclusion

We reported on searches for the Standard Model Higgs boson with the ATLAS detector at the LHC. The datasets correspond to integrated luminosities ranging from 4.6 fb$^{-1}$ to 4.9 fb$^{-1}$ of
Figure 4. The observed (solid) and expected (dashed) 95% CL cross section upper limits for the individual search channels and the combination, normalized to the SM Higgs boson production cross section, as a function of the Higgs boson mass for the full Higgs boson mass (left) and low mass hypotheses range (right) [16]. The expected limits are those for the background-only hypothesis i.e. in the absence of a Higgs boson signal.

Figure 5. The observed (full line) and expected (dashed line) 95% CL combined upper limits on the SM Higgs boson production cross section divided by the SM expectation as a function of $m_H$ in the full mass range (left) and low mass region (right) considered in this analysis [16]. The dotted curves show the median expected limit in the absence of a signal and the green and yellow bands indicate the corresponding $\pm 1\sigma$ and $\pm 2\sigma$.

proton-proton collisions collected at $\sqrt{s} = 7$ TeV in 2011. Several channels were considered and a comprehensive statistical combination performed over the mass range from 110 GeV to 600 GeV. An excess is observed and it is compatible with a SM Higgs boson in the low mass region at around 126 GeV. The datasets collected in 2012 at $\sqrt{s} = 8$ TeV will be essential in understanding this excess further. The Higgs production cross section in the low mass region is enhanced by about 20% at that energy and therefore looks promising for subsequent searches.

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Figure 6. On the left, the local probability $p_0$ for a background-only experiment to be more signal-like than the observation, for individual channels and the combination in the low mass range of 110–150 GeV [16]. The full curves give the observed individual and combined $p_0$. The dashed curves show the median expected value under the hypothesis of a SM Higgs boson signal at that mass. The horizontal dashed lines indicate the $p_0$ corresponding to significances of $1\sigma$, $2\sigma$, and $3\sigma$. On the right, the combined best-fit signal strength as a function of the Higgs boson mass hypothesis in the low mass range is shown [16]. The interval around the best fit value of corresponds to a variation of $-2 \ln \lambda(\mu) < 1$.

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