Search for the Standard Model Higgs boson in the decay channel
$H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ with $4.8 \text{ fb}^{-1}$ of $pp$ collisions at $\sqrt{s} = 7 \text{ TeV}$

The ATLAS collaboration

Abstract

A search for the Standard Model Higgs boson in the decay channel $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^-\ell'^+\ell'^-$, where $\ell, \ell' = e, \mu$, is presented. Proton-proton collision data at $\sqrt{s} = 7$ TeV recorded with the ATLAS detector and corresponding to an average integrated luminosity of $4.8 \text{ fb}^{-1}$ are compared to the Standard Model background expectations. Upper limits on the production cross section of a Standard Model Higgs boson with a mass between 110 GeV and 600 GeV are derived. The Standard Model Higgs boson is excluded at 95% confidence level in the mass ranges $135 \text{ GeV} - 156 \text{ GeV}$, $181 \text{ GeV} - 234 \text{ GeV}$ and $255 \text{ GeV} - 415 \text{ GeV}$. The largest deviations from the background expectation are observed for $m_H = 125$ GeV with a $p_0$-value of 1.8%, $m_H = 244$ GeV with a $p_0$-value of 1.1% and $m_H = 500$ GeV with a $p_0$-value of 1.4%. Once the look-elsewhere effect is considered, none of these excesses is significant by itself.
1 Introduction

The search for the Standard Model (SM) Higgs boson [1–3] is a major goal of the Large Hadron Collider (LHC) programme. Direct searches at the CERN LEP $e^+e^-$ collider excluded at 95% confidence level (CL) the production of a SM Higgs with $m_H < 114.4$ GeV [4]. The searches at the Fermilab Tevatron $p\bar{p}$ collider have excluded at 95% CL the region $156$ GeV $< m_H < 177$ GeV [5]. At the LHC, the latest results of the ATLAS SM Higgs searches [6] based on data collected during the early part of the 2011 LHC run exclude the Higgs boson mass ($m_H$) ranges $146^{−230}_{+256}$ GeV, $256^{−282}_{+296}$ GeV and $310^{−400}_{+459}$ GeV [7]. A preliminary combination of $1.0^{−2.3}_{+1.0}$ fb$^{-1}$ of LHC data per experiment exclude the SM Higgs in the region $141$ GeV $< m_H < 476$ GeV at 95% CL [8].

In ATLAS several final states are used to search for the SM Higgs boson [9–17]. The search for the SM Higgs through the decay $H \rightarrow ZZ(\ast) \rightarrow \ell^+\ell^−\ell′^+\ell′^−$, where $\ell, \ell′ = e, \mu$ provides good sensitivity in a wide mass range. The results of the previous search in this channel, with $2.1$ fb$^{-1}$ [10], showed exclusion in three mass regions between $191$ GeV and $224$ GeV. This note presents an update of the ATLAS search for a SM Higgs boson in this channel for the mass range from $110$ GeV to $600$ GeV$^1$. Three distinct final states, $\mu\mu\mu\mu$ ($4\mu$), $ee\mu\mu$ ($2e2\mu$), and $eeee$ ($4e$), are selected. The largest background to this search comes from continuum $ZZ(\ast)$ production. For $m_H < 180$ GeV, contributions from $Z$ + jets and $t\bar{t}$ processes, where the additional charged leptons arise either from decays of hadrons with heavy ($b$ and $c$-quark) flavour content or from light-flavour-jets misidentified as leptons, are important. The $pp$ collision data were recorded with the ATLAS detector at the LHC at $\sqrt{s} = 7$ TeV and correspond to an average integrated luminosity of $4.8$ fb$^{-1}$ [18], more than twice that of Ref. [10]. With respect to Ref. [10] the electron identification has been refined to improve efficiency. The electron tracks have been refitted using the Gaussian Sum Filter [19,20] which corrects for energy losses due to bremsstrahlung, offering more accurate track parameter measurements. Moreover, the muon momentum resolution has improved due to improved alignment of the inner detector and muon spectrometer.

2 The ATLAS Detector

The ATLAS detector [21] is a multi-purpose particle physics apparatus with forward-backward symmetric cylindrical geometry$^2$. The inner tracking detector (ID) consists of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker. The ID is surrounded by a thin superconducting solenoid providing a 2T magnetic field. A high-granularity lead-liquid argon (LAr) sampling calorimeter measures the energy and the position of electromagnetic showers. An iron-scintillator tile calorimeter provides hadronic coverage in the central rapidity range. The end-cap and forward rapidity regions are instrumented with LAr calorimetry for both electromagnetic and hadronic measurements. The muon spectrometer (MS) surrounds the calorimeters and consists of three large superconducting toroids, each with eight coils, a system of precision tracking chambers, and detectors for triggering. A three-level trigger system selects events to be recorded for offline analysis.

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$^1$The kinematic acceptance of this search has not been optimized for low mass Higgs bosons.

$^2$ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point. The z-axis is along the beam pipe, the x-axis points to the centre of the LHC ring and the y-axis points upward. Cylindrical coordinates ($r,\phi$) are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity $\eta$ is defined as $\eta = −\ln[\tan(\theta/2)]$ where $\theta$ is the polar angle.
3 Data and Simulation Samples

The accumulated data are subjected to quality requirements ensuring that the relevant detector components were operating normally. The resulting average integrated luminosity of 4.8 fb$^{-1}$ corresponds to 4.81 fb$^{-1}$ and 4.91 fb$^{-1}$ for the $4\mu$, $2e2\mu$ and $4e$ final states, respectively.

The $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ signal is modelled using the POWHEG Monte Carlo (MC) event generator [22, 23], which calculates separately the gluon and vector-boson fusion production mechanisms with matrix elements up to next-to-leading order (NLO). The Higgs boson transverse momentum, $p_T$, spectrum in the gluon fusion process is reweighted to the calculation of Ref. [24], providing QCD corrections up to next-to-leading order and QCD soft-gluon resummations up to next-to-next-to-leading log (NNLL). POWHEG is interfaced to PYTHIA [25] for showering and hadronization, which in turn is interfaced to PHOTOS [26] for QED radiative corrections in the final state and to TAUOLA [27, 28] for the simulation of $\tau$ decays. For the Higgs boson associated production with a $W$ or a $Z$ boson, PYTHIA is used.

The cross sections for Higgs boson production, the corresponding branching fractions, as well as their uncertainties [29], are derived to next-to-next-to-leading order (NNLO) in QCD for the gluon fusion [30–35], vector-boson fusion [36] and the associated production with a $W$ or $Z$ boson [37] processes. In addition, QCD soft-gluon resummations up to NNLL are available for the gluon fusion process [38], while the NLO electroweak (EW) corrections are applied to the gluon fusion [39, 40], the vector-boson fusion [41, 42] and the associated production with a $W$ or $Z$ boson [43] processes. These cross section calculations do not take into account the width of the Higgs boson, which is implemented through a Breit-Wigner line shape applied at the event generator level. Recent studies [44–46] have indicated that effects related to off-shell Higgs boson production and interference with other SM processes may become sizeable at the highest masses ($m_H > 400$ GeV) considered in this search. In the absence of a full calculation, a conservative estimate of the possible size of such effects was included as a signal normalization systematic uncertainty following a parameterization as a function of $m_H : 150\% \times (m_H [\text{TeV}])^3$, for $m_H \geq 300$ GeV [47]. The Higgs boson decay branching ratio to the four-lepton final state is predicted by PROPHET4F [48,49], which includes the complete NLO QCD+EW corrections, interference effects between identical final state fermions and leading two-loop heavy Higgs boson corrections to the four-fermion width. Table 1 gives the production cross sections and branching ratios for $H \rightarrow 4\ell$ for several Higgs boson masses.

Table 1: Higgs boson production cross sections for gluon fusion, vector-boson fusion and associated production with a $W$ or $Z$ boson in $pp$ collisions at $\sqrt{s} = 7$ TeV. The quoted uncertainties correspond to the total theoretical systematic uncertainty. The branching ratio of $H \rightarrow 4\ell$, with $\ell = e, \mu$, is reported in the last column.

<table>
<thead>
<tr>
<th>$m_H$ [GeV]</th>
<th>$\sigma (gg \rightarrow H)$ [pb]</th>
<th>$\sigma (qq \rightarrow Hqq)$ [pb]</th>
<th>$\sigma (qq \rightarrow WH)$ [pb]</th>
<th>$\sigma (qq \rightarrow ZH)$ [pb]</th>
<th>BR ($H \rightarrow 4\ell$) $\times 10^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>130</td>
<td>$14.1^{+3.7}_{-2.1}$</td>
<td>$1.154^{+0.022}_{-0.027}$</td>
<td>$0.501 \pm 0.020$</td>
<td>$0.278 \pm 0.014$</td>
<td>0.19</td>
</tr>
<tr>
<td>150</td>
<td>$10.5^{+2.0}_{-1.6}$</td>
<td>$0.962^{+0.028}_{-0.021}$</td>
<td>$0.300 \pm 0.012$</td>
<td>$0.171 \pm 0.009$</td>
<td>0.38</td>
</tr>
<tr>
<td>200</td>
<td>$5.2^{+0.9}_{-0.8}$</td>
<td>$0.637^{+0.022}_{-0.015}$</td>
<td>$0.103 \pm 0.005$</td>
<td>$0.061 \pm 0.004$</td>
<td>1.15</td>
</tr>
<tr>
<td>300</td>
<td>$2.4 \pm 0.3$</td>
<td>$0.301^{+0.014}_{-0.008}$</td>
<td>$0.020 \pm 0.001$</td>
<td>$0.012 \pm 0.001$</td>
<td>1.38</td>
</tr>
<tr>
<td>400</td>
<td>$2.0 \pm 0.3$</td>
<td>$0.162^{+0.010}_{-0.005}$</td>
<td>$\cdots$</td>
<td>$\cdots$</td>
<td>1.21</td>
</tr>
<tr>
<td>600</td>
<td>$0.33 \pm 0.06$</td>
<td>$0.058^{+0.005}_{-0.002}$</td>
<td>$\cdots$</td>
<td>$\cdots$</td>
<td>1.23</td>
</tr>
</tbody>
</table>

The $ZZ^{(*)}$ continuum background is generated using PYTHIA, taking into account $Z - \gamma$ interference. For the inclusive total cross section and the shape of the $m_{ZZ^{(*)}}$ spectrum, the MCFM [50, 51] prediction is used, which includes both quark-antiquark annihilation at QCD NLO and gluon fusion. The inclusive
Z boson production, $Z + \text{jets}$, is modelled using ALPGEN [52] and is divided into $Z + \text{light-flavour-jets}$, which includes also $Zc\bar{c}$ at the massless $c$-quark approximation and $Zb\bar{b}$ from parton showers, and $Zb\bar{b}$ using massive matrix elements. The overlaps between the two samples are removed. Specifically, $b\bar{b}$ pairs with separation $\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} \geq 0.4$ between the $b$-quarks are taken from the matrix-element calculation, whereas for $\Delta R < 0.4$ the parton-shower $b\bar{b}$ pairs are taken. PYTHIA is also used as a cross-check of the ALPGEN results. In this search the $Z + \text{jets}$ background is normalized using data control samples, but for comparisons the QCD NNLO FEWZ [53,54] and the MCFM [50,51] cross section calculations are used for the inclusive $Z$ boson and $Zb\bar{b}$ production, respectively. The $t\bar{t}$ background is modelled using MC@NLO [55] and is normalized to the approximate NNLO cross section calculated using HATHOR [56]. Both ALPGEN and MC@NLO are interfaced to HERWIG [57] for parton shower hadronization and to JIMMY [58] for the underlying event simulations.

All generated events undergo a full detector simulation performed using GEANT4 [59, 60]. Additional $pp$ interactions in the same bunch crossing (pile-up) are included in the simulation. The MC samples are reweighted to reproduce the observed distribution of the mean number of interactions per bunch crossing in the data.

## 4 Physics Object Identification and Event Selection

The data considered in this analysis were selected using single-lepton triggers. The trigger threshold on the transverse energy, $E_T$, of electrons was $20 - 22$ GeV depending on the LHC instantaneous luminosity, while for muons the $p_T$ threshold was $18$ GeV. Both triggers are more than 99.5% efficient for events passing the offline selection described below.

Electron candidates consist of clusters of energy deposited in the electromagnetic calorimeter associated to ID tracks. The electron candidates must satisfy a set of identification criteria [61], which require the shower profiles to be consistent with those expected for electromagnetic showers and a well reconstructed ID track pointing to the corresponding cluster. The electron transverse momentum is computed from the cluster energy and the track direction at the interaction point.

Muon candidates are reconstructed by matching ID tracks with either full or partial tracks in the MS [62,63]. For the former case, the two independent momentum measurements are combined, whereas for the latter case the momentum is measured using the ID information only, with the MS providing muon identification. To reject cosmic rays, muon tracks are required to have a transverse impact parameter with respect to the primary vertex, defined as the reconstructed vertex with the highest $\sum p_T^2$ of associated tracks among the reconstructed vertices with at least three associated tracks, of less than 1 mm.

Leptons from Higgs boson decays are expected to be isolated and to originate from the primary vertex. The longitudinal impact parameter of the leptons is required to be within 10 mm from the primary vertex. Track and calorimeter isolation requirements, together with requirements on the transverse impact parameter significance of the lepton, are applied to further reduce the $Z + \text{jets}$ and $t\bar{t}$ background contributions. The transverse impact parameter significance of the lepton is defined as its impact parameter in the transverse plane with respect to the primary vertex, divided by the corresponding uncertainty.

The sum of the $p_T$ of tracks within $\Delta R < 0.2$ of the lepton divided by the lepton $p_T$ is required to be less than 0.15, while the sum of the $E_T$ of the calorimeter cells within $\Delta R < 0.2$ around the lepton divided by the lepton $p_T$ is required to be less than 0.3. The track of the lepton candidate and the energies of cells associated to it are excluded from the calculation of the isolation energy. For the calorimeter isolation of electrons, in particular, the transverse energies in the $5 \times 7$ electromagnetic calorimeter cells around the cluster barycenter are excluded [61]. To reduce the impact of pile-up, the tracks included in the $p_T$ sum for track isolation must be associated with the primary vertex, and the transverse energy included in the $E_T$ sum for calorimeter isolation is corrected by subtracting an average offset as a function of the number
of reconstructed vertices in the event. In events with four-lepton invariant mass below 190 GeV, the transverse impact parameter significance for the two lowest $p_T$ leptons in the quadruplet is required to be less than 3.5 and 6 for muons and electrons respectively. The selection efficiency of the isolation and impact parameter requirements has been studied using data both for isolated leptons, with $Z \rightarrow \ell\ell$ decays, and non-isolated leptons from semi-leptonic $b$ and $c$-quark decays in a heavy-flavour enriched dijet sample. Good agreement is observed between data and simulation.

Higgs boson candidates are searched for by selecting two same-flavour, opposite-sign isolated lepton pairs in an event. Each lepton must satisfy $p_T > 7$ GeV and be measured in the pseudorapidity range $|\eta| < 2.47$ for electrons and $|\eta| < 2.7$ for muons. At least two leptons in the quadruplet must have $p_T > 20$ GeV. The leptons are required to be well-separated from each other with $\Delta R > 0.1$. The invariant mass of the lepton pair closest to the nominal $Z$ boson mass ($m_Z$) is denoted $m_{12}$ and it is required that $|m_Z - m_{12}| < 15$ GeV. The invariant mass of the remaining, lepton pair, $m_{34}$, is required to be lower than 115 GeV and greater than a threshold depending on the reconstructed four-lepton mass, $m_4\ell$, as summarized in Table 2. The final discriminating variable is $m_4\ell$, where the Higgs boson production would appear as a clustering of events. In Fig. 1 the invariant mass distributions for the 4µ and 4e channels are presented for a simulated signal sample with $m_H = 130$ GeV. The width of the reconstructed Higgs boson mass distribution is dominated by experimental resolution at low $m_H$ values, while at high $m_H$ the reconstructed width is dominated by the natural width of the Higgs boson with a full-width at half-maximum of approximately 35 GeV at $m_H = 400$ GeV.

Table 2: Thresholds applied to $m_{34}$ for reference values of $m_{4\ell}$ (see text). For other $m_{4\ell}$ values, the selection requirement is obtained via linear interpolation.

<table>
<thead>
<tr>
<th>$m_{4\ell}$ (GeV)</th>
<th>≤120</th>
<th>130</th>
<th>140</th>
<th>150</th>
<th>160</th>
<th>165</th>
<th>180</th>
<th>190</th>
<th>≥200</th>
</tr>
</thead>
<tbody>
<tr>
<td>threshold (GeV)</td>
<td>15</td>
<td>20</td>
<td>25</td>
<td>30</td>
<td>30</td>
<td>35</td>
<td>40</td>
<td>50</td>
<td>60</td>
</tr>
</tbody>
</table>

5 Background Estimation

The composition of the background is verified in a control region defined by the analysis selection, but without applying the charge, isolation and impact parameter requirements on the second lepton pair. The $m_{34}$ distributions in this control sample are presented in Fig. 2. For large values of $m_{34}$ the ZZ background dominates, while for low values of $m_{34}$ the dominant background source depends on the flavour of the second lepton pair. In final states with an $ee$ second pair, the $Z+$light-flavour-jets background is dominant, while the $Zb\bar{b}$ production dominates the final states with a $\mu\mu$ second pair. The normalization of the $t\bar{t}$ background, which also contributes substantially in the latter final state, is verified using a control region with opposite-sign electron-muon pairs consistent with the $Z$ boson mass and two additional same-flavour leptons. The $ZZ^{(*)}$ background is normalized using MC, while the $Z+$jets is normalized using data. The observed background rate, which is found to be in good agreement with expectation, is extrapolated to the signal region by means of the MC simulation.

6 Systematic Uncertainties

Uncertainties on lepton reconstruction and identification efficiency, and on the momentum resolution and momentum scale are determined using samples of $W$, $Z$ and $J/\psi$ decays. The muon efficiency uncertainty results in an acceptance uncertainty on the signal and the irreducible background which is uniform over the mass range of interest and amounts to 0.22% (0.16%) for the 4µ (2e2µ) channel. The
Figure 1: Invariant mass distributions for simulated (a) $H \rightarrow ZZ^{(*)} \rightarrow 4\mu$ and (b) $H \rightarrow ZZ^{(*)} \rightarrow 4e$ for $m_H = 130$ GeV. The fraction of events outside the $\pm 2\sigma$ region is found to be 15% for $4\mu$ and 18% for $4e$ for $m_H = 130$ GeV.

Figure 2: Invariant mass distribution of the second lepton pair: (a) $\mu \mu$ and (b) $ee$. The kinematic selections of the analysis have been applied. Isolation requirements have been applied on the first lepton pair. No charge requirements were applied to the second lepton pair.

uncertainty on the electron efficiency results in an acceptance uncertainty of 2.3% (1.6%) for the $4e$ ($2e2\mu$) channel at $m_{4\ell} = 600$ GeV and reaching 8.0% (4.1%) at $m_{4\ell} = 110$ GeV. The effect of the muon momentum resolution and scale uncertainty is found to be small. For electrons the energy resolution uncertainty is relatively small, while the uncertainty on $m_{4\ell}$ due to the electron energy scale uncertainty
is estimated to be 0.6% (0.3%) for the 4e(2e2µ) channel. Fitting energy scales to the data can cause fluctuations to align, so to be conservative the energy scale uncertainty is neglected when combining results in the current analysis.

A conservative theoretical uncertainty of 15% is assigned to the ZZ\(^{(s)}\) background contribution [64]. The Z+light-flavour-jets and Zb\(\bar{b}\) backgrounds are evaluated using data. A systematic uncertainty of 45% and 40%, respectively, is assigned on their normalization to account for the statistical uncertainty in the control sample and the MC-based extrapolation to the signal region. The theoretical uncertainties on the \(t\bar{t}\) cross-section, approximately 10% [56], are included. The additional uncertainty in the \(t\bar{t}\) selection efficiency, estimated to be 10%, is negligible in comparison with the errors on the larger backgrounds.

The theoretical uncertainties on the Higgs boson production cross section are 15–20% for the gluon fusion process, 3–9% for the vector-boson fusion and 3–4% for the associated production (\(WH/ZH\)) process [29], depending on the Higgs boson mass. They include uncertainties on the QCD scale and on the parton distribution functions [65–68]. An additional 2% uncertainty is added to the signal selection efficiency due to the modelling of the signal kinematics. This is evaluated by comparing signal samples generated with PYTHIA and the default POWHEG samples.

The overall uncertainty on the integrated luminosity for the complete 2011 dataset is 3.9%, based on the calibration described in Ref. [18] with an additional uncertainty for the extrapolation to the later data-taking period with higher instantaneous luminosity.

7 Results

The number of events observed in each final state, evaluated separately for \(m_4l < 180\) GeV and \(m_4l \geq 180\) GeV, are compared with the expectations for background and signal for various \(m_H\) hypotheses in Table 3. In total 71 candidate events are selected by the analysis: 24 4\(\mu\), 30 2e2\(\mu\), and 17 4\(e\) events, while in the same mass range 62±9 events are expected from the background processes; 18.6±2.8 4\(\mu\), 29.7±4.5 2e2\(\mu\) and 13.4±2.0 4\(e\). The \(m_{12}\) and \(m_{34}\) mass spectra are shown in Fig. 3. The \(m_{4l}\) distribution for the total background and several signal hypotheses is compared to the data in Fig. 4. In Fig. 5, the \(p_T\) and \(\eta\) distributions of the leptons of the selected candidates are provided.

Upper limits are set on the Higgs boson production cross section at 95% CL, using the \(CL_s\) modified frequentist formalism [69] with the profile likelihood test statistic [70]. The test statistic is evaluated with a maximum likelihood fit of signal and background models to the observed \(m_4l\) distribution. Figure 6 shows the expected and observed 95% CL cross section upper limits as a function of \(m_H\) and Table 4 summarizes the numerical values for selected \(m_H\) points. The SM Higgs boson is excluded at 95% CL in the mass ranges 135 GeV – 156 GeV, 181 GeV – 234 GeV and 255 GeV – 415 GeV. The expected exclusion ranges are 137 GeV – 158 GeV and 185 GeV – 400 GeV.

The \(p_0\)-value is the probability of upward fluctuations in the background as high as or higher than the excesses observed in data. The consistency of the observed results with the background-only hypothesis expressed as \(p_0\)-values is shown in Fig. 7 over the full mass range of the analysis. The most significant deviations from the background-only hypothesis are observed for \(m_H = 125\) GeV with a local \(p_0\)-value of 1.8% (2.1\(\sigma\)), \(m_H = 244\) GeV with a local \(p_0\)-value of 1.1% (2.3\(\sigma\)) and \(m_H = 500\) GeV with a \(p_0\)-value of 1.4% (2.2\(\sigma\)). These values do not account for the so-called \textit{look-elsewhere effect}, taking into account that such an excess (or larger) can appear anywhere in the search range as a result of an upward fluctuation of the background.

For an estimate of the \textit{look-elsewhere effect}, similarly to Ref. [8], the method of Ref. [71] is used. When considering the complete mass range of this search, the global \(p_0\)-value for all the three excesses becomes more than 50%. In particular for the excess at \(m_H = 125\) GeV, if the mass range is (a posteriori) constrained to the lowest mass region not excluded at 99% by the recent LHC combined Higgs search results [8] (\(m_H < 146\) GeV), the global \(p_0\)-value becomes of \(O(30\%)\). From these it is concluded that,
Table 3: The expected number of signal and background events, with their systematic uncertainty, separated into “Low $m_{4\ell}$” ($m_{4\ell} < 180$ GeV) and “High-$m_{4\ell}$” ($m_{4\ell} \geq 180$ GeV) regions. The observed numbers of events are also presented.

<table>
<thead>
<tr>
<th></th>
<th>$\mu\mu\mu\mu$</th>
<th>$ee\mu\mu$</th>
<th>$eeee$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Int. Luminosity</strong></td>
<td>4.81 fb$^{-1}$</td>
<td>4.81 fb$^{-1}$</td>
<td>4.91 fb$^{-1}$</td>
</tr>
<tr>
<td>$ZZ^(*)$</td>
<td>2.0±0.3</td>
<td>2.8±0.6</td>
<td>1.3±0.3</td>
</tr>
<tr>
<td>$Z, Zb\bar{b}$, and $t\bar{t}$</td>
<td>0.16±0.06</td>
<td>0.02±0.01</td>
<td>0.17±0.08</td>
</tr>
<tr>
<td>Total Background</td>
<td>2.2±0.3</td>
<td>4.2±0.8</td>
<td>2.9±0.8</td>
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</table>

<table>
<thead>
<tr>
<th>$m_H$</th>
<th>0.58 ± 0.10</th>
<th>0.73 ± 0.13</th>
<th>0.25 ± 0.05</th>
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<tr>
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<td>1.00 ± 0.17</td>
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<td>0.43 ± 0.08</td>
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<td>2.1 ± 0.3</td>
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<td>$m_H$</td>
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<td>$m_H$</td>
<td>0.34 ± 0.04</td>
<td>0.62 ± 0.10</td>
<td>0.30 ± 0.06</td>
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</table>

Figure 3: Invariant mass distributions (a) $m_{12}$ and (b) $m_{34}$ for the selected candidates. The data (dots) are compared to the background expectations from the dominant $ZZ^(*)$ process and the sum of $t\bar{t}$, $Zb\bar{b}$ and $Z+$light-flavour-jets processes. Error bars represent 68.3% central confidence intervals.

once the look-elsewhere effect is considered, none of the observed local excesses is significant by itself.
Figure 4: $m_4\ell$ distribution of the selected candidates, compared to the background expectation. Error bars represent 68.3% central confidence intervals. The signal expectation for several $m_H$ hypotheses is also shown. The resolution of the reconstructed Higgs mass is dominated by detector resolution at low $m_H$ values and by the Higgs boson width at high $m_H$.

Figure 5: (a) $p_T$ distribution and (b) $\eta$ distribution for the leptons of the 71 candidates surviving the selection criteria. The expected background distributions are also shown. Error bars represent 68.3% central confidence intervals.

8 Summary

A search for the Standard Model Higgs boson in the decay channel $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ based on $4.8 \text{ fb}^{-1}$ of data recorded by the ATLAS detector at $\sqrt{s} = 7 \text{ TeV}$ during the 2011 run has been presented. The SM
Figure 6: The expected (dashed) and observed (full line) 95% CL upper limits on the Higgs boson production cross section as a function of the Higgs boson mass, divided by the expected SM Higgs boson cross section. The green and yellow bands indicate the expected sensitivity with $\pm 1\sigma$ and $\pm 2\sigma$ fluctuations, respectively.

Table 4: Median expected and observed 95% CL upper limits on the Higgs boson production cross section for several Higgs boson masses, divided by the expected SM Higgs boson cross section.

<table>
<thead>
<tr>
<th>Mass (GeV)</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>5.06</td>
<td>5.00</td>
</tr>
<tr>
<td>130</td>
<td>1.53</td>
<td>1.81</td>
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<td>300</td>
<td>0.78</td>
<td>0.53</td>
</tr>
<tr>
<td>400</td>
<td>1.00</td>
<td>0.73</td>
</tr>
<tr>
<td>600</td>
<td>4.82</td>
<td>8.22</td>
</tr>
</tbody>
</table>

Higgs boson is excluded at 95% confidence level in the mass ranges 135 GeV – 156 GeV, 181 GeV – 234 GeV and 255 GeV – 415 GeV. The largest deviations from the background expectation are observed for $m_H = 125$ GeV with a $p_0$-value of 1.8%, $m_H = 244$ GeV with a $p_0$-value of 1.1% and $m_H = 500$ GeV with a $p_0$-value of 1.4%. Once the look-elsewhere effect is considered, none of these excesses is significant by itself.
Figure 7: The consistency of the observed results with the background-only hypothesis expressed as $p_0$-values is shown. The dashed line shows the median expected significance in the hypothesis of a Standard Model Higgs boson production. The two horizontal dashed lines indicate the $p_0$-values corresponding to local significances of $2\sigma$ and $3\sigma$. In (a) the full mass range is presented, while in (b) the low mass range is presented.
References


[7] CMS Collaboration, Search for standard model Higgs boson in pp collisions at \(\sqrt{s} = 7\) TeV and integrated luminosity up to 1.7 fb\(^{-1}\), CMS-PAS-HIG-11-022.


[11] ATLAS Collaboration, Search for the Standard Model Higgs boson in the \(H \rightarrow WW \rightarrow \ell\ell\nu\nu\) decay mode using 1.7 fb\(^{-1}\) of data collected with the ATLAS detector at \(\sqrt{s} = 7\) TeV, ATLAS-CONF-2011-134.


[13] ATLAS Collaboration, Search for a heavy Standard Model Higgs boson in the channel \(H \rightarrow ZZ \rightarrow \ell^+\ell^-q\bar{q}\) using the ATLAS detector, arXiv:1108.5064 [hep-ex], accepted by Phys. Lett. B.


[16] ATLAS Collaboration, Search for neutral MSSM Higgs bosons decaying to $\tau^+\tau^-$ pairs in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector, ATLAS-CONF-2011-132.

[17] ATLAS Collaboration, Search for the Standard Model Higgs boson in the decay mode $H \rightarrow \tau^+\tau^- \rightarrow \ell\ell + 4\nu$ in Association with jets in Proton-Proton Collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector, ATLAS-CONF-2011-133.


A Additional Plots

Figure 8: Multiplicity of additional muons with $p_T > 7$ GeV in events with a reconstructed $Z \rightarrow \ell \ell$ decay before and after the subtraction of muons originating from light quarks and ZZ, WZ and $t\bar{t}$ decays. For the cases with two additional muons, their invariant mass is required to be less than 72 GeV. The MC expectation for the heavy flavour component, $Q$, is also presented. The uncertainties shown include both statistical and systematic effects.

Figure 9: Invariant mass distribution of the first lepton pair: (a) $\mu \mu$ and (b) $ee$. The kinematic selections of the analysis have been applied. Isolation requirements have been applied on the first lepton pair. No charge requirements were applied to the second lepton pair.
Figure 10: Event displays of a $4\mu$ candidate event with $m_{4\ell} = 124.6$ GeV. The masses of the lepton pairs are 89.7 GeV and 24.6 GeV.
Figure 11: Event displays of a $2e2\mu$ candidate event with $m_{4\ell} = 124.3$ GeV. The masses of the lepton pairs are 76.8 and 45.7 GeV.
Figure 12: Event display of a $2\mu 2e$ candidate event with $m_{4\ell} = 123.6$ GeV. The masses of the lepton pairs are 89.3 and 30.0 GeV.