Search for the Standard Model Higgs boson in the decay channel
\( H \rightarrow ZZ^{(*)} \rightarrow 4\ell \) with the ATLAS detector

The ATLAS collaboration

Abstract

The search for the Standard Model Higgs boson in the decay channel \( H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^-\ell^+\ell^- \), where \( \ell = e, \mu \), is presented. Proton-proton collision data at \( \sqrt{s} = 7 \) TeV recorded with the ATLAS detector and corresponding to an average integrated luminosity of 1.1 fb\(^{-1}\) are compared to the Standard Model expectations. Upper limits on the production cross section of a Standard Model Higgs boson with a mass between 110 and 600 GeV are derived. The observed (expected) 95\% confidence level upper limit on the production cross section for a Higgs boson with a mass of 200 GeV, near the most sensitive point of this search, is 2.0 (1.7) times the Standard Model prediction.
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 have led to a lower limit on the Higgs boson mass, $m_H$, of 114.4 GeV at 95% confidence level (CL) [4]. The searches at the Fermilab Tevatron $p\bar{p}$ collider have excluded at 95% CL the region $158 \text{ GeV} < m_H < 173 \text{ GeV}$ [5]. Results from the 2010 LHC run extended the search in the region $200 \text{ GeV} < m_H < 600 \text{ GeV}$ by excluding a SM Higgs boson with cross section larger than 5-20 times the SM prediction [6,7].

This note presents the search by the ATLAS experiment for the SM Higgs boson in the channel $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^-\ell'^+\ell'^-$, where $\ell, \ell' = e, \mu$, in the mass range from 110 to 600 GeV. Three distinct final states, $\ell\ell\ell\ell$ (4\ell), $ee\mu\mu$ (2e2\mu), and $eeee$ (4e), are selected. The largest background to this search comes from the $ZZ^{(*)}$ production. For $m_H < 180 \text{ GeV}$, contributions from $Z + \text{jets}$ and $t\bar{t}$ processes, where the additional leptons arise either from semi-leptonic decays of heavy flavour or light jets misidentified as leptons, are important. The proton-proton collision data were recorded with the ATLAS detector at the LHC at $\sqrt{s} = 7 \text{ TeV}$ and correspond to an average integrated luminosity of 1.1 $\text{fb}^{-1}$ [8]. The previously published ATLAS results in this channel [6] are improved by using about 27 times more integrated luminosity.

2 The ATLAS Detector

The ATLAS detector [9] is a multipurpose particle physics apparatus with forward-backward symmetric cylindrical geometry. 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.

3 Data and Monte Carlo Samples

The accumulated data are subjected to quality requirements ensuring that the relevant detector components are operational. The average integrated luminosity of 1.1 $\text{fb}^{-1}$ corresponds to 1.21 $\text{fb}^{-1}$, 1.07 $\text{fb}^{-1}$, and 1.07 $\text{fb}^{-1}$ for the 4\mu, 2e2\mu, and 4e final states respectively.

The $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ signal is modelled in the range 110 to 600 GeV using the POWHEG Monte Carlo (MC) event generator [10,11], which calculates separately the gluon and vector-boson fusion production mechanisms of the Higgs boson with matrix elements up to next-to-leading order (NLO). The Higgs boson $p_T$-spectrum is reweighted to the calculation of ref. [12], corresponding to QCD corrections up to next-to-leading order and QCD soft-gluon resummations up to next-to-next-to-leading log. POWHEG is interfaced to PYTHIA [13] for showering and hadronization, which in turn is interfaced to PHOTOS [14] for QED radiative corrections in the final-state and to TAUOLA [15,16] for the simulation of $\tau$ decays. The

\footnote{ATLAS uses a right-handed coordinate system originated 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.}
Higgs boson $p_T$ spectrum is reweighted to the calculation of Ref. [12], corresponding to QCD corrections up to next-to-leading order and QCD soft-gluon resummations up next-to-next-to-leading log.

The cross sections for Higgs boson production, the corresponding branching fractions, as well as their uncertainties, are compiled in Ref. [17]. They correspond to next-to-next-to-leading order (NNLO) in QCD for the gluon fusion [18–23] and vector boson fusion [24]. In addition, QCD soft-gluon resummations up to next-to-next-to-leading log (NNLL) are available for the gluon fusion process [25], while the NLO electroweak (EW) corrections are applied to both the gluon fusion [26, 27] and vector boson fusion [28, 29]. The Higgs boson decay branching ratio to the four-lepton final state is predicted by $\text{PROPHECY4F}$ [30, 31], including the complete NLO QCD+EW corrections, including all interference effects and leading two-loop heavy Higgs boson corrections to the four-fermion width. Table 1 gives the production cross-sections for the $H \rightarrow 4\ell$ ($\ell = e, \mu$) for typical Higgs boson masses.

Table 1: Higgs boson production cross-sections for both gluon and vector-boson fusion processes in $pp$ collisions at $\sqrt{s} = 7 \text{ TeV}$. The cross-sections include the branching ratio of $H \rightarrow 4\ell$, $\ell = e, \mu$.

<table>
<thead>
<tr>
<th>$m_H$ (GeV)</th>
<th>130</th>
<th>150</th>
<th>200</th>
<th>240</th>
<th>300</th>
<th>400</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma \cdot \text{BR}(H \rightarrow 4\ell)$ (fb)</td>
<td>2.87</td>
<td>4.38</td>
<td>6.77</td>
<td>5.35</td>
<td>3.75</td>
<td>2.66</td>
<td>1.11</td>
</tr>
</tbody>
</table>

The $ZZ^{(*)}$ background is generated using $\text{PYTHIA}$, taking into account $Z - \gamma$ interference. For the inclusive total cross section and the shape of the $m_{ZZ^{(*)}}$ spectrum the MCFM [32, 33] prediction is used, including both quark-antiquark annihilation at QCD NLO and gluon fusion. Inclusive $Z$ boson and $Zb\bar{b}$ processes are modelled using $\text{ALPGEN}$ [34], removing overlaps between the two samples. More specifically, $bb$ pairs with separation $\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} \geq 0.4$ between the jets are taken from the matrix-element calculation, while for $\Delta R < 0.4$ the parton-shower jets are used. The total inclusive cross section for $Z$ boson production is normalized to the QCD NNLO prediction by $\text{FEWZ}$ [35, 36], while $Zb\bar{b}$ is normalized to the MCFM prediction [32, 33]. Finally, the $t\bar{t}$ background is modelled using $\text{MC@NLO}$ [37] and is normalized to the approximate NNLO cross section calculated using $\text{HATHOR}$ [38]. Both $\text{ALPGEN}$ and $\text{MC@NLO}$ are interfaced to $\text{HERWIG}$ [39] for parton shower hadronization and to $\text{JIMMY}$ [40] for the underlying event simulations.

All generated events undergo a full detector simulation performed using $\text{GEANT4}$ [41, 42].

As a result of the intensity increase of LHC an average number of five interactions per bunch crossing has been measured in data. In order to adequately take into account the impact of pileup on lepton reconstruction efficiency and isolation, these effects have been included in all ATLAS simulations.

4 Physics Object Identification and Event Selection

The data were collected using single-lepton triggers with thresholds on transverse energy, $E_T$, of 20 GeV for electrons and on transverse momentum, $p_T$, of 18 GeV for muons. Both triggers are more than 99.5% efficient for events passing the selection described below.

Electron candidates consist of clusters of energy deposited in the electromagnetic calorimeter associated to inner detector tracks. The electrons must satisfy the ATLAS “medium” electron criteria that require the shower profiles to be consistent with those expected from an electromagnetic shower shape and a well reconstructed ID charged track pointing to the corresponding clusters [43].

Muon candidates are reconstructed by matching inner detector tracks with either full or partial tracks in the muon spectrometer [44–46]. For the former case, the two independent momentum measurements are combined, while for the latter case the muon spectrometer provides only the muon identification
To reject cosmic rays, tracks are required to be consistent with having originated from the primary vertex, defined as the reconstructed vertex with the highest \( \sum p_T^2 \) of associated tracks.

Leptons from Higgs boson decays are expected to be isolated and to originate from a common vertex. Track and calorimeter isolation as well as transverse impact parameter significance requirements are therefore applied to further reduce the \( Z + \text{jets} \) and \( t\bar{t} \) contributions. The sum of \( p_T \) of tracks within \( \Delta R < 0.20 \) from the lepton divided by the lepton \( p_T \) is required to be less than 0.15, while the sum \( E_T \) of the calorimeter cells within \( \Delta R < 0.20 \) around the lepton divided by the lepton \( p_T \) is required to be less than 0.30. In the case of electrons, the calorimeter cells corresponding to the electromagnetic shower are subtracted from the cone. The cut on the impact parameter significance is tuned to guarantee more than 95% efficiency for an isolated lepton. The selection efficiency of the isolation and impact parameter requirements has been studied using data both for isolated leptons, with \( Z \to \ell\ell \) events, and non-isolated leptons from semi-leptonic heavy flavour decays, with heavy-flavour enriched dijet sample, and found to be well described by the simulation.

Higgs boson candidates are formed by selecting two same-flavour, opposite-sign isolated lepton pairs in an event. Each lepton must satisfy \( p_T > 7 \text{ GeV} \) and be measured in the pseudorapidity range \( |\eta| < 2.47 \) for electrons and \( |\eta| < 2.5 \) for muons. For the transition region between the barrel and the end-cap calorimeters \( 1.37 < \eta < 1.52 \), the electron \( p_T \) threshold is increased to 15 GeV. At least two leptons must have \( p_T > 20 \text{ GeV} \). The leptons are required to be well separated from each other, \( \Delta R > 0.1 \). The invariant mass of the lepton pair closest to the nominal Z boson mass (\( m_Z \)) is denoted by \( m_{12} \). It is required that \( |m_Z - m_{12}| < 15 \text{ GeV} \). The invariant mass of the remaining lepton pair, \( m_{34} \), is required to be 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 on top of the background.

### Table 2: Summary of thresholds applied to \( m_{34} \) for reference values of \( m_{4\ell} \).

<table>
<thead>
<tr>
<th>( m_{4\ell} ) (GeV)</th>
<th>( \leq 120 )</th>
<th>130</th>
<th>140</th>
<th>150</th>
<th>160</th>
<th>165</th>
<th>180</th>
<th>190</th>
<th>( \geq 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 dominant \( ZZ^{(*)} \) background is estimated using MC simulation. Generated events are required to pass the complete analysis selection and the final rate is normalized to the integrated luminosity.

The \( t\bar{t} \) background is also estimated using MC simulation. Comparing data to MC predictions in a control sample of opposite sign electron-muon pairs consistent with the Z boson mass and with one or two additional leptons, verifies that the \( t\bar{t} \) background is small with respect to the dominant \( ZZ^{(*)} \) process and under control.

The \( Z+\text{jets} \) background is normalized on a data control sample. The control sample is formed by selecting events with a pair of same-flavour, opposite-sign isolated leptons consistent with the Z boson mass, \( |m_Z - m_{12}| < 15 \text{ GeV} \), and a second same-flavour, opposite-sign lepton pair where only kinematic, but no isolation or impact parameter, requirements are applied. At this stage, the dominant background source depends on the flavour of the second lepton pair: \( Zb\bar{b} \) production dominates the final states with a second muon-pair and \( Z+\text{light jets} \) the final states with a second electron-pair. In Fig. 1 distributions of the number of additional muons in events with a reconstructed \( Z \to \ell\ell \) decay and of their transverse momentum are compared with MC expectations. The small contributions from \( t\bar{t}, ZZ^{(*)} \), and muons

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Figure 1: (a) Multiplicity with $p_T > 7$ GeV and (b) $p_T$ distribution of additional muons in events with a reconstructed $Z \rightarrow \ell\ell$ decay, $|m_Z - m_{12}| < 15$ GeV, before and after the subtraction of muons originating from light quarks and $ZZ$, $WZ$ and $t\bar{t}$ decays. The Monte Carlo expectation for the heavy flavour component, $Q$, is also presented. The quoted uncertainties include both statistical and systematic effects.

from in-flight $\pi$ and $K$ decays are subtracted. The yield of the background, 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, momentum resolution and momentum scale are constrained using the accumulated samples of $W$/$Z$ bosons 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 1.7% (1.2%) for the $4\mu$ ($2e2\mu$) channel. The electron efficiency for the $4e$ ($2e2\mu$) channel results in an acceptance uncertainty of 3% (2%) at $m_{4\ell} = 600$ GeV and reaches 15% (6%) at $m_{4\ell} = 110$ GeV for the $4e$ ($2e2\mu$) channel.

A conservative theoretical uncertainty of 15% is assigned to the $ZZ^{(*)}$ background contribution [47]. The $Z + jets$ and $Zb\bar{b}$ contributions to the four lepton final state are evaluated on data. A systematic uncertainty between 20% and 40% is assigned on the normalization to account for the statistical uncertainty in the control sample and the extrapolation to the signal region. The uncertainty on the $t\bar{t}$ cross section is found to be 10% by adding linearly the contributions from variations of the scale and of the parton distribution functions.

The theoretical uncertainties on the Higgs boson production cross section are 15–20% for the gluon fusion process and 3–9% for the vector-boson fusion process [17], depending on the Higgs boson mass\(^{2}\). These errors are composed of uncertainties in QCD scale and parton distribution functions [49–52]. 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 instead of POWHEG.

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\(^{2}\)The limits presented in this search assume cross sections based on on-shell Higgs boson production and decay and use MC generators with an ad-hoc Breit-Wigner Higgs line shape. Recently potentially important effects related to off-shell Higgs boson production and interference effects between the Higgs boson signal and backgrounds have been discussed [17,48]. The inclusion of such effect may affect limits at very high Higgs masses ($m_H > 400$ GeV).
Table 3: The expected number of signal and background events, with their systematic uncertainty, separated into “Low mass” \((m_{4\ell} < 180 \text{ GeV})\) and “High mass” \((m_{4\ell} \geq 180 \text{ GeV})\) regions. The observed number of events is also presented.

<table>
<thead>
<tr>
<th>(m_{4\ell})</th>
<th>(m_{4\ell})</th>
<th>(m_{4\ell})</th>
<th>(m_{4\ell})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(ZZ^{(*)})</td>
<td>(0.84\pm0.13)</td>
<td>(4.5\pm0.7)</td>
<td>(0.80\pm0.12)</td>
</tr>
<tr>
<td>(Z, Z\bar{b}, \text{and } t\bar{t})</td>
<td>(0.03\pm0.01)</td>
<td>(0.01\pm0.01)</td>
<td>(0.15\pm0.06)</td>
</tr>
<tr>
<td>Total Background</td>
<td>(0.87\pm0.13)</td>
<td>(4.5\pm0.7)</td>
<td>(0.95\pm0.13)</td>
</tr>
</tbody>
</table>

The overall uncertainty for the total integrated luminosity is 3.7% [8].

7 Results

Table 3 shows the number of events observed in each final state, separately for \(m_{4\ell} < 180 \text{ GeV}\) and \(m_{4\ell} \geq 180 \text{ GeV}\), compared with the expectations for background. The expected signal yields for various \(m_H\) values are also presented. In total 18 candidate events are selected by the analysis: ten \(4\mu\), six \(2e2\mu\), and two \(4e\) events. In the same mass range 14.6 events are expected from the described background processes. The mass spectra for \(m_{12}, m_{34}, \text{and } m_{4\ell}\) are shown in Fig. 2, while the kinematic distributions of the leptons are presented in Fig. 3 and Fig. 4. The selected events have been examined visually and no reconstruction issues were identified. Typical event displays are presented in Figs. 5, 6, 7. In Fig. 8, the \(m_{4\ell}\) distribution is shown along with the expected background and the expected signal for several \(m_H\) hypotheses.

Upper limits are set on the Higgs boson cross section at 95% CL, using the \(CL_s\) modified frequentist formalism [53] with the profile likelihood test statistic [54]. Figure 9 shows the expected and observed exclusions as a function of \(m_H\) and Table 4 summarizes the numerical values for selected \(m_H\) points. The consistency with the background-only hypothesis is quantified using the \(p\)-value, the probability that a background-only experiment will fluctuate more than a given observation. The most significant deviation from the background-only hypothesis is observed at \(m_H = 246 \text{ GeV}\) with a \(p\)-value of 3%. This calculation does not account for the look-elsewhere effect.

8 Summary

The search for the decay \(H \rightarrow ZZ^{(*)} \rightarrow 4\ell\) in the data accumulated by the ATLAS detector corresponding to 1.1 \(fb^{-1}\) has been presented. No significant excess of candidates is observed in the mass range between 110 and 600 \text{ GeV} with respect to the expected SM background. The observed (expected) 95% CL upper
Figure 2: Invariant mass distributions (a) $m_{12}$, (b) $m_{34}$, and (c) $m_{4\ell}$ for the selected candidates. All plots show comparisons with background expectation from the dominant $ZZ^*$ and the sum of $t\bar{t}$, $Zb\bar{b}$ and $Z+\text{jets}$ processes. Error bars represent 68.3% central confidence intervals.

Figure 3: $p_T$ distribution (a) and $\eta$ distribution (b) for the leptons of the 18 candidates surviving the selection criteria. The corresponding shapes for the expected background contributions are also shown.

limit on the Higgs boson production cross section, in units of the SM rate, is 2.0 (1.7) at $m_H = 200$ GeV, which is the most sensitive point of this search.
Figure 4: Scatter plot of $m_{12}$ and $m_{34}$ for the 18 candidates surviving the selection criteria. The corresponding shape for the total expected background contribution is also shown.

Figure 5: Event display of a $4\ell$ candidate event with $m_{4\ell} = 270.1$ GeV. The masses of the lepton pairs are 85.0 and 111.3 GeV respectively.
Figure 6: Event display of a $4\mu$ candidate event with $m_{4\mu} = 143.5$ GeV. The masses of the lepton pairs are 90.6 and 47.4 GeV respectively.

Figure 7: Event display of a $2e2\mu$ candidate event with $m_{\ell\ell} = 209.7$ GeV. The masses of the lepton pairs are 85.9 and 85.5 GeV respectively.
Figure 8: $m_{4\ell}$ 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 experimental performances at low $m_H$ values and by the natural Higgs boson width at high $m_H$.

Table 4: Observed and median expected 95% CL upper limit on the SM Higgs boson production cross section, in multiples of the SM rate, as a function of the Higgs boson mass in GeV, obtained with $CL_s$.

<table>
<thead>
<tr>
<th>Mass (GeV)</th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>130</td>
<td>7.9</td>
<td>6.5</td>
</tr>
<tr>
<td>150</td>
<td>2.9</td>
<td>2.7</td>
</tr>
<tr>
<td>200</td>
<td>2.0</td>
<td>1.7</td>
</tr>
<tr>
<td>240</td>
<td>3.2</td>
<td>2.1</td>
</tr>
<tr>
<td>300</td>
<td>2.2</td>
<td>2.6</td>
</tr>
<tr>
<td>400</td>
<td>2.5</td>
<td>2.9</td>
</tr>
<tr>
<td>600</td>
<td>27.6</td>
<td>16.3</td>
</tr>
</tbody>
</table>
Figure 9: Expected (dashed) and observed (full line) 95% CL upper limit on the SM Higgs boson production cross section as a function of the Higgs boson mass, expressed in multiples of the SM rate. Figures (a),(b),(c), (d) are different presentations of the same result.
References


