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Authors
Aad, G
Abbott, B
Abdallah, J
et al.

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

ATLAS Collaboration

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A B S T R A C T

This Letter presents a search for the Standard Model Higgs boson in the decay channel $H \rightarrow ZZ^{(*)} \rightarrow \ell^{+}\ell^{-}\ell'^{+}\ell'^{-}$, where $\ell, \ell' = e$ or $\mu$, using proton–proton collisions at $\sqrt{s} = 7 \, \text{TeV}$ recorded with the ATLAS detector and corresponding to an integrated luminosity of $4.8 \, \text{fb}^{-1}$. The four-lepton invariant mass distribution is compared with Standard Model background expectations to derive upper limits on the cross section of a Standard Model Higgs boson with a mass between 110 GeV and 600 GeV. The mass ranges 134–156 GeV, 182–233 GeV, 256–265 GeV and 268–415 GeV are excluded at the 95% confidence level. The largest upward deviations from the background-only hypothesis are observed for Higgs boson masses of 125 GeV, 244 GeV and 500 GeV with local significances of 2.1, 2.2 and 2.1 standard deviations, respectively. Once the look-elsewhere effect is considered, none of these excesses are significant.

1. Introduction

The search for the Standard Model (SM) Higgs boson [1–3] is one of the most important aspects of the CERN Large Hadron Collider (LHC) physics program. Direct searches performed at the CERN Large Electron–Positron Collider (LEP) excluded at 95% confidence level (CL) the production of a SM Higgs boson with mass, $m_{H}$, less than 114.4 GeV [4]. The searches at the Fermilab Tevatron $p\bar{p}$ collider have excluded at 95% CL the region $156 < m_{H} < 177$ GeV [5]. At the LHC, results from data collected in 2010 excluded the search in the region $200 < m_{H} < 600$ GeV by excluding a Higgs boson with cross section larger than 5–20 times the SM prediction [6,7]. In ATLAS these results were extended further using the first 1.04–2.28 fb$^{-1}$ of data recorded in 2011 [8–13]. In particular, the $H \rightarrow WW^{(*)} \rightarrow \ell^{+}\ell^{-}v\nu$ search [13] excluded at 95% CL the region $145 < m_{H} < 206$ GeV.

The search for the SM Higgs boson through the decay $H \rightarrow ZZ^{(*)} \rightarrow \ell^{+}\ell^{-}\ell'^{+}\ell'^{-}$, where $\ell, \ell' = e$ or $\mu$, provides good sensitivity over a wide mass range. Previous results from ATLAS in this channel [9] excluded three mass regions between 191 GeV and 224 GeV at 95% CL with a 2.1 fb$^{-1}$ data sample. This Letter presents an update of this search in the mass range from 110 GeV to 600 GeV, superseding Ref. [9]. Three distinct final states, $\mu^{+}\mu^{-}\mu^{+}\mu^{-}$ ($4\mu$), $e^{+}e^{-}\mu^{+}\mu^{-}$ ($2e2\mu$), and $e^{+}e^{-}e^{+}e^{-}$ ($4e$), are selected. The largest background to this search comes from continuum ($Z^{(*)}/\gamma^{*}$)($Z^{(*)}/\gamma^{*}$) production, referred to as $ZZ^{(*)}$ hereafter.

For $m_{H} < 180$ GeV, there are also important background contributions from $Z$-jets and $t\bar{t}$ production, where the additional charged lepton candidates arise either from decays of hadrons with $b$- or $c$-quark content or from misidentification of jets.

The $\sqrt{s} = 7 \, \text{TeV}$ pp collision data were recorded during 2011 with the ATLAS detector at the LHC and correspond to an integrated luminosity of 4.8 fb$^{-1}$ [14,15]. This analysis is using more than twice the integrated luminosity of Ref. [9], including the data therein. The electron identification efficiency has been improved; furthermore the electron tracks have been refitted using a Gaussian-sum filter [16], which corrects for energy losses due to bremsstrahlung. The analysis also benefits from recent significant improvements in the alignment of the inner detector and the muon spectrometer.

2. The ATLAS detector

The ATLAS detector [17] is a multi-purpose particle physics detector with forward–backward symmetric cylindrical geometry. The inner tracking detector (ID) [18] covers $|\eta| < 2.5$ and 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 2 T axial magnetic field. A high-granularity lead/liquid-argon (LAr) sampling calorimeter surrounds the ID, covering $|\eta| < 4.9$. The calorimeter is based on liquid-argon cells, segmented by a Fine Wires Calorimeter (FWC) that provides fast measurement of the energy deposit of electromagnetic showers.
calorimeter [19] measures the energy and the position of electromagnetic showers with |η| < 3.2. LAr sampling calorimeters are also used to measure hadronic showers in the end-cap (1.5 < |η| < 3.2) and forward (3.1 < |η| < 4.9) regions, while an iron/scintillator tile calorimeter [20] measures hadronic showers in the central region (|η| < 1.7). The muon spectrometer (MS) [21] surrounds the calorimeters and consists of three superconducting air-core toroids, each with eight coils, a system of precision tracking chambers (|η| < 2.7), and fast tracking chambers for triggering. A three-level trigger system [22] selects events to be recorded for offline analysis.

3. Data and simulation samples

The data are subjected to quality requirements: events recorded during periods when the relevant detector components were not operating normally are rejected. The resulting integrated luminosity is 4.8 fb⁻¹, 4.8 fb⁻¹ and 4.9 fb⁻¹ for the 4µ, 2e2µ and 4e final states, respectively.

The H → ZZ(*) → 4ℓ signal is modelled using the POWHEG Monte Carlo (MC) event generator [23,24], which calculates separately the gluon–gluon and vector-boson fusion production mechanisms with matrix elements up to next-to-leading order (NLO). The Higgs boson transverse momentum (pT) spectrum in the gluon fusion process is reweighted to match the calculation of Ref. [25], which includes quantum chromodynamics (QCD) corrections up to NLO and QCD soft-gluon resummations up to next-to-next-to-leading logarithm (NNLL). POWHEG is interfaced to PYTHIA [26] for showering and hadronization, which in turn is interfaced to PHOTOS [27] for quantum electrodynamics (QED) radiative corrections in the final state and to TAUOLA [28,29] for the simulation of τ lepton decays. PYTHIA is used to simulate the production of a Higgs boson in association with a W or a Z boson.

The Higgs boson production cross sections and decay branching ratios [30–33], as well as their uncertainties, are taken from Refs. [34,35]. The cross sections for the gluon fusion process have been calculated at next-to-leading order (NLO) in QCD [36–38], and then at next-to-next-to-leading order (NNLO) [39–41]. In addition, QCD soft-gluon resummations up to NNLL are applied for the gluon fusion process [42]. The NLO electroweak (EW) corrections are applied [43,44]. These results are compiled in Refs. [45–47] assuming factorization between QCD and EW corrections. The cross sections for the vector-boson fusion process are calculated with full NLO QCD and EW corrections [48–50], and approximate NNLO QCD corrections are available [51]. The associated productions with a W or Z boson are calculated at NLO [52] and at NNLO [53] in QCD, and NLO EW radiative corrections [54] are applied. The uncertainty in the production cross section due to the choice of QCD scale is ±12% for the gluon fusion process, and ±17% for the vector-boson fusion, associated WH production, and associated ZH production processes. The uncertainty in the production cross section due to the parton distribution function (PDF) and αs is ±8% for gluon-initiated process and ±4% for quark-initiated processes [55–59].

The Higgs boson decay branching ratio to the four-lepton final state is predicted by PROPHET [31,32], 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 → ZZ(*) → 4ℓ for several Higgs boson masses.

The cross section calculations do not take into account the width of the Higgs boson, which is implemented through a relativistic Breit–Wigner line shape applied at the event-generator level. It has been suggested [35,60–62] that effects related to off-shell Higgs boson production and interference with other SM processes may become sizeable for the highest masses (mH > 400 GeV) considered in this search. In the absence of a full calculation, a conservative estimate of the possible size of such effects is included as a signal normalization systematic uncertainty following a parameterization as a function of mH: 150% × mH [TeV], for mH > 300 GeV [35].

The ZZ(*) continuum background is modelled using PYTHIA. The MCFM [63,64] prediction, including both quark–antiquark annihilation and gluon fusion at QCD NLO, is used for the inclusive total cross section and the shape of the invariant mass of the ZZ(*) system (mZZ*). The QCD scale uncertainty has a ±5% effect on the expected ZZ(*) background, and the effect due to the PDF and αs uncertainties is ±4% (±8%) for quark-initiated (gluon-initiated) processes. An additional theoretical uncertainty of ±10% on the inclusive ZZ(*) cross section is conservatively included due to the missing higher-order QCD corrections for the gluon-initiated process, and a correlated uncertainty on the predicted mZZ* spectrum is estimated by varying the gluon-initiated contribution by 100% [65].

The Z + jets production is modelled using ALPGEN [66] and is divided into two sources: Z + light jets – which includes Zc jet in the massless c-quark approximation and Zbb from parton showers – and Zbb using matrix-element calculations that take into account the b-quark mass. The MLM [67] matching scheme is used to remove any double counting of identical jets produced via the matrix-element calculation and the parton shower, but this scheme is not implemented for b-jets. Therefore, b̅b pairs with separation ΔR = √(Δφ)² + (Δη)² > 0.4 between the b-quarks are taken from the matrix-element calculation, whereas for ΔR < 0.4 the parton-shower bb̅ pairs are used. In this search the Z + jets background is normalized using control samples from data. For comparisons with simulation, the QCD NNLO EWZ [68,69] and MCFM cross section calculations are used for inclusive Z boson and Zbb production, respectively. The ℓℓ background is modelled using MC@NLO [70] and is normalized to the approximate NNLO cross section calculated using HATHOR [71]. The effect of the QCD scale uncertainty on the cross section is ±4%, while the effect of PDF and αs uncertainties is ±7%. Both ALPGEN and MC@NLO are interfaced to HERWIG [72] for parton shower hadronization and to JIMMY [73] for the underlying event simulation.

### 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 √s = 7 TeV [34]. The quoted uncertainties correspond to the total theoretical systematic uncertainty. The production cross section for associated production with a W or Z boson is negligibly small for mH > 300 GeV. The decay branching ratio for H → 4ℓ, with ℓ = e or µ, is reported in the last column [34].

<table>
<thead>
<tr>
<th>mH (GeV)</th>
<th>σ(gg → f) (pb)</th>
<th>σ(qq → Hgg) (pb)</th>
<th>σ(qq → WH) (pb)</th>
<th>σ(qq → ZH) (pb)</th>
<th>BR(H → ZZ(*) → 4ℓ) (10⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>130</td>
<td>14.1⁺²⁻⁷</td>
<td>1.154⁻²⁻⁰</td>
<td>0.501 ± 0.020</td>
<td>0.278 ± 0.014</td>
<td>0.19</td>
</tr>
<tr>
<td>150</td>
<td>10.5⁺²⁻⁹</td>
<td>0.962⁻²⁻⁰</td>
<td>0.300 ± 0.012</td>
<td>0.171 ± 0.009</td>
<td>0.38</td>
</tr>
<tr>
<td>200</td>
<td>5.2⁺²⁻⁹</td>
<td>0.637⁻²⁻⁰</td>
<td>0.101 ± 0.005</td>
<td>0.061 ± 0.004</td>
<td>1.15</td>
</tr>
<tr>
<td>400</td>
<td>2.0 ± 0.3</td>
<td>0.16⁻²⁻⁰</td>
<td>0.005 ± 0.000</td>
<td>0.005 ± 0.000</td>
<td>1.21</td>
</tr>
<tr>
<td>600</td>
<td>0.33 ± 0.06</td>
<td>0.058⁻²⁻⁰</td>
<td>0.005 ± 0.000</td>
<td>0.005 ± 0.000</td>
<td>1.23</td>
</tr>
</tbody>
</table>
Generated events are fully simulated using the ATLAS detector simulation [74] within the GEANT4 framework [75]. Additional pp interactions in the same and nearby bunch crossings (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. Lepton identification and event selection

The data considered in this analysis are selected using single-lepton or di-lepton triggers. For the single-muon trigger the \( p_T \) threshold is 18 GeV, while for the single-electron trigger the transverse energy, \( E_T \), threshold is 20–22 GeV depending on the LHC instantaneous luminosity. For the di-muon and di-electron triggers the thresholds are \( p_T = 10 \) GeV for each of the muons, and \( E_T = 12 \) GeV for each of the electrons, respectively.

Electron candidates consist of clusters of energy deposited in the electromagnetic calorimeter that are associated to ID tracks. Electron tracks have been refitted using a Gaussian-sum filter. The electron candidates must satisfy a set of identification criteria [76] that 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 complete or partial tracks reconstructed in the MS [77]. If a complete track is present, the two independent momentum measurements are combined; otherwise the momentum is measured using the ID information only. To reject cosmic rays, muon tracks are required to have a transverse impact parameter, defined as the difference of the coordinates of the reconstructed vertex with the highest \( p_T \) of the muon and the primary vertex. Each lepton must satisfy a set of isolation and impact parameter significance requirements.

Table 2

Lower thresholds applied to \( m_{34} \) for reference values of \( m_{34} \). For \( m_{45} \) values between these reference values the selection requirement is obtained via linear interpolation.

<table>
<thead>
<tr>
<th>( m_{34} ) (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>( m_{34} ) 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>

The lepton track and the energies of calorimeter cells associated to the lepton divided by the lepton \( p_T \) are required to be less than 0.3.

The data considered in this analysis are selected using single-lepton or di-lepton triggers. For the single-muon trigger the \( p_T \) threshold is 18 GeV, while for the single-electron trigger the transverse energy, \( E_T \), threshold is 20–22 GeV depending on the LHC instantaneous luminosity. For the di-muon and di-electron triggers the thresholds are \( p_T = 10 \) GeV for each of the muons, and \( E_T = 12 \) GeV for each of the electrons, respectively.

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tions are presented for $Z + \mu\mu$ events, while in Figs. 2(b) and 2(d) the corresponding distributions are presented for $Z + ee$ events. The shapes and normalizations of the backgrounds discussed earlier are in good agreement with data; this is observed both for large values of $m_{34}$, where the $ZZ^{(*)}$ background dominates, and for low $m_{34}$ values.

6. Systematic uncertainties

Uncertainties in lepton reconstruction and identification efficiency, and on the momentum resolution and scale, are determined using samples of $W$, $Z$ and $J/\psi$ decays. The muon efficiency uncertainty results in a relative acceptance uncertainty in the signal and the $ZZ^{(*)}$ background which is uniform over the mass range of interest, and amounts to 0.22% (0.16%) for the $4\mu$ ($2e2\mu$) channel. The uncertainty in the electron efficiency results in a relative acceptance uncertainty of 2.3% (1.6%) for the $4e$ ($2e2\mu$) channel at $m_{4\ell} = 600$ GeV and reaches 8.0% (4.1%) at $m_{4\ell} = 110$ GeV. The effects of muon momentum resolution and scale uncertainties are found to be negligible. The energy resolution uncertainty for electrons is negligible, while the electron energy scale uncertainty results in an uncertainty of less than 0.6% (0.3%) on the mass scale of the $m_{4\ell}$ distribution for the $4e$ ($2e2\mu$) channel.

The selection efficiencies of the isolation and impact parameter requirements are studied using data for both isolated and non-isolated leptons. Isolated leptons are obtained from $Z \rightarrow \ell\ell$ decays, while additional leptons reconstructed in events with $Z \rightarrow \ell\ell$ decays constitute the sample of non-isolated leptons. Additional checks are performed with non-isolated leptons from semi-leptonic $b$- and $c$-quark decays in a heavy-flavour enriched di-jet sample. Good agreement is observed between data and simulation and the systematic uncertainty is, in general, estimated to be small with respect to the other systematic uncertainties. An exception is found in the case of isolated electrons with $E_T < 15$ GeV, where due to the small number of $Z \rightarrow e^+e^-$ events and the substantial QCD backgrounds an additional uncertainty of 5% is added.

An additional uncertainty in the signal selection efficiency is added due to the modelling of the signal kinematics. This is evaluated by varying the Higgs boson $p_T$ spectrum in the gluon fusion process according to the PDF and QCD scale uncertainties.

The $Z +$ light jets and $Zb\bar{b}$ backgrounds are evaluated using data. Systematic uncertainties of 45% and 40%, respectively, are assigned to their normalization to account for the statistical uncertainty in the yield of the control sample, the uncertainty in the composition of the control sample, and the uncertainty in the MC-based extrapolation to the signal region.

The overall uncertainty in the integrated luminosity for the complete 2011 dataset is 3.9%, based on the calibration described in Refs. [14,15] including an additional uncertainty for the extrapolation to the later data-taking period with higher instantaneous luminosity.

7. Results

In total, 71 candidate events are selected by the analysis: 24 $4\mu$, 30 $2e2\mu$, and 17 $4e$ events. From the background processes, $62 \pm 9$ events are expected: $18.6 \pm 2.8$ $4\mu$, $29.7 \pm 4.5$ $2e2\mu$ and $13.4 \pm 2.0$ $4e$. In Table 3, the number of events observed in each final state is summarized and compared to the expected backgrounds, separately for $m_{4\ell} < 180$ GeV and $m_{4\ell} \geq 180$ GeV, and to the expected signal for various $m_H$ hypotheses. The $m_{12}$ and $m_{34}$ mass spectra are shown in Fig. 3. The expected $m_{4\ell}$ distributions for the total background and several signal hypotheses are compared to the data in Fig. 4.

Upper limits are set on the Higgs boson production cross section at 95% CL, using the $C_l\alpha$ modified frequentist formalism [78] with the profile likelihood ratio test statistic [79]. The test statistic is evaluated with a binned maximum-likelihood fit of signal and background models to the observed $m_{4\ell}$ distribution. Fig. 5 shows the observed and expected 95% CL cross section upper limits, calculated using ensembles of simulated pseudo-experiments, as a function of $m_H$. The SM Higgs boson is excluded at 95% CL in the mass ranges $134–156$ GeV, $182–233$ GeV, $256–265$ GeV and $268–415$ GeV. The expected exclusion ranges are $136–157$ GeV and $8.0% ± 0.0%$ at $m_H = 130$ GeV. The fitted range for the Gaussian is chosen to be $−2 \sigma$ to $2 \sigma$ ($−1.5 \sigma$ to $2.5 \sigma$) for the $4\mu$ ($4e$) channel. The reduced mean value of the reconstructed invariant mass in the $4\mu$ channel arises from energy losses due to bremsstrahlung [76]. The fraction of events outside the $±2\sigma$ region is found to be 15% for $4\mu$ and 18% for $4e$. 

The $Z + \mu\mu$ events with $m_H = 130$ GeV. The fitted range for the Gaussian is chosen to be $−2 \sigma$ to $2 \sigma$ ($−1.5 \sigma$ to $2.5 \sigma$) for the $4\mu$ ($4e$) channel. The reduced mean value of the reconstructed invariant mass in the $4\mu$ channel arises from energy losses due to bremsstrahlung [76]. The fraction of events outside the $±2\sigma$ region is found to be 15% for $4\mu$ and 18% for $4e$. 

\[ m_{4\ell} \rightarrow H \rightarrow ZZ^{(*)} \rightarrow 4\ell, 2e2\mu, 4e \]
Fig. 2. Invariant mass distributions of the lepton pairs in the control sample defined by a Z boson candidate and an additional same-flavour lepton pair. The sample is divided according to the flavour of the additional lepton pair. In (a) the $m_{12}$ and in (c) the $m_{34}$ distributions are presented for $Z \rightarrow \mu^+\mu^-/e^+e^- + \mu\mu$ events. In (b) the $m_{12}$ and in (d) the $m_{34}$ distributions are presented for $Z \rightarrow \mu^+\mu^-/e^+e^- + ee$ events. The kinematic selections of the analysis are applied. Isolation requirements are applied to the first lepton pair only.

Table 3

The expected numbers of 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, compared to the observed numbers of events. The expectations for a Higgs boson signal for five different $m_H$ values are also given.

<table>
<thead>
<tr>
<th>$m_H$ (GeV)</th>
<th>Low-$m_{4\ell}$</th>
<th>High-$m_{4\ell}$</th>
<th>Low-$m_{4\ell}$</th>
<th>High-$m_{4\ell}$</th>
<th>Low-$m_{4\ell}$</th>
<th>High-$m_{4\ell}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>4.8 fb$^{-1}$</td>
<td>4.8 fb$^{-1}$</td>
<td>4.9 fb$^{-1}$</td>
<td>4.9 fb$^{-1}$</td>
<td>4.9 fb$^{-1}$</td>
<td>4.9 fb$^{-1}$</td>
</tr>
<tr>
<td>Data</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$m_H = 125$ GeV with a local $p_0$ of 1.6% (2.1 standard deviations)</td>
<td>1.00 ± 0.17</td>
<td>1.22 ± 0.21</td>
<td>1.22 ± 0.21</td>
<td>1.22 ± 0.21</td>
<td>0.43 ± 0.08</td>
<td></td>
</tr>
<tr>
<td>$m_H = 150$ GeV</td>
<td>2.1 ± 0.4</td>
<td>2.9 ± 0.4</td>
<td>2.9 ± 0.4</td>
<td>2.9 ± 0.4</td>
<td>1.12 ± 0.18</td>
<td></td>
</tr>
<tr>
<td>$m_H = 200$ GeV</td>
<td>4.9 ± 0.7</td>
<td>7.7 ± 1.0</td>
<td>7.7 ± 1.0</td>
<td>7.7 ± 1.0</td>
<td>3.1 ± 0.4</td>
<td></td>
</tr>
<tr>
<td>$m_H = 400$ GeV</td>
<td>2.0 ± 0.3</td>
<td>3.3 ± 0.5</td>
<td>3.3 ± 0.5</td>
<td>3.3 ± 0.5</td>
<td>1.49 ± 0.21</td>
<td></td>
</tr>
<tr>
<td>$m_H = 600$ GeV</td>
<td>0.34 ± 0.04</td>
<td>0.62 ± 0.10</td>
<td>0.62 ± 0.10</td>
<td>0.62 ± 0.10</td>
<td>0.30 ± 0.06</td>
<td></td>
</tr>
</tbody>
</table>

$m_H = 125$ GeV with a local $p_0$ of 1.6% (2.1 standard deviations), $m_H = 244$ GeV with a local $p_0$ of 1.3% (2.2 standard deviations) and $m_H = 500$ GeV with a local $p_0$ of 1.8% (2.1 standard deviations). The median expected local $p_0$ in the presence of a SM Higgs boson are 10.6% (1.3 standard deviations), 0.14% (3.0 standard deviations) and 7.1% (1.5 standard deviations) for $m_H = 125$ GeV, 244 GeV and 500 GeV, respectively. An alternative calculation, using the asymptotic approximation of Ref. [79], yielded compatible results – within 0.2 standard deviations – in the entire mass range.
Fig. 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 $ZZ^\ast$ process and the sum of $t\bar{t}$, $Zb\bar{b}$ and $Z + \text{light jets}$ processes. Error bars represent 68.3% central confidence intervals.

Fig. 4. $m_4\ell$ distribution of the selected candidates, compared to the background expectation for (a) the 100–250 GeV mass range and (b) the full mass range of the analysis. 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 $m_H$.

The quoted values do not account for the so-called look-elsewhere effect, which takes into account that such an excess (or a larger one) can appear anywhere in the search range as a result of an upward fluctuation of the background. When considering the complete mass range of this search, using the method of Ref. [80], the global $p_0$-value for each of the three excesses becomes of $O(50\%)$. Thus, once the look-elsewhere effect is considered, none of the observed local excesses are significant.

8. Summary

A search for the SM Higgs boson in the decay channel $H \rightarrow ZZ^\ast \rightarrow 4\ell$ based on 4.8 fb$^{-1}$ of data recorded by the ATLAS detector at $\sqrt{s} = 7$ TeV during the 2011 run has been presented. The SM Higgs boson is excluded at 95% CL in the mass ranges 134–156 GeV, 182–233 GeV, 256–265 GeV and 268–415 GeV. The largest upward deviations from the background-only hypothesis are observed for $m_H = 125$ GeV, 244 GeV and 500 GeV with local significances of 2.1, 2.2 and 2.1 standard deviations, respectively. Once the look-elsewhere effect is considered, none of these excesses are significant.

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95% CL upper limits on \(\sigma_{\text{SM}}\) divided by the expected SM Higgs boson cross section. The dark (green) and light (yellow) bands indicate the expected limits with \(\pm 1\sigma\) and \(\pm 2\sigma\) fluctuations, respectively.

For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.

- **Fig. 5.** The expected (dashed) and observed (full line) 95% CL upper limits on the Standard Model Higgs boson production cross section as a function of \(m_{\phi}\), divided by the expected SM Higgs boson cross section.

- **Fig. 6.** The observed local \(p_0\), the probability that the background fluctuates to the observed number of events or higher, is shown as the solid line. The dashed curve shows the expected median local \(p_0\) for the signal hypothesis when tested at \(m_{\phi}\). The two horizontal dashed lines indicate the \(p_0\) values corresponding to local significances of \(2\sigma\) and \(3\sigma\).

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ATLAS Collaboration

Bold institute names denote a representative from that institution.
Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
Also at TRIUMF, Vancouver, BC, Canada.
Also at Department of Physics, California State University, Fresno, CA, United States.
Also at Novosibirsk State University, Novosibirsk, Russia.
Also at Fermilab, Batavia, IL, United States.
Also at Department of Physics, University of Coimbra, Coimbra, Portugal.
Also at Università di Napoli Parthenope, Napoli, Italy.
Also at Institute of Particle Physics (IPP), Canada.
Also at Department of Physics, Middle East Technical University, Ankara, Turkey.
Also at Louisiana Tech University, Ruston, LA, United States.
Also at Department of Physics and Astronomy, University College London, London, United Kingdom.
Also at Group of Particle Physics, University of Montreal, Montreal, QC, Canada.
Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
Also at Manhattan College, New York, NY, United States.
Also at School of Physics, Shandong University, Shandong, China.
Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.
Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
Also at Section de Physique, Université de Genève, Geneva, Switzerland.
Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal.
Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.
Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
Also at California Institute of Technology, Pasadena, CA, United States.
Also at LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France.
Also at High Energy Physics Group, Shandong University, Shandong, China.
Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.
Also at Department of Physics, Oxford University, Oxford, United Kingdom.
Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
Also at Department of Physics, The University of Michigan, Ann Arbor, MI, United States.
Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France.
Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.
Deceased.