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


DOI
10.1016/j.physletb.2012.03.005

Publication date
2012

Document Version
Final published version

Published in
Physics Letters B

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).
Search for the Standard Model Higgs boson in the decay channel $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ with 4.8 fb$^{-1}$ of $pp$ collision data at $\sqrt{s} = 7$ TeV with ATLAS\(^\star\)

**ATLAS Collaboration**\(^\star\)

### A R T I C L E   I N F O

Article history:
- Received 7 February 2012
- Accepted 2 March 2012
- Available online 7 March 2012
- Editor: W.-D. Schlatter

**Keywords:**
- LHC
- ATLAS
- Higgs
- Leptons

### 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 $\sqrt{s} = 7$ TeV recorded with the ATLAS detector and corresponding to an integrated luminosity of 4.8 fb$^{-1}$. The four-lepton invariant mass distribution is compared with Standard Model background expectations to derive upper limits on the cross section. In particular, the $m_H < 177$ GeV [5].

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.

For $m_H < 180$ GeV, there are also important background contributions from $Z +$jets and $tt$ 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 $\sqrt{s} = 7$ 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.

### 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 also excluded at 95% CL the region $156 < m_H < 177$ GeV [5].

At the LHC, results from data collected in 2010 extended 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 $H \rightarrow WW^{(*)} \rightarrow \ell^+\nu\ell^-\bar{\nu}$ 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$\mu$), $e^+e^-\mu^+\mu^-$ (2$\mu 2\mu$), 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.

\(^\star\) E-mail address: atlas.publications@cern.ch.

\(^\dagger\) 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 ($\rho, \phi$) 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.
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 large 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 $μτ$, $e2μ$ and $4e$ final states, respectively.

The $H \rightarrow ZZ^{(*)} \rightarrow 4ℓ$ 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 ($p_T$) 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 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 $^{+12}_{-8}$% for the gluon fusion process, and $^{+11}_{-10}$% for the vector-boson fusion, associated $W$H production, and associated $ZH$ production processes [34]. The uncertainty in the production cross section due to the parton distribution function (PDF) and $α_s$ 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 $H \rightarrow ZZ^{(*)} \rightarrow 4ℓ$ for several Higgs boson masses.

Table 1

<table>
<thead>
<tr>
<th>$m_H$ (GeV)</th>
<th>$σ(gg \rightarrow H)$ (pb)</th>
<th>$σ(qq' \rightarrow Hq'q'')$ (pb)</th>
<th>$σ(qq' \rightarrow WH)$ (pb)</th>
<th>$σ(qq' \rightarrow ZH)$ (pb)</th>
<th>$BR(H \rightarrow ZZ^{(*)} \rightarrow 4ℓ)$ (10$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>130</td>
<td>$1.14^{+2.27}_{-0.20}$</td>
<td>$1.54^{+0.02}_{-0.03}$</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>$10.5^{+0.9}_{-0.8}$</td>
<td>$9.6^{+0.02}_{-0.01}$</td>
<td>$3.00 \pm 0.012$</td>
<td>$1.71 \pm 0.009$</td>
<td>0.38</td>
</tr>
<tr>
<td>200</td>
<td>$5.2^{+0.9}_{-0.7}$</td>
<td>$6.3^{+0.02}_{-0.01}$</td>
<td>$1.01 \pm 0.005$</td>
<td>$0.60 \pm 0.004$</td>
<td>1.15</td>
</tr>
<tr>
<td>400</td>
<td>$2.0 \pm 0.3$</td>
<td>$1.6^{+0.01}_{-0.00}$</td>
<td>$&lt;10^{-3}$</td>
<td>$&lt;10^{-3}$</td>
<td>1.21</td>
</tr>
<tr>
<td>600</td>
<td>$0.33 \pm 0.06$</td>
<td>$0.05 \pm 0.00$</td>
<td>$&lt;10^{-3}$</td>
<td>$&lt;10^{-3}$</td>
<td>1.23</td>
</tr>
</tbody>
</table>

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 ($m_{ZZ^{(*)}}$). The QCD scale uncertainty has a $±5$% effect on the expected $ZZ^{(*)}$ background, and the effect due to the PDF and $α_s$ 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 $m_{ZZ^{(*)}}$ 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 $Zc\bar{c}$ in the massless c-quark approximation and $Zb\bar{b}$ from parton showers — and $Zb\bar{b}$ 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, $b\bar{b}$ pairs with separation $ΔR = (∆φ)^2 + (∆η)^2 > 0.4$ between the $b$-quarks are taken from the matrix-element calculation, whereas for $ΔR < 0.4$ the parton-shower $b\bar{b}$ 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 $Zb\bar{b}$ production, respectively. The $t\bar{t}$ 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 $^{±5}$%, while the effect of PDF and $α_s$ 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 2

<table>
<thead>
<tr>
<th>( m_{34} ) (GeV)</th>
<th>( m_{34} ) threshold (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \leq 120 )</td>
<td>15</td>
</tr>
<tr>
<td>130</td>
<td>20</td>
</tr>
<tr>
<td>140</td>
<td>25</td>
</tr>
<tr>
<td>150</td>
<td>30</td>
</tr>
<tr>
<td>160</td>
<td>30</td>
</tr>
<tr>
<td>165</td>
<td>35</td>
</tr>
<tr>
<td>180</td>
<td>40</td>
</tr>
<tr>
<td>190</td>
<td>50</td>
</tr>
<tr>
<td>( \geq 200 )</td>
<td>60</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 transverse impact parameter significance, defined as the transverse impact parameter divided by the corresponding uncertainty, for the two lowest \( p_T \) leptons in the quadruplet is required to be less than 3.5 (6) for muons (electrons).

The combined signal reconstruction and selection efficiencies for \( m_{H} = 130 \) GeV (\( m_{H} = 360 \) GeV) are 27% (60%) for the \( 4\mu \) channel, 18% (52%) for the \( 2e2\mu \) channel and 14% (45%) for the \( 4e \) channel. The final discriminating variable is \( m_{34} \), for which Higgs boson production would appear as a clustering of events. In Fig. 1, the invariant mass distributions for the \( 4\mu \) 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 for \( m_{H} < 350 \) GeV, while for higher \( m_{H} \) the reconstructed width is dominated by the natural width of the Higgs boson; the predicted full-width at half-maximum is approximately 35 GeV at \( m_{H} = 400 \) GeV.

5. Background estimation

The expected background yield and its composition is estimated using MC simulation normalized to the theoretical cross section for ZZ* production and by data-driven methods for the \( Z + \) jets and \( t\bar{t} \) processes.

A control sample consisting of \( Z \rightarrow \ell^+\ell^- \) candidates with an additional loosely selected no isolation or impact parameter requirements – same-flavour lepton pair is used to study the contributions of \( Zb\bar{b} \) and \( Z + \) light jets. The \( Zb\bar{b} \) background dominates the \( Z + \mu\mu \) sample, and the \( Z + \) light jets background dominates in the \( Z + ee \) sample. The heavy flavour contribution in the \( Z + \mu\mu \) control sample is estimated by subtracting from the data the light jet component. The latter is obtained in a data-driven manner by using measurements of the rate at which other particles are misidentified as muons. The \( Z + \) light jets contribution in the \( Z + ee \) final state is estimated by extrapolation, using MC simulation, from a background-dominated region defined by inverting the electron identification requirement on the transverse shower shape of the electromagnetic energy deposit. These data-driven backgrounds are extrapolated to the signal region by applying the efficiencies found in MC simulation, and verified using data, for the isolation and impact parameter significance requirements.

The normalization of the \( t\bar{t} \) background, which also contributes substantially in the \( Z + \mu\mu \) final state, is verified using a control region of events containing an opposite-sign electron–muon pair consistent with the \( Z \) boson mass and two additional same-flavour leptons.

Fig. 2 displays the invariant masses of lepton pairs in events with a \( Z \) boson candidate and an additional same-flavour lepton pair, selected by following the kinematic requirements of the analysis, and by applying isolation requirements to the first lepton pair only. The events are divided according to the flavour of the additional lepton pair into \( Z + \mu\mu \) and \( Z + ee \) samples. In Figs. 2(a) and 2(c) the \( m_{12} \) and \( m_{34} \) distribu-
The fraction of events outside the ±2σ region is found to be 15% for 4μ and 18% for 4e.

The Z + light jets and Zb̄b̄ 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 4μ, 30 2e2μ, and 17 4e events. From the background processes, 62±9 events are expected: 18.6±2.8 4μ, 29.7±4.5 2e2μ, and 13.4±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_{4ℓ} < 180 GeV and m_{4ℓ} ≥ 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_{4ℓ} 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 CL_{s} 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_{4ℓ} 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 184–400 GeV.

The significance of an excess is given by the probability, p_{S}, that a background-only experiment is more signal-like than that observed. In Fig. 6 the p_{S}-values, calculated using an ensemble of simulated pseudo-experiments, are given as a function of m_{H} for the full mass range of the analysis. The most significant upward deviations from the background-only hypothesis are observed for
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 $Z \rightarrow \mu^+ \mu^- + e^+ e^- + e^+ e^-$ events. In (b) the $m_{12}$ and in (d) the $m_{34}$ distributions are presented for $Z \rightarrow \mu^+ \mu^- + e^+ e^- + e^+ e^-$ 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>Int. luminosity</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>$ZZ^{(*)}$</td>
<td>2.1 ± 0.3</td>
<td>16.3 ± 2.4</td>
<td>2.8 ± 0.6</td>
<td>25.2 ± 3.8</td>
<td>1.2 ± 0.3</td>
<td>10.4 ± 1.5</td>
</tr>
<tr>
<td>$Z +$ jets and $t\bar{t}$</td>
<td>0.16 ± 0.06</td>
<td>0.02 ± 0.01</td>
<td>1.4 ± 0.5</td>
<td>0.17 ± 0.08</td>
<td>1.6 ± 0.7</td>
<td>0.18 ± 0.08</td>
</tr>
<tr>
<td>Total background</td>
<td>2.2 ± 0.3</td>
<td>16.3 ± 2.4</td>
<td>4.3 ± 0.8</td>
<td>25.4 ± 3.8</td>
<td>2.8 ± 0.8</td>
<td>10.6 ± 1.5</td>
</tr>
<tr>
<td>Data</td>
<td>3</td>
<td>21</td>
<td>3</td>
<td>27</td>
<td>2</td>
<td>15</td>
</tr>
<tr>
<td>$m_H = 130$ GeV</td>
<td>1.00 ± 0.17</td>
<td>1.22 ± 0.21</td>
<td>0.43 ± 0.08</td>
<td>1.12 ± 0.18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_H = 150$ GeV</td>
<td>2.1 ± 0.4</td>
<td>2.9 ± 0.4</td>
<td>3.1 ± 0.4</td>
<td>1.49 ± 0.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_H = 200$ GeV</td>
<td>4.9 ± 0.7</td>
<td>7.7 ± 1.0</td>
<td>4.9 ± 0.7</td>
<td>1.06 ± 0.19</td>
<td></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>0.30 ± 0.06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_H = 600$ GeV</td>
<td>0.34 ± 0.04</td>
<td>0.62 ± 0.10</td>
<td>0.34 ± 0.04</td>
<td>0.62 ± 0.10</td>
<td></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 $ZZ^*(\gamma)$ 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 $H \rightarrow ZZ^*(\gamma) \rightarrow 4\ell$ 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.

Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPERJ, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; ARTEMIS and ERC, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNAS, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN,
Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MINISW, Poland; GRICES and FCT, Portugal; MERSYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR, MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICCINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

Open access

This article is published Open Access at sciencedirect.com. It is distributed under the terms of the Creative Commons Attribution License 3.0, which permits unrestricted use, distribution, and reproduction in any medium, provided the original authors and source are credited.

References

Physics, Nanjing University, Jiangsu, China

106 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands

105 Dipartimento di Fisica, Università di Napoli, Napoli, Italy

104 INFN Sezione di Napoli; INFN Gruppo Collegato di Cosenza; INFN Sezione di Napoli; INFN Sezione di Cosenza (INFN Sezione di Napoli; INFN Gruppo Collegato di Cosenza; INFN Sezione di Napoli (INFN Sezione di Napoli; INFN Gruppo Collegato di Cosenza; INFN Sezione di Napoli)

103 Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States

102 Department of Physics, Northern Illinois University, DeKalb, IL, United States
107 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
108 Department of Physics, New York University, New York, NY, United States
109 Ohio State University, Columbus, OH, United States
110 Faculty of Science, Okayama University, Okayama, Japan
111 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States
112 Department of Physics, Oklahoma State University, Stillwater, OK, United States
113 Palacký University, RCFPM, Olomouc, Czech Republic
114 Center for High Energy Physics, University of Oregon, Eugene, OR, United States
115 LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France
116 Graduate School of Science, Osaka University, Osaka, Japan
117 Department of Physics, University of Oslo, Oslo, Norway
118 Department of Physics, Oxford University, Oxford, United Kingdom
119 (a) INFN Sezione di Pavia; (b) Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Pavia, Italy
120 Department of Physics, University of Pennsylvania, Philadelphia, PA, United States
121 Petersburg Nuclear Physics Institute, Gatchina, Russia
122 (a) INFN Sezione di Padova; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
123 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States
124 (a) Laboratorio de Instrumentacao e Fisica Experimental de Particulas – LIP, Lisboa, Portugal; (b) Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
125 Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
126 Faculty of Mathematics and Physics, Charles University in Prague, Czech Republic
127 Czech Technical University in Prague, Prague, Czech Republic
128 State Research Center for High Energy Physics, Protvino, Russia
129 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
130 Physics Department, University of Regina, Regina, SK, Canada
131 Ritsumeikan University, Kusatsu, Shiga, Japan
132 (a) INFN Sezione di Roma I; (b) Dipartimento di Fisica, Università La Sapienza, Roma, Italy
133 (c) INFN Sezione di Roma Tor Vergata; (d) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
134 (e) INFN Sezione di Roma Tre; (f) Dipartimento di Fisica, Università Roma Tre, Roma, Italy
135 (g) Facultad de Ciencias Adu Chock, Rsehas Universitaires de Hautes Energes – Université Hassan II, Casablanca; (h) Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat; (i) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPEHA-Marrakech; (j) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (k) Faculté des Sciences, Université Mohammed V, Rabat, Morocco
136 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France
137 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States
138 Physics Department, University of Washington, Seattle, WA, United States
139 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
140 Physics Department, Shinshu University, Nagano, Japan
141 Fachbereich Physik, Universität Siegen, Siegen, Germany
142 Department of Physics, Simon Fraser University, Burnaby, BC, Canada
143 SLAC National Accelerator Laboratory, Stanford, CA, United States
144 (a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
145 (a) Department of Physics, University of Johannesburg, Johannesburg; (b) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
146 (a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden
147 Physics Department, Royal Institute of Technology, Stockholm, Sweden
148 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, NY, United States
149 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
150 School of Physics, University of Sydney, Sydney, Australia
151 Institute of Physics, Academia Sinica, Taipei, Taiwan
152 Department of Physics, Technion – Israel Inst. of Technology, Haifa, Israel
153 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
154 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
155 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
156 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
157 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
158 Department of Physics, University of Toronto, Toronto, ON, Canada
159 (a) TRIUMF, Vancouver, BC; (b) Department of Physics and Astronomy, York University, Toronto, ON, Canada
160 Institute of Pure and Applied Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8571, Japan
161 Science and Technology Center, Tufts University, Medford, MA, United States
162 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
163 Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States
164 (a) INFN Gruppo Collegato di Udine; (b) ICTP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
165 Department of Physics, University of Illinois, Urbana, IL, United States
166 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
167 Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
168 Department of Physics, University of British Columbia, Vancouver, BC, Canada
169 Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
170 Waseda University, Tokyo, Japan
171 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
172 Departments of Physics, University of Wisconsin, Madison, WI, United States
173 Fachhochschule für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
174 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
175 Department of Physics, Yale University, New Haven, CT, United States
176 Yerevan Physics Institute, Yerevan, Armenia
177 Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France

a Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas – LIP, Lisboa, Portugal.
b Also at Faculdade de Ciencias and CNFNUL, Universidade de Lisboa, Lisboa, Portugal.
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, Guangzhou, 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 à 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.