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):

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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

**ATLAS Collaboration***

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

Article history:
Received 7 February 2012
Received in revised form 29 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 of a SM Higgs boson with masses of 125 GeV, 244 GeV and 500 GeV with local significances of 2.1, 2.2 and 2.1 standard deviations, respectively. 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.

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**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 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, $\mu^+\mu^-\mu^+\mu^-$ ($4\mu$), $e^+e^-\mu^+\mu^-$ (2e2\mu), and $e^+e^-e^+e^-$ (4e), are selected. The largest background to this search comes from continuum ($Z^{(*)}/\gamma^*)$ production, referred to as $ZZ^{(*)}$ hereafter.

For $m_H < 180$ GeV, there are also important background contributions from $Z+\text{jets}$ 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 $\sqrt{s} = 7$ 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 provides good sensitivity to electrons and photons.

footnote: 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.
Higgs boson transverse momentum (nm) with matrix elements up to next-to-leading order (NLO). The production cross section for associated production with a W or Z boson is negligibly small for $m_H > 300$ GeV. The decay branching ratio for $H \rightarrow 4\ell$, with $\ell = e$ or $\mu$, is reported in the last column [34].

<table>
<thead>
<tr>
<th>$m_H$ [GeV]</th>
<th>$\sigma(gg \rightarrow H)$ [pb]</th>
<th>$\sigma(\bar{q}q \rightarrow Hq)$ [pb]</th>
<th>$\sigma(q\bar{q} \rightarrow WH)$ [pb]</th>
<th>$\sigma(q\bar{q} \rightarrow ZH)$ [pb]</th>
<th>BR($H \rightarrow ZZ^{(*)} \rightarrow 4\ell$) [$10^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>130</td>
<td>1.41 $^{+0.22}_{-0.18}$</td>
<td>1.15 $^{+0.02}_{-0.02}$</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 $^{+1.6}_{-1.1}$</td>
<td>9.62 $^{+0.28}_{-0.21}$</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 $^{+0.9}_{-0.7}$</td>
<td>6.37 $^{+0.02}_{-0.01}$</td>
<td>1.01 $\pm 0.005$</td>
<td>0.061 $\pm 0.004$</td>
<td>1.15</td>
</tr>
<tr>
<td>400</td>
<td>2.0 $\pm 0.3$</td>
<td>1.62 $^{+0.01}_{-0.00}$</td>
<td>$\approx$</td>
<td>$\approx$</td>
<td>1.21</td>
</tr>
<tr>
<td>600</td>
<td>0.33 $\pm 0.06$</td>
<td>0.058 $^{+0.00}_{-0.00}$</td>
<td>$\approx$</td>
<td>$\approx$</td>
<td>1.23</td>
</tr>
</tbody>
</table>

The Higgs boson decay branching ratio to the four-lepton final state is predicted by PROPHET4[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 $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ 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 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 ($m_H > 400$ GeV) considered in this search. In the absence of a full calculation, a conservative estimate of the possible size of such effects is included as a signal normalization systematic uncertainty following a parameterization as a function of $m_H$: $150\% \times m_H^3$ [TeV], for $m_H > 300$ 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 ($m_{ZZ^{(*)}}$). The QCD scale uncertainty has a ±5% effect on the expected $ZZ^{(*)}$ background, and the effect due to the PDF and $\alpha_s$ 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 $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} > 0.4$ 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 used. In this search the Z + jets background is normalized using control samples from data. For comparisons with simulation, the QCD NNLO FWWZ [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 ±4%, while the effect of PDF and $\alpha_s$ 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.
momentum is computed from the cluster energy and the track di-
track pointing to the corresponding cluster. The electron transverse
that require the shower profiles to be consistent with those ex-
etron tracks have been refitted using a Gaussian-sum filter. The
the electromagnetic calorimeter that are associated to ID tracks.
ary vertex, of less than 1 mm. The primary vertex is defined
impact parameter in the transverse plane with respect to the pri-
are required to have a transverse impact parameter, defined as the
using the ID information only. To reject cosmic rays, muon tracks
as the reconstructed vertex with the highest

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 trans-
verse energy, \( E_T \), threshold is 20–22 GeV depending on the LHC
instantaneous luminosity. For the di-muon and di-electron trigger
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 ex-
pected 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 di-
rection at the interaction point.

Muons are reconstructed by matching ID tracks with
either complete or partial tracks reconstructed in the MS [77].
The complete track is present, the two independent momentum mea-
surements 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
impact parameter in the transverse plane with respect to the pri-
mary vertex, of less than 1 mm. The primary vertex is defined
as the reconstructed vertex with the highest \( \sum p_T^2 \) of associated
tracks among the reconstructed vertices with at least three associ-
ated tracks.

This analysis searches for Higgs boson candidates by selecting
two same-flavour, opposite-sign lepton pairs in an event. The
impact parameter of the leptons along the beam axis is required to
be within 10 mm of the primary vertex. Each lepton must sat-
sfy \( p_T > 7 \) GeV and be measured in the pseudorapidity range
\( |\eta| < 2.47 \) for electrons and \( |\eta| < 2.7 \) for muons. At least two lep-
tons in the quadruplet must have \( p_T > 20 \) GeV. The leptons are
required to be separated from each other by \( \Delta R > 0.1 \). The invari-
ant mass of the same-flavour and opposite-sign lepton pair closest
to the Z boson mass \( (m_Z) \) is denoted by \( m_{12} \) and \( |m_Z - m_{12}| < 15 \) GeV is required. The invariant mass of the remaining same-
flavour and opposite-sign lepton pair, \( m_{34} \), is required to be in the
range \( m_{min} < m_{34} < 115 \) GeV, where \( m_{min} \) depends on the recon-
structed four-lepton invariant mass, \( m_{4\ell} \), as shown in Table 2.

The \( Z + \) jets and \( t\bar{t} \) background contributions are further re-
duced by applying track- and calorimeter-based isolation and im-
pact parameter requirements on the leptons. For a lepton to be
isolated, the sum of the \( p_T \) of tracks within \( \Delta R < 0.2 \) of the lep-
ton 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 with \( \Delta R < 0.2 \) around
the lepton divided by the lepton \( p_T \) is required to be less than 0.3.
The lepton track and the energies of calorimeter cells associated to
it are excluded from the sum. Any contributions arising from other

leptons of the quadruplet are subtracted. To reduce the impact of
event 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 cor-
rected by subtracting a small amount of energy that depends on
the number of reconstructed vertices in the event. In events with
four-lepton invariant mass \( (m_{4\ell}) \) below 190 GeV, 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 \( m_{4\ell} \), 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 domi-
nated by experimental resolution for \( m_H < 350 \) GeV, while for \( m_H \) the reconstructed width is dominated by the natu-
ral 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 re-
quirements \( - \) same-flavour lepton pair is used to study the contri-
butions 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 domi-
nates 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 parti-
cles are misidentified as muons. The \( Z + \) light jets contribution in the
\( Z + ee \) final state is estimated by extrapolation, using MC sim-
ulation, 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, where
\( Z \rightarrow \mu^+\mu^-/e^+e^- \). In Figs. 2(a) and 2(c) the \( m_{12} \) and \( m_{34} \) distribu-

\[ m_{4\ell} (\text{GeV}) \begin{array}{cccccccc}
\leq 120 & 130 & 140 & 150 & 160 & 165 & 180 & 190 \\
\geq 200 & 25 & 30 & 35 & 40 & 50 & 60 \\
\end{array} \\
m_{34} \text{ threshold (GeV)} \]

\[ \begin{array}{cccccccc}
15 & 20 & 25 & 30 & 35 & 40 & 50 & 60 \\
\end{array} \]

Generated events are fully simulated using the ATLAS detec-
tor 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 inter-
actions per bunch crossing in the data.
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 $m_{3\ell}$, where the $ZZ^{(*)}$ background dominates, and for low $m_{3\ell}$ 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$\mu$ (2$e$2$\mu$) channel. The uncertainty in the electron efficiency results in a relative acceptance uncertainty of 2.3% (1.6%) for the 4$e$ (2$e$2$\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 electron energy resolution uncertainty for electrons is negligible, while the electron energy scale uncertainty results in an acceptance uncertainty of less than 0.6% (0.3%) on the mass scale of the $m_{4\ell}$ distribution for the 4$e$ (2$e$2$\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 $Z \rightarrow ee$ 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 MCBased 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 2$e$2$\mu$, and 17 4$e$ events. From the background processes, 62 ± 9 events are expected: 18.6 ± 2.8 $4\mu$, 29.7 ± 4.5 2$e$2$\mu$ and 13.4 ± 2.0 4$e$. 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 $m_{1\tau}$ and $m_{3\ell}$ 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 CLs 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 184–400 GeV.

The significance of an excess is given by the probability, $p_\nu$, that a background-only experiment is more signal-like than that observed. In Fig. 6 the $p_\nu$-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 $Z(\rightarrow \mu^+\mu^-/e^+e^-) + \mu\mu$ 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>$\mu^+\mu^-\mu^+\mu^-$</th>
<th>$e^+e^-\mu^+\mu^-$</th>
<th>$e^+e^-e^+e^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_H = 130$ GeV</td>
<td>2.1 ± 0.3</td>
<td>16.3 ± 2.4</td>
<td>2.8 ± 0.6</td>
</tr>
<tr>
<td>$m_H = 150$ GeV</td>
<td>0.16 ± 0.06</td>
<td>0.02 ± 0.01</td>
<td>1.4 ± 0.5</td>
</tr>
<tr>
<td>$m_H = 200$ GeV</td>
<td>2.2 ± 0.3</td>
<td>16.3 ± 2.4</td>
<td>4.3 ± 0.8</td>
</tr>
<tr>
<td>$m_H = 400$ GeV</td>
<td>0.34 ± 0.04</td>
<td>0.62 ± 0.10</td>
<td>2.8 ± 0.8</td>
</tr>
<tr>
<td>$m_H = 600$ GeV</td>
<td>0.34 ± 0.04</td>
<td>0.62 ± 0.10</td>
<td>2.8 ± 0.8</td>
</tr>
</tbody>
</table>

$\mu^+\mu^-\mu^+\mu^-$ 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 FAPESP, 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,
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 $m_{\mathrm{H}}$, 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. 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 $m_{\mathrm{H}}$. The two horizontal dashed lines indicate the $p_0$ values corresponding to local significances of $2\sigma$ and $3\sigma$.

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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, RCPTM, 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 Pisa; (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 CATIE, 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 Institute 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 (a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
134 (a) INFN Sezione di Roma Tre; (b) Dipartimento di Fisica, Università Roma Tre, Roma, Italy
135 (a) Faculté des Sciences Ain Chock, Résidences Universitaires de Hautes Énergies – Université Hassan II, Casablanca; (b) Centre National de l’Energie des Sciences Techniques Nucléaires, Rabat; (c) Facultés des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) 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 Department of Physics, University of Washington, Seattle, WA, United States
139 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
140 Department of Physics, 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, Tsufts 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 Fisica Corpuscular (IFIC) and Departamento de Fisica 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 Department of Physics, University of Wisconsin, Madison, WI, United States
173 Fakultät 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 CFNUL, Universidade de Lisboa, Lisboa, Portugal.