



# 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<sup>☆</sup>

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## ABSTRACT

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.

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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  $156 < m_H < 177 \text{ GeV}$  [5]. At the LHC, results from data collected in 2010 extended the search in the region  $200 < m_H < 600 \text{ GeV}$  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  $\text{fb}^{-1}$  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  $145 < m_H < 206 \text{ GeV}$ .

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  $2.1 \text{ fb}^{-1}$  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  $m_H < 180 \text{ GeV}$ , 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  $4.8 \text{ fb}^{-1}$  [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.<sup>1</sup> 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

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<sup>1</sup> 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.

**Table 1**

Higgs boson production cross sections for gluon fusion, vector-boson fusion and associated production with a  $W$  or  $Z$  boson in  $pp$  collisions at  $\sqrt{s} = 7$  TeV [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  $m_H > 300$  GeV. The decay branching ratio for  $H \rightarrow 4\ell$ , with  $\ell = e$  or  $\mu$ , is reported in the last column [34].

$m_H$ [GeV]	$\sigma(gg \rightarrow H)$ [pb]	$\sigma(qq' \rightarrow Hqq')$ [pb]	$\sigma(q\bar{q} \rightarrow WH)$ [pb]	$\sigma(q\bar{q} \rightarrow ZH)$ [pb]	$BR(H \rightarrow ZZ^{(*)} \rightarrow 4\ell)$ [ $10^{-3}$ ]
130	$14.1^{+2.7}_{-2.1}$	$1.154^{+0.032}_{-0.027}$	$0.501 \pm 0.020$	$0.278 \pm 0.014$	0.19
150	$10.5^{+2.0}_{-1.6}$	$0.962^{+0.028}_{-0.021}$	$0.300 \pm 0.012$	$0.171 \pm 0.009$	0.38
200	$5.2^{+0.9}_{-0.8}$	$0.637^{+0.022}_{-0.015}$	$0.103 \pm 0.005$	$0.061 \pm 0.004$	1.15
400	$2.0 \pm 0.3$	$0.162^{+0.010}_{-0.005}$	–	–	1.21
600	$0.33 \pm 0.06$	$0.058^{+0.005}_{-0.002}$	–	–	1.23

calorimeter [19] measures the energy and the position of electromagnetic showers with  $|\eta| < 3.2$ . LAr sampling calorimeters are also used to measure hadronic showers in the end-cap ( $1.5 < |\eta| < 3.2$ ) and forward ( $3.1 < |\eta| < 4.9$ ) regions, while an iron/scintillator tile calorimeter [20] measures hadronic showers in the central region ( $|\eta| < 1.7$ ). 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 ( $|\eta| < 2.7$ ), 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  $4.8 \text{ fb}^{-1}$ ,  $4.8 \text{ fb}^{-1}$  and  $4.9 \text{ fb}^{-1}$  for the  $4\mu$ ,  $2e2\mu$  and  $4e$  final states, respectively.

The  $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$  signal is modelled using the POWHEG Monte Carlo (MC) event generator [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  $\tau$  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  $\pm 1\%$  for the vector-boson fusion, associated  $WH$  production, and associated  $ZH$  production processes [34]. The uncertainty in the production cross section due to the parton distribution function (PDF) and  $\alpha_s$  is  $\pm 8\%$  for gluon-initiated process and  $\pm 4\%$  for quark-initiated processes [55–59].

The Higgs boson decay branching ratio to the four-lepton final state is predicted by PROPHECY4F [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 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 ( $m_H > 400$  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  $m_H \geq 300$  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  $\pm 5\%$  effect on the expected  $ZZ^{(*)}$  background, and the effect due to the PDF and  $\alpha_s$  uncertainties is  $\pm 4\%$  ( $\pm 8\%$ ) for quark-initiated (gluon-initiated) processes. An additional theoretical uncertainty of  $\pm 10\%$  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 FEWZ [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  $^{+4}_{-9}\%$ , while the effect of PDF and  $\alpha_s$  uncertainties is  $\pm 7\%$ . 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**

Lower thresholds applied to  $m_{34}$  for reference values of  $m_{4\ell}$ . For  $m_{4\ell}$  values between these reference values the selection requirement is obtained via linear interpolation.

$m_{4\ell}$ (GeV)	$\leq 120$	130	140	150	160	165	180	190	$\geq 200$
$m_{34}$ threshold (GeV)	15	20	25	30	30	35	40	50	60

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 impact parameter in the transverse plane with respect to the primary 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 associated 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 satisfy  $p_T > 7$  GeV and be measured in the pseudorapidity range  $|\eta| < 2.47$  for electrons and  $|\eta| < 2.7$  for muons. At least two leptons in the quadruplet must have  $p_T > 20$  GeV. The leptons are required to be separated from each other by  $\Delta R > 0.1$ . The invariant 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 reconstructed four-lepton invariant mass,  $m_{4\ell}$ , as shown in Table 2.

The  $Z$  + jets and  $t\bar{t}$  background contributions are further reduced by applying track- and calorimeter-based isolation and impact 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 lepton divided by the lepton  $p_T$  is required to be less than 0.15, while the sum of the  $E_T$  of the calorimeter cells 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 corrected 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 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.

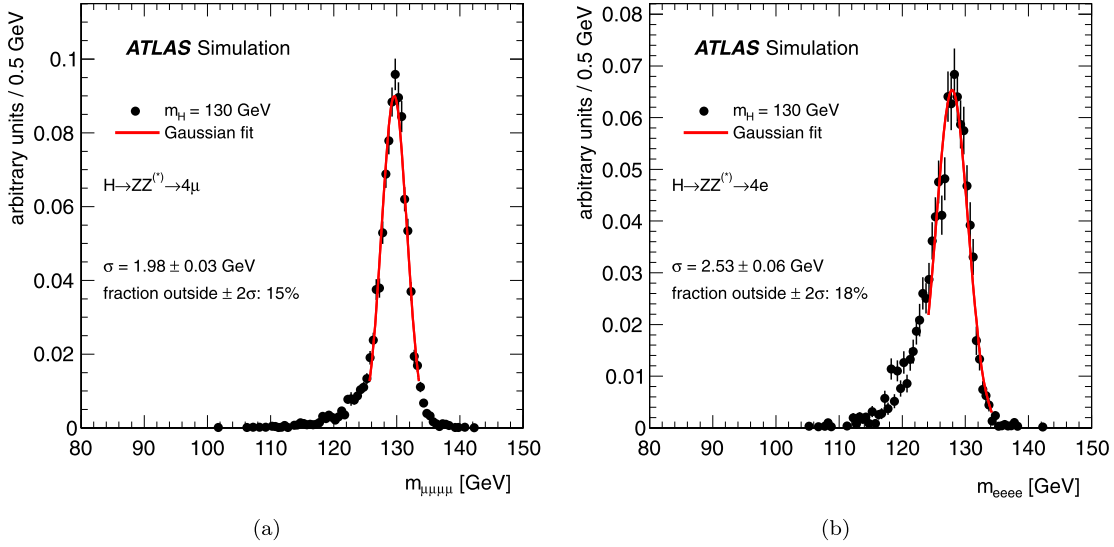
#### 5. Background estimation

The expected background yield and its composition is estimated using MC simulation normalized to the theoretical cross section for  $Z Z^{(*)}$  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, where  $Z \rightarrow \mu^+ \mu^- / e^+ e^-$ . In Figs. 2(a) and 2(c) the  $m_{12}$  and  $m_{34}$  distribu-



**Fig. 1.** Invariant mass distributions for simulated (a)  $H \rightarrow ZZ^{(*)} \rightarrow 4\mu$  and (b)  $H \rightarrow ZZ^{(*)} \rightarrow 4e$  events for  $m_H = 130$  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  $4e$  channel arises from energy losses due to bremsstrahlung [76]. The fraction of events outside the  $\pm 2\sigma$  region is found to be 15% for  $4\mu$  and 18% for  $4e$ .

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.

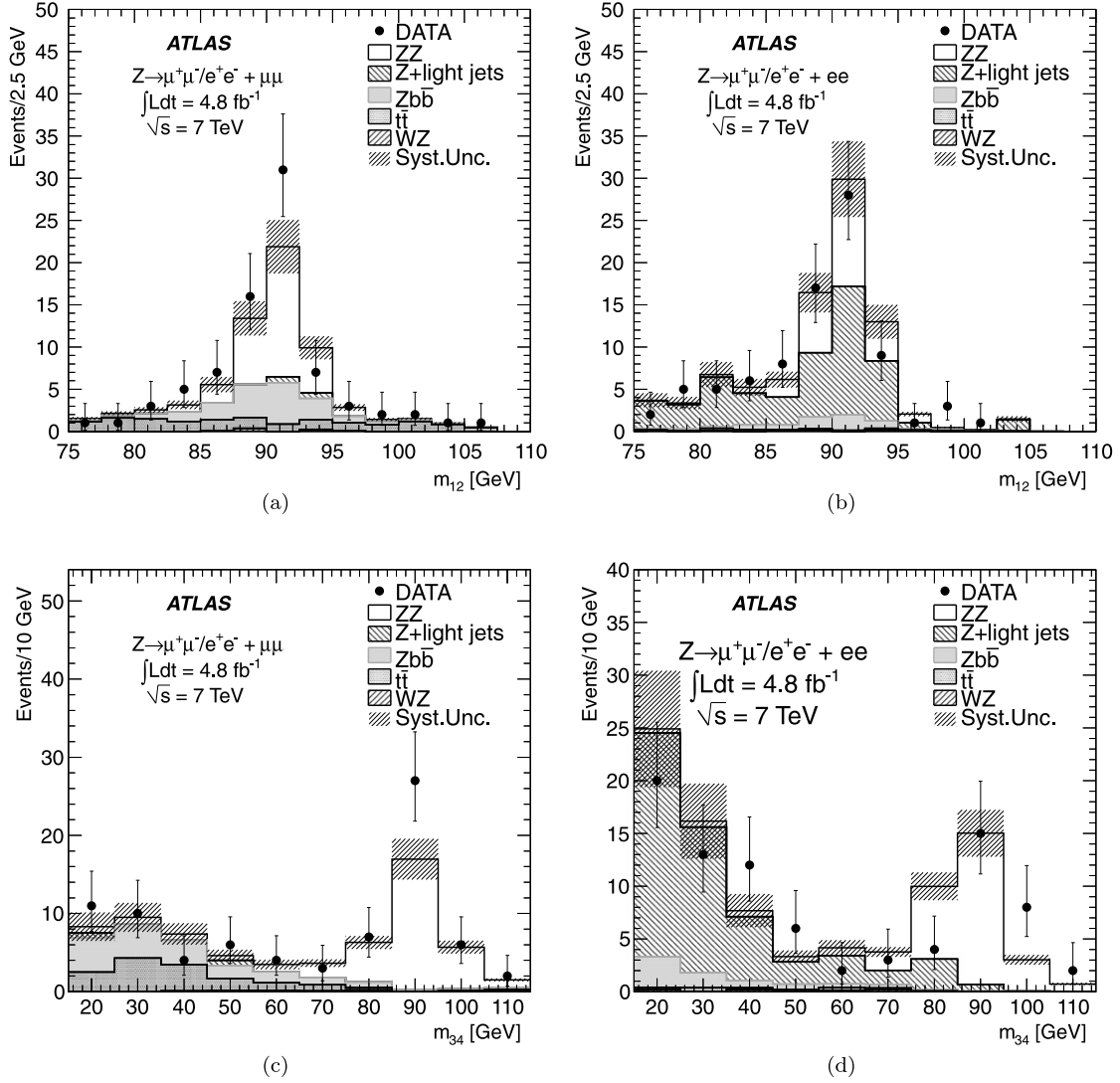
## 7. Results

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  $CL_s$  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  $m_{4\ell}$  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,  $p_0$ , that a background-only experiment is more signal-like than that observed. In Fig. 6 the  $p_0$ -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.

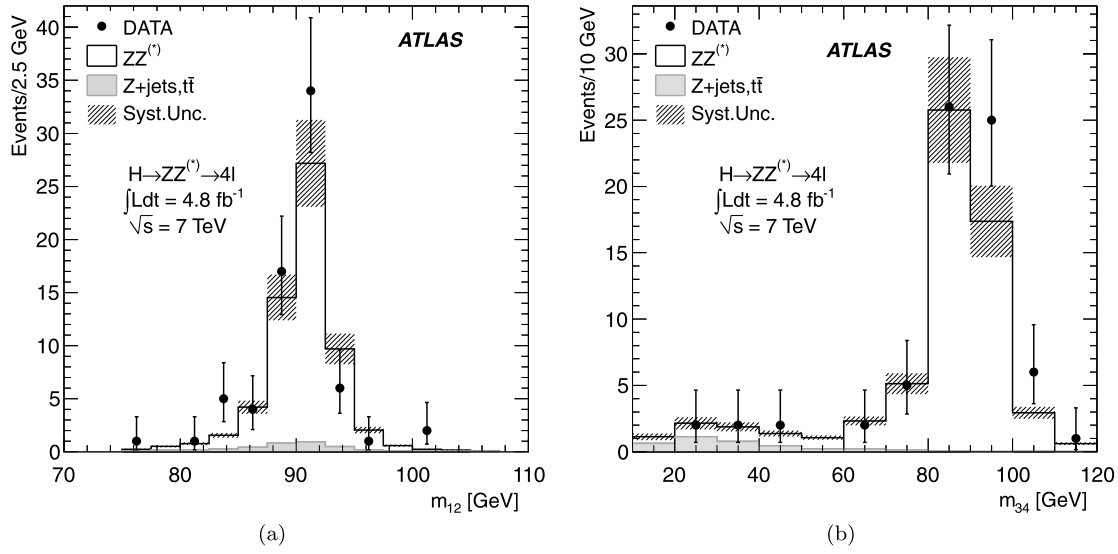
**Table 3**

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.

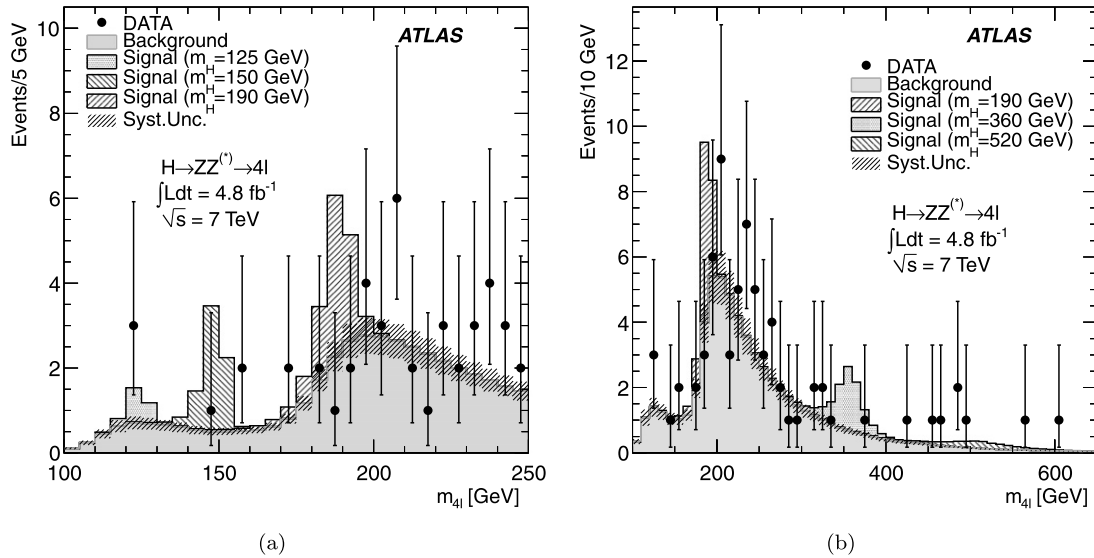
	$\mu^+\mu^-\mu^+\mu^-$		$e^+e^-\mu^+\mu^-$		$e^+e^-e^+e^-$	
	Low- $m_{4\ell}$	High- $m_{4\ell}$	Low- $m_{4\ell}$	High- $m_{4\ell}$	Low- $m_{4\ell}$	High- $m_{4\ell}$
Int. luminosity	4.8 fb <sup>-1</sup>		4.8 fb <sup>-1</sup>		4.9 fb <sup>-1</sup>	
ZZ(*)	2.1 ± 0.3	16.3 ± 2.4	2.8 ± 0.6	25.2 ± 3.8	1.2 ± 0.3	10.4 ± 1.5
Z + jets and $t\bar{t}$	0.16 ± 0.06	0.02 ± 0.01	1.4 ± 0.5	0.17 ± 0.08	1.6 ± 0.7	0.18 ± 0.08
Total background	2.2 ± 0.3	16.3 ± 2.4	4.3 ± 0.8	25.4 ± 3.8	2.8 ± 0.8	10.6 ± 1.5
Data	3	21	3	27	2	15
$m_H = 130$ GeV	1.00 ± 0.17		1.22 ± 0.21		0.43 ± 0.08	
$m_H = 150$ GeV	2.1 ± 0.4		2.9 ± 0.4		1.12 ± 0.18	
$m_H = 200$ GeV	4.9 ± 0.7		7.7 ± 1.0		3.1 ± 0.4	
$m_H = 400$ GeV	2.0 ± 0.3		3.3 ± 0.5		1.49 ± 0.21	
$m_H = 600$ GeV	0.34 ± 0.04		0.62 ± 0.10		0.30 ± 0.06	

$m_H = 125$  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 stan-

dard 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  $ZZ^{(*)}$  process and the sum of  $t\bar{t}$ ,  $Zb\bar{b}$  and  $Z$  + 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

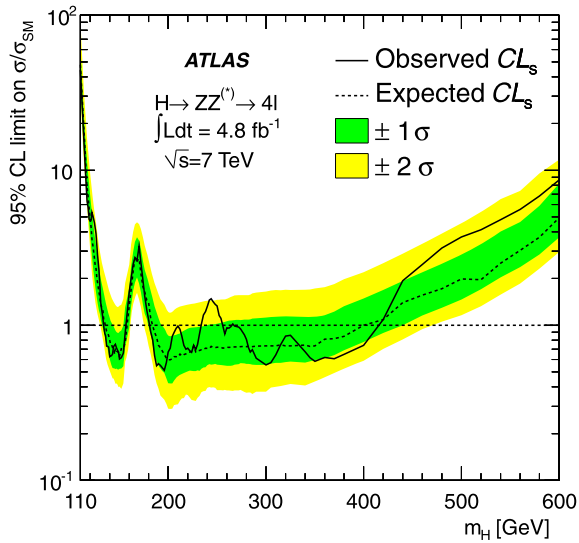
A search for the SM Higgs boson in the decay channel  $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$  based on  $4.8 \text{ fb}^{-1}$  of data recorded by the ATLAS detector at  $\sqrt{s} = 7 \text{ TeV}$  during the 2011 run has been presented. The SM Higgs boson is excluded at 95% CL in the mass ranges 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  $m_H = 125 \text{ GeV}$ , 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.

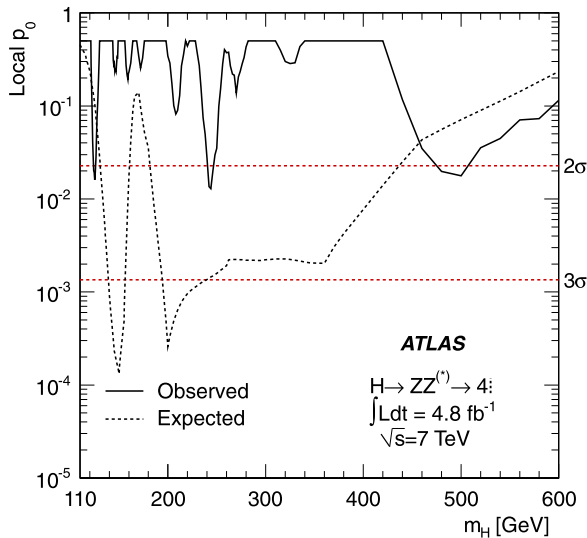
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**Fig. 5.** The expected (dashed) and observed (full line) 95% CL upper limits on the Standard Model Higgs boson production cross section as a function of  $m_H$ , divided by the expected SM Higgs boson cross section. The dark (green) and light (yellow) 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  $m_H$ . The two horizontal dashed lines indicate the  $p_0$  values corresponding to local significances of  $2\sigma$  and  $3\sigma$ .

Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERYs (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTd, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, 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.

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