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Search for a Standard Model Higgs boson in the mass range 200–600 GeV in the $H \to ZZ \to \ell^+\ell^- q\bar{q}$ decay channel with the ATLAS detector ☆

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ABSTRACT

A search for a heavy Standard Model Higgs boson decaying via $H \to ZZ \to \ell^+\ell^- q\bar{q}$, where $\ell = e$ or μ, is presented. The search uses a data set of pp collisions at $\sqrt{s} = 7$ TeV, corresponding to an integrated luminosity of 4.7 fb^{-1} collected in 2011 by the ATLAS detector at the CERN LHC. No significant excess of events above the estimated background is found. Upper limits at 95% confidence level on the production cross section of a Higgs boson with a mass in the range between 200 and 600 GeV are derived. A Standard Model Higgs boson with a mass in the range 300 GeV $\leqslant m_H \leqslant$ 322 GeV or 353 GeV $\leqslant m_H \leqslant$ 410 GeV is excluded at 95% CL. The corresponding expected exclusion range is 351 GeV $\leqslant m_H \leqslant$ 404 GeV at 95% CL.

1. Introduction

In the Standard Model (SM), the as-yet-unobserved Higgs boson [1–3] gives mass to the weak vector bosons and other particles. 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]. Searches at the Fermilab Tevatron $p\bar{p}$ collider have excluded at 95% CL the regions 100–106 GeV and 147–179 GeV [5]. At the ATLAS experiment at the LHC, the search was extended as far as 600 GeV using up to 4.9 fb^{-1} of $\sqrt{s} = 7$ TeV data recorded through 2011 (including an earlier version of this analysis with less data), ruling out the production of a SM Higgs boson at 95% CL in the regions 112.5–115.5 GeV, 131–237 GeV, and 251–468 GeV [6]. Corresponding results from CMS [7], using 4.6–4.8 fb^{-1} of $\sqrt{s} = 7$ TeV data, excluded at 95% CL the region 127–600 GeV.

If m_H is larger than twice the Z boson mass, m_Z, the Higgs boson is expected to decay to two on-shell Z bosons with a large branching ratio. This Letter reports a search for a SM Higgs boson in the mass range 200–600 GeV decaying to a pair of Z bosons, where one Z boson decays into two leptons and the other to two quarks: $H \to ZZ \to \ell^+\ell^- q\bar{q}$ with $\ell \equiv e, \mu$. The analysis uses the full data set of 4.7 fb^{-1} recorded by the ATLAS experiment in 2011. Previous results from the ATLAS Collaboration in this channel [6,8], using up to 2.05 fb^{-1} of data, excluded a SM Higgs boson production cross section between 1.2 and 12 times the SM cross section over this mass range. The corresponding exclusions from the CMS Collaboration with 4.6 fb^{-1} of data are between 1.0 and 4 times the SM cross section over the same mass range [9].

2. Data and Monte Carlo samples

The data used in this search were recorded by the ATLAS experiment during the 2011 LHC run with pp collisions at $\sqrt{s} = 7$ TeV. They correspond to an integrated luminosity of approximately 4.7 fb^{-1} after data quality selections to require that all systems used in this analysis were operational. The data were collected using single-lepton triggers with a transverse momentum (p_T) threshold of 20 to 22 GeV for electrons and 18 GeV for muons, supplemented with a dielectron trigger with a threshold of 12 GeV. The resulting trigger criteria are about 95% efficient in the muon channel and close to 100% efficient in the electron channel, relative to the selection criteria described below. Collision events are selected by requiring a reconstructed primary vertex with at least three associated tracks with $p_T > 0.4$ GeV. The average number of collisions per bunch crossing in this data sample is about nine.

The $H \to ZZ \to \ell^+\ell^- q\bar{q}$ signal is modelled with the POWHEG Monte Carlo (MC) event generator [10,11], which calculates separately the gluon and vector-boson fusion Higgs boson production mechanisms up to next-to-leading order (NLO). Generated signal events are hadronised with PYTHIA [12], interfaced to PHOTOS [13] to model final-state radiation and TAUOLA [14,15] to simulate τ decays. The parton distribution function (PDF) is MRSTMCAL [16]. The Higgs boson p_T spectrum is reweighted to match Ref. [17], which provides QCD corrections up to NLO and QCD soft-gluon resummations up to next-to-next-to-leading logarithms. The small contribution from Z boson decay to τ leptons is also included.

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The Higgs boson production cross sections and decay branching ratios as well as their uncertainties, are taken from Refs. [18,19]. The predicted cross sections for the gluon fusion processes are based on calculations to next-to-next-to-leading order (NNLO) in QCD [20–25], and also include QCD soft-gluon resummations up to next-to-next-to-leading logarithms [26] and NLO electroweak (EW) corrections [27,28]. These results are compiled in Refs. [29–31] and assume factorisation between QCD and EW corrections. The cross sections for the vector-boson fusion processes are calculated with full NLO QCD and EW corrections [32–34] and approximate NNLO QCD corrections [35]. The uncertainty in the production cross section due to the choice of the QCD scale is $^{+12}_{-8}\%$ for the gluon fusion process and ±1% for the vector-boson fusion process [18,19]. The uncertainty in the production cross section due to uncertainties in the PDFs and α_s is ±8% for the gluon-initiated process and ±4% for quark-initiated processes [36–40]. The Higgs boson decay branching ratio [41] to the four-fermion final state is calculated with PROPHECY4F [42,43]. The combined production cross section and decay branching ratio for the $H \to ZZ \to \ell^+\ell^-q\bar{q}$ channel ranges from 140 ± 20 fb for $m_H = 200$ GeV to 10 ± 2 fb for $m_H = 600$ GeV.

The cross section calculations do not take into account the width of the Higgs boson, which increases from 1.4 GeV at $m_H = 200$ GeV to 120 GeV at $m_H = 600$ GeV, and which is implemented through a relativistic Breit–Wigner line shape applied at the event generator level. It has been suggested [19,44–46] 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. Currently, in the absence of a full calculation for the different production mechanisms, a conservative estimate of the possible size of such effects is included as a signal normalisation systematic uncertainty parameterised as a function of m_H as $1.5 \times m_H^3$ [TeV], for $m_H \geqslant 300$ GeV [19].

The $Z+$light-jets background is modelled with the ALPGEN generator [47] with the CTEQ6L1 PDF set [48], interfaced to HERWIG [49] for parton showers and hadronisation, while SHERPA [50] with the CTEQ6L1 PDF set is used for $Z+$heavy-flavour events. Top quark production, both $t\bar{t}$ and single-top, is modelled using the MC@NLO generator [51] with the CT10 PDF set [38], interfaced to HERWIG for parton showers and hadronisation.

The SM ZZ process is an irreducible background for $H \to ZZ$. The $q\bar{q} \to ZZ$ process (also WZ) is modelled using HERWIG with the MRSTMCAL PDF set, interfaced to PHOTOS and TAUOLA. Alternative samples with PYTHIA and MC@NLO are used for systematics studies: HERWIG and PYTHIA use only leading-order matrix elements, but they can generate off-shell vector bosons, while MC@NLO generates only on-shell bosons. The $q\bar{q} \to ZZ$ production cross section has been calculated up to NLO in QCD [52]. Due to the large gluon flux at the LHC, NNLO gluon pair quark-box diagrams ($gg \to ZZ$) are significant and the $q\bar{q}$ cross section is increased by 6% to account for this additional contribution [53].

Those simulations that use HERWIG for hadronisation use JIMMY [54] for the modelling of the underlying event, while PYTHIA and SHERPA implement their own underlying event model.

3. Event selection

The ATLAS detector [55] has a forward–backward symmetric cylindrical geometry.[1] An inner tracking detector immersed in a 2 Tesla axial magnetic field covers $|\eta| < 2.5$ with silicon detectors and straw tubes. A liquid-argon electromagnetic calorimeter is divided into barrel ($|\eta| < 1.475$), endcap ($1.375 < |\eta| < 3.1$), and forward ($3.1 < |\eta| < 4.9$) regions. Hadronic calorimeters (using liquid argon or scintillating tiles as active materials) surround the electromagnetic calorimeter and cover $|\eta| < 4.9$. A muon spectrometer measures the deflection of muon tracks in the field of three large toroidal magnets and covers $|\eta| < 2.7$. A three-level trigger system selects events to be recorded for offline analysis.

The offline selection starts with the reconstruction of either a $Z \to ee$ or a $Z \to \mu\mu$ lepton pair. Electron and muon candidates must satisfy $p_T > 20$ GeV and $|\eta| < 2.5$, in addition to standard ATLAS quality requirements [56–58], and must also be isolated from surrounding tracks. Electrons within $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.2$ of a muon are rejected. The two muons in a pair are required to have opposite charge, but this requirement is not imposed for electrons because larger energy losses from showering in material in the inner tracking detector lead to higher charge misidentification probabilities. The invariant mass of the lepton pair $m_{\ell\ell}$ must lie within the range 83–99 GeV, and events with any additional selected electrons or muons are rejected to reduce background from WZ production where both bosons decay leptonically.

$H \to ZZ \to \ell^+\ell^-q\bar{q}$ decays contain a pair of jets from $Z \to q\bar{q}$ decay. Events are thus required to contain at least two jets with $p_T > 25$ GeV and $|\eta| < 2.5$. Jets are reconstructed with the anti-k_t algorithm [59] with radius parameter $R = 0.4$. They are calibrated using energy- and η-dependent correction factors based on MC simulation and validated with data [60]; this calibration includes effects of energy from additional proton–proton interactions. Jets within $\Delta R = 0.4$ of an electron or in which less than 75% of the momentum of the associated tracks originates from the primary vertex are rejected. The missing transverse momentum, with magnitude E_T^{mis}, is the (negative) vectorial sum of the transverse momenta of all cells in the calorimeters with $|\eta| < 4.9$, calibrated appropriately based on their identification as electrons, photons, τ leptons, jets, or unassociated calorimeter cells, and all selected muons in the event [61]. Calorimeter deposits associated with muons are subtracted from E_T^{mis} to avoid double counting. Since no high-p_T neutrinos are present in the signal, events are required to satisfy $E_T^{\text{mis}} < 50$ GeV, which primarily reduces the background from $t\bar{t}$ production.

Jets originating from b-quarks can be discriminated from other jets (“tagged”) based on the relatively long lifetime of hadrons containing b-quarks. This discrimination is important for this analysis because about 21% of signal events contain b-jets from $Z \to b\bar{b}$ decay, while b-jets are produced less often ($\sim 2\%$) in the dominant $(Z \to \ell\ell) +$ jets background. A jet is tagged by taking the set of tracks associated with the jet and looking for either a secondary vertex or for tracks that have a significant impact parameter with respect to the primary event vertex [62]. This information is combined into a single discriminating variable and a selection is applied that gives an efficiency of about 70% (20%) for identifying true b-jets (c-jets) with a light-quark jet rejection of about 130 [63,64]. To optimise the expected sensitivity, the analysis is divided into “tagged” and “untagged” subchannels, containing events with exactly two and with fewer than two b-tags, respectively. Events with more than two b-tags ($< 3\%$ of the data sample with two b-tags) are rejected.

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[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis coinciding with the axis of the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

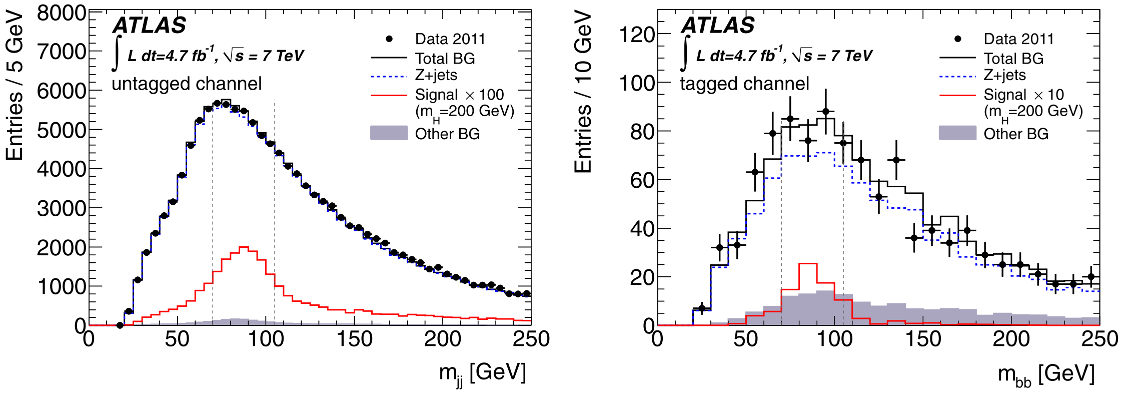


Fig. 1. Distributions of the invariant mass of selected dijet pairs, m_{jj}, for the data and the MC simulation, in the untagged (left) and tagged (right) samples, which contain fewer than two b-jets and exactly two b-jets respectively. Scale factors and corrections described in Section 4 have been applied. The signal has been scaled up by a factor of 100 (10) in the untagged (tagged) case to be more visible. The vertical lines show the range of the m_{jj} selection.

Events are required to have at least one candidate $Z \to q\bar{q}$ decay with dijet invariant mass m_{jj} within 70–105 GeV in order to be consistent with a Z boson decay. This selection is asymmetric around the Z boson mass to account for non-Gaussian tails extending to lower masses. The jets forming a candidate must also be separated by $\Delta R > 0.7$, as the phase space region with jets close together is poorly modelled by MC simulation. For untagged events, all pairs of jets formed from the three highest-p_T jets are considered. All such pairs are retained with unit weight, leading to the possibility of multiple candidates per event. The fraction of untagged events with multiple pairs retained is 13–16% (2–5%) for the low-m_H (high-m_H) selection defined below. For tagged events, the two tagged jets are used to form the dijet invariant mass; their energies are scaled up by 5% to take into account the average energy scale difference between heavy- and light-quark jets. The resulting dijet invariant mass distributions are well described by the MC simulation, as shown in Fig. 1.

The selection criteria above define the "low-m_H" selection, which is applied when searching for a Higgs boson with $m_H <$ 300 GeV. For higher Higgs boson masses, the Z bosons from the $H \to ZZ$ decay have large momenta in the laboratory reference frame, decreasing the opening angles between their decay products. Accordingly, in addition to the low-m_H selection, the following requirements are applied for $m_H \geqslant 300$ GeV: the two jets must have $p_T > 45$ GeV and the azimuthal difference between the two leptons ($\Delta\phi_{\ell\ell}$) and the two jets ($\Delta\phi_{jj}$) must both be less than $\pi/2$. These criteria define the "high-m_H" selection.

Following this event selection, an $H \to ZZ \to \ell^+\ell^- q\bar{q}$ signal should appear as a peak in the invariant mass distribution of the $\ell\ell jj$ system, with $m_{\ell\ell jj}$ around m_H. To improve the Higgs boson mass resolution, the energies of the jets forming each dijet pair are scaled event-by-event by a single multiplicative factor to set the dijet invariant mass m_{jj} to the nominal mass of the Z boson. The resolution is improved by a factor of 2.4 at $m_H = 200$ GeV; the improvement decreases with increasing m_H due to the increase in the natural width of the Higgs boson. The total efficiency for the selection of signal events is about 8% over most of the mass range.

4. Background estimates

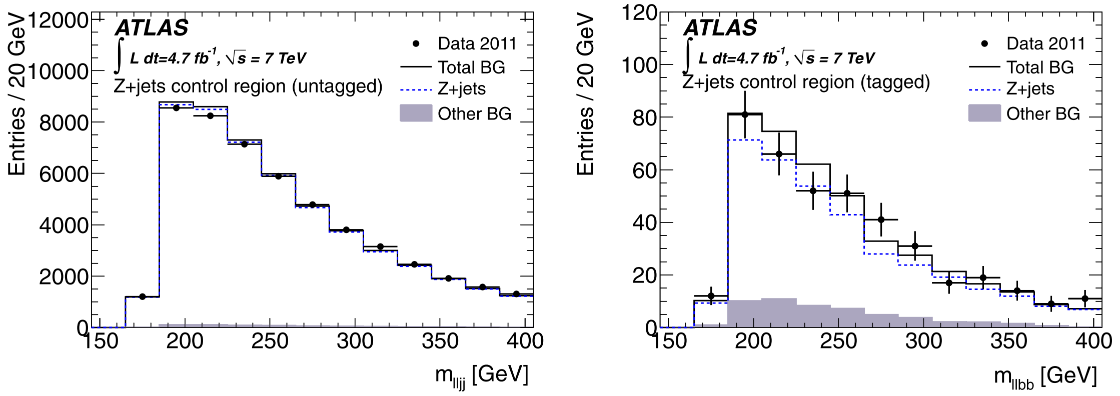
The main background to this analysis is Z boson production in association with jets (Z + jets). The shapes of the relevant kinematic distributions for this background are taken from MC simulation, with a small data-driven correction for the low-m_H untagged selection, while the normalisations for all selections are derived directly from data.

The flavour composition of the Z + jets sample is determined from three exclusive MC samples containing at least one true b-jet, at least one true c-jet, and all light jets, respectively. The relative normalisations of the three components are adjusted by fitting the distribution of the MC b-tagging discriminant to data.

To set the overall Z + jets normalisation, the $m_{\ell\ell jj}$ distribution is compared between data and MC simulation for events in which the dijet invariant mass m_{jj} is in sidebands of the Z boson mass: 40–70 GeV or 105–150 GeV (see Figs. 2(a) and 2(b)). The numbers of events in the sidebands, after subtraction of the contribution from other background sources, are then used to derive scale factors to correct the normalisation of the Z + jets MC simulation to that observed in the data. The scale factors are determined for the untagged channel separately for the low- and high-m_H selections; the results agree within statistical uncertainties. In the tagged channel, there are too few events in the sidebands to determine the scale factor for the high-m_H selection, hence the low-m_H scale factor is used for both selections. Since the top quark background is not negligible, the Z + jets MC normalisations are determined in a simultaneous fit to the Z + jets control region and the corresponding top quark control region (see below). The overall data to MC scale factors for Z + jets are approximately 0.9 for light-jets, 1.9 for c-jets, and 1.5 for b-jets.

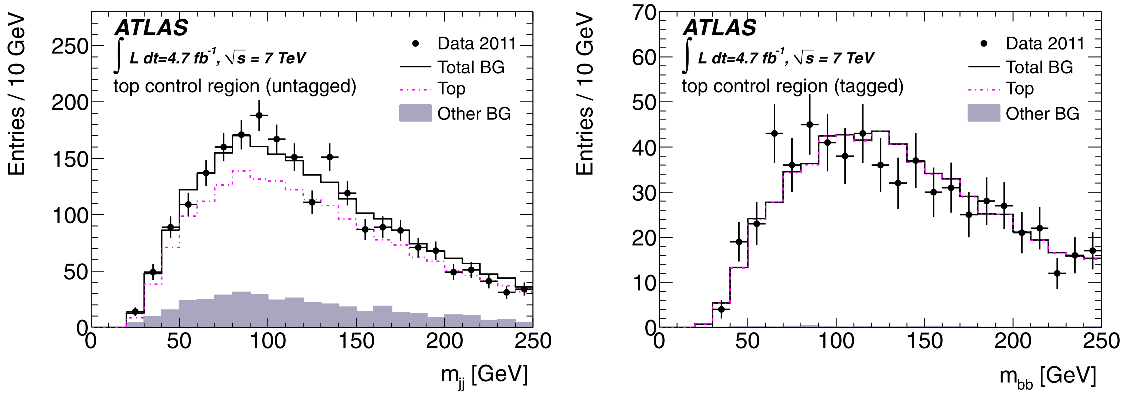
In the m_{jj} sidebands of the untagged low-m_H selection, the Z + jets MC simulation is about 3% above the data at $m_{\ell\ell jj} =$ 200 GeV and about 1% below it at $m_{\ell\ell jj} = 300$ GeV (see Fig. 2(a)). Since similar results are seen for both the low and high mass sidebands, a linear fit to the ratio of data to MC simulation in the $m_{\ell\ell jj}$ sideband distribution is used to correct the prediction in the signal region. For the high-m_H untagged selection and the tagged selections no difference between the data and MC distributions is seen within statistical uncertainties. Thus, no correction is applied to these samples, but similar fits to the one described above are used to evaluate systematic uncertainties on the Z + jets $m_{\ell\ell jj}$ shape.

The second most significant background is top quark production, which is most important in the tagged channel. The shapes of the relevant kinematic distributions are taken from MC simulation and the normalisation from data, using the top quark control region defined by the $m_{\ell\ell}$ sidebands 60–76 GeV or 106–150 GeV, with the E_T^{mis} selection reversed. Figs. 2(c) and 2(d) show the m_{jj} distributions for these control regions for the untagged and tagged selections respectively; good agreement is found after scaling up the MC prediction by about 5% for the untagged selection and 20% for the tagged selection. The contribution to this background from the production of single top quarks is negligible.



(a) m_{jj} sidebands, untagged sample.

(b) m_{jj} sidebands, tagged sample.



(c) $m_{\ell\ell}$ sidebands,untagged sample.

(d) $m_{\ell\ell}$ sidebands,tagged sample.

Fig. 2. Distributions from the background control samples, after application of scale factors, for the low-m_H selection. Top row: the $\ell\ell jj$ invariant mass for 40 GeV $< m_{jj} <$ 70 GeV or 105 GeV $< m_{jj} <$ 150 GeV for (a) the untagged and (b) the tagged sample. Bottom row: the invariant mass of the jj system for events with 60 GeV $< m_{\ell\ell} <$ 76 GeV or 106 GeV $< m_{\ell\ell} <$ 150 GeV and $E_T^{\mathrm{mis}} > 50$ GeV for (c) the untagged sample and (d) the tagged sample.

As in Ref. [8], the small irreducible background from diboson (ZZ and WZ) production is estimated directly from MC simulation. The background due to multijet events in which jets are misidentified as isolated electrons is estimated from data using a sample of events containing electron candidates that fail the selection requirements but pass loosened requirements. The multijet background to the muon channel was found to be negligible. The background from $W+$jets production was also found to be negligible.

5. Systematic uncertainties

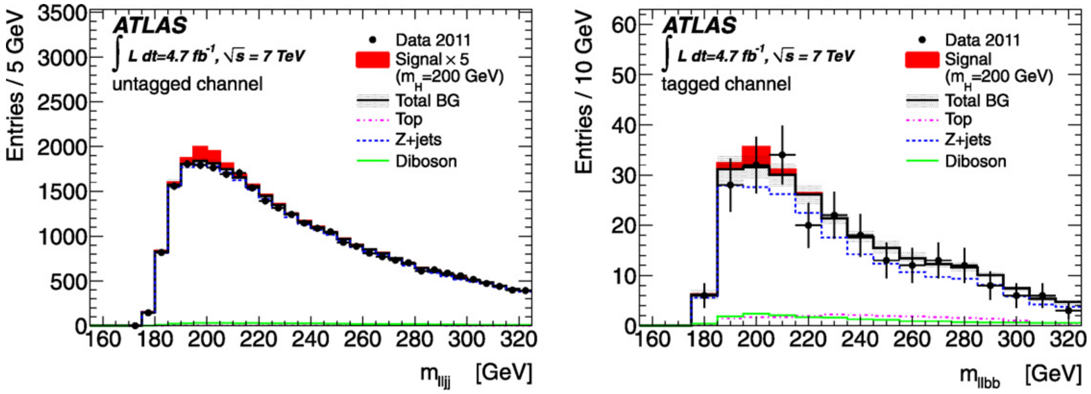
The theoretical uncertainties on the Higgs boson production cross section from Refs. [18,19] are 15–20% for the gluon fusion process and 3–9% for the vector-boson fusion process, depending on the Higgs boson mass. As mentioned in Section 2, an additional uncertainty $\propto m_H^3$ is applied for $m_H \geqslant 300$ GeV. The selection efficiency uncertainty due to the production process modelling is estimated by varying parameters of the signal MC simulation, including the amount of initial- and final-state radiation, the factorisation and normalisation scales, and the underlying event model; a further comparison uses PYTHIA instead of POWHEG. This procedure gives a 3% (12%) uncertainty for the low- (high-) m_H selection.

The uncertainty on the procedure used to determine the normalisation of the $Z+$jets background, described in Section 4, is evaluated by comparing the scale factors obtained from the upper or lower sideband separately. It is taken as the difference between the scale factors or the statistical uncertainty, whichever is larger. This procedure gives 1.7% for the low-m_H untagged selection, 2.2% for the high-m_H untagged selection, and 5.5% for both tagged selections. The uncertainty in the flavour composition of the $Z+$jets background is estimated by varying the relative fraction of $Z+c$-jets by ±30% as determined by altering the selection criteria applied in the fitting procedure described in Section 4. An uncertainty due to the modelling of the $m_{\ell\ell jj}$ shape as described in Section 4 is also applied. Additional uncertainties on the shape of the $Z+$jets background are estimated by finding variations of the MC m_{jj} and Z boson p_T distributions that sufficiently cover any differences between MC simulation and data in the m_{jj} sidebands.

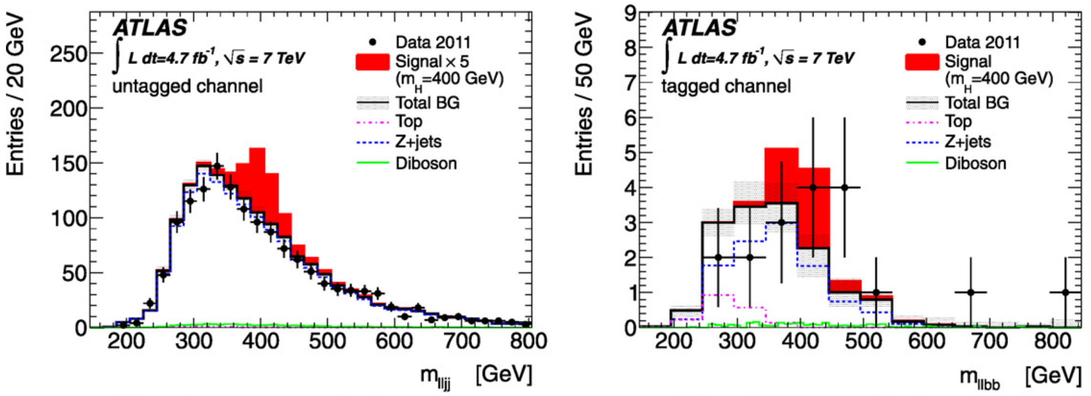
The uncertainty on the procedure used to determine the normalisation of the $t\bar{t}$ background is derived from the statistical uncertainties on the normalisation scale factors. It is found to be 2.7% for the untagged selection and 4.0% for the tagged selection. The diboson cross sections have a combined 5% QCD scale and PDF uncertainty [19]; adding an additional 10% uncertainty, corresponding to the maximum difference seen between MC@NLO and K-factor scaled PYTHIA results, yields an overall uncertainty of 11% on the diboson background normalisation. A 50% systematic uncertainty is assigned to the normalisation of the multijet background in the electron channel by comparing the result of fitting the $m_{\ell\ell}$ distribution before and after the requirement of at least two jets. An overall 3.9% uncertainty from the integrated luminosity [65,66] is added to the uncertainties on all MC processes that are not normalised from data (i.e. excluding $Z+$jets and top quark production), correlated across all samples.

Table 1
The expected numbers of signal and background candidates in the $H \rightarrow ZZ \rightarrow \ell^+\ell^- q\bar{q}$ channel, along with the numbers of candidates observed in data, for an integrated luminosity of 4.7 fb^{-1}. The low-m_H analysis is applied when searching for a Higgs boson with $m_H < 300$ GeV and the high-m_H analysis for $m_H \geqslant 300$ GeV. The first error indicates the statistical uncertainty, the second error the systematic uncertainty.

	Untagged		Tagged	
	Low-m_H	High-m_H	Low-m_H	High-m_H
Z + jets	$36\,190 \pm 80 \pm 640$	$1450 \pm 14 \pm 35$	$239 \pm 6 \pm 15$	$11 \pm 1 \pm 2$
Top	$85 \pm 3 \pm 10$	$7.1 \pm 0.7 \pm 0.8$	$23 \pm 1 \pm 3$	$1.9 \pm 0.4 \pm 0.5$
Multijet	$15 \pm 0 \pm 8$	$0.2 \pm 0.0 \pm 0.1$	< 0.1	< 0.1
ZZ	$348 \pm 3 \pm 47$	$25 \pm 1 \pm 3$	$22 \pm 1 \pm 4$	$2.3 \pm 0.3 \pm 0.4$
WZ	$434 \pm 4 \pm 70$	$45 \pm 1 \pm 7$	$0.7 \pm 0.2 \pm 0.3$	< 0.2
Total background	$37\,070 \pm 80 \pm 670$	$1530 \pm 14 \pm 37$	$285 \pm 6 \pm 18$	$15 \pm 1 \pm 2$
Data	36 898	1444	286	18
Signal				
$m_H = 200$ GeV	$118 \pm 2 \pm 19$		$6.4 \pm 0.4 \pm 1.3$	
$m_H = 300$ GeV		$24.3 \pm 0.7 \pm 4.1$		$2.1 \pm 0.2 \pm 0.4$
$m_H = 400$ GeV		$40.5 \pm 0.5 \pm 6.4$		$4.4 \pm 0.2 \pm 1.0$
$m_H = 500$ GeV		$18.5 \pm 0.2 \pm 3.1$		$2.0 \pm 0.1 \pm 0.5$
$m_H = 600$ GeV		$6.3 \pm 0.1 \pm 1.1$		$0.7 \pm 0.0 \pm 0.2$



(a) Low-m_H, untagged selection. (b) Low-m_H, tagged selection.



(c) High-m_H, untagged selection. (d) High-m_H, tagged selection.

Fig. 3. The invariant mass of the $\ell\ell jj$ system for both the untagged (a, c) and tagged (b, d) channels, for the low-m_H (top row) and high-m_H (bottom row) selections. The hatched band represents the systematic error on the total background prediction. Examples of the expected Higgs boson signal for $m_H = 200$ and 400 GeV are also shown; in the untagged plots (a, c), the signal has been scaled up by a factor of five to make it more visible.

Contributions to systematic uncertainties also arise from detector effects, including the lepton and jet trigger and identification efficiencies, the energy or momentum calibration and resolution of the leptons and jets, and the b-tagging efficiency and mistag rates. These detector-related uncertainties are applied to all MC processes. The dominant uncertainty on the tagged sample comes from the b-tagging efficiency and corresponds to an average uncertainty of 9% on the signal [63,64]. For the untagged sample, the uncertainties on the jet energy scale and resolution contribute 3% and 4% respectively to the uncertainty on the signal [60].

The normalisations of the Z + jets and top quark backgrounds are redetermined for each systematic variation following the procedures described in Section 4.

6. Results

Table 1 shows the numbers of candidates observed in data for each of the four selections compared with the background expectations. Fig. 3 shows the $m_{\ell\ell jj}$ distributions for both the tagged and untagged channels for the low- and high-m_H selections.

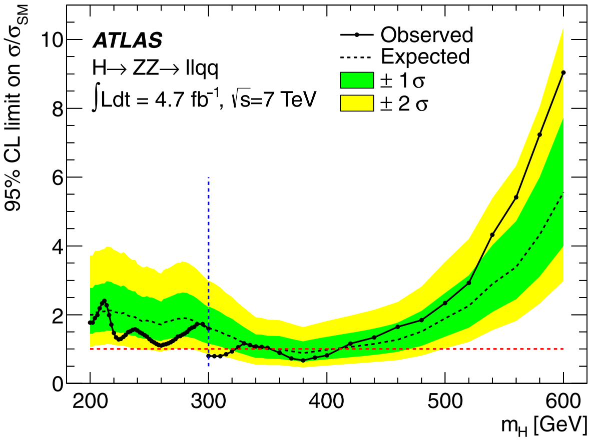


Fig. 4. The expected (dashed line) and observed (solid line) upper limits on the total cross section divided by the expected SM Higgs boson cross section, calculated using CL_s at 95%. The inner and outer bands, obtained from pseudo-experiments, indicate the $\pm 1\sigma$ and $\pm 2\sigma$ ranges in which the limit is expected to lie in the absence of a signal. The horizontal dashed line shows the SM value of unity. The discontinuity in the limit at $m_H = 300$ GeV is due to the transition between the use of the low- and high-m_H selections.

No significant excess of events above the expected background is seen; the smallest p_0 value is 0.15 at $m_H = 540$, where p_0 represents the probability that a background-only experiment would yield a result that is more signal-like than the observed result. Upper limits are set on the SM Higgs boson cross section at 95% CL as a function of mass, using the CL_s modified frequentist formalism with the profile likelihood test statistic [67, 68]. This method is based on a likelihood that compares, bin-by-bin using Poisson statistics, the observed $m_{\ell\ell jj}$ distribution to either the expected background or the sum of the expected background and a mass-dependent hypothesised signal. The tagged and untagged channels, which contribute approximately equally across the m_H range, are combined by forming the product of their likelihoods; systematic uncertainties, with their correlations, are incorporated as nuisance parameters. Fig. 4 shows the resulting upper limit on the cross section for Higgs boson production and decay in the channel $H \to ZZ \to \ell^+\ell^- q\bar{q}$ relative to the Standard Model cross section as a function of the hypothetical Higgs boson mass. The discontinuity in the limit at $m_H = 300$ GeV is due to the transition between the use of the low- and high-m_H selections. Since the high-m_H selection is a very small subset of the low-m_H selection, there is little correlation between the observed limits on either side of the boundary.

7. Summary

A search for the SM Higgs boson in the decay mode $H \to ZZ \to \ell^+\ell^- q\bar{q}$ has been performed in the Higgs mass range 200 to 600 GeV using 4.7 fb^{-1} of $\sqrt{s} = 7$ TeV pp data recorded by the ATLAS experiment at the LHC. No significant excess over the expected background is found. A Standard Model Higgs boson is excluded at a 95% CL within the range 300 GeV $\leqslant m_H \leqslant$ 322 GeV and 353 GeV $\leqslant m_H \leqslant$ 410 GeV. The corresponding expected exclusion range is 351 GeV $\leqslant m_H \leqslant$ 404 GeV at 95% CL.

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