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Search for a heavy Standard Model Higgs boson in the channel $H \to ZZ \to \ell^+\ell^- q\bar{q}$ using 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 $\ell = e, \mu$, is presented. The search is performed using a data set of pp collisions at $\sqrt{s} = 7$ TeV, corresponding to an integrated luminosity of 1.04 fb^{-1} collected in 2011 by the ATLAS detector at the CERN LHC collider. No significant excess of events above the estimated background is found. Upper limits at 95% confidence level on the production cross section (relative to that expected from the Standard Model) of a Higgs boson with a mass in the range between 200 and 600 GeV are derived. Within this mass range, there is at present insufficient sensitivity to exclude a Standard Model Higgs boson. For a Higgs boson with a mass of 360 GeV, where the sensitivity is maximal, the observed and expected cross section upper limits are factors of 1.7 and 2.7, respectively, larger than the Standard Model prediction.

1. Introduction

The search for the Standard Model (SM) Higgs boson [1–3] is one of the most crucial goals of the LHC physics program. Direct searches at the CERN LEP e^+e^- collider have set a lower limit of 114.4 GeV on the Higgs boson mass (m_H) at 95% confidence level (CL) [4]. Searches by the CDF and D0 experiments at the Fermilab Tevatron $p\bar{p}$ collider have explored the Higgs boson mass range up to 200 GeV and exclude the region 156 GeV $< m_H <$ 177 GeV [5].

The higher centre-of-mass energy ($\sqrt{s}$) of the LHC enables the search to be extended to much larger Higgs boson masses. Results from the 2010 run of the LHC, with $\sqrt{s} = 7$ TeV and an integrated luminosity of about 40 pb^{-1}, have excluded a SM-like Higgs boson with a cross section above $\sim$ 5–20 times the SM prediction in the mass range 200–600 GeV [6,7]. Although this mass range is indirectly excluded at 95% CL by global fits to SM observables [8], it is crucial to complement such indirect limits by direct searches; further, possible extensions to the SM can conspire to allow a heavy Higgs boson to be compatible with existing measurements [9].

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 high branching fraction [10–13]. In this Letter, we consider the Higgs boson mass range 200–600 GeV and search for a SM Higgs boson decaying to a pair of Z bosons, where one Z boson decays leptonically and the other hadronically: $H \to ZZ \to \ell^+\ell^- q\bar{q}$ with $\ell \equiv e, \mu$. This analysis uses 1.04 fb^{-1} of data recorded by the ATLAS experiment in the first half of 2011. The statistical sensitivity of the analysis is enhanced by treating events in which the hadronically-decaying Z boson decays to b quarks as a separate subsample. The largest background to this signal is $Z+$jets production, with smaller contributions from $t\bar{t}$ and diboson (ZZ, WZ) production.

2. ATLAS detector

The ATLAS detector [14] consists of several subsystems. An inner tracking detector is immersed in a 2 Tesla magnetic field produced by a superconducting solenoid. Charged particle position measurements are made by silicon detectors in the pseudorapidity range $|\eta| < 2.5$ and by a straw tube tracker in the range $|\eta| < 2.0$.[1] The calorimeters cover $|\eta| < 4.9$ with a variety of detector technologies. The liquid-argon electromagnetic calorimeter is divided into barrel ($|\eta| < 1.475$) and endcap ($1.375 < |\eta| < 3.2$) regions. The hadronic calorimeters (using liquid argon or scintillating tiles as active materials) surround the electromagnetic calorimeter and cover $|\eta| < 4.9$. The muon spectrometer measures the deflection of muon tracks in the field of three large superconducting toroid magnets. It is instrumented with separate trigger ($|\eta| < 2.4$) and high-precision tracking ($|\eta| < 2.7$) chambers.

[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 $\eta = -\ln\tan(\theta/2)$. For the purpose of the electron fiducial selection, this is calculated relative to the geometric centre of the detector; otherwise, it is relative to the primary vertex.

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3. 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 1.04 fb^{-1} after data quality selections to require that all systems used in this analysis were operational. The data were collected using primarily single-lepton triggers with a transverse momentum (p_{T}) threshold of 20 GeV for electrons and 18 GeV for muons. 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 $p_{\mathrm{T}} > 0.4$ GeV. The average number of collisions per bunch crossing in this data sample is about six.

The $H \to ZZ \to \ell^+\ell^- q\bar{q}$ signal is modelled using the POWHEG Monte Carlo (MC) event generator [15,16], which calculates separately the gluon and vector-boson fusion production mechanisms of the Higgs boson with matrix elements up to next-to-leading order. Events generated with POWHEG are hadronized with PYTHIA [17], which in turn is interfaced via PHOTOS [18] to model final-state radiation and via TAUOLA [19] to simulate τ decays. The $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}/\ell^+\ell^-\ell^+\ell^-$ processes are also simulated and included as part of the signal, as are $Z \to \tau\tau$ decays. These additional signal channels comprise $< 3\%$ of the acceptance of this analysis. The signal is also simulated with PYTHIA in order to estimate the systematic uncertainty due to the modelling of the signal kinematic distributions. The total inclusive cross sections for Higgs boson production with their corresponding uncertainties are taken from Refs. [10–13,20–36]. 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.

Various background processes are modelled with several event generators. The ALPGEN generator [37], interfaced to HERWIG [38] for parton showers and hadronization, is used to simulate $W/Z +$ jets events. The MC@NLO generator [39], interfaced to JIMMY [40] for the simulation of underlying events, is used for top quark and diboson production. The PYTHIA event generator is used to produce alternative samples of $Z +$ jet events to study systematic uncertainties.

The SM ZZ process is an irreducible background for $H \to ZZ$. The $qq \to ZZ$ process is modelled using the MC@NLO generator, which only includes contributions from on-shell Z bosons. Thus, an alternative sample produced with PYTHIA, calculated at leading order but including off-shell Z bosons, is used to study systematic uncertainties. The $q\bar{q} \to ZZ$ production cross section has been calculated up to next-to-leading order in QCD [41]. Due to the large gluon flux at the LHC, next-to-next-to-leading order gluon pair quark-box diagrams ($gg \to ZZ$) are significant and the cross section is scaled up by 6% to account for this additional contribution [42].

4. Reconstruction and identification of physics objects

Electron candidates are reconstructed from energy clusters in the electromagnetic calorimeter that have matching tracks in the inner detector. The candidates are required to pass identification criteria based on the electromagnetic shower shape, track quality, and track-cluster matching [43]. Muon candidates are reconstructed by matching tracks found in the inner detector with either full or partial tracks in the muon spectrometer [43]. To reject cosmic rays, muon candidates must be consistent with originating from the primary vertex. Both electrons and muons must be isolated, defined as follows. The transverse momenta of tracks within a cone of radius $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.2$ around the lepton candidate track, excluding the candidate track itself, are summed. This sum must be less than 10% of the transverse momentum of the candidate. This cut rejects jets that would otherwise mimic an electron, as well as leptons originating from heavy-flavour decays. Both electrons and muons must satisfy $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.5$ (2.47 for electrons), and electrons must not be close to any identified muon ($\Delta R > 0.2$).

Jets are reconstructed from energy clusters in the calorimeter using an anti-k_t algorithm [44] with a radius parameter $R = 0.4$. The jet energies are calibrated using p_{T}- and η-dependent correction factors based on Monte Carlo simulation and validated on data [45,46]. Only jets with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$ are considered. A jet is rejected if an identified electron candidate is found within $\Delta R < 0.4$ to avoid double counting. It is also discarded if less than 75% of the transverse momentum of its associated tracks originates from the primary vertex; this rejects jets that originate from other collisions in the same bunch crossing.

Missing transverse momentum, $E_{\mathrm{T}}^{\mathrm{miss}}$, caused by the presence of neutrinos in an event, is an important characteristic to help separate signal from background, and is calculated by summing the vector transverse momenta of all calorimeter energy clusters with $|\eta| < 4.5$ and all identified muons.

Jets which originate from b-quarks can be discriminated from other jets based on the relatively long lifetime ($c\tau \approx 450$ μm) of hadrons containing b-quarks. This is accomplished by considering the set of tracks associated with the jet and either reconstructing a secondary vertex from among them, or finding tracks that have a significant impact parameter with respect to the primary event vertex [47]. Information from both methods is combined into a single discriminating variable, and a cut applied that gives an efficiency of about 70% for identifying real b-jets ("b-tagging"), with a light-quark jet rejection of about 50.

Corrections are applied to MC events to account for various small differences between data and simulation observed and determined in a variety of samples, including $(J/\psi, \Upsilon, Z) \to \ell\ell$ and $W \to \ell\nu$. Quantities corrected include the average number of minimum-bias events per crossing, trigger and lepton identification efficiencies, and the lepton energy scale and resolution.

5. Event selection

The first step in the event selection is to reconstruct a $Z \to \ell\ell$ decay. Events must contain exactly two same-flavour selected leptons. The two muons of a pair must have opposite charge; this is not required for electrons because larger energy losses from bremsstrahlung lead to higher charge misidentification probabilities. The pair's invariant mass must lie within the range 76 GeV $< m_{\ell\ell} <$ 106 GeV ($\approx m_Z \pm 15$ GeV).

In addition to the $Z \to \ell\ell$ decay, the $H \to ZZ \to \ell^+\ell^- q\bar{q}$ final state contains a pair of jets resulting from $Z \to qq$ decay and no high-p_{T} neutrinos. Thus, events must contain at least two jets and satisfy $E_{\mathrm{T}}^{\mathrm{miss}} < 50$ GeV. The latter requirement reduces mostly background from $t\bar{t}$ production.

About 21% of signal events contain b-jets from $Z \to b\bar{b}$ decay, while a b-jet pair is rare ($\sim 2\%$) in the dominant $Z +$ jets background. Accordingly, the analysis is divided into a "tagged" subchannel, containing events with two b-tags, and an "untagged" subchannel, containing events with less than two b-tags. Events with more than two b-tags (approximately 3% of the data sample with $\geqslant 2$ jets) are rejected.

Events are then required to have at least one candidate $Z \to qq$ decay with dijet invariant mass satisfying 70 GeV $< m_{jj} <$ 105 GeV in order to be consistent with a Z boson decay. This cut is asymmetric around the Z boson mass since there are non-Gaussian

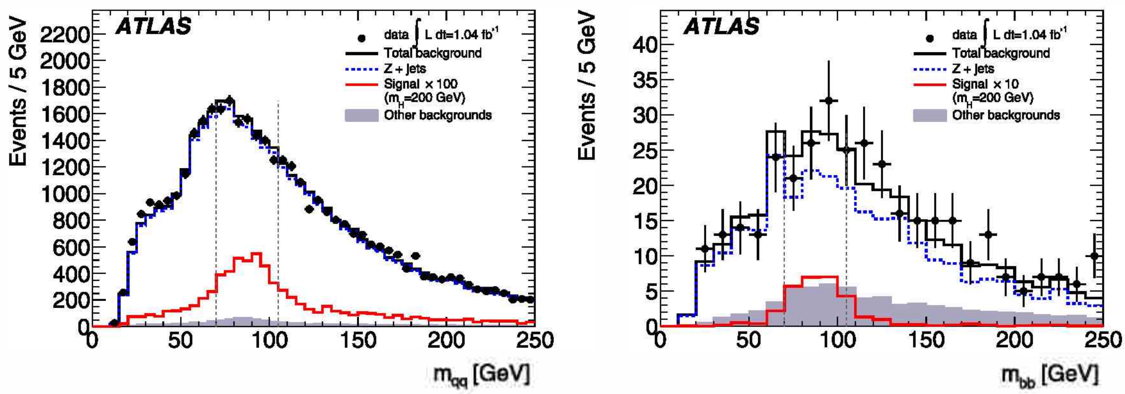


Fig. 1. Distributions of the invariant mass of selected dijet pairs, m_{jj}, for the data and the MC simulation, for the untagged (left) and tagged (right) samples. The signal has been scaled up to make it more visible. The vertical lines show the range of the m_{jj} selection.

tails extending to lower masses. For untagged events, all pairs of jets formed from the three leading 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 more than one pair retained per event is 10–16% for the low-m_H selection and 2–5% for the high-m_H selection). If the event is tagged, then the two tagged jets are used to form the dijet invariant mass and their energies are scaled up by 5% to take into account the average jet energy scale difference between heavy- and light-quark jets. The dijet invariant mass distributions before the m_{jj} requirement are shown in Fig. 1.

These event selections define the "low-m_H" selections. For larger Higgs boson masses, the Z bosons from $H \to ZZ$ decays have large momenta in the laboratory reference frame, resulting in smaller opening angles between their decay products. Therefore, "high-m_H" selections are defined by the following additional requirements: (1) the two jets must have $p_T > 45$ GeV, and (2) $\Delta\phi_{\ell\ell} < \pi/2$ and $\Delta\phi_{jj} < \pi/2$. These selections are applied when searching for a Higgs boson with $m_H \geqslant 300$ GeV, for which they improve the sensitivity.

Following this event selection, an $H \to ZZ \to \ell^+\ell^- q\bar{q}$ signal is expected to 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 by a single multiplicative factor to set the dijet invariant mass m_{jj} to the nominal mass of the Z boson. The total efficiency for the selection of signal events is about 13% for $m_H = 200$ GeV and 18% for $m_H = 600$ GeV.

6. Background estimates

The principal background to this analysis is Z boson production in association with jets (Z + jets). The shape of this background is derived from ALPGEN Monte Carlo simulations and checked against data, while the normalisation is derived directly from data. Fig. 2(a) and (b) show the $m_{\ell\ell jj}$ distribution after the jet and E_T^{miss} requirements for events with the dijet invariant mass in sidebands of the Z boson mass: 40 GeV $< m_{jj} <$ 70 GeV or 105 GeV $< m_{jj} <$ 150 GeV. The Monte Carlo gives a good description of the shape, but predicts about 10% more events than are seen in the data. The numbers of events in the sidebands, after subtraction of the small contribution from other background sources, are used to derive scale factors to correct the normalisation of the Z + jets Monte Carlo to that observed in the data. For the untagged channel, scale factors are derived separately for the low- and high-m_H selections; for the tagged channel, the low-m_H selection is used to derive a single scale factor, as the tagged high-m_H selection has very few events in the sidebands. Furthermore, as the shapes derived from the tagged ALPGEN MC samples suffer from significant statistical fluctuations, the shapes derived for the untagged selection are used for the tagged backgrounds, with appropriate scale factors applied. The shapes are found to agree within statistical uncertainties between the tagged and untagged MC samples.

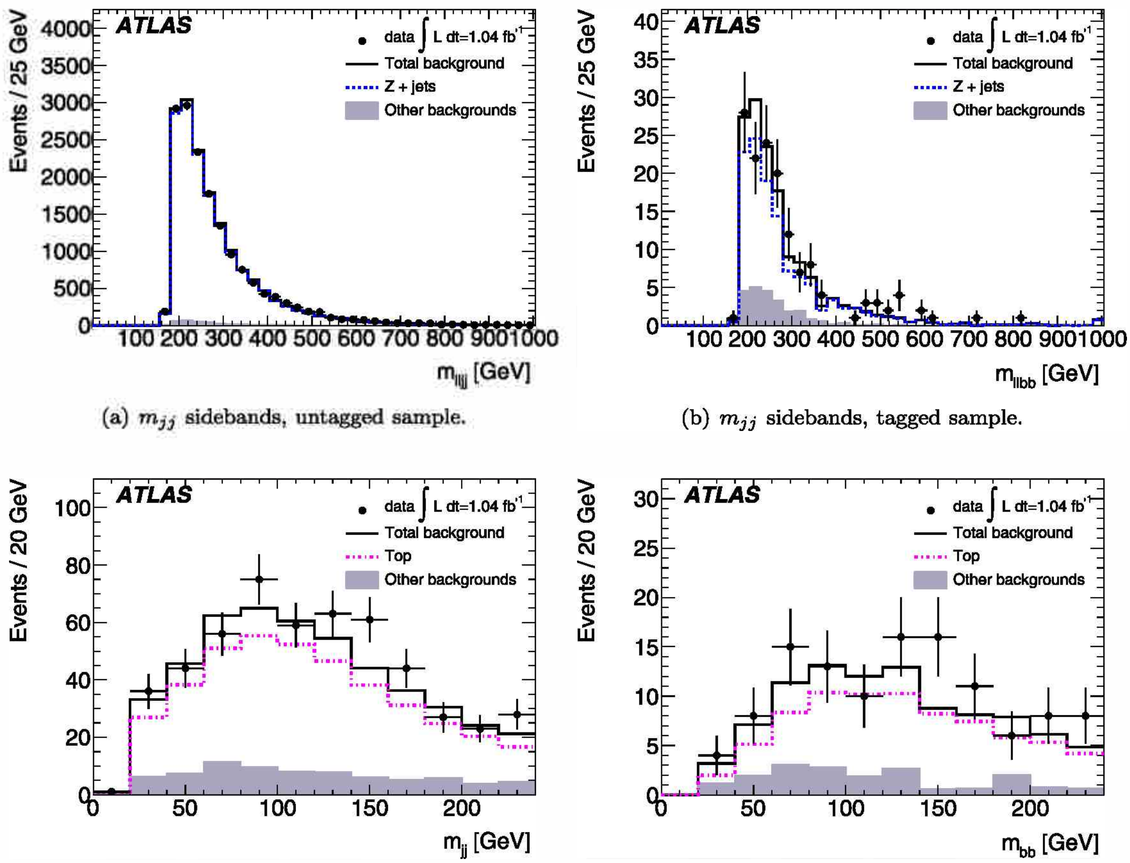
Another significant background to this analysis is top quark production. As for Z + jets, the shape is taken from Monte Carlo and the normalisation is checked against data, using the sideband 60 GeV $< m_{\ell\ell} <$ 76 GeV or 106 GeV $< m_{\ell\ell} <$ 150 GeV of the dilepton mass distribution. Fig. 2(c) and (d) show the m_{jj} distributions for these sidebands, both for the untagged selection (with the E_T^{miss} selection reversed) and the tagged selection. The normalisation of the $t\bar{t}$ component of top quark production is calculated at NNLO using HATHOR [48]; for the single-top component, the MC@NLO normalisation is used. As the Monte Carlo agrees with the data within uncertainties, no scale factor is applied to the simulation in this case.

The small irreducible background from ZZ production is difficult to constrain from data due to the large Z + jets background component and possible contamination from the signal. Thus, this background is estimated entirely from Monte Carlo simulation. The small backgrounds from WZ and W + jets production are also taken from Monte Carlo simulation.

The background from multijet events in which jets are misidentified as isolated leptons is estimated from data. For the electron channel, a sample of events is selected that contains electron candidates that fail the selection requirements but pass loosened requirements; the normalisation is determined by a multicomponent fit to the $m_{\ell\ell}$ distribution in events containing at least two jets. The multijet background in the muon channel is estimated by dividing the dimuon + jets events into four categories based on whether the muons are isolated or non-isolated and on whether or not the invariant mass of the muon pair lies near the Z boson mass peak. The number of background events with two isolated muons with invariant mass consistent with Z boson decay can then be determined from the numbers of events observed in the other three categories (which contain negligible contamination from the signal) under the assumption that the two variables (isolation criteria and invariant mass) are uncorrelated. The muon channel multijet background is found to be negligible.

7. Systematic uncertainties

The theoretical uncertainties on the Higgs boson production cross section compiled in Ref. [10] are 15–20% for the gluon fusion process and 3–9% for the vector-boson fusion process, depending



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

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

(c) $m_{\ell\ell}$ sidebands, $E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV, untagged sample.

(d) $m_{\ell\ell}$ sidebands, $E_{\mathrm{T}}^{\mathrm{miss}} < 50$ GeV, tagged sample.

Fig. 2. Distributions from the background control samples, after application of scale factors. Top row: the $\ell\ell jj$ invariant mass for 40 GeV $< m_{jj} <$ 70 GeV or 105 GeV $< m_{jj} <$ 150 GeV after the jet and $E_{\mathrm{T}}^{\mathrm{miss}}$ requirements, 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 for (c) the untagged sample with the additional requirement $E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV and (d) the tagged sample with $E_{\mathrm{T}}^{\mathrm{miss}} < 50$ GeV.

on the Higgs boson mass.[2] Signal samples generated with PYTHIA instead of POWHEG are also used to evaluate the uncertainty on the selection efficiency due to the modelling of the signal kinematics. This results in a 3% (6%) uncertainty for the low- (high-) m_H selection.

The uncertainty in the normalisation of the $Z+$jets background from the procedure described in Section 6 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. It is found to be 1.4% for the low-m_H untagged selection, 8.1% for the high-m_H untagged selection, and 18% for the tagged selections. The uncertainty on the shapes of the $Z+$jets (and ZZ) backgrounds is estimated using an alternate Monte Carlo sample generated with PYTHIA instead of ALPGEN (or MC@NLO). The uncertainty on the $t\bar{t}$ cross section is found by adding the contributions from variations of the QCD renormalisation and factorisation scales and from the CTEQ6.6 [34] parton distribution function (PDF) error set; the result is 9%. The diboson backgrounds, which are estimated directly from Monte Carlo, have a combined 5% scale and CTEQ6.6 PDF uncertainty on the cross section; 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%. A 100% systematic uncertainty is assigned to the normalisation of the multijet background in the electron channel from the procedure described in Section 6 by comparing the result of fitting the $m_{\ell\ell}$ distribution before and after the requirement of at least two jets. The normalisation uncertainty for the small $W+$jets background is taken to be 50%.

An overall 3.7% uncertainty from the total integrated luminosity [50] is added to the uncertainties on all Monte Carlo processes (excluding $Z+$jets, which is normalised to data), correlated across all samples.

There are also systematic uncertainty contributions 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. The dominant uncertainty on the tagged sample comes from the b-tagging efficiency, which corresponds to an average of 16% (23%) for the signal for the low- (high-) m_H selection. For the untagged sample, the uncertainty on the jet energy scale is a major contribution, giving rise to an average uncertainty of 5% on the signal.

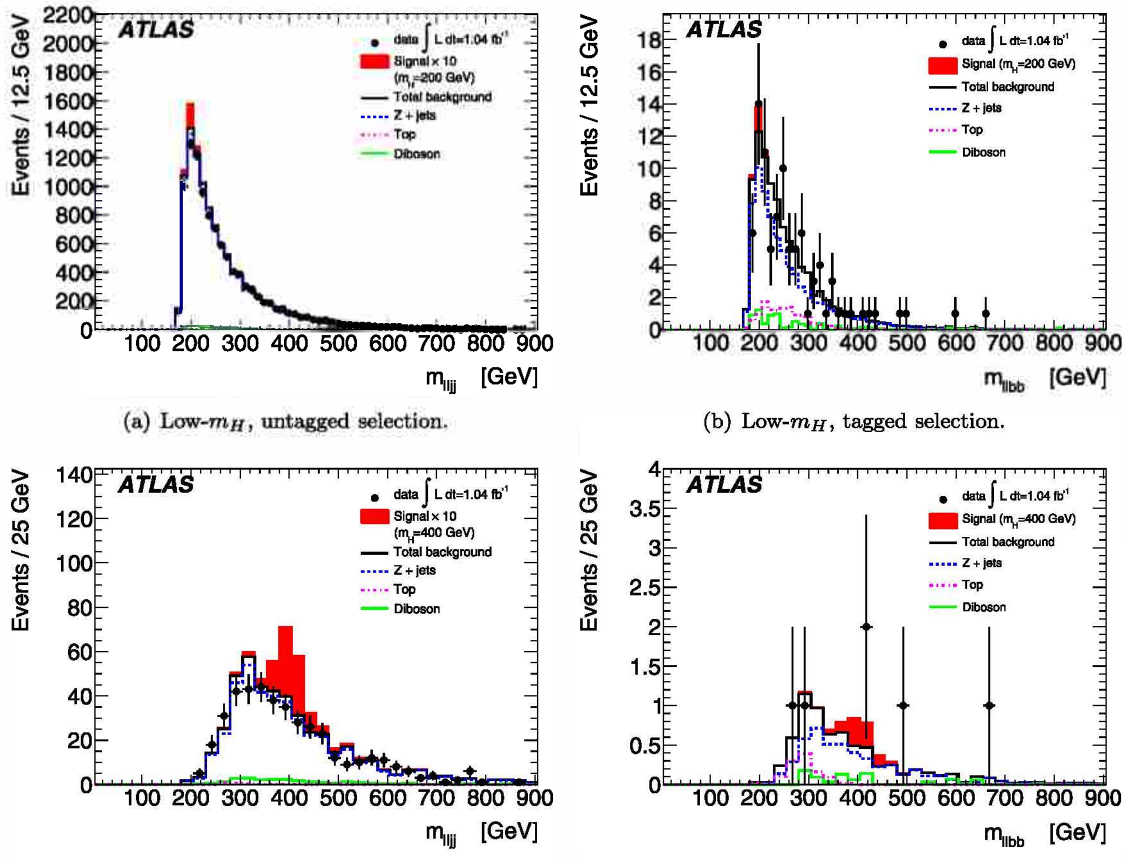
8. Results

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.

[2] The limits presented in this search assume cross sections based on on-shell Higgs boson production and decay and use Monte Carlo generators with an ad-hoc Breit–Wigner Higgs boson line shape. Potentially important effects related to off-shell Higgs boson production and interference between the Higgs boson signal and backgrounds have recently been discussed [10,49]. The inclusion of such effects may affect limits at very high Higgs boson masses ($m_H > 400$ GeV).

Table 1
The expected numbers of signal and background candidates in the $H \to ZZ \to \ell^+\ell^- q\bar{q}$ channel, along with the numbers of candidates observed in data, for an integrated luminosity of 1.04 fb^{-1}. 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	$10\,352 \pm 60 \pm 160$	$420 \pm 12 \pm 30$	$72 \pm 1 \pm 15$	$4.9 \pm 0.2 \pm 1.0$
W + jets	$10 \pm 2 \pm 5$	$0.2 \pm 0.2 \pm 0.1$	< 0.1	< 0.1
Top	$40 \pm 1 \pm 6$	$3.0 \pm 0.3 \pm 0.6$	$13 \pm 1 \pm 3$	$1.1 \pm 0.2 \pm 0.3$
Multijet	$64 \pm 3 \pm 60$	$2.0 \pm 0.5 \pm 2.0$	$0.3 \pm 0.2 \pm 0.3$	< 0.1
ZZ	$107 \pm 4 \pm 15$	$8.5 \pm 1.1 \pm 1.8$	$6.9 \pm 1.0 \pm 2.0$	$0.8 \pm 0.2 \pm 0.3$
WZ	$143 \pm 3 \pm 30$	$17 \pm 1 \pm 3$	$0.5 \pm 0.2 \pm 0.3$	< 0.1
Total background	$10\,718 \pm 60 \pm 170$	$450 \pm 13 \pm 30$	$92 \pm 1 \pm 15$	$6.9 \pm 0.4 \pm 1.2$
Data	10 495	419	91	6
Signal				
$m_H = 200$ GeV	$33 \pm 1 \pm 6$		$2.2 \pm 0.2 \pm 0.6$	
$m_H = 300$ GeV		$7.0 \pm 0.3 \pm 1.5$		$0.6 \pm 0.1 \pm 0.2$
$m_H = 400$ GeV		$9.8 \pm 0.3 \pm 1.8$		$1.1 \pm 0.1 \pm 0.3$
$m_H = 500$ GeV		$5.5 \pm 0.1 \pm 1.0$		$0.6 \pm 0.0 \pm 0.2$
$m_H = 600$ GeV		$2.5 \pm 0.1 \pm 0.5$		$0.3 \pm 0.0 \pm 0.1$



(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. Examples of the expected Higgs boson signal for $m_H = 200$ and 400 GeV are also shown; in the untagged plots, the signal has been scaled up by a factor of 10 to make it more visible.

No significant excess of events above the expected background is observed. 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 [51, 52]. This 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. Systematic uncertainties, with their correlations, are incorporated as nuisance parameters, and the tagged and untagged channels are combined by forming the product of their likelihoods. 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 prediction of the Standard Model as a function of the hypothetical Higgs boson mass.

9. 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

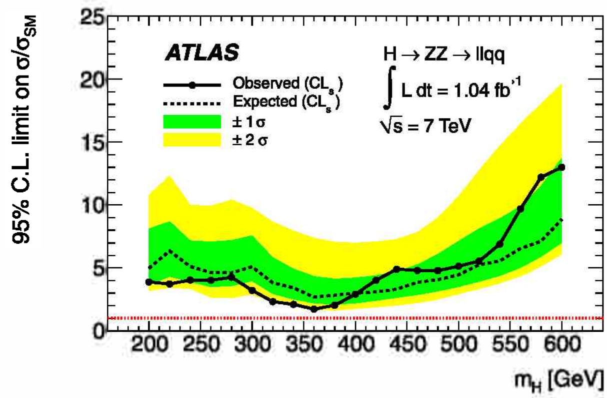


Fig. 4. The expected (dashed line) and observed (solid line) upper limits on the total cross section divided by the expected SM Higgs boson cross section, calculated using CL_s at 95%. The green (dark) and yellow (light) bands, obtained from interpolating pseudoexperiments, indicate the one- and two-sigma ranges in which the limit is expected to lie in the absence of a signal. The dotted line shows the SM value of unity.

to 600 GeV using 1.04 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. With the present integrated luminosity, there is insufficient sensitivity to exclude a SM Higgs boson in this channel at 95% CL. The ratio of the Higgs boson production cross section upper limits reported here to the SM Higgs boson production cross section ranges from 1.7 at $m_H = 360$ GeV to about 13 at $m_H = 600$ GeV. These limits are the most stringent to date in this channel.

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