Search for a standard model Higgs boson in the $H \rightarrow ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ decay channel using 4.7 fb^{-1} of $\sqrt{s} = 7$ TeV data with the ATLAS detector ☆

ATLAS Collaboration ⋆

ARTICLE INFO

ABSTRACT

A search for a Standard Model Higgs boson decaying via $H \rightarrow ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$, where ℓ represents electrons or muons, is presented. It is based on proton–proton collision data at $\sqrt{s} = 7$ TeV, collected by the ATLAS experiment at the LHC during 2011 and corresponding to an integrated luminosity of 4.7 fb^{-1}. The data agree with the expected Standard Model backgrounds. Upper limits on the Higgs boson production cross section are derived for Higgs boson masses between 200 GeV and 600 GeV and the production of a Standard Model Higgs boson with a mass in the range 319–558 GeV is excluded at the 95% confidence level.

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1. Introduction

The search for the Higgs boson [1–3], which in the Standard Model (SM) gives mass to the weak vector bosons and fermions, is one of the most important aspects of the CERN Large Hadron Collider (LHC) physics programme. Direct searches performed at the CERN Large Electron–Positron Collider (LEP) have excluded, at a 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 region $156 < m_H < 177$ GeV [5,6]. At the LHC, the combination of ATLAS searches [7], using 1.0–4.9 fb^{-1} of $\sqrt{s} = 7$ TeV data, excluded at the 95% CL the production of a SM Higgs boson in the regions $112.9 < m_H < 115.5$ GeV, $131 < m_H < 238$ GeV and $251 < m_H < 466$ GeV. The CMS combined result [8] using 4.6–4.8 fb^{-1} of $\sqrt{s} = 7$ TeV data excluded the production of a SM Higgs boson at the 95% CL in the region $127 < m_H < 600$ GeV.

The $ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ decay channel offers a substantial branching fraction in combination with a good separation from potential background processes owing to the large transverse momentum, p_T, of the electron or muon pair from the leptonic Z boson decay and the large missing transverse momentum from the Z boson decaying to neutrinos. Earlier results in this channel, published in Ref. [9], using 1.0 fb^{-1}, were subsequently updated in Ref. [7] with 2.0 fb^{-1} and exclude at the 95% CL the presence of a SM Higgs boson in the range $310 < m_H < 470$ GeV. The most recent CMS analysis [10] in this channel based on 4.6 fb^{-1} excluded at 95% CL $270 < m_H < 440$ GeV.

The data sample considered in the search presented in this Letter was recorded by the ATLAS experiment during the 2011 LHC run at a centre-of-mass energy $\sqrt{s} = 7$ TeV. The integrated luminosity of the data sample, considering only data-taking periods where all relevant detector subsystems were operational, is 4.7 fb^{-1} with an uncertainty of 3.9% [11,12].

2. The ATLAS detector

The ATLAS detector [13] is a multi-purpose particle physics detector with forward–backward symmetric cylindrical geometry.[1] The inner tracking detector (ID) 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 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/scintillating-tile calorimeter measures hadronic showers in the central region ($|\eta| < 1.7$). The muon spectrometer 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 ($|\eta| < 2.4$). A three-level trigger system selects events to be recorded for offline analysis.

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[1] 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, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity η is defined as $\eta = -\ln[\tan(\theta/2)]$ where θ is the polar angle.

3. Data and simulation samples

The $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ signal is modelled using the POWHEG [14,15] event generator, which includes matrix elements for the gluon fusion and vector-boson fusion (VBF) production mechanisms of the Higgs boson up to next-to-leading-order (NLO). POWHEG is interfaced to PYTHIA [16] for the modelling of parton showers. The modelling of final-state radiation is performed with PHOTOS [17], and TAUOLA [18,19] is used for the simulation of τ decays. The Higgs boson p_T spectrum in the gluon fusion process is reweighted to the calculation of Ref. [20], which provides QCD corrections up to NLO and QCD soft-gluon resummations up to next-to-next-to-leading logarithms (NNLL).

$H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$, $H \to ZZ \to \ell^+\ell^-q\bar{q}$ and $H \to ZZ \to \ell^+\ell^-\ell^+\ell^-$ samples are also simulated using the same generators as for the $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ samples. These channels, together with the $H \to ZZ \to \tau^+\tau^-\nu\bar{\nu}$ final state, which is included in the $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ samples, contribute to the signal yield and are considered as part of the signal. In particular, $H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ decays contribute as much as 70% to the signal expectation after the full selection for $m_H = 200$ GeV, decreasing to 13% at $m_H = 300$ GeV, and to less than 4.5% for Higgs boson masses larger than 400 GeV. Statistical independence of the analysis with respect to other ATLAS Higgs boson searches [21–23] is ensured through mutually exclusive selection requirements on the dilepton invariant mass, the number of leptons and the missing transverse momentum in the event.

The Higgs boson production cross sections and decay branching ratios, as well as their uncertainties, are taken from Refs. [24,25]. The cross sections for the gluon fusion process have been calculated to NLO in QCD in Refs. [26–28], and to next-to-next-to-leading-order (NNLO) in Refs. [29–31]. In addition, QCD soft-gluon resummations, calculated in the NNLL approximation [32], are applied for the gluon fusion process. NLO electroweak (EW) corrections are also applied [33,34]. These results are compiled in Refs. [35–37] and assume factorisation between QCD and EW corrections. The cross sections for VBF processes are calculated with full NLO QCD and EW corrections [38–40], and approximate NNLO QCD corrections are included [41]. The uncertainty in the production cross section due to the choice of QCD scale is typically $^{+12}_{-8}$% for the gluon fusion process, and ± 1% for the VBF process [24]. The uncertainty in the production cross section due to the parton distribution function (PDF) and α_s is ± 8% for gluon-initiated processes and ± 4% for quark-initiated processes [42–45]. The Higgs boson decay branching ratio [46] to the four-fermion final state is predicted by PROPHECY4F [47,48].

The Higgs boson cross sections are calculated with a zero-width approximation. For the Higgs decay, a relativistic Breit–Wigner line shape is applied at the event-generator level. It has been suggested [25,49–51] that effects related to off-shell Higgs boson production and interference with other SM processes may become sizeable for the highest Higgs boson masses ($m_H > 400$ GeV) considered in this search. Currently, in the absence of a full lineshape calculation for the production mechanisms as well as a correct account of the interference with SM ZZ production, an estimate of the possible size of such effects is included as a signal normalisation systematic uncertainty, following a parameterisation as a function of m_H: $1.5 \times [m_H/\text{TeV}]^3$, for $m_H \geq 300$ GeV [25].

Different event generators are chosen to model a range of important background processes. The ALPGEN generator [52] interfaced to HERWIG [53] for parton showers and hadronisation is used to simulate inclusive W/Z boson backgrounds. MC@NLO [54], interfaced to HERWIG and JIMMY [55], is used for the production of top-pair, single-top and diboson (WW, WZ and ZZ) backgrounds. PYTHIA is used to simulate $b\bar{b}$ and $c\bar{c}$ samples as well as alterna-

tive samples for the inclusive Z boson and ZZ backgrounds. All simulated background samples are scaled to the highest-precision calculations available for the relevant process. An overview of the relevant predictions and their uncertainties is given in Ref. [56].

Generated events are simulated using the ATLAS detector simulation [57] within the GEANT4 framework [58]. Additional pp interactions in the same and nearby bunch crossings (pile-up) are included in the simulation. The Monte Carlo (MC) samples are reweighted to reproduce the observed distribution of the number of interactions per bunch crossing in the data.

Data used for the search in the muon channel are collected using a single muon trigger with a p_T threshold of 18 GeV, while in the electron case a logical OR between a single electron trigger with a threshold varying from 20 to 22 GeV and a dielectron trigger with a p_T threshold of 12 GeV is used.

The overall trigger efficiencies are estimated from MC events after correction of the simulated lepton trigger efficiencies to those observed in data. For signal events passing the full selection criteria, the trigger efficiency is close to 100% in the electron channel and between 94% and 97% in the muon channel. The systematic uncertainties on the trigger efficiency are negligible when compared to the other selection uncertainties.

During the course of the 2011 data-taking, the average number of pile-up interactions increased due to increased beam currents and stronger beam focusing. This changed the average number of interactions per bunch crossing at the start of a fill, from about six in the earlier periods to about 15 in the later periods. The missing transverse momentum resolution is affected by the level of pile-up, resulting in a significant change in the signal-to-background ratio between the earlier and the later periods. To retain the best sensitivity, the search is therefore split between the earlier (2.3 fb^{-1}) and the later (2.4 fb^{-1}) periods, hereafter referred to as the "low pile-up data" and the "high pile-up data", respectively. The selection is unaltered between the periods.

4. Lepton identification and event selection

Electron candidates consist of clusters of energy deposited in the electromagnetic calorimeter that are associated with tracks reconstructed in the ID. The electron candidates must satisfy a set of identification criteria [59] 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. Furthermore, the electron candidates are required to have $p_T > 20$ GeV and pseudorapidity $|\eta| < 2.47$. The electron transverse momentum is computed from the cluster energy and the track direction at the interaction point.

Muons are identified by reconstructing tracks in the muon spectrometer. These tracks are then extrapolated back to the beam line to find a matching ID track. Details of muon reconstruction and identification can be found in Ref. [60]. Only muons with $p_T > 20$ GeV and $|\eta| < 2.5$ are considered.

Jets are used in this analysis to reject backgrounds from events with heavy-quark decays or from events with fake missing transverse momentum E_T^{miss} due to mis-measured jets. For this purpose, jets are reconstructed from clusters of energy deposits in the calorimeters using the anti-k_t algorithm [61] with a radius parameter $R = 0.4$. Jets are calibrated using p_T- and η-dependent correction factors based on MC simulation and validated with data [62]; this calibration corrects for effects of energy from additional proton–proton interactions. Only jets with $p_T > 25$ GeV and $|\eta| < 2.5$ are considered.

Two conditions are applied to remove leptons associated with jets, such as those originating from semi-leptonic decays of b-hadrons. Leptons are not considered in the analysis if the scalar
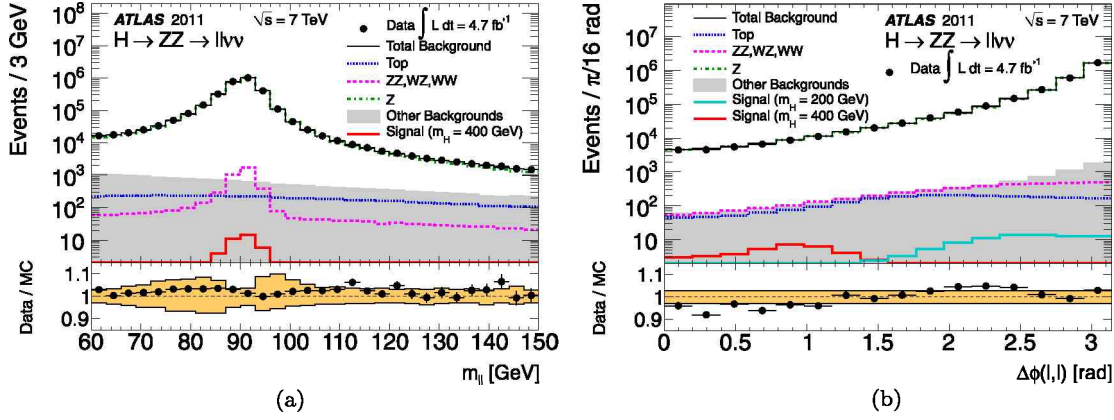
Fig. 1. (a) The dilepton invariant mass distribution for events with exactly two oppositely-charged electrons or muons. (b) The azimuthal separation between leptons for events with exactly two oppositely-charged electrons or muons with an invariant mass satisfying $|m_Z - m_{\ell\ell}| < 15$ GeV. The inset at the bottom of the figures shows the ratio of the data to the combined background expectations as well as a band corresponding to the combined systematic uncertainties. In both figures the line corresponding to the Z boson background is mostly hidden under the line for the total background. The background contribution labelled "Other Backgrounds" includes multijet and inclusive W boson production.
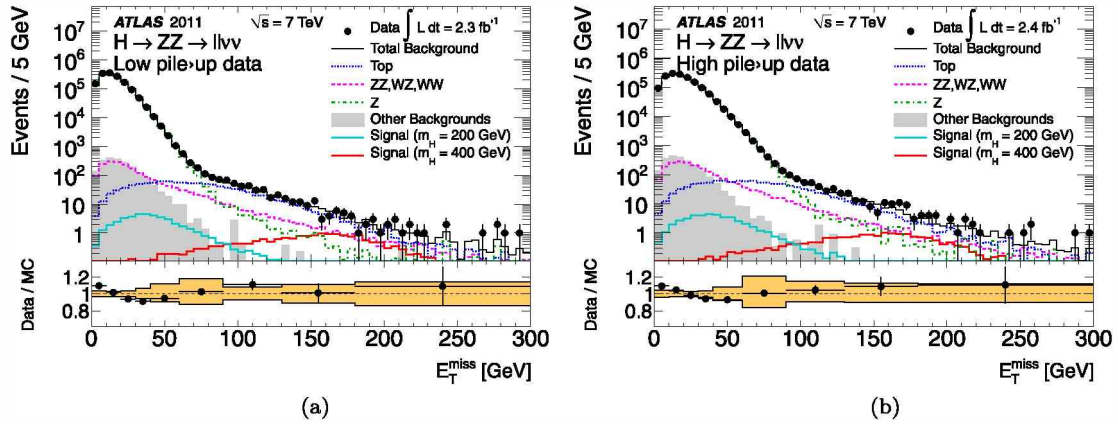

Fig. 2. The $E_{\mathrm{T}}^{\mathrm{miss}}$ distributions for events with exactly two oppositely-charged electrons or muons satisfying $|m_Z - m_{\ell\ell}| < 15$ GeV, for (a) the low pile-up data and (b) the high pile-up data. The insets at the bottom show the ratio of the data to the combined background expectations as well as a band corresponding to the combined systematic uncertainties. The background contribution labelled "Other Backgrounds" includes multijet and inclusive W boson production.

sum of ID track momenta, not associated with the lepton, in a cone of $\Delta R \equiv \sqrt{\Delta\phi^2 + \Delta\eta^2} < 0.2$ around the lepton direction is greater than 10% of the p_{T} of the lepton itself or if the lepton is within a distance $\Delta R = 0.4$ of the nearest jet.

The missing transverse momentum is measured as the negative vectorial sum of the transverse momenta measured in 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 [63]. Calorimeter deposits associated with muons are subtracted to avoid double counting.

Events are required to contain a reconstructed primary vertex, with at least three associated tracks with $p_{\mathrm{T}} > 0.4$ GeV, and exactly two oppositely-charged electrons or muons, consistent with having originated from the primary vertex. Furthermore, events are rejected if they contain a third lepton, as defined above, but with a loosened p_{T} requirement of at least 10 GeV. The dilepton mass distribution is shown in Fig. 1(a). Inclusive Z boson production is the dominant background at this stage of the analysis. To suppress backgrounds from top, inclusive W boson, and multijet production, the dilepton invariant mass, $m_{\ell\ell}$, is required to satisfy $|m_Z - m_{\ell\ell}| < 15$ GeV.

To reduce the background from top quark production, events with one or more b-tagged jets are rejected, where the b-tagging is based on a multivariate algorithm which uses information from

both the impact parameter with respect to the primary vertex of tracks associated to the jet and the presence of displaced secondary vertices associated to the jet's tracks. Jets with a loosened p_{T} threshold of 20 GeV and $|\eta| < 2.5$ are considered in the b-tag veto. The selection applied on the b-tagging discriminant achieves an efficiency of about 85% (50%) for identifying b-jets (c-jets) [64] and a light-jet rejection factor of about ten [65] in inclusive top-pair events.

To exploit the mass-dependent kinematic features of $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ production, the search is subdivided into a low Higgs boson mass region ($m_H < 280$ GeV) and a high Higgs boson mass region ($m_H \geqslant 280$ GeV), where dedicated selection criteria are applied to two important discriminating variables used to reduce the background contributions: $E_{\mathrm{T}}^{\mathrm{miss}}$ and the azimuthal angle between the two leptons, $\Delta\phi(\ell, \ell)$. Events can contribute to one or both search regions depending on whether they satisfy the selection criteria applied on these variables. Figs. 1(b) and 2 show the distributions of these variables after the application of the $m_{\ell\ell}$ window. Since inclusive Z boson production gives rise to a steeply falling $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution, systematic uncertainties on the $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction are particularly important in order to estimate this background correctly.

The dominant contribution to the $E_{\mathrm{T}}^{\mathrm{miss}}$ uncertainty comes from the knowledge of the jet energy scale. A degradation of the $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution is observed in the data taken during the periods with a
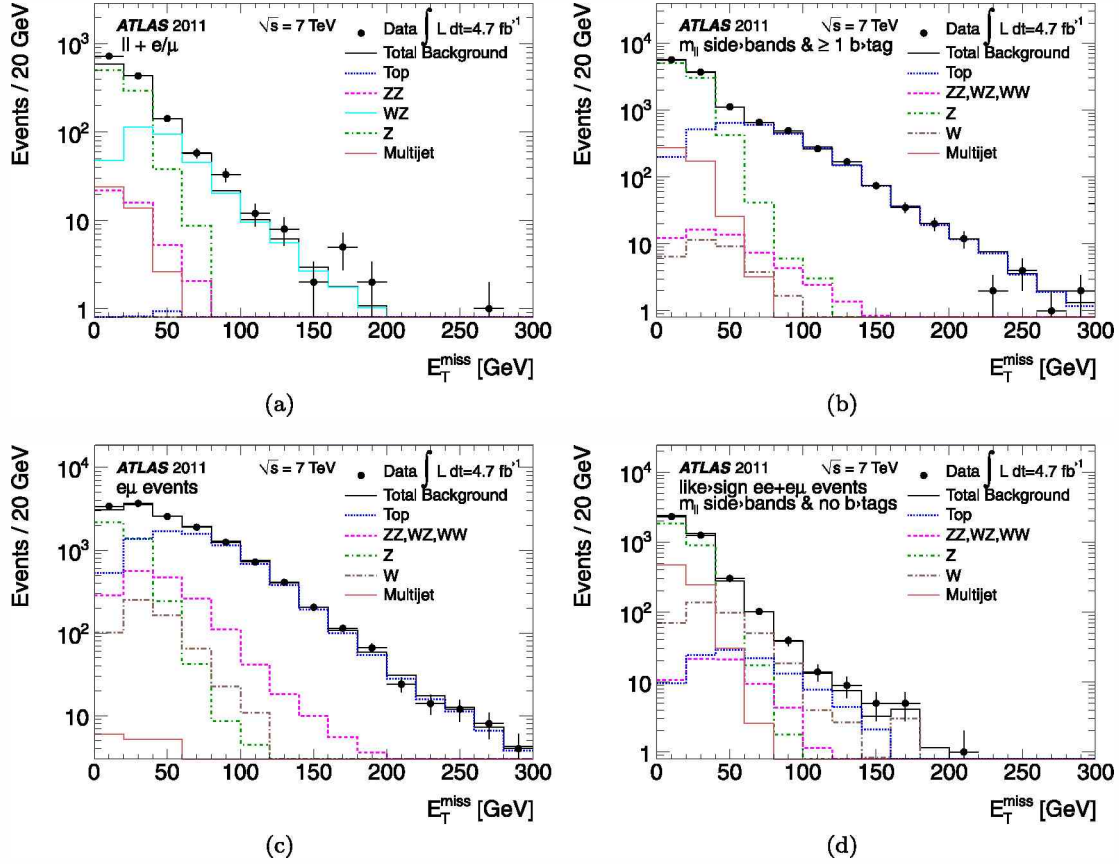
Fig. 3. The E_T^{miss} distribution in the different control regions: Figure (a) is a WZ control region with events containing exactly three leptons. Figure (b) is a top-quark control region populated with events containing at least one b-jet and a lepton pair in the sidebands of dilepton mass distribution. Figure (c) is a second top-quark control region populated with events with an oppositely-charged $e\mu$ pair. Figure (d) is an inclusive W boson control region populated with events with no b-tagged jets and a same-charge ee or $e\mu$ pair in the sidebands of dilepton mass distribution.

larger average number of interactions per bunch crossing, as is illustrated in Fig. 2. In particular, this increases the background from inclusive Z boson production in the high pile-up periods, mostly in the low mass search region.

Fig. 2 shows that, at high E_T^{miss}, the data and the combined background expectation agree within systematic uncertainties. In the low m_H region, events are required to satisfy $E_T^{miss} > 66$ GeV, whilst in the high m_H region the requirement is $E_T^{miss} > 82$ GeV. These selection criteria reduce significantly the backgrounds from processes with no or modest genuine missing transverse momentum originating from unobserved neutrinos. In the low m_H region a significant fraction of signal events is also removed by this criterion.

The boost of the Z bosons originating from a Higgs boson decay increases with m_H, thus reducing the expected opening angle between the leptons. In the low (high) m_H region an upper bound, $\Delta\phi(\ell, \ell) < 2.64$ (2.25), is therefore applied. In the low m_H region a lower bound, $\Delta\phi(\ell, \ell) > 1$, is also applied, to reduce backgrounds from events in which the lepton pair did not originate from a Z boson decay. In the high m_H region, events are also rejected if the azimuthal angle between the missing transverse momentum vector and the direction of the $Z \to \ell\ell$ boson candidate is $\Delta\phi(\vec{p}_T^{miss}, \vec{p}_T^{\ell\ell}) < 1$.

Finally, to further reduce the background from events with fake E_T^{miss} due to mis-measured jets, events are rejected if the azimuthal angle between $\vec{p}_T^{miss}$ and the nearest jet in the event satisfies $\Delta\phi(\vec{p}_T^{miss}, \vec{p}_T^{jet}) < 1.5$ for the low m_H search and $\Delta\phi(\vec{p}_T^{miss}, \vec{p}_T^{jet}) < 0.5$ for the high m_H region.

The efficiency of the event selection is very similar in the electron and muon channels, ranging from 3.1% for $m_H = 200$ GeV to about 43% for $m_H = 600$ GeV.

5. Background normalisation and control regions

Standard Model pair-production of Z bosons has a final state identical to the signal, and is therefore expected to survive most of the applied selection criteria and form a continuum in the transverse mass distribution (defined in Section 7). The normalisation for this background is obtained from a calculation including next-to-leading-order terms [66] with an additional 6% term to account for missing quark-box diagrams ($gg \to ZZ$) [67]. An 11% normalisation uncertainty is assigned to this background. This combines the theoretical uncertainty for Z pair production estimated in Ref. [25] with an additional modelling uncertainty related to the used Monte Carlo model, estimated from comparison to other models. The ZZ background is taken from the MC simulation. A systematic uncertainty to account for shape uncertainties is derived using PYTHIA as an alternative event generator. WW and WZ backgrounds are normalised in a similar way. For the WZ background the normalisation is verified using a control sample in which the presence of exactly three leptons is required, where the minimum p_T for the third lepton is 10 GeV. Fig. 3(a) shows the E_T^{miss} distribution in this control region, which is dominated by WZ background for $E_T^{miss} > 40$ GeV and is well modelled by the MC simulations, in the high E_T^{miss} region.

The background from top-quark events is taken from the MC prediction. This prediction is verified to agree with data in two
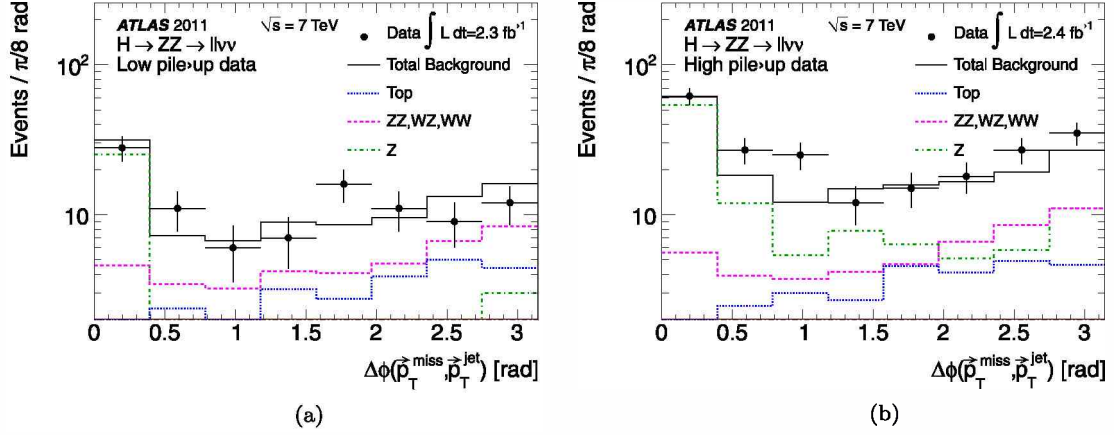
Fig. 4. The azimuthal separation between the missing transverse momentum vector, $\vec{p}_T^{\,\mathrm{miss}}$, and the nearest jet in the event $\Delta\phi(\vec{p}_T^{\,\mathrm{miss}}, \vec{p}_T^{\,\mathrm{jet}})$ after the E_T^{miss} requirement, for the high m_H search region. Figure (a) refers to the low pile-up data and figure (b) to the high pile-up data.

Table 1
The expected number of background and signal events along with the observed numbers of candidates in the data, separated into the low and high m_H search regions and the low and high pile-up periods. The quoted uncertainties are statistical and systematic, respectively.

Source	Low m_H search		High m_H search	
	Low pile-up data	High pile-up data	Low pile-up data	High pile-up data
Z	$40.1 \pm 5.0 \pm 7.9$	$265 \pm 13 \pm 67$	$0.8 \pm 0.3 \pm 0.8$	$11.6 \pm 2.1 \pm 2.9$
W	$4.6 \pm 2.2 \pm 4.6$	$5.8 \pm 1.8 \pm 5.8$	$1.5 \pm 0.8 \pm 1.5$	$2.2 \pm 1.3 \pm 2.2$
Top	$23.2 \pm 1.3 \pm 5.4$	$27.9 \pm 1.3 \pm 5.3$	$16.0 \pm 1.1 \pm 4.0$	$17.2 \pm 1.0 \pm 3.9$
Multijet	$1.1 \pm 0.2 \pm 0.5$	$1.1 \pm 0.2 \pm 0.6$	$0.1 \pm 0.1 \pm 0.0$	$0.1 \pm 0.1 \pm 0.0$
ZZ	$33.4 \pm 0.7 \pm 3.9$	$36.7 \pm 0.7 \pm 4.3$	$28.4 \pm 0.6 \pm 3.4$	$31.9 \pm 0.7 \pm 3.8$
WZ	$23.3 \pm 1.0 \pm 2.8$	$25.2 \pm 1.0 \pm 3.0$	$17.1 \pm 0.8 \pm 2.1$	$18.9 \pm 0.8 \pm 2.3$
WW	$25.5 \pm 0.8 \pm 3.0$	$32.4 \pm 0.9 \pm 3.8$	$9.4 \pm 0.5 \pm 1.1$	$13.3 \pm 0.5 \pm 1.6$
Total	$151 \pm 6 \pm 11$	$394 \pm 13 \pm 67$	$73.3 \pm 1.8 \pm 6.1$	$95.2 \pm 2.9 \pm 6.9$
Data	158	442	77	109
m_H [GeV]	Signal expectation			
200	$10.3 \pm 0.2 \pm 1.8$	$11.1 \pm 0.2 \pm 1.9$		
300			$16.4 \pm 0.3 \pm 2.9$	$17.5 \pm 0.3 \pm 3.1$
400			$14.4 \pm 0.2 \pm 2.5$	$15.4 \pm 0.2 \pm 2.7$
500			$6.2 \pm 0.1 \pm 1.1$	$6.5 \pm 0.1 \pm 1.1$
600			$2.7 \pm 0.0 \pm 0.5$	$2.9 \pm 0.0 \pm 0.5$

independent control samples: the first uses the dilepton mass side-band and requires at least one identified b-jet (Fig. 3(b)), while the second selects events containing oppositely-charged electron–muon pairs (Fig. 3(c)).

Additional backgrounds can arise from multijet events or inclusive W boson production due to heavy flavour decays or jets misidentified as leptons. The normalisation of the inclusive W boson background in this search is obtained from a control sample of events with a like-sign electron–electron or electron–muon pair in the sidebands of the dilepton mass distribution and with no b-tagged jets. Fig. 3(d) shows the E_T^{miss} distribution following this procedure. At large E_T^{miss} this distribution is dominated by the inclusive W boson background.

The multijet background in the electron channel is determined using a data sample based on a loosened electron selection. This sample, which is dominated by jet events, is scaled to describe the tails of the $m_{\ell\ell}$ distribution. In the muon channel, the background from heavy flavour decays is studied using simulation, whereas other muon sources from multijet events are constrained using a sample of like-sign muon pairs in data. In both cases the background is found to be negligible.

The background from inclusive Z boson production is taken from the MC prediction and verified in a control region populated with events rejected by the $\Delta\phi(\vec{p}_T^{\,\mathrm{miss}}, \vec{p}_T^{\,\mathrm{jet}})$ selection criterion after the E_T^{miss} requirement. The full $\Delta\phi(\vec{p}_T^{\,\mathrm{miss}}, \vec{p}_T^{\,\mathrm{jet}})$ distribution is

shown in Fig. 4. At low $\Delta\phi(\vec{p}_T^{\,\mathrm{miss}}, \vec{p}_T^{\,\mathrm{jet}})$, where the inclusive Z boson background dominates, a small discrepancy is observed between the data and the expected backgrounds. This discrepancy is within the systematic uncertainties applied on the inclusive Z boson background.

The signal efficiencies and overall background expectations are similar in the electron and muon channels; therefore only combined results are presented. The numbers of candidate $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ events selected in data and the expected yields from signal and background processes are shown in Table 1.

6. Systematic uncertainties

The systematic uncertainties applied in this search include experimental uncertainties related to the selection and calibration of electrons, muons and jets, which are also all explicitly propagated to the E_T^{miss} calculation. Uncertainties on the $b(c)$-tagging efficiency as well as the light-jet mis-tagging rate are also applied.

Normalisation uncertainties for the signal (gluon fusion $^{+14\%}_{-10\%}$ and VBF 4%) [24] and for the diboson backgrounds (11%, see Section 5) are obtained from theory; uncertainties for the inclusive Z boson production (2.5%), top quark production (9%), inclusive W boson production (100%) and for multijet production in the electron channel (50%) are estimated from data. These normalisation uncertainties are not the full systematic uncertainties applied
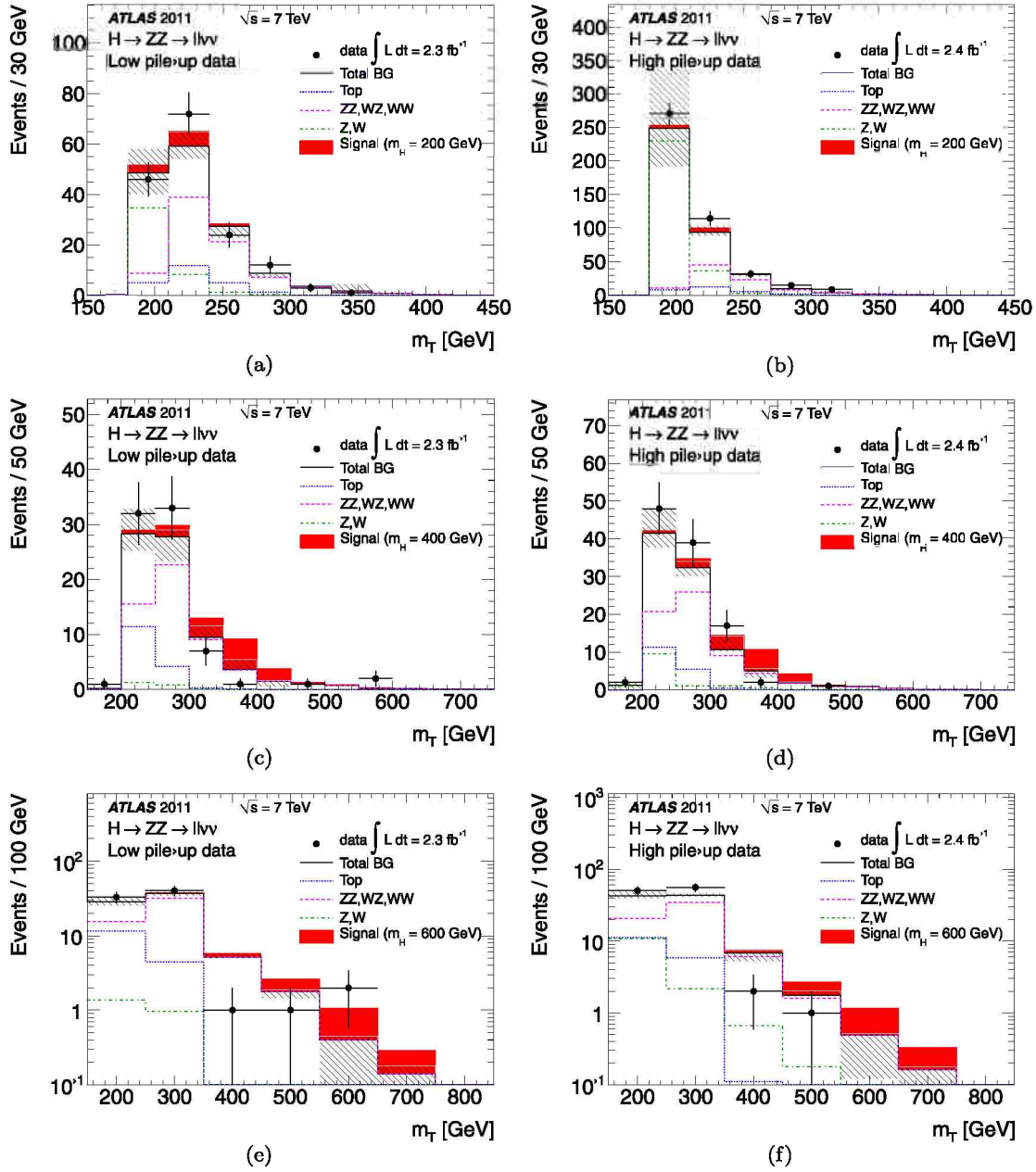
Fig. 5. The transverse mass distribution of $H \to ZZ \to \ell^+ \ell^- \nu \bar{\nu}$ candidates. Figures (a) and (b) refer to the low m_H search region and figures (c) to (f) to the high m_H search region. The top, centre and bottom figures show the expected signal for a Higgs boson with a mass of 200 GeV, 400 GeV and 600 GeV, respectively. Figures on the left correspond to the low pile-up data and figures on the right to the high pile-up data. The hashed area represents the combined systematic uncertainties on the total expected background.

on these backgrounds. Where a normalisation uncertainty is obtained from data, additional detector related systematic uncertainties are applied if they are likely to affect the background in the control region and in the signal region differently. Where a normalisation error is taken from theory, full detector related systematic uncertainties are applied.

For the signal, an additional uncertainty is applied to account for the possible effect of theoretical uncertainties on the acceptance. This uncertainty is estimated from signal samples containing variations in the modelling of initial- and final-state radiation, the renormalisation and factorisation scales, which are varied to half and twice their nominal values, as well as variations in the underlying event tune, which was changed from the default AUET2B [68] to PERUGIA2011 [69], both based on LHC data. An overall uncertainty of 8.4% (3.4%) is assigned in the low (high) mass search

regions, obtained by the addition in quadrature of the largest deviations observed for each variation.

The luminosity uncertainty is 3.7% and 4.1% for the low and high pile-up data, respectively, based on the calibration described in Refs. [11,12]. Where appropriate, systematic uncertainties are treated as correlated between the signal and the different background expectations. The total systematic uncertainty on the signal and on each of the background contributions can be seen in Table 1. In most cases the assigned normalisation uncertainties dominate the total systematic uncertainty, except for the inclusive Z boson background, for which the jet energy scale and resolution uncertainties dominate, and the top-quark background for which the b-tagging uncertainty dominates. In the low m_H search using the high pile-up data, the uncertainty on the inclusive Z boson background uncertainty dominates the overall uncertainty.
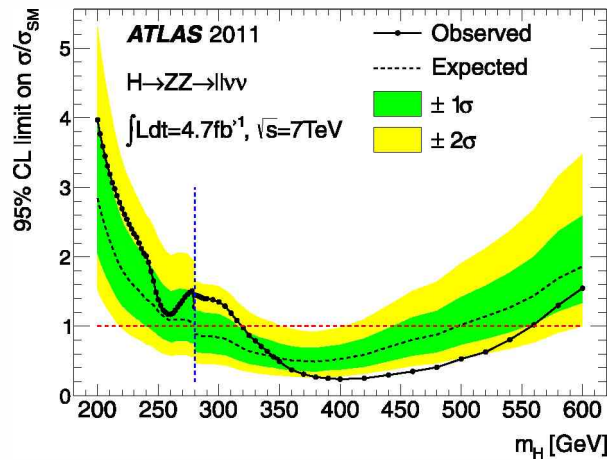
Fig. 6. Observed and expected 95% CL upper limits on the Higgs boson production cross section divided by the SM prediction, together with the green (inner) and yellow (outer) bands which indicate the $\pm 1\sigma$ and $\pm 2\sigma$ fluctuations, respectively, around the median sensitivity. The limits are based on 4.7 fb^{-1} of data at $\sqrt{s} = 7$ TeV. The line at 280 GeV indicates the transition from the low m_H to the high m_H search region.

7. Results

After the event selection, the Higgs boson search is performed by looking for an excess of data over the SM background expectation in the transverse mass distribution of the selected $ee\nu\nu$ and $\mu\mu\nu\nu$ events. The transverse mass is calculated from the lepton pair and the $\vec{p}_T^{\text{miss}}$ vector as:

$$m_T^2 \equiv \left[\sqrt{m_Z^2 + |\vec{p}_T^{\ell\ell}|^2} + \sqrt{m_Z^2 + |\vec{p}_T^{\text{miss}}|^2} \right]^2 - \left[\vec{p}_T^{\ell\ell} + \vec{p}_T^{\text{miss}} \right]^2.$$

Fig. 5 shows the m_T distributions in the low and high m_H search regions with the expected signal for a Higgs boson mass of 200 GeV, 400 GeV and 600 GeV. The low pile-up and high pile-up data are shown separately.

The number and distribution of candidate $H \to ZZ \to \ell^+ \ell^- \nu\bar{\nu}$ events observed in the data agree with the expected backgrounds. No indication of an excess is seen, with a smallest p_0-value of 0.05 at $m_H = 280$ GeV, 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 Higgs boson production cross section relative to its predicted SM value as a function of m_H. The limits are extracted from a maximum likelihood fit to the m_T distribution following the CL_s modified frequentist formalism [70] with the profile likelihood test statistic [71]. All systematic uncertainties are taken into account. The likelihood function includes the parameters that describe the systematic uncertainties and their correlations. No significant pulls are observed on any of these parameters.

Fig. 6 shows the expected and observed limits at the 95% CL. Bands are shown, indicating the expected sensitivity with $\pm 1\sigma$ and $\pm 2\sigma$ fluctuations. At low values of m_H the transverse mass resolution induces correlations in the observed limit between neighbouring mass points. While at high values of m_H, where the observed limits are lower than expected over a broad range, the width of the SM Higgs is large and these correlations are therefore stronger. The mass range between 280–497 GeV is expected to be excluded while observation shows that a SM Higgs is excluded at the 95% CL in the range of 319–558 GeV.

8. Summary

Results of a search for a heavy SM Higgs boson with a mass in the range $200 < m_H < 600$ GeV decaying to $ZZ \to \ell^+ \ell^- \nu\bar{\nu}$ have been presented. These results are based on a data sample corresponding to an integrated luminosity of 4.7 fb^{-1} and $\sqrt{s} = 7$ TeV, recorded with the ATLAS detector at the LHC. No evidence for a signal is observed and cross section limits are placed over the mass range considered in this search, excluding the production of a SM Higgs boson in the region $319 < m_H < 558$ GeV at the 95% CL.

reproduction in any medium, provided the original authors and source are credited.

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