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Search for the Higgs boson in the $H \to WW \to \ell\nu jj$ decay channel at $\sqrt{s} = 7$ TeV with the ATLAS detector ☆

ATLAS Collaboration ⋆

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ABSTRACT

A search for the Standard Model Higgs boson has been performed in the $H \to WW \to \ell\nu jj$ channel using 4.7 fb^{-1} of pp collision data recorded at a centre-of-mass energy of $\sqrt{s} = 7$ TeV with the ATLAS detector at the Large Hadron Collider. Higgs boson candidates produced in association with zero, one or two jets are included in the analysis to maximize the acceptance for both gluon fusion and weak boson fusion Higgs boson production processes. No significant excess of events is observed over the expected background and limits on the Higgs boson production cross section are derived for a Higgs boson mass in the range 300 GeV $< m_H <$ 600 GeV. The best sensitivity is reached for $m_H = 400$ GeV, where the observed (expected) 95% confidence level upper bound on the cross section for $H \to WW$ produced in association with zero or one jet is 2.2 pb (1.9 pb), corresponding to 1.9 (1.6) times the Standard Model prediction. In the Higgs boson plus two jets channel, which is more sensitive to the weak boson fusion process, the observed (expected) 95% confidence level upper bound on the cross section for $H \to WW$ production with $m_H = 400$ GeV is 0.7 pb (0.6 pb), corresponding to 7.9 (6.5) times the Standard Model prediction.

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1. Introduction

In the Standard Model (SM), a scalar field with a non-zero vacuum expectation value breaks the electroweak symmetry, gives masses to the W/Z bosons and fermions [1–6], and manifests itself directly as a particle, the Higgs boson [2,3,5]. A primary goal of the Large Hadron Collider (LHC) is to test the SM mechanism of electroweak symmetry breaking by searching for Higgs boson production in high-energy proton–proton collisions. At LHC energies, the Higgs boson is predominantly produced via gluon fusion ($gg \to H$) and via weak boson fusion ($qq \to qqH$).

Results of Higgs boson searches in various channels using data up to an integrated luminosity of approximately 5 fb^{-1} have recently been reported by both the ATLAS and CMS Collaborations [7,8]. The ATLAS analysis excludes a Higgs boson with mass in the ranges 112.9–115.5 GeV, 131–238 GeV and 251–466 GeV while the CMS analysis excludes the range 127–600 GeV at 95% confidence level (CL). Direct searches at LEP and the Tevatron exclude Higgs boson masses $m_H < 114.4$ GeV [9] and 156 GeV $< m_H <$ 177 GeV [10] respectively at 95% CL.

For $m_H \gtrsim 135$ GeV, the dominant decay mode of the Higgs boson is $H \to WW^{(*)}$. For $m_H \gtrsim 200$ GeV, the $H \to WW \to \ell\nu jj$ channel, where one W boson decays into two quarks leading to a pair of jets ($W \to jj$) and the other decays into a charged lepton and a neutrino ($W \to \ell\nu$) where $\ell = e$ or μ, becomes interesting since jets from the Higgs boson decay are, on average, more energetic than the jets from the dominant background (W + jets). An advantage of $H \to WW \to \ell\nu jj$ over channels with two final-state neutrinos is the possibility of reconstructing the Higgs boson mass using kinematical constraints to estimate the component of the neutrino momentum along the beam axis.

This Letter describes a search for the SM Higgs boson in the $H \to WW \to \ell\nu jj$ channel using the ATLAS detector at the LHC, based on 4.7 fb^{-1} of pp collision data collected at a centre-of-mass energy $\sqrt{s} = 7$ TeV during 2011. The present search supersedes a previous analysis in the same Higgs boson decay channel published by the ATLAS Collaboration [11]. The distribution of the $\ell\nu jj$ invariant mass $m(\ell\nu jj)$, reconstructed using the $\ell\nu$ invariant mass constraint $m(\ell\nu) = m(W)$ and the requirement that two of the jets in the event are consistent with a $W \to jj$ decay, is used to search for a Higgs boson signal. Feed-down from τ lepton decays is included in this analysis for both background and signal, i.e. $H \to WW \to \tau\bar{\nu}_\tau jj \to \ell\bar{\nu}_\ell\nu_\tau\bar{\nu}_\tau jj$.

The present search is restricted to $m_H > 300$ GeV in order to ensure a smoothly varying non-resonant background. The search is further limited to $m_H < 600$ GeV since, for higher Higgs boson masses, the jets from $W \to jj$ decay begin to overlap due to the large boost of the W boson, and the natural width of the Higgs

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boson exceeds 100 GeV. The best sensitivity to Higgs boson production in this analysis is expected for $m_H \sim 400$ GeV.

2. The ATLAS detector

The ATLAS experiment [12] uses a multipurpose particle detector with forward–backward symmetric cylindrical geometry[1] covering the pseudorapidity range $|\eta| < 2.5$ for charged particles and $|\eta| < 4.9$ for jet measurements. The inner tracking detector (ID) 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. The superconducting solenoid is surrounded by a high-granularity liquid-argon (LAr) sampling electromagnetic (EM) calorimeter. An iron/scintillator tile calorimeter provides hadronic coverage in the central rapidity range. The end-cap and forward regions are instrumented with LAr calorimeters for both electromagnetic and hadronic measurements. The muon spectrometer surrounds the calorimeters and consists of three large superconducting toroids, each with eight coils, a system of precision tracking chambers, and detectors for triggering.

3. Data and simulation samples

The data were collected using single-muon and single-electron triggers [13]. The single-muon trigger required the transverse momentum (p_T) of the muon with respect to the beam line to exceed 18 GeV; for the single-electron trigger, the threshold varied from 20 GeV to 22 GeV. The trigger object quality requirements were tightened throughout the data-taking period to cope with increasing instantaneous luminosity. For signal electrons satisfying $p_T > 25$ GeV, the trigger efficiency is in the plateau region and ranges between 95% and 97%, depending on the $|\eta|$ of the electron. The muon triggers reaches its efficiency plateau below a signal muon p_T threshold of 20 GeV. The plateau efficiency ranges from about 70% for $|\eta| < 1.05$ to 88% for $1.05 < |\eta| < 2.4$.

Using the ATLAS simulation framework [14], detailed Monte Carlo (MC) studies of signal and backgrounds have been performed. The interaction with the ATLAS detector is modelled with GEANT4 [15] and the events are processed through the same reconstruction chain that is used to perform the reconstruction of data events. The effect of multiple pp interactions in the same and nearby bunch crossings (pile-up) is modelled by superimposing several simulated minimum-bias events on the simulated signal and background events. Simulated MC events are weighted to match the distribution of interactions per beam crossing in the dataset.

4. Object selection

The pp collision vertices in each bunch crossing are reconstructed using the inner tracking system [16]. To remove cosmic-ray and beam-induced backgrounds, events are required to have at least one reconstructed primary vertex with at least three associated tracks with $p_T > 400$ MeV. If multiple collision vertices are reconstructed, the vertex with the largest summed p_T^2 of the associated tracks is selected as the primary vertex.

Each electron candidate is reconstructed from clustered energy deposits in the EM calorimeter with an associated track. It is further required to satisfy a tight set of identification criteria with an efficiency of approximately 80% for electrons from $W \to e\nu$ decays with transverse energy 20 GeV $< E_T <$ 50 GeV [17]. While the energy measurement is taken from the EM calorimeter, the pseudorapidity η and azimuthal angle ϕ are taken from the associated track. The cluster is required to be in the range $|\eta| < 2.47$, excluding the transition region between barrel and end-cap calorimeters, $1.37 < |\eta| < 1.52$, and small calorimeter regions affected by temporary operational problems. The track associated with the electron candidate is required to point back to the reconstructed primary vertex with a transverse impact parameter significance $|d_0/\sigma_{d_0}| < 10$ and with an impact parameter along the beam direction of $|z_0| < 1$ mm. Electrons are further required to be isolated: the sum of the transverse energies (excluding the electron itself) in calorimeter cells inside a cone $\Delta R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.3$ around the cluster barycentre must satisfy $\sum(E_T^{\mathrm{calo}})/p_T^e < 0.14$ and the scalar sum of the transverse momenta of all tracks (excluding the electron track itself) with $p_T > 1$ GeV from the primary vertex in the same cone must satisfy $\sum(p_T^{\mathrm{track}})/p_T^e < 0.13$.

Muons are reconstructed by combining tracks in the inner detector and the muon spectrometer. The identification efficiency is measured to be $(92.8 \pm 0.2)\%$ for muons with transverse momentum $p_T > 20$ GeV [18]. Tracks are required to pass basic quality cuts on the number and type of hits in the inner detector. They must lie within the range $|\eta| < 2.4$. The tracks must satisfy the same z_0 cut as electrons and $|d_0/\sigma_{d_0}| < 3$. They must also be isolated, with the sum of the transverse energies (excluding those attributed to the muon itself) in calorimeter cells inside a cone $\Delta R = 0.3$ around the muon satisfying $\Sigma(E_T^{\mathrm{calo}})/p_T^{\mu} < 0.14$. Furthermore, the scalar sum of the transverse momenta of all tracks (excluding the muon track itself) with $p_T > 1$ GeV from the primary vertex inside a cone $\Delta R = 0.4$ around the muon must satisfy $\sum(p_T^{\mathrm{track}})/p_T^{\mu} < 0.15$.

Jets are reconstructed from topological clusters of energy deposited in the calorimeters using the anti-k_t algorithm [19] with radius parameter $R = 0.4$. The reconstructed jet energy is calibrated using p_T- and η-dependent correction factors based on MC simulation and validated with data [20]. The selected jets are required to have $p_T > 25$ GeV and $|\eta| < 4.5$. Jets are considered b-tagged if they satisfy the requirement $|\eta| < 2.8$ and are consistent with having originated from the decay of a b-quark. This latter requirement is determined by a b-tagging algorithm which uses a combination of impact parameter significance and secondary vertex information and exploits the topology of weak decays of b- and c-hadrons. The algorithm is tuned to achieve an 80% b-jet identification efficiency, which results in a tagging rate for light quark jets of approximately 6% [21,22]. The missing transverse momentum and its magnitude E_T^{miss} are reconstructed from calibrated jets, leptons and photons, and take into account soft clustered energy in the calorimeters [23]. Energy deposited by muons is subtracted in the E_T^{miss} calculation to avoid double counting.

5. Event selection

Events are classified based on the number of jets selected in addition to the two jets from the Higgs boson decay candidate. For events to be selected as Higgs boson candidates without an additional jet ($H + 0j$) or with exactly one additional jet ($H + 1j$), the channels which are more sensitive to the gluon fusion process, the following conditions must be met: only one reconstructed lepton candidate (electron or muon) with $p_T > 40$ GeV, no additional leptons with $p_T > 20$ GeV, $E_T^{\mathrm{miss}} > 40$ GeV, and exactly two jets ($\ell\nu jj + 0$ jet sample) or exactly three jets ($\ell\nu jj + 1$ jet sample)

[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, measured with respect to the z-axis, as $\eta = -\ln[\tan(\theta/2)]$.

with $p_T > 25$ GeV and $|\eta| < 4.5$. The two jets with invariant mass (m_{jj}) closest to the mass of the W boson are required to satisfy 71 GeV $< m_{jj} <$ 91 GeV. One of these two jets must satisfy $p_T > 60$ GeV and the other must satisfy $p_T > 40$ GeV. These two jets are taken as the W boson decay jets and are required to lie within the range $|\eta| < 2.8$, where the jet energy scale is best known (with an uncertainty of 5% or less for $p_T > 40$ GeV, depending on p_T and $|\eta|$ over this range [20]), and have $\Delta R_{jj} < 1.3$ to suppress $W+$jets background. In order to reduce top quark background, the event is rejected if either of the W boson decay jets is b-tagged.

For the $\ell\nu jj + 2j$ selection ($H + 2j$), which is more sensitive to the weak boson fusion Higgs boson production mode, the following requirements are applied. The charged lepton p_T and the E_T^{miss} must both exceed 30 GeV. There must be at least four jets with $p_T > 25$ GeV and $|\eta| < 4.5$. The two jets with invariant mass closest to the mass of the W boson are required to satisfy 71 GeV $< m_{jj} <$ 91 GeV. These jets are labelled as the W boson decay jets. Because of the small signal cross section in this channel, the W boson decay jets are not required to lie within $|\eta| < 2.8$, in order to increase the acceptance. The event is required to satisfy a set of "forward jet tagging" cuts designed to select $qq \to qqH$ events. The two highest-p_T jets apart from the W boson decay jets are labelled as the "tag" jets, and they are required to be in opposite hemispheres ($\eta_{j1} \cdot \eta_{j2} < 0$). They are also required to be well-separated in pseudorapidity ($\Delta\eta_{jj} = |\eta_{j1} - \eta_{j2}| > 3$). The lepton is required to be between the two tag jets in pseudorapidity. The two tag jets must have large invariant mass ($m_{jj} > 600$ GeV) and there must be no additional jets in the range $|\eta| < 3.2$. The event is rejected if it contains a b-tagged jet.

The $\ell\nu jj + 0/1j$ selection differs from the selection used Ref. [11]. The selection criteria are optimized to improve the expected Higgs boson sensitivity for masses above 300 GeV and require a more complex parameterization of the background shape, as discussed in Section 8.

After the $\ell\nu jj + 0$ and $\ell\nu jj + 1$ selections, the gluon fusion process is expected to contribute approximately 98% and 92% to the total signal yield, respectively, with the remainder primarily due to the weak boson fusion process. After the $\ell\nu jj + 2$ selection, the weak boson fusion process is expected to contribute approximately 68% of the total signal yield, with the remainder primarily due to the gluon fusion process.

6. Expected backgrounds

In both the $\ell\nu jj + 0/1j$ and $\ell\nu jj + 2j$ selections, the background is expected to be dominated by $W+$jets production. Other important backgrounds are $Z+$jets, $t\bar{t}$, single top quark, diboson (WW, WZ, ZZ, $W\gamma$ and $Z\gamma$) production, and multijets (MJ) from strong interaction processes that can be selected due either to the presence of leptons from heavy-flavour decays or jets misidentified as leptons.

Although MC predictions are not used to model the background in the Higgs boson search results, a combination of MC and data-driven methods is used to understand the background composition at this intermediate stage. Backgrounds due to $W/Z+$jets, $t\bar{t}$, and diboson production are modelled using the ALPGEN [24], MC@NLO [25], and HERWIG [26] generators, respectively. Single top production is modelled using AcerMC [27] and single top produced in association with a W boson is modelled with MC@NLO. The small contribution from $W/Z+\gamma$ events is estimated from events simulated using MadGraph/MadEvent [28]. The CT10 parton distribution function (PDF) set [29] is used for the MC@NLO samples, CTEQ6L1 [30] for the ALPGEN and MadGraph samples, and MRSTMCal [31] for the AcerMC samples.

The shapes of MJ background distributions are modelled using histograms derived from data samples selected in the same way as for the $H \to WW \to \ell\nu jj$ selection, except that the electron identification requirements are loosened and the isolation requirement on muons is inverted. In the loosened selection, electrons satisfying the complete set of identification criteria are not included. Expected contributions from top quark ($t\bar{t}$ and single top) production and electroweak boson (including diboson) production to the MJ shape histograms are subtracted using MC predictions.

To normalize the MJ background contribution in a given channel ($e\nu jj+0j$, $\mu\nu jj+0j$, $e\nu jj+1j$, $\mu\nu jj+1j$, $e\nu jj+2j$, $\mu\nu jj+2j$), a fit to the E_T^{miss} distribution using templates for each background contribution are performed. The E_T^{miss} template is constructed from the loose lepton control sample after the selection is further relaxed by omitting the E_T^{miss} criteria. The normalization of this MJ template and the corresponding template for $W/Z+$jets taken from MC are fitted to the observed E_T^{miss} distribution in data after the final selection without a E_T^{miss} cut, with other backgrounds estimated using the MC simulation and fixed to their expectation for 4.7 fb^{-1}. The relative contributions from $W+$jets and $Z+$jets into the $W/Z+$jets template are fixed according to the SM cross sections. The scale factors for the MJ and $W/Z+$jets templates derived from these fits are used to normalize the MJ and $W/Z+$jets background contributions in comparisons between data and these background expectations.

The MC simulation predicts that $W/Z+$jets events constitute (72 ± 14)% of the total background for $\ell\nu jj + 0/1j$ and (77 ± 15)% for $\ell\nu jj + 2j$, while the top quark backgrounds contribute with (19 ± 5)% and (9 ± 2)% for $\ell\nu jj + 0/1j$ and $\ell\nu jj + 2j$ respectively.

7. *WW* mass reconstruction

To reconstruct the invariant mass $m(\ell\nu jj)$ of the WW system, the neutrino momentum is required. Its transverse momentum p_T^ν is taken from the measured E_T^{miss} while the neutrino longitudinal momentum p_z^ν is computed using the second degree equation given by the mass constraint $m(\ell\nu) = m(W)$. In the case of two real solutions, the solution with smaller neutrino longitudinal momentum $|p_z^\nu|$ is taken, based on simulation studies. In the case of complex solutions, the event is rejected. This requirement rejects (20 ± 1)% of MC signal events at $m_H = 400$ GeV, while for MC $W+$jets the corresponding rejection is (30 ± 1)%. These estimates include only statistical uncertainties. Larger fractions of events are rejected in $\ell\nu jj + 1j$ than in $\ell\nu jj + 0j$ independent of lepton flavour. In collision data (30 ± 1)% of the events are rejected by this requirement, consistent with the expectations from the $W+$jets background simulation.

8. Signal and background modelling

The Higgs boson signal is expected to appear as a peak in the $m(\ell\nu jj)$ distribution. Its width, before detector effects, varies from about 10 GeV at $m_H = 300$ GeV to about 70 GeV at $m_H = 550$ GeV. The non-resonant background for the $\ell\nu jj + 0/1j$ channel is modelled by a smooth function of the form $f(x) = [1/(1 + |a(x - m)|^b)] \times \exp[-c(x - 200)]$, where x is $m(\ell\nu jj)$ in GeV and a, b, c, and m are free parameters with the appropriate units. In the $\ell\nu jj + 2j$ channel, the background is modelled by the sum of two exponential functions. The parameters of the fitted function in each of these models are not subjected to any external constraint. The functional form for the background model is well motivated by studies using MC simulation, and is tested by fits to the $m(\ell\nu jj)$ distributions obtained through event selection in the W sidebands, with m_{jj} just below (45 GeV $< m_{jj} <$ 60 GeV) or

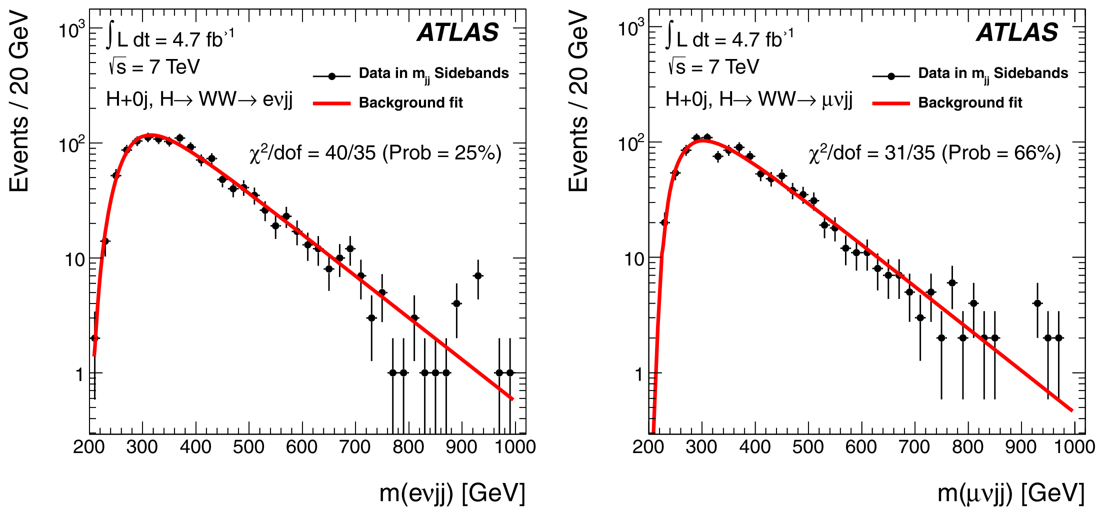

Fig. 1. Fits of the background model described in the text to the reconstructed invariant mass $m(\ell\nu jj)$ when m_{jj} is in the W sidebands for the $\ell\nu jj+0j$ selection. The left (right) figure shows the electron (muon) channel distribution. The χ^2/dof and χ^2 probability of these fits are also shown in the figure.

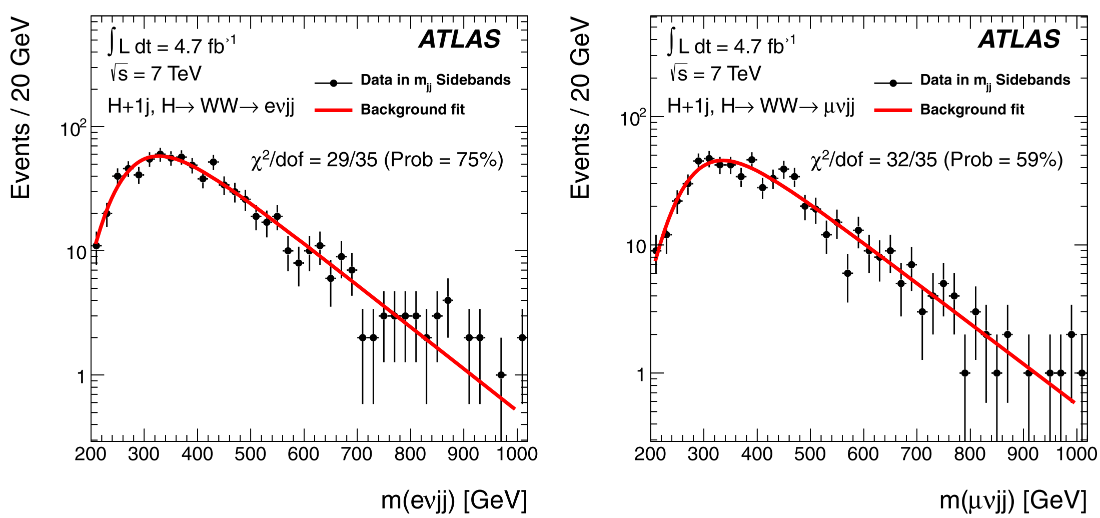

Fig. 2. Fits of the background model described in the text to the reconstructed invariant mass $m(\ell\nu jj)$ when the m_{jj} is in the W sidebands for the $\ell\nu jj+1j$ selection. The left (right) figure shows the electron (muon) channel distributions. The χ^2/dof and χ^2 probability of these fits are also shown in the figure.

just above ($100\ \text{GeV} < m_{jj} < 115\ \text{GeV}$) the W boson peak. Figs. 1 and 2 show fits of the $\ell\nu jj$ mass to the background model for $\ell\nu jj+0j$ and $\ell\nu jj+1j$ selections with m_{jj} in the W sidebands. The χ^2 probabilities of these fits are between 25% and 75%, providing support for the background functional form used in this analysis.

MC simulation is used to study the expected Higgs boson contribution to the $m(\ell\nu jj)$ distributions. Both the gluon fusion and the weak boson fusion signal production processes are simulated using the POWHEG [32,33] event generator interfaced to PYTHIA [34] using MRSTMCal [31] PDFs and are normalized to the next-to-next-to-leading order cross sections [35] shown in Table 1. The $m(\ell\nu jj)$ distribution for the expected signal at each hypothesized m_H is modelled using the functional form $1/(a+(x-m_1)^2+b(x-m_2)^4)$ with parameters (a, b, m_1 and m_2) determined from a fit to the MC simulation of the expected Higgs boson signal. The $m(l\nu jj)$ fractional resolution is $8.8 \pm 1.3\%$ at $m_H = 400$ GeV, the uncertainty arising mostly from the $E_{\mathrm{T}}^{\mathrm{miss}}$ and jet energy scale as described below, and shows a $1/\sqrt{m_H}$ dependence over the range of this analysis.

Table 1
Cross sections for Standard Model Higgs boson production and the branching ratio (BR) for $H \to WW \to \ell\nu jj$ ($\ell = e$ or μ) as a function of Higgs boson mass m_H. The cross section and its associated uncertainties are described in Ref. [36]. The branching ratio includes $W \to \tau \to \ell$, and the uncertainties from the subchannels [37] are added in quadrature with the $H \to WW$ uncertainty, which is 0.5% below 500 GeV and $0.1m_H^4$ for $m_H \gtrsim 500$ GeV.

m_H [GeV]	$\sigma(gg \to H)$ [pb]	$\sigma(qq \to H)$ [pb]	BR($H \to \ell^{\pm}\nu jj$)
300	2.4 ± 0.4	0.30 ± 0.01	0.237 ± 0.003
400	2.0 ± 0.3	$0.162^{+0.010}_{-0.005}$	0.199 ± 0.002
500	0.85 ± 0.15	$0.095^{+0.007}_{-0.003}$	0.187 ± 0.002
600	0.33 ± 0.06	$0.058^{+0.005}_{-0.002}$	0.191 ± 0.003

9. Systematic uncertainties

The systematic uncertainty due to the background modelling is included by treating the uncertainties on the background model parameters resulting from fits to the data as nuisance parameters in the statistical interpretation of the data. Both the background model and the sum of signal and background models are found to

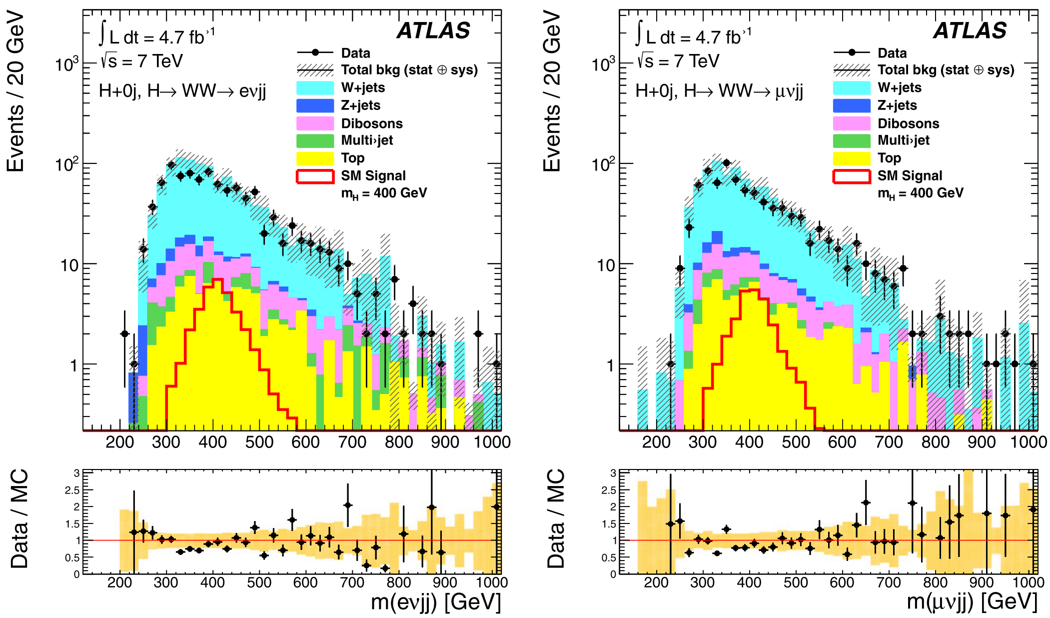

Fig. 3. The reconstructed invariant mass $m(\ell\nu jj)$ in the data and expected backgrounds using MC simulation for the $\ell\nu jj + 0j$ selection. The left (right) figure shows the electron (muon) channel distribution. The expected Higgs boson signal for $m_H = 400$ GeV is also shown. The bottom panels show the data divided by the MC expectation as markers, and the shaded (orange in the web version) region indicates the systematic uncertainty on the background expectation from MC simulation.

be good fits to the data. For $m_H = 400$ GeV, the χ^2 probabilities are 33% and 31% for the background-only and background-plus-signal fits, respectively. Therefore, alternative parameterizations of the background expectation that are consistent with the data will also be consistent with the background model within its uncertainties. This is tested by fitting both the signal region and the sideband regions of the data with two alternative parameterizations that use polynomials of varying order to describe the decreasing background component instead of exponential functions. Differences in the fitted background yield between these parameterizations and the nominal background model are less than 5%, while the uncertainty from the nuisance parameters and statistical uncertainty is 10–12%.

The remaining systematic uncertainties are related to the Higgs boson signal. The fit includes nuisance parameters which account for the uncertainty in the reconstruction efficiency. The trigger efficiencies, the electron and muon reconstruction efficiencies, lepton energy resolution and scale are varied within their uncertainties, giving an uncertainty in the signal efficiency of less than 1%. Varying the jet energy scale [20] within its uncertainties yields an uncertainty of up to 8% in the expected signal in the $\ell\nu jj + 0/1j$ channel for $m_H \geqslant 400$ GeV. Smearing the jet energies within the uncertainty on their resolutions [38] results in a signal uncertainty of 7% for $m_H = 400$ GeV and 5% for $m_H = 600$ GeV. The reconstructed E_T^{miss} [23] is also affected by the uncertainties on the energy scales and resolutions of reconstructed leptons and jets. The signal uncertainties given above include the propagation of these effects to the reconstructed E_T^{miss}. The propagation to E_T^{miss} adds a small contribution to the overall signal uncertainty. In addition, a 7% uncertainty on the degradation of the E_T^{miss} resolution and scale due to pile-up effects is estimated, which results in a negligible uncertainty on the signal efficiency. The looser selection criteria for the $\ell\nu jj + 2j$ channel result in an 11% uncertainty on the signal efficiency from the jet energy scale at $m_H = 400$ GeV while the uncertainty due to the jet energy resolution is 16%. The uncertainty on the b-tagging efficiency [39] gives a maximum uncertainty of 8% on the signal efficiency and shows no strong dependence on m_H or the selection criteria.

The uncertainties on jet energy resolution and jet energy scale, which also have an impact on E_T^{miss}, lead to systematic uncertainties on the Higgs boson mass resolution (5%) and on the Higgs boson mass scale (2%). These uncertainties are not included since their effect on the fitted Higgs boson yield is considerably smaller than the systematic uncertainty on the signal acceptance due to jet energy scale and resolution.

The Higgs boson signal expectation includes a 3.9% systematic uncertainty due the luminosity determination [40,41] and a 19.4% uncertainty on the predicted Higgs boson cross section [35], taken to be independent of the mass. Off-shell effects and interference between the signal and background processes are discussed in Refs. [35,42,43]. To account for the uncertainties from these effects, an uncertainty of $150\% \times m_H^3$ (m_H in TeV) on the signal cross section is included in the statistical interpretation of the data, where the m_H^3 form is motivated by the scaling of the Higgs boson width with m_H and the normalization factor of 150% is chosen to give $\sim$30% at $m_H = 600$ GeV [35].

10. Results and conclusions

Figs. 3, 4 and 5 show the $m(\ell\nu jj)$ distributions and the ratio of data to background expectation from MC simulation for the six different final states considered in this analysis, along with bands showing the total background uncertainty. The simulated background is not used in the statistical interpretation of the data. Instead, the parameterizations described in Section 8 are used to model the background.

The Higgs boson signal yield in each final state is determined using a binned maximum likelihood fit to the observed $m(\ell\nu jj)$ distribution in the range 200 GeV $< m(\ell\nu jj) <$ 2000 GeV. As a check, fits over a smaller range (200 GeV $< m(\ell\nu jj) <$ 1000 GeV) were also performed and the results were found to be consistent with the results presented here.

The difference between data and the fitted background is shown in Fig. 6. The expected signals for $m_H = 400$ GeV and $m_H = 600$ GeV are also shown, each scaled to the 95% CL limit on the production cross section.

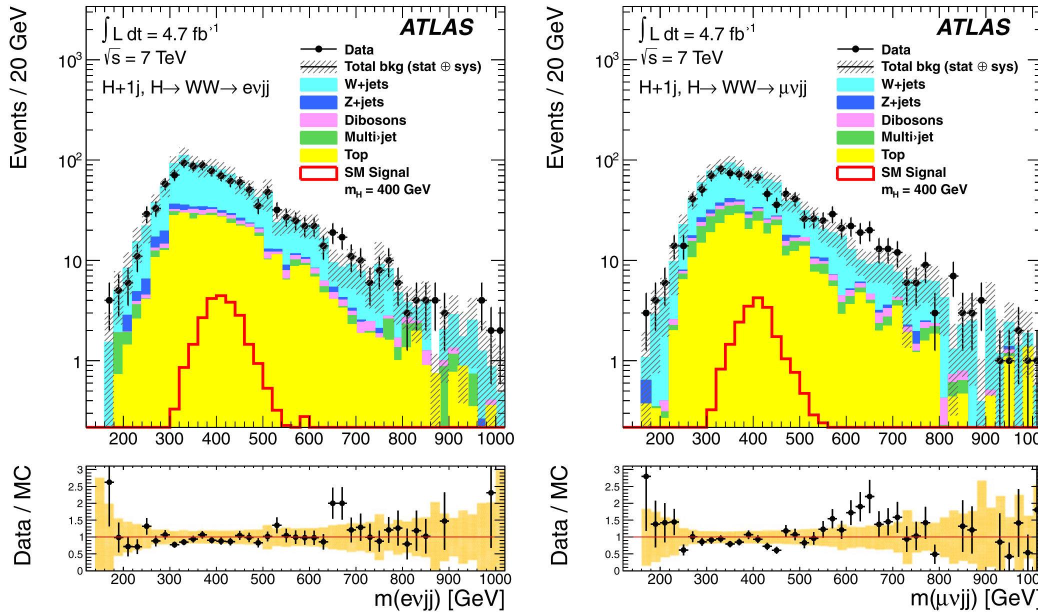

Fig. 4. The reconstructed invariant mass $m(\ell\nu jj)$ in the data and expected backgrounds using MC simulation for the $\ell\nu jj+1j$ selection. The left (right) figure shows the electron (muon) channel distribution. The expected Higgs boson signal for $m_H = 400$ GeV is also shown. The bottom panels show the data divided by the MC expectation as markers, and the shaded (orange in the web version) region indicates the systematic uncertainty on the background expectation from MC simulation.

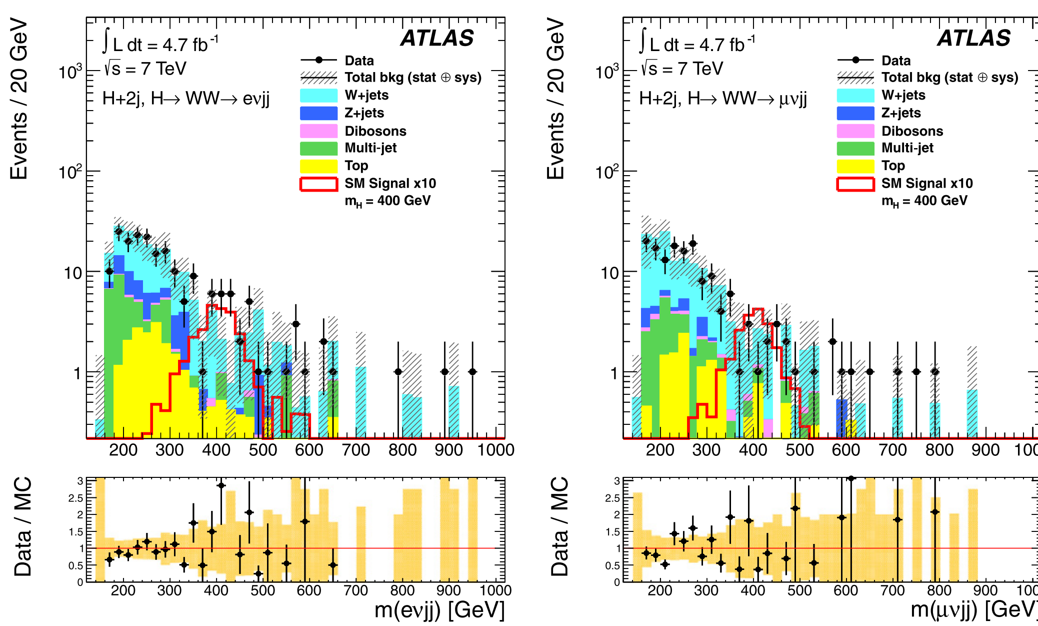

Fig. 5. The reconstructed invariant mass $m(\ell\nu jj)$ in the data and expected backgrounds using MC simulation for the $\ell\nu jj+2j$ selection. The left (right) figure shows the electron (muon) channel distribution. The expected Higgs boson signal for $m_H = 400$ GeV is also shown, scaled up by a factor of 10 for visibility. The bottom panels show the data divided by the MC expectation as markers, and the shaded (orange in the web version) region indicates the systematic uncertainty on the background expectation from MC simulation.

Fig. 6 shows that there is no indication of a significant excess of data above the background model. Limits on SM Higgs boson production are extracted using the profile likelihood ratio [44] as a test statistic and following the CL$_s$ procedure described in Refs. [45,7].

Fig. 7 shows the 95% CL upper bound on the cross section times branching ratio for Higgs boson production with respect to the Standard Model prediction, as a function of m_H. The best sensitivity is reached at $m_H = 400$ GeV, where the 95% confidence level upper bound on the cross section for $H \to WW$ production using the combined $H+0j$ and $H+1j$ channels is observed (expected) to be 2.2 pb (1.9 pb) corresponding to 1.9 (1.6) times the Standard Model prediction. In the $H+2j$ channel, which is more sensitive to Higgs boson production via weak boson fusion, the 95% confidence level upper bound on the cross section for $H \to WW$ production with $m_H = 400$ GeV is observed (expected) to be 0.7 pb (0.6 pb) corresponding to 7.9 (6.5) times the Standard Model prediction. Fig. 8 shows the limits obtained when combining the $H+2j$ channel with the $H+0/1j$ channels. Fig. 9 shows the probability p_0 to observe a fluctuation in $300 < m(\ell\nu jj) < 600$ GeV at least as

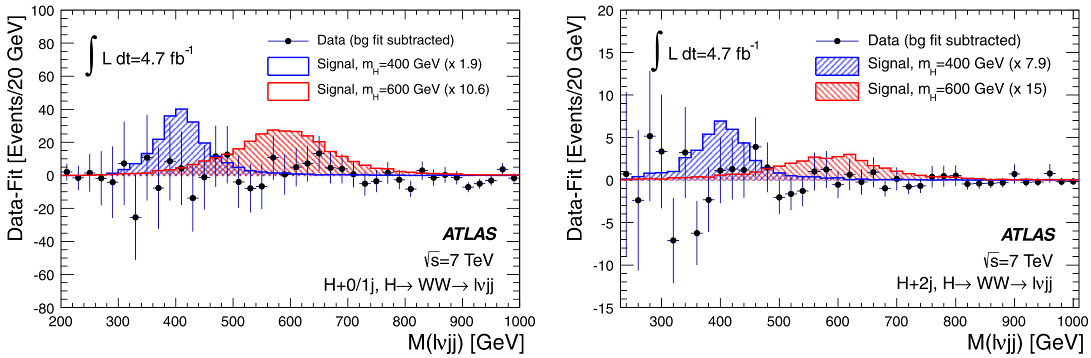

Fig. 6. The difference between data and the fitted background under a no-signal hypothesis, for the (left) $\ell\nu jj + 0/1j$ selection and (right) $\ell\nu jj + 2j$ selection, both summed over lepton flavours. The expected contribution from SM Higgs boson decays is also shown for $m_H = 400$ GeV and $m_H = 600$ GeV, multiplied by a factor equal to the ratio of 95% CL limit on its production to the SM prediction. Uncertainties on the signal normalization and the background shape are not shown in the plots but are taken into account in the limit setting.

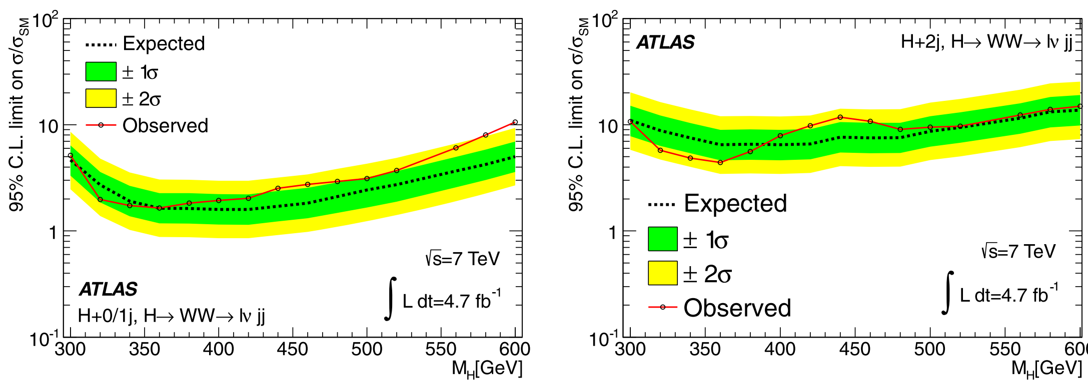

Fig. 7. The expected and observed 95% CL upper limits on the Higgs boson production cross section divided by the SM prediction. The left figure shows the combination of $H + 0j$ with $H + 1j$ and the right figure shows the $H + 2j$ limits. For any hypothesized Higgs boson mass, the background contribution used in the calculation of this limit is obtained from a fit to the $m(\ell\nu jj)$ distribution. The dark (green in the web version) and light (yellow in the web version) bands show the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties on the expected limit.

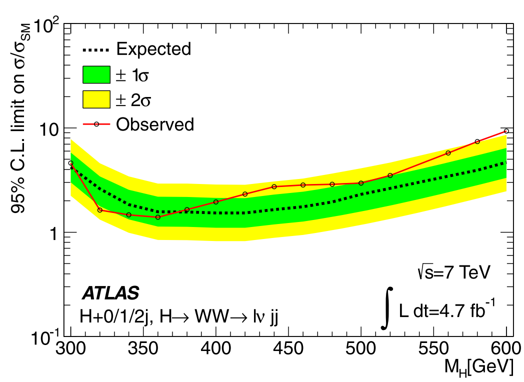

Fig. 8. The expected and observed 95% CL upper limits on the Higgs boson production cross section divided by the SM prediction. This figure shows the combination of the $H + 0j$, $H + 1j$ and $H + 2j$ channels. The background contribution used in the calculation of this limit is obtained from a fit to the $m(\ell\nu jj)$ distribution. The dark (green in the web version) and light (yellow in the web version) bands show the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties on the expected limit.

large as the one observed in data if there is no signal contribution, where the signal and background are modelled as described in Section 8. The expected p_0 for $H + 0/1j$ if there were a SM Higgs at 400 GeV is 0.091, and the observed value is 0.276. For $H + 2j$, the expected p_0 is 0.369 and the observed is 0.293. The significance is computed as $\sqrt{-2\log\lambda}$ where λ is the likelihood ratio obtained by the fit, and the significance is converted into the probability p_0 using the Gauss error function.

In summary, a search for the SM Higgs boson has been performed in the $H \to WW \to \ell\nu jj$ channel using 4.7 fb^{-1} of pp collisions at $\sqrt{s} = 7$ TeV recorded by the ATLAS detector. No significant excess of events over the expected background has been observed. Exclusion limits on SM Higgs boson production at 95% CL are reported over the Higgs boson mass range of 300–600 GeV.

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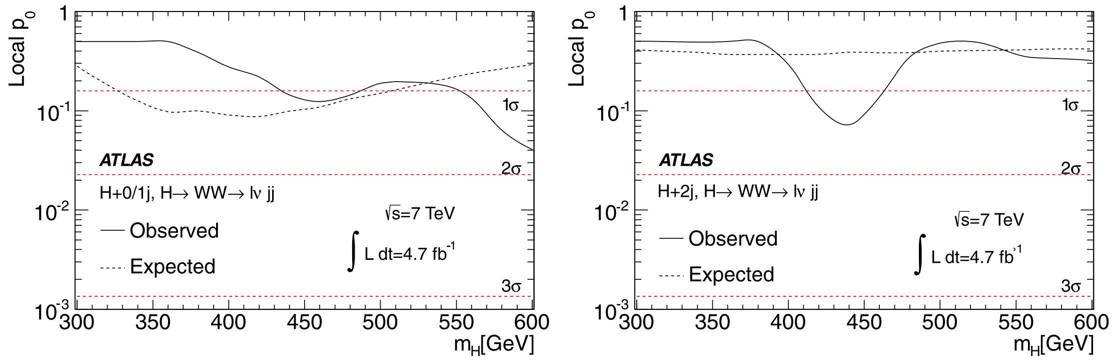

Fig. 9. Local p_0 for the SM Higgs boson search in the $H + 0/1j$ channel (left) and $H + 2j$ channel (right). The dashed line shows the expected p_0 value for a Standard Model Higgs boson as a function of its mass.

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