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Search for the Standard Model Higgs boson in the $H \to WW^{(\star)} \to \ell\nu\ell\nu$ decay mode with 4.7 fb^{-1} of ATLAS data at $\sqrt{s} = 7$ TeV ☆

ATLAS Collaboration ⋆

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ABSTRACT

A search for the Standard Model Higgs boson in the $H \to WW^{(\star)} \to \ell\nu\ell\nu$ ($\ell = e, \mu$) decay mode is presented. The search is performed using proton–proton collision data corresponding to an integrated luminosity of 4.7 fb^{-1} at a centre-of-mass energy of 7 TeV collected during 2011 with the ATLAS detector at the Large Hadron Collider. No significant excess of events over the expected background is observed. An upper bound is placed on the Higgs boson production cross section as a function of its mass. A Standard Model Higgs boson with mass in the range between 133 GeV and 261 GeV is excluded at 95% confidence level, while the expected exclusion range is from 127 GeV to 233 GeV.

1. Introduction

The Higgs boson is the only elementary particle in the Standard Model (SM) of particle physics that has not yet been observed. It is intimately related to the Higgs mechanism [1–3] which in the SM gives mass to all other massive elementary particles. The search for this particle is a centrepiece of the Large Hadron Collider (LHC) physics programme.

Indirect limits on the Higgs boson mass of $m_H < 158$ GeV at 95% confidence level (CL) have been set using global fits to precision electroweak results [4]. Direct searches at LEP and the Tevatron have excluded at 95% CL a SM Higgs boson with a mass below 114.4 GeV [5] and in the regions 147 GeV $< m_H <$ 179 GeV and 100 GeV $< m_H <$ 106 GeV [6], respectively.

The results of searches in various channels using data corresponding to an integrated luminosity of approximately 5 fb^{-1} have been reported recently by the ATLAS Collaboration, excluding the mass ranges 112.9–115.5 GeV, 131–238 GeV, and 251–466 GeV [7]; and by the CMS Collaboration, excluding the mass range from 127 GeV to 600 GeV [8].

In the $H \to WW^{(\star)} \to \ell\nu\ell\nu$ channel (with $\ell = e, \mu$), ATLAS reported the results of a search using the first 2.05 fb^{-1} of data from 2011, which excluded a SM Higgs boson in the mass range 145 GeV $< m_H <$ 206 GeV at 95% CL [9]. The analysis described in this Letter uses the full 2011 dataset, which after requiring that all detector components are fully functional corresponds to 4.7 fb^{-1} of proton–proton (pp) collisions at $\sqrt{s} = 7$ TeV. The selection criteria described in Ref. [9] are modified to gain sensitivity at low m_H and to cope with increased instantaneous luminosities. The previous cut-based approach is extended by adding events with two jets and by fitting for the presence of a signal using a transverse mass variable. A similar search has been performed by the CMS Collaboration [10].

2. Data and simulated samples

The data used for this analysis were collected in 2011 using the ATLAS detector, a multi-purpose particle physics experiment with a forward-backward symmetric cylindrical geometry and near 4π coverage in solid angle [11]. It consists of an inner tracking system surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and an external muon spectrometer incorporating large superconducting air-core toroid magnets. The combination of these systems provides charged particle measurements together with highly efficient and precise lepton measurements over the pseudorapidity[1] range $|\eta| < 2.5$. Jets are reconstructed over the full coverage of the calorimeters, $|\eta| < 4.9$; this calorimeter coverage also provides a precise measurement of the missing transverse momentum.

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

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The data used in the present analysis were collected using inclusive single-muon and single-electron triggers. The single-muon trigger required the transverse momentum of the muon with respect to the beam line, p_T, to exceed 18 GeV; for the single-electron trigger the threshold varied from 20 to 22 GeV. The trigger object quality requirements were tightened throughout the data-taking period to cope with the increasing instantaneous luminosity.

In this analysis, the signal contributions that are considered include the dominant gluon fusion production process ($gg \to H$, denoted as ggF), the vector-boson fusion production process ($qq' \to qq'H$, denoted as VBF) and the Higgs-strahlung process ($qq' \to WH, ZH$, denoted as WH/ZH). For the decay of the Higgs boson, only the $H \to WW^{(\star)} \to \ell\nu\ell\nu$ mode is considered, with final states featuring two charged leptons ($\ell = e, \mu$, including small contributions from leptonic τ decays). The branching fraction for this decay, as a function of m_H, is taken from the HDECAY [12] program.

The signal cross section is computed to next-to-next-to-leading order (NNLO) [13–18] in QCD for the ggF process. Next-to-leading order (NLO) electroweak (EW) corrections are also applied [19, 20], as well as QCD soft-gluon resummations up to next-to-next-to-leading log (NNLL) [21]. These calculations are detailed in Refs. [22–24], and assume factorisation between QCD and EW corrections. Full NLO QCD and EW corrections [25–27] and approximate NNLO QCD corrections [28] are used to calculate the cross sections for VBF signal production. The cross sections of the associated WH/ZH production processes are calculated up to NNLO QCD corrections [29,30] and NLO EW corrections [31].

The Monte Carlo (MC) generators used to model signal and background processes are listed in Table 1. For most processes, separate programs are used to generate the hard scattering process and to model the parton showering and hadronisation stages. Wherever HERWIG [32] is used for the latter, JIMMY [33] is used for the simulation of the underlying event. The MLM matching scheme [34] is used for the description of the W + jets and $Z/\gamma^\star$ + jets processes.

The CT10 parton distribution function (PDF) set [47] is used for the MC@NLO samples, CTEQ6L1 [48] for the ALPGEN, SHERPA, and MadGraph samples, and MRSTMCal [49] for the PYTHIA and AcerMC samples. Acceptances and efficiencies are obtained from a full simulation [50] of the ATLAS detector using GEANT4 [51]. This includes a realistic treatment of the event pile-up conditions (the data are affected by the detector response to multiple pp collisions occurring in the same or in different bunch crossings) in the 2011 data; from the first 2.3 fb^{-1} to the last 2.4 fb^{-1} of data taken, the average number of pp interactions per bunch crossing increased from 6.3 to 11.6.

Table 1

MC generators used to model the signal and background processes, and corresponding cross sections (given for both $m_H = 125$ GeV and $m_H = 240$ GeV in the case of the signal processes). The ggF Higgs boson p_T spectrum is reweighted to agree with the prediction from HqT [35]. All three single-top production channels (s-channel, t-channel, and Wt) are included. The number quoted for the inclusive $Z/\gamma^\star$ process (also referred to in the text as the Drell–Yan process) is for generated dilepton invariant masses exceeding 10 GeV. Kinematic criteria are also applied in the generation of $W(\to \ell\nu)\gamma$ events (the photon must have $p_T > 10$ GeV and be separated from the charged lepton by $\Delta R = \sqrt{(\Delta\eta^2) + (\Delta\phi^2)} > 0.1$) and $W(\to \ell\nu)\gamma^\star(\to \ell'\ell')$ events (the higher and lower transverse momenta of the leptons from the $\gamma^\star$ decay must exceed 15 GeV and 5 GeV, respectively). Leptonic decay modes (charged leptonic decay modes only for $Z/\gamma^\star$ production) are summed over, except for $t\bar{t}$, single-top, WZ, and ZZ production; in these cases inclusive cross sections are quoted. The quoted signal production cross sections include the $H \to WW^{(\star)} \to \ell\nu\ell\nu$ branching fractions but no branching fractions for the W and Z boson in WH/ZH production.

Process	Generator	m_H (GeV)	$\sigma \cdot$ Br (pb)
ggF	POWHEG [36,37] +	125	0.347
	PYTHIA [38]	240	0.265
VBF	POWHEG +	125	27×10^{-3}
	PYTHIA	240	34×10^{-3}
WH/ZH	PYTHIA	125	20×10^{-3}
		240	6×10^{-3}
$q\bar{q}/g \to WW$	MC@NLO [39] + HERWIG		4.68
$gg \to WW$	GG2WW [40] + HERWIG		0.14
$t\bar{t}$	MC@NLO + HERWIG		167
$tW/tb/tqb$	AcerMC [41] + PYTHIA		85
inclusive W	ALPGEN [42] + PYTHIA		32×10^3
inclusive $Z/\gamma^\star$	ALPGEN [42] + PYTHIA		15×10^3
ZZ	SHERPA [43]		5.6
WZ	MC@NLO		18.0
$W\gamma$	ALPGEN		345
$W\gamma^\star$ [44]	MadGraph [45,46]		6.5

3. Event selection

Events are required to have a primary vertex consistent with the beam spot position, with at least three associated tracks with $p_T > 400$ MeV. Overall quality criteria are applied in order to suppress non-collision backgrounds such as cosmic-ray muons, beam-related backgrounds, or noise in the calorimeters.

$H \to WW^{(\star)} \to \ell\nu\ell\nu$ candidates (with $\ell = e, \mu$) are pre-selected by requiring exactly two oppositely charged leptons with p_T thresholds of 25 GeV and 15 GeV for the leading and sub-leading lepton, respectively. For muons, the range $|\eta| < 2.4$ is used; for electrons, the range $|\eta| < 2.47$ is used, with the region $1.37 < |\eta| < 1.52$ (corresponding to the boundary between barrel and end-cap calorimeters) excluded. The selected electron candidates are reconstructed using a combination of tracking and calorimetric information [52], while the muon candidates are identified by matching tracks reconstructed in the inner detector and in the muon spectrometer [53]. At least one of the selected leptons is required to match a triggering object. Leptons from heavy-flavour decays and jets satisfying the lepton identification criteria are suppressed by requiring the leptons to be isolated: the scalar sum of the p_T of charged particles and of the calorimeter energy deposits within $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.3$ of the lepton direction are each required to be less than approximately 0.15 times the lepton p_T, with slight differences between track- and calorimeter-based criteria and between electrons and muons.

The Drell–Yan process leads to two same-flavour, opposite-sign high-p_T leptons. In the ee and $\mu\mu$ channels (the channels are indicated by the charged lepton flavours), this background is suppressed by requiring the dilepton invariant mass to be greater than 12 GeV, and to differ from the Z-boson mass m_Z by at least 15 GeV. For the $e\mu$ channel, the dilepton invariant mass is required to be greater than 10 GeV.

Drell–Yan events and multijet production via QCD processes are suppressed by requiring large E_T^{miss}. The E_T^{miss} is the magnitude of $\boldsymbol{p}_T^{miss}$, the negative vector sum of the reconstructed objects' transverse momenta, including muons, electrons, photons, jets, and clusters of calorimeter cells not associated with these objects. The quantity $E_{T,rel}^{miss}$ used in this analysis is defined as: $E_{T,rel}^{miss} = E_T^{miss} \sin\Delta\phi_{min}$, with $\Delta\phi_{min} \equiv \min(\Delta\phi, \frac{\pi}{2})$. Here, $\Delta\phi$ is the angle between $\boldsymbol{p}_T^{miss}$ and the transverse momentum of the nearest lepton or jet with $p_T > 25$ GeV. For the ee and $\mu\mu$ channels, the multijet and Drell–Yan events are suppressed by requiring $E_{T,rel}^{miss} > 45$ GeV. In the $e\mu$ channel, Drell–Yan events originate predominantly from $\tau\tau$ production, where the small leptonic τ decay branching fractions lead to a much smaller background. In this channel, the requirement is relaxed to $E_{T,rel}^{miss} > 25$ GeV. After the isolation and $E_{T,rel}^{miss}$ cuts, the multijet background is found to be negligible.

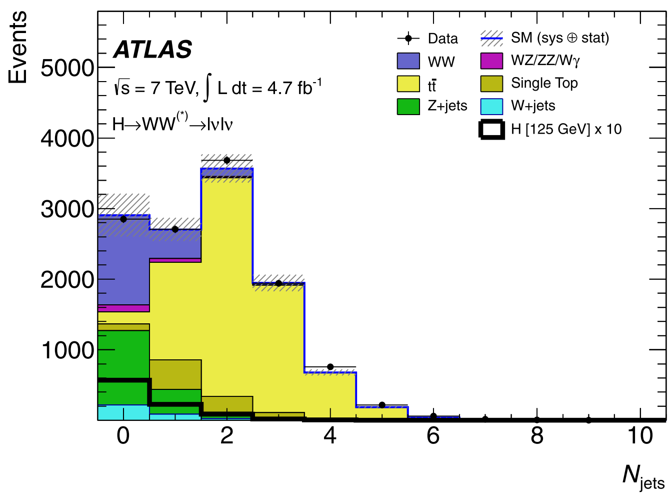

Fig. 1. Multiplicity of jets within the acceptance described in the text, for events satisfying the pre-selection criteria. The lepton flavours are combined. The hashed area indicates the total uncertainty on the background prediction. The expected signal for a SM Higgs boson with $m_H = 125$ GeV is superimposed (multiplied by a factor 10 for better visibility).

Fig. 1 shows the multiplicity distribution of jets reconstructed using the anti-k_t algorithm [54], with radius parameter $R = 0.4$, for all events satisfying the pre-selection criteria described above. Only jets with $p_T > 25$ GeV and $|\eta| < 4.5$ are considered. This threshold is increased to 30 GeV in the region $2.75 < |\eta| < 3.25$, which corresponds to the boundary between two calorimeter systems and is more sensitive to reconstruction issues arising from event pile-up. The background rate and composition depend significantly on jet multiplicity, as does the signal topology: without accompanying jets, the signal originates almost entirely from the ggF process and the background is dominated by approximately equal fractions of WW and Drell–Yan events. In contrast, when produced in association with two or more jets, the signal contains a much larger contribution from the VBF process and the background is dominated by $t\bar{t}$ production. To maximise the sensitivity, further selection criteria that depend on the jet multiplicity are applied to the pre-selected sample. The data are subdivided into 0-jet, 1-jet and 2-jet channels according to the jet counting defined above, with the 2-jet channel also including higher jet multiplicities. In addition, slightly different requirements are used for $m_H < 200$ GeV, 200 GeV $\leqslant m_H \leqslant$ 300 GeV, and 300 GeV $< m_H <$ 600 GeV; in the following these are referred to as low m_H, intermediate m_H, and high m_H selections, respectively. These mass-dependent selections are not mutually exclusive, thus events may contribute to more than one mass region. The different requirements for these channels and mass ranges are described in more detail below.

Due to spin correlations in the $WW^{(\star)}$ system arising from the spin-0 nature of the Higgs boson, the charged leptons tend to emerge from the interaction point in the same direction. In the low m_H selection this kinematic feature is exploited for all jet multiplicities by requiring that the azimuthal angular difference between the leptons, $\Delta\phi_{\ell\ell}$, be less than 1.8 radians, and that the dilepton invariant mass, $m_{\ell\ell}$, be less than 50 GeV for the 0-jet and 1-jet channels. For the 2-jet channel, the $m_{\ell\ell}$ upper bound is increased to 80 GeV (the $|m_{\ell\ell} - m_Z| > 15$ GeV cut is always applied for the same-flavour channels). For $m_H \geqslant 200$ GeV, the leptons tend to have higher p_T and larger angular separation. Therefore, the $\Delta\phi_{\ell\ell}$ cut is omitted and the $m_{\ell\ell}$ upper bound is increased to 150 GeV. For $m_H > 300$ GeV, the $m_{\ell\ell} < 150$ GeV criterion is also omitted.

In the 0-jet channel, the magnitude $p_T^{\ell\ell}$ of the transverse momentum of the dilepton system, $\mathbf{p}_T^{\ell\ell} = \mathbf{p}_T^{\ell1} + \mathbf{p}_T^{\ell2}$, is required to be greater than 30 GeV for the $e\mu$ channel and greater than 45 GeV for the ee and $\mu\mu$ channels. This improves the rejection of the Drell–Yan background.

In the 1-jet channel, backgrounds from top quark decays are suppressed by rejecting events containing a b-tagged jet, as determined using a b-tagging algorithm which uses a combination of impact parameter significance and secondary vertexing information and exploits the topology of weak decays of b- and c-hadrons [55]. The algorithm is tuned to achieve an 80% b-jet identification efficiency in $t\bar{t}$ events while yielding a light-jet tagging rate of approximately 6% [56]. The total transverse momentum, p_T^{tot}, defined as the magnitude of the vector sum $\mathbf{p}_T^{\text{tot}} = \mathbf{p}_T^{\ell1} + \mathbf{p}_T^{\ell2} + \mathbf{p}_T^{\text{j}} + \mathbf{p}_T^{\text{miss}}$, is required to be smaller than 30 GeV to suppress $t\bar{t}$, single-top, and Drell–Yan background events with jets with p_T below threshold. The $\tau\tau$ invariant mass, $m_{\tau\tau}$, is computed under the assumption that the reconstructed leptons are τ lepton decay products, that the neutrinos produced in the τ decays are collinear with the leptons [57], and that they are the only source of E_T^{miss}. Events in which the computed energies of both putative τ leptons are positive (the collinear approximation does not always yield physical solutions) are rejected if $|m_{\tau\tau} - m_Z| < 25$ GeV.

The 2-jet selection follows the 1-jet selection described above (with the p_T^{tot} definition modified to include all selected jets). In addition, the following jet-related cuts are applied: the two highest-p_T jets in the event, the "tag" jets, are required to lie in opposite pseudorapidity hemispheres ($\eta_{\text{j1}} \times \eta_{\text{j2}} < 0$), with no additional jet within $|\eta| < 3.2$; the tag jets must be separated in pseudorapidity by a distance $|\Delta\eta_{\text{jj}}|$ of at least 3.8 units; finally, the invariant mass of the two tag jets, m_{jj}, must be at least 500 GeV.

A transverse mass variable, m_T [58], is used in this analysis to test for the presence of a signal. This variable is defined as:

$$m_T = \sqrt{\left(E_T^{\ell\ell} + E_T^{\text{miss}}\right)^2 - \left|\mathbf{p}_T^{\ell\ell} + \mathbf{p}_T^{\text{miss}}\right|^2}, \qquad (1)$$

where $E_T^{\ell\ell} = \sqrt{|\mathbf{p}_T^{\ell\ell}|^2 + m_{\ell\ell}^2}$. The predicted numbers of signal and background events at each stage of the low m_H selection procedure outlined above are presented in Table 2. Fig. 2 shows the distributions of the transverse mass after all the low m_H selection criteria in the 0-jet and 1-jet analyses, for all lepton flavours combined. No distribution is shown for the 2-jet channel as only a single event (with $m_T = 131$ GeV) is selected in the data.

4. Background normalisation and control samples

For the 0-jet and 1-jet analyses, all the main backgrounds from SM processes producing two isolated high-p_T leptons (WW, top, Drell–Yan) are estimated using partially data-driven techniques based on normalising the MC predictions to the data in control regions dominated by the relevant background source. Only the small background from diboson processes other than WW is estimated using MC simulation. For the 2-jet analysis, the WW and Drell–Yan backgrounds are also estimated using MC simulation. The backgrounds from fake leptons, which include true leptons from heavy flavour decays in jets, are fully estimated from data. The control samples are obtained from the data with selections similar to those used in the signal region but with some criteria reversed or modified to obtain signal-depleted, background-enriched samples. This helps to reduce the sensitivity of the background predictions to the systematic uncertainties detailed in Section 5. In the following, such control samples are described for the WW, $Z/\gamma^\star +$jets, top, and $W+$ jets backgrounds. The quoted uncertainties on the background estimates are those associated with the low m_H selection.

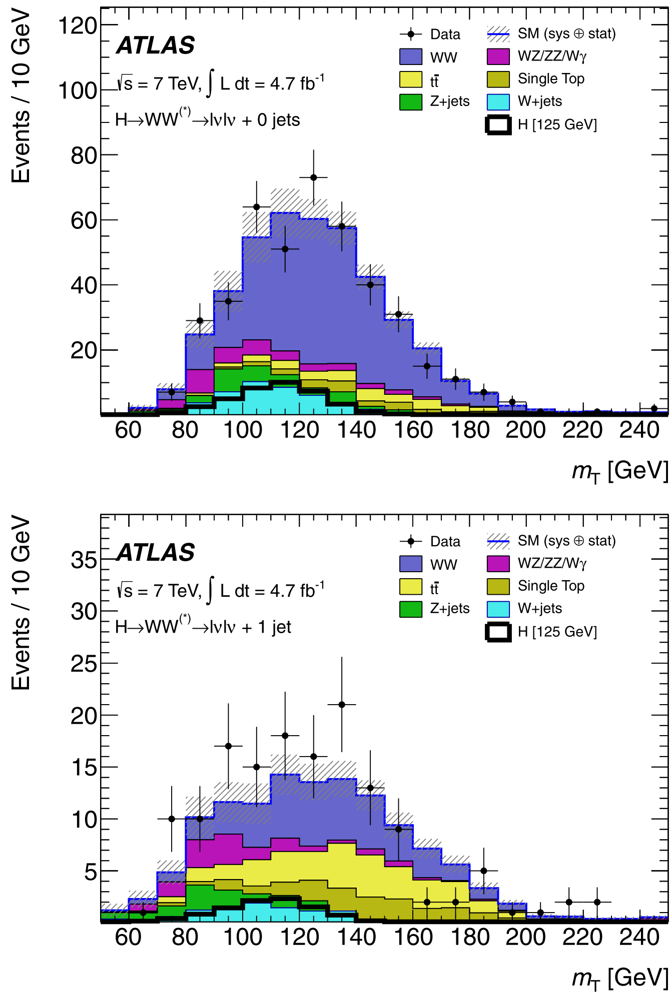

Fig. 2. Transverse mass, m_T, distribution in the 0-jet (top) and 1-jet (bottom) channels, for events satisfying all criteria for the low m_H selection. The lepton flavours are combined. The expected signal for a SM Higgs boson with $m_H = 125$ GeV is superimposed. The hashed area indicates the total uncertainty on the background prediction.

4.1. WW control sample

The WW background MC predictions in the 0-jet and 1-jet analyses, summed over lepton flavours, are normalised using control regions defined with the same selections as for the signal regions except that the $\Delta\phi_{\ell\ell}$ requirement is removed. In addition, the upper selection bound on $m_{\ell\ell}$ is replaced with a lower bound $m_{\ell\ell} > 80$ GeV ($m_{\ell\ell} > m_Z + 15$ GeV) for the $e\mu$ (ee and $\mu\mu$) final states. The numbers of events in the WW control regions in the data agree well with the MC predictions, as can be seen in Table 2. The total uncertainty on the predicted WW background in the signal region is 9% for the 0-jet and 22% for the 1-jet analyses.

This control region is used only for the low m_H selection in the 0-jet and 1-jet analyses. In the intermediate and high m_H selections, or in the 2-jet analysis, a high-statistics signal-depleted region cannot be isolated in the data; in these cases, the MC prediction is used.

4.2. $Z/\gamma^\star +$ jets control sample

In the ee and $\mu\mu$ final states and separately in the 0-jet and 1-jet analyses, a $Z/\gamma^\star +$ jets control region is constructed, after application of all selection criteria except that on $\Delta\phi_{\ell\ell}$, by considering a region with a modified criterion, 20 GeV $< E_{\mathrm{T,rel}}^{\mathrm{miss}} <$ 45 GeV. The number of events in this region, with non-$Z/\gamma^\star +$ jets contributions subtracted using the MC prediction, is then scaled by the ratio of events counted in the $E_{\mathrm{T,rel}}^{\mathrm{miss}} > 45$ GeV region to that in the 20 GeV $< E_{\mathrm{T,rel}}^{\mathrm{miss}} <$ 45 GeV region, for $|m_{\ell\ell} - m_Z| < 15$ GeV. Biases in the method are evaluated and corrected for using simulated events. The acceptance of the $\Delta\phi_{\ell\ell}$ selection criterion is taken from data. The resulting uncertainty on the $Z/\gamma^\star +$jets background in the signal region amounts to 38% and 33% in the 0-jet and 1-jet channels, respectively.

In the $e\mu$ channel of the 0-jet analysis, the background is estimated using the MC simulation and cross-checked with data using a control region dominated by $Z \to \tau\tau$ decays, which is constructed by requiring 10 GeV $< m_{\ell\ell} <$ 80 GeV, $\Delta\phi_{\ell\ell} > 2.5$, and $p_T^{\ell\ell} < 30$ GeV. A $E_{\mathrm{T,rel}}^{\mathrm{miss}}$ threshold of 25 GeV is used to calculate the data/MC scale factor, matching the cut applied to this channel in the signal selection. The resulting scale factor is consistent with unity within the uncertainty of about 10%. Owing to the difficulty of constructing a control region for higher jet multiplicities, a similar cross-check cannot be performed for the 1-jet and 2-jet analyses.

4.3. Top control sample

The estimated number of top quark background events in the 0-jet signal region is extrapolated from the number of events satisfying the pre-selection criteria described in Section 3. This sample is dominated by top quark backgrounds, as shown in Fig. 1. The contribution of non-top backgrounds to this sample is subtracted using estimates based on MC simulations. The scale factor used to propagate the $t\bar{t}$ contribution in this sample to the signal region is estimated as the square of the efficiency for one top quark decay to satisfy the jet veto criterion (estimated using another control sample, defined by the presence of an additional b jet), with a correction computed using simulated events to account for single-top background contributions [59]. The overall efficiency for the requirements on $p_T^{\ell\ell}$, $m_{\ell\ell}$, and $\Delta\phi_{\ell\ell}$ is taken from simulation. The total uncertainty on the top quark background estimate in events with no jets is 22%.

In the 1-jet and 2-jet analyses, the top quark background MC prediction is normalised to the data using a control sample defined by reversing the b-jet veto and removing the requirements on $\Delta\phi_{\ell\ell}$ and $m_{\ell\ell}$. The resulting samples are dominated by top quark backgrounds (both $t\bar{t}$ and single-top production), with little contribution from other sources. Good agreement between data and MC for the numbers of events in the 1-jet and 2-jet control regions is observed (see Table 2). The total uncertainties on the estimated top quark background in the 1-jet and 2-jet signal regions amount to 23% and 40%, respectively.

4.4. $W+$ jets control sample

The $W+$ jets background contribution is estimated using a data sample of events where one of the two leptons satisfies the identification and isolation criteria described in Section 3, and the other lepton (denoted "anti-identified") fails these criteria while satisfying a loosened selection. All other selection criteria follow those applied in the signal region. The dominant contribution to this background comes from $W +$ jets production with jets faking electrons. The contamination in the signal region is then obtained by scaling the number of events in the data control sample by a normalisation "fake factor". The fake factor is estimated as a function of the anti-identified lepton p_T using an inclusive dijet data sample, after subtracting the residual contributions from real leptons arising from leptonic W and Z decays.

Table 2
The expected numbers of signal and background events after the requirements of the low m_H selection listed in the first column, as well as the observed numbers of events. The signal is for $m_H = 125$ GeV. The W + jets background is estimated entirely from data, whereas MC predictions normalised to data in control regions are used for the WW, $Z/\gamma^\star$ + jets, $t\bar{t}$, and $tW/tb/tqb$ processes. Contributions from other background sources are taken from MC predictions. Only statistical uncertainties associated with the number of events in the MC samples and in the data control regions are shown. The expected numbers of signal and background events, and the observed numbers of events, are shown also in the control regions; here, with the exception of W + jets, no normalisation scale factors are applied to the expected background contributions. The bottom part of the table lists the number of expected and observed events for each lepton channel after the $\Delta\phi_{\ell\ell}$ cut.

	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	$Z/\gamma^\star$ + jets	W + jets	Total Bkg.	Obs.
0-jet									
Jet Veto	56.7 ± 0.2	1273 ± 79	97 ± 4	174 ± 12	95 ± 7	1039 ± 28	217 ± 4	2890 ± 120	2849
$m_{\ell\ell} < 50$ GeV	45.2 ± 0.2	312 ± 20	41 ± 3	29 ± 2	19 ± 2	168 ± 10	70 ± 2	639 ± 28	645
$p_T^{\ell\ell}$ cut	40.1 ± 0.2	282 ± 18	35 ± 3	28 ± 2	18 ± 2	28 ± 6	49 ± 2	439 ± 26	443
$\Delta\phi_{\ell\ell} < 1.8$	39.0 ± 0.2	276 ± 17	33 ± 2	27 ± 2	18 ± 2	28 ± 6	44 ± 1	425 ± 26	429
1-jet									
1 jet	22.7 ± 0.1	343 ± 54	56 ± 3	1438 ± 60	436 ± 19	357 ± 17	85 ± 3	2720 ± 140	2706
b-jet veto	20.9 ± 0.1	319 ± 50	52 ± 3	412 ± 18	139 ± 7	332 ± 16	76 ± 3	1330 ± 84	1369
$\lvert\mathbf{p}_T^{tot}\rvert < 30$ GeV	14.0 ± 0.1	226 ± 35	34 ± 2	181 ± 8	80 ± 4	108 ± 8	37 ± 2	666 ± 51	684
$Z \to \tau\tau$ veto	14.0 ± 0.1	220 ± 34	34 ± 2	173 ± 8	77 ± 4	85 ± 7	37 ± 2	627 ± 50	644
$m_{\ell\ell} < 50$ GeV	10.9 ± 0.1	49 ± 8	14 ± 2	33 ± 2	18 ± 1	24 ± 3	12 ± 1	148 ± 12	170
$\Delta\phi_{\ell\ell} < 1.8$	10.1 ± 0.1	44 ± 7	13 ± 2	31 ± 2	17 ± 1	10 ± 2	10 ± 1	126 ± 10	145
2-jet									
≥ 2 jets	11.4 ± 0.1	142 ± 2	26 ± 2	5939 ± 17	339 ± 5	120 ± 7	40 ± 4	6605 ± 20	6676
Central jet veto	9.0 ± 0.1	113 ± 2	20 ± 1	3279 ± 13	238 ± 4	89 ± 6	25 ± 3	3765 ± 15	3811
b-jet veto	7.6 ± 0.1	98 ± 1	18 ± 1	353 ± 4	51 ± 2	77 ± 5	19 ± 2	615 ± 8	667
Opp. hemispheres	4.2 ± 0.1	46 ± 1	7 ± 1	149 ± 3	21 ± 1	32 ± 3	9 ± 1	264 ± 5	269
$\lvert\Delta\eta_{jj}\rvert > 3.8$	1.8 ± 0.1	8.4 ± 0.4	0.9 ± 0.2	23.2 ± 1.0	2.2 ± 0.4	5.8 ± 1.7	1.7 ± 0.4	42.2 ± 2.1	40
$m_{jj} > 500$ GeV	1.3 ± 0.1	3.9 ± 0.3	0.4 ± 0.1	10.4 ± 0.6	1.0 ± 0.3	0.7 ± 0.4	0.9 ± 0.3	17.3 ± 0.9	13
$m_{\ell\ell} < 80$ GeV	0.9 ± 0.1	1.1 ± 0.2	0.1 ± 0.1	1.4 ± 0.2	0.4 ± 0.1	0.2 ± 0.2	0.2 ± 0.2	3.2 ± 0.4	2
$\Delta\phi_{\ell\ell} < 1.8$	0.8 ± 0.1	0.8 ± 0.1	0.1 ± 0.1	0.9 ± 0.2	0.1 ± 0.1	negl.	negl.	1.8 ± 0.3	1
Control regions									
WW 0-jet	0.3 ± 0.1	471 ± 3	26 ± 1	87 ± 2	42 ± 2	7 ± 2	49 ± 2	682 ± 5	697
WW 1-jet	0.1 ± 0.1	128 ± 2	12 ± 1	89 ± 2	34 ± 2	9 ± 2	11 ± 1	282 ± 4	270
Top 1-jet	1.2 ± 0.1	20 ± 1	1.9 ± 0.5	434 ± 4	169 ± 4	7 ± 2	4 ± 1	635 ± 6	676
Top 2-jet	0.1 ± 0.1	0.4 ± 0.1	negl.	10.0 ± 0.7	1.0 ± 0.3	negl.	negl.	11.4 ± 0.7	10

Lepton channels	0-jet ee	0-jet $\mu\mu$	0-jet $e\mu$	1-jet ee	1-jet $\mu\mu$	1-jet $e\mu$
Total bkg.	60 ± 5	116 ± 10	249 ± 12	19 ± 2	34 ± 4	72 ± 6
Signal	4.0 ± 0.1	9.4 ± 0.1	25.7 ± 0.2	1.2 ± 0.1	2.5 ± 0.1	6.4 ± 0.1
Observed	52	138	239	19	36	90

The W candidates are identified by requiring the transverse mass $m_T^W = \sqrt{2p_T^\ell E_T^{miss} \cdot (1 - \cos\Delta\phi)}$ to satisfy $m_T^W > 30$ GeV. In this expression, p_T^ℓ is the lepton transverse momentum and $\Delta\phi$ is the difference in azimuth between the lepton and missing transverse momentum directions. The Z candidates are identified by requiring two opposite-sign leptons of the same flavour and $|m_{\ell\ell} - m_Z| < 15$ GeV. The small remaining lepton contamination, which includes $W\gamma$ and $W\gamma^\star$ events, is subtracted using MC simulation. The fake factor uncertainty is the main uncertainty on the W + jets background contribution. This uncertainty is dominated by differences in jet properties between dijet and W + jets samples evaluated with simulated events, with smaller contributions originating from trigger effects and the subtraction of the contamination from real leptons from leptonic W and Z decays. The total uncertainty on this background is estimated to be approximately 60%.

5. Systematic uncertainties

Theoretical uncertainties on the signal production cross sections are determined following Refs. [60,61]. QCD renormalisation and factorisation scales are varied up and down independently by a factor of two. Independent uncertainties on the ggF signal production are assumed for the inclusive cross section and the cross section for production with at least one or two jets. The resulting uncertainties on the cross sections in exclusive jet multiplicity analyses are taken into account, as well as anti-correlations caused by transitions between jet multiplicities. The relative 0-jet (1-jet) cross section uncertainties depend on m_H, rising from ±21% (±31%) at $m_H = 125$ GeV and $m_H = 240$ GeV to ±42% (±31%) at $m_H = 600$ GeV [61–63]. The 2-jet analysis is mainly sensitive to the VBF process. The impact of the scale variations on the combined VBF signal cross section and jet veto acceptance is 4% [61]. In this analysis, around 25% of the signal events are produced via ggF, where the relative uncertainty is around 25%. For the high mass range, an additional uncertainty due to the Higgs lineshape description in the POWHEG MC generator is added in quadrature for both the ggF and the VBF channel and amounts to $150\% \times (m_H/1\ \text{TeV})^3$ [61,64–66]. The uncertainties associated with the underlying event and parton showering are taken into account in the acceptance uncertainty, but they are negligible compared to the scale uncertainties on the cross sections in exclusive jet bins.

PDF uncertainties are estimated, following Refs. [47,67–69], by the envelopes of error sets as well as different PDF sets, applied separately to quark–quark, quark–gluon, and gluon–gluon initiated processes. The relative PDF uncertainty on the dominant ggF signal process is about 8%; the VBF uncertainty varies from ±2% at $m_H = 125$ GeV to ±4% at $m_H = 600$ GeV. Uncertainties on the modelling of signal and background processes are estimated by using alternative generators, such as MC@NLO for the ggF process, ALPGEN for WW production, and POWHEG for $t\bar{t}$ production. The uncertainties associated with the underlying event and parton showering are taken into account in the acceptance uncertainty, but they are negligible compared to the scale uncertainties on the cross sections in exclusive jet bins.

The main experimental uncertainties are related to the jet energy scale which is determined from a combination of test beam, simulation, and *in situ* measurements. The uncertainty on the jet

Table 3
The expected numbers of signal ($m_H = 125$ GeV and 240 GeV) and background events after the full low m_H and intermediate m_H selections, including a cut on the transverse mass of $0.75 m_H < m_T < m_H$ for $m_H = 125$ GeV and $0.6 m_H < m_T < m_H$ for $m_H = 240$ GeV. The observed numbers of events are also displayed. The uncertainties shown are the combination of the statistical and all systematic uncertainties, taking into account the constraints from control samples. These results and uncertainties differ from those given in Table 2 due to the application of the additional m_T cut. All numbers are summed over lepton flavours.

	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	$Z/\gamma^* +$ jets	$W +$ jets	Total Bkg.	Obs.
0-jet									
$m_H = 125$ GeV	26 ± 7	108 ± 12	12 ± 2	7 ± 2	5 ± 1	14 ± 6	27 ± 16	172 ± 21	174
$m_H = 240$ GeV	61 ± 16	450 ± 48	24 ± 3	73 ± 15	42 ± 9	6 ± 3	36 ± 24	632 ± 64	627
1-jet									
$m_H = 125$ GeV	6 ± 2	16 ± 3	5 ± 2	8 ± 2	4 ± 2	5 ± 2	5 ± 3	42 ± 6	56
$m_H = 240$ GeV	24 ± 8	95 ± 20	9 ± 1	84 ± 23	39 ± 16	5 ± 2	8 ± 7	241 ± 48	232
2-jet									
$m_H = 125$ GeV	0.5 ± 0.1	0.2 ± 0.2	negl.	0.2 ± 0.1	negl.	$0.0^{+0.1}_{-0.0}$	negl.	0.4 ± 0.3	0
$m_H = 240$ GeV	2.6 ± 0.4	1.2 ± 0.8	0.1 ± 0.1	2.2 ± 1.0	0.3 ± 0.2	negl.	0.1 ± 0.1	3.9 ± 1.5	2

energy scale varies from 14% to 2% as a function of jet p_T and η for jets with $p_T > 25$ GeV and $|\eta| < 4.5$ [70]; for central jets it is at most 4%. An additional contribution from event pile-up is estimated to vary between 5% and 0.5%, depending on jet p_T and η, for jets with $p_T > 25$ GeV. The uncertainty on the jet energy resolution is estimated from *in situ* measurements. The resolution varies from 25% to 5%, and its uncertainty from 5% to 2%, as a function of jet p_T and η. The reconstruction, identification, and trigger efficiencies for electrons and muons, as well as their momentum scales and resolutions, are estimated using $Z \to \ell\ell$, $J/\psi \to \ell\ell$, and $W \to \ell\nu$ decays. With the exception of the uncertainty on the electron efficiency, which varies between 2% and 5% as a function of p_T and η, the resulting uncertainties are all smaller than 1%. Jet energy scale and lepton momentum scale uncertainties are propagated to the E_T^{miss} computation. Additional contributions arise from jets with $p_T < 20$ GeV as well as from low-energy calorimeter deposits not associated with reconstructed physics objects [71]; their effect on the total background event yield ranges from 1% to 8%. Finally, uncertainties on the modelling of event pile-up contributions are estimated by varying their effect on low-energy calorimeter deposits; the impact on the background yield varies between 1% and 5%. The efficiency of the b-tagging algorithm is calibrated using samples containing muons reconstructed in the vicinity of jets [56]. The resulting uncertainty on the b-jet tagging efficiency varies between 5% and 14% as a function of jet p_T. The uncertainty on the integrated luminosity is 3.9% [72,73].

In this analysis, a fit to the m_T distribution is performed in order to obtain the signal yield for each mass hypothesis. The m_T shapes for the individual backgrounds and signal do not exhibit a statistically significant dependence on the majority of the theoretical and experimental uncertainties. The remaining uncertainties that do produce statistically significant variations of the m_T shape have no appreciable effect on the final results. Hence, the uncertainty on the shape of the total background is dominated by the uncertainties on the normalisations of the individual backgrounds.

Systematic uncertainties are evaluated for the control regions described in Section 4 in the same fashion as for the signal region. For the backgrounds normalised using these control regions, only the relative normalisation between the backgrounds in the signal and control regions is affected.

6. Results

The expected numbers of signal ($m_H = 125$ GeV) and background events at several stages of the low m_H selection are presented in Table 2. The rightmost column shows the observed numbers of events in the data. The uncertainties shown include only the statistical uncertainties on the predictions from simulation and on the normalisation of the dominant backgrounds. After all selection criteria, the dominant background in the 0-jet channel comes from continuum WW production, with smaller contributions from top ($t\bar{t}$ and single-top) and $W +$ jets events. In the 1-jet and 2-jet channels, the WW and top backgrounds are comparable.

Table 4
Main relative systematic uncertainties on the predicted numbers of signal ($m_H = 125$ GeV) and background events for each of the three jet multiplicity analyses. The same m_T criteria as in Table 3 are imposed in addition to the low m_H signal selection criteria. All numbers are summed over lepton flavours. The effect of the quoted inclusive signal cross section renormalisation and factorisation scale uncertainties on exclusive jet multiplicities is explained in Section 5.

Source (0-jet)	Signal (%)	Bkg. (%)
Inclusive ggF signal ren./fact. scale	19	0
1-jet incl. ggF signal ren./fact. scale	10	0
$W +$ jets fake factor	0	10
Parton distribution functions	8	2
WW normalisation	0	6
Jet energy scale	6	0
Source (1-jet)	**Signal (%)**	**Bkg. (%)**
1-jet incl. ggF signal ren./fact. scale	27	0
2-jet incl. ggF signal ren./fact. scale	15	0
Missing transverse momentum	8	3
$W +$ jets jets fake factor	0	7
b-tagging efficiency	0	7
Parton distribution functions	7	1
Source (2-jet)	**Signal (%)**	**Bkg. (%)**
Jet energy scale	13	36
$Z/\gamma^* + 2$ jets MC modelling	0	24
Diboson ren./fact. scale	0	22

Table 3 shows the numbers of events expected from signal and background and observed in data, after application of all selection criteria. To reflect better the sensitivity of the analysis, an additional mass-dependent cut on m_T has been applied: $0.75 m_H < m_T < m_H$ for $m_H = 125$ GeV and $0.6 m_H < m_T < m_H$ for $m_H = 240$ GeV. The uncertainties shown in Table 3 include those of Table 2 as well as the systematic uncertainties discussed in Section 5, constrained by the use of the control regions discussed in Section 4. The uncertainties are those that enter into the fitting procedure described below. Table 4 shows the effect of the main sources of systematic uncertainty on the signal ($m_H = 125$ GeV) and background predictions for the three jet multiplicity analyses. Similarly to Table 3, the additional m_T cut is applied and the constraints from control regions are included.

The statistical analysis of the data employs a binned likelihood function $\mathcal{L}(\mu, \boldsymbol{\theta})$ constructed as the product of Poisson probability terms in each lepton flavour channel. The mass-dependent cuts on m_T described above are not used. Instead, the 0-jet (1-jet) signal regions are subdivided into five (three) m_T bins. For the 2-jet signal region (where the small number of events remaining after the selection does not allow the use of shape information), and for the

WW and top control regions, only the results integrated over $m_{\rm T}$ are used. Because of event pile-up conditions changing throughout data-taking and leading to a progressively worsening $E_{\rm T}^{\rm miss}$ resolution, separate likelihood terms are constructed (both for the signal and the control regions) for the first 2.3 fb^{-1} and the remaining 2.4 fb^{-1} dataset. A "signal strength" parameter, μ, multiplies the expected Standard Model Higgs boson production signal in each bin. Signal and background predictions depend on systematic uncertainties that are parameterised by nuisance parameters $\boldsymbol{\theta}$, which in turn are constrained using Gaussian functions. The expected signal and background event counts in each bin are functions of $\boldsymbol{\theta}$. The parameterisation is chosen such that the rates in each channel are log-normally distributed for a normally distributed θ. The test statistic q_μ is then constructed using the profile likelihood: $q_\mu = -2\ln(\mathcal{L}(\mu, \hat{\boldsymbol{\theta}}_\mu)/\mathcal{L}(\hat{\mu}, \hat{\boldsymbol{\theta}}))$, where $\hat{\mu}$ and $\hat{\boldsymbol{\theta}}$ are the parameters that maximise the likelihood (with the constraint $0 \leqslant \hat{\mu} \leqslant \mu$), and $\hat{\boldsymbol{\theta}}_\mu$ are the nuisance parameter values that maximise the likelihood for a given μ. This test statistic is used to compute exclusion limits following the modified frequentist method known as CL_s [74,75].

Fig. 3 shows the observed and expected cross section upper limits at 95% CL, as a function of m_H and normalised to the SM cross section, for the combined 0-jet, 1-jet and 2-jet analyses. The limits exclude a Standard Model Higgs boson with a mass in the range from 133 GeV to 261 GeV at 95% CL, while the expected exclusion range in the absence of a signal is 127 GeV $\leqslant m_H \leqslant$ 233 GeV. No significant excess of events over the expected background is observed over the entire mass range (the lowest p-value observed is 0.15).

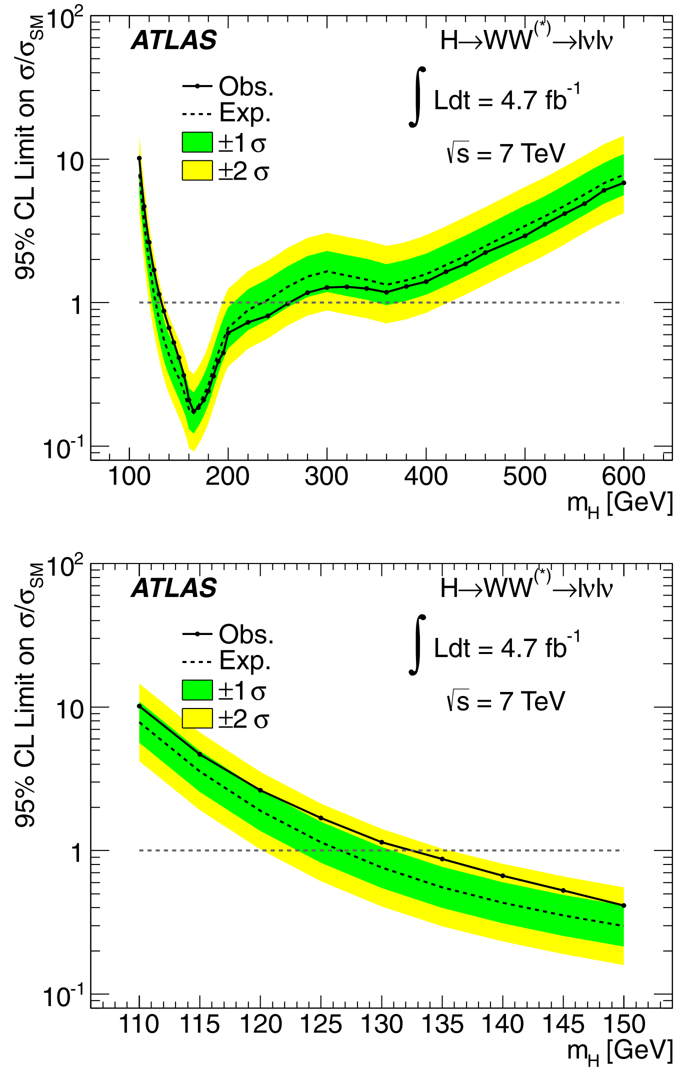

Fig. 3. Observed (solid) and expected (dashed) 95% CL upper limits on the Higgs boson production cross section, normalised to the SM cross section, as a function of m_H, over the full mass range considered in this analysis (top) and restricted to the range $m_H < 150$ GeV (bottom). The inner (green in the web version) and outer (yellow in the web version) regions indicate the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty bands on the expected limit, respectively. The results for nearby masses are highly correlated due to the limited mass resolution (5–8 GeV, as inferred from a study of the effect of a hypothetical $m_H = 125$ GeV signal on the behaviour of q_μ ($\mu = 1$) as a function of m_H) in this final state.

7. Conclusion

A search for the SM Higgs boson has been performed in the $H \to WW^{(\star)} \to \ell\nu\ell\nu$ channel using the full data sample (4.7 fb^{-1}) of pp collision data from the Large Hadron Collider at $\sqrt{s} = 7$ TeV recorded in 2011 with the ATLAS detector. No significant excess of events over the expected background is observed. A SM Higgs boson with mass in the range from 133 GeV to 261 GeV is excluded at 95% CL, while the expected exclusion range is 127 GeV $\leqslant m_H \leqslant$ 233 GeV.

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Boisvert [76], T. Bold [37], V. Boldea [25a], N.M. Bolnet [136], M. Bomben [78], M. Bona [75], M. Boonekamp [136], C.N. Booth [139], S. Bordoni [78], C. Borer [16], A. Borisov [128], G. Borissov [71], I. Borjanovic [12a], M. Borri [82], S. Borroni [87], V. Bortolotto [134a,134b], K. Bos [105], D. Boscherini [19a], M. Bosman [11], H. Boterenbrood [105], D. Botterill [129], J. Bouchami [93], J. Boudreau [123], E.V. Bouhova-Thacker [71], D. Boumediene [33], C. Bourdarios [115], N. Bousson [83], A. Boveia [30], J. Boyd [29], I.R. Boyko [64], I. Bozovic-Jelisavcic [12b], J. Bracinik [17], P. Branchini [134a], A. Brandt [7], G. Brandt [118], O. Brandt [54], U. Bratzler [156], B. Brau [84], J.E. Brau [114], H.M. Braun [175], S.F. Brazzale [164a,164c], B. Brelier [158], J. Bremer [29], K. Brendlinger [120], R. Brenner [166], S. Bressler [172], D. Britton [53], F.M. Brochu [27], I. Brock [20], R. Brock [88], E. Brodet [153], F. Broggi [89a], C. Bromberg [88], J. Bronner [99], G. 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