Physics Letters B 718 (2012) 369–390

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Search for the Standard Model Higgs boson produced in association with a vector boson and decaying to a b-quark pair with the ATLAS detector ☆

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ARTICLE INFO

Article history:
Received 1 July 2012
Received in revised form 14 September 2012
Accepted 23 October 2012
Available online 26 October 2012
Editor: H. Weerts

Keywords:
Standard Model Higgs boson
ATLAS
LHC

ABSTRACT

This Letter presents the results of a direct search with the ATLAS detector at the LHC for a Standard Model Higgs boson of mass $110 \leqslant m_H \leqslant 130$ GeV produced in association with a W or Z boson and decaying to $b\bar{b}$. Three decay channels are considered: $ZH \to \ell^+\ell^- b\bar{b}$, $WH \to \ell\nu b\bar{b}$ and $ZH \to \nu\bar{\nu}b\bar{b}$, where ℓ corresponds to an electron or a muon. No evidence for Higgs boson production is observed in a dataset of 7 TeV pp collisions corresponding to 4.7 fb^{-1} of integrated luminosity collected by ATLAS in 2011. Exclusion limits on Higgs boson production, at the 95% confidence level, of 2.5 to 5.5 times the Standard Model cross section are obtained in the mass range 110–130 GeV. The expected exclusion limits range between 2.5 and 4.9 for the same mass interval.

1. Introduction

The search for the Standard Model (SM) Higgs boson [1–3] is one of the most important endeavours of the Large Hadron Collider (LHC). The $H \to b\bar{b}$ decay corresponds to the highest branching ratio for a low-mass Higgs boson in the SM. Observing this decay would provide direct sensitivity to the Higgs boson coupling to fermions. The results of searches in various channels using data corresponding to an integrated luminosity of up to 4.9 fb^{-1} have been reported recently by both the ATLAS and CMS collaborations [4,5]. The Higgs boson has been excluded at the 95% confidence level (CL) below 114.4 GeV by the LEP experiments [6], in the regions 100–106 GeV and 147–179 GeV at the Tevatron $p\bar{p}$ collider [7], and in the regions 112.9–115.5 GeV and 127–600 GeV by the LHC experiments [4,5]. This Letter reports on a search for the SM Higgs boson performed for the $H \to b\bar{b}$ decay mode, over the mass range 110–130 GeV where this decay mode dominates.

Due to the large backgrounds present in the dominant production process $gg \to H \to b\bar{b}$, the analysis reported here is restricted to Higgs boson production in association with a vector boson, WH and ZH [8–12], where the vector boson provides an additional final state signature, allowing for significant background suppression. An additional handle against the backgrounds is provided by exploiting the better signal-over-background level of the kinematic regions where the weak bosons have high transverse momenta [13]. These channels are also important contributors to Higgs boson searches at CMS [14] and the Tevatron [7].

This Letter presents searches in the $ZH \to \ell^+\ell^- b\bar{b}$, $WH \to \ell\nu b\bar{b}$ and $ZH \to \nu\bar{\nu}b\bar{b}$ channels, where ℓ is either an electron or a muon, including electrons and muons from tau lepton decays. The data used were recorded by the ATLAS experiment during the 2011 LHC run at a centre-of-mass energy of $\sqrt{s} = 7$ TeV and correspond to integrated luminosities of 4.6 to 4.7 fb^{-1} [15,16], depending on the analysis channel. The leptonic decay modes of the weak bosons are selected to suppress backgrounds containing only jets in the final state. In the $ZH \to \nu\bar{\nu}b\bar{b}$ channel, the multijet background is suppressed by requiring a large missing transverse energy.

2. The ATLAS detector

The ATLAS detector [17] consists of four main subsystems. An inner tracking detector is immersed in the 2 T magnetic field produced by a superconducting solenoid. Charged particle position and momentum measurements are made by silicon detectors in the pseudorapidity[1] range $|\eta| < 2.5$ and by a straw tube tracker in the range $|\eta| < 2.0$. Calorimeters cover $|\eta| < 4.9$ with a variety of detector technologies. The liquid-argon electromagnetic calorimeter is divided into barrel ($|\eta| < 1.475$) and end-cap ($1.375 < |\eta| < 3.2$) sections. The hadronic calorimeters (using

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

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http://dx.doi.org/10.1016/j.physletb.2012.10.061

liquid argon or scintillating tiles as active materials) surround the electromagnetic calorimeter and cover $|\eta| < 4.9$. The muon spectrometer measures the deflection of muon tracks in the field of three large air-core toroidal magnets, each containing eight superconducting coils. It is instrumented with separate trigger chambers (covering $|\eta| < 2.4$) and high-precision tracking chambers (covering $|\eta| < 2.7$).

3. Data and Monte Carlo samples

The collision data used in this analysis are selected such that all elements of the ATLAS detector were delivering high-quality data. In the $ZH \to \ell^+\ell^- b\bar{b}$ and the $WH \to \ell\nu b\bar{b}$ analyses, events were primarily collected using single-lepton triggers with a transverse momentum (p_T) threshold of 20 GeV for electrons, which was raised to 22 GeV as the instantaneous luminosity increased, and 18 GeV for muons. In the $ZH \to \ell^+\ell^- b\bar{b}$ analysis, these triggers were supplemented with a di-electron trigger with a threshold of 12 GeV. The lepton trigger efficiency is measured using a sample of $Z \to \ell^+\ell^-$ events. The resulting efficiencies, relative to the offline selection, are close to 100% for $ZH \to e^+e^- b\bar{b}$ and $WH \to e\nu b\bar{b}$. The efficiencies are around 95% for the $ZH \to \mu^+\mu^- b\bar{b}$ channel and 90% for the $WH \to \mu\nu b\bar{b}$ channel, due to the lower angular coverage of the muon trigger chambers with respect to the precision tracking chambers. The missing transverse energy (E_T^{miss}) trigger used for the $ZH \to \nu\bar{\nu} b\bar{b}$ channel has a threshold of 70 GeV and an efficiency above 50% for E_T^{miss} above 120 GeV. This efficiency exceeds 99% for E_T^{miss} above 170 GeV. The efficiency curve is measured in a sample of $W \to \mu\nu$ + jet events collected using muon triggers, which do not rely on the presence of E_T^{miss}. The Monte Carlo (MC) simulation predicts the trigger efficiency to be 5% higher than that observed in collision data for $120\ \text{GeV} \leqslant E_T^{miss} < 160$ GeV and agrees for $E_T^{miss} \geqslant 160$ GeV. A correction factor of 0.95 ± 0.01 is therefore applied to the MC in the lower E_T^{miss} region, and no trigger efficiency correction is applied elsewhere.

Due to practical constraints, several MC generators were used to simulate signal and background processes. The WH and ZH signal processes are modelled using MC events produced by the Pythia [18] event generator, interfaced with the MRST modified leading-order (LO*) [19] parton distribution functions (PDFs), using the AUET2B tune [20] for the parton shower, hadronization and multiple parton interactions. The total cross sections for these channels, as well as their corresponding uncertainties, are taken from the LHC Higgs Cross Section Working Group report [21]. Differential next-to-leading order (NLO) electroweak corrections as a function of the W or Z transverse momentum have also been applied [22,12]. The Higgs boson decay branching ratios are calculated with Hdecay [23].

The background processes are modelled with several different event generators. The Powheg [24–26] generator, in combination with MSTW 2008 NLO PDFs [27] and interfaced with the Pythia program for the parton shower and hadronization, is used to simulate $W+\geqslant 1b$ jet events. The Sherpa generator [28] is used to simulate $Z+\geqslant 1b$ jet and $Z+\geqslant 1c$ jet events. The Alpgen generator [29] interfaced with the Herwig program [30] is used to simulate $W+\geqslant 1c$ jet, $W+\geqslant 1$ light jet (i.e. not a c or b jet) and $Z+\geqslant 1$ light jet events. The above background simulations include γ^* production and Z/γ^* interference where appropriate. The MC@NLO generator [31], using CT10 NLO PDFs [32] and interfaced to Herwig, is used for the production of top-quarks (single-top and top-quark pair production). The Herwig generator, is used to simulate the diboson (ZZ, WZ and WW) samples. The Herwig generator uses the AUET2 tune [33] for the parton shower and hadronization model, relies on MRST LO* PDFs (except for top production) and is in all cases interfaced to Jimmy [34] for the modelling of multiple parton interactions. The diboson cross sections normalized to NLO QCD computations [35,36]. MC samples are passed through the full ATLAS detector simulation [37] based on the Geant4 [38] program.

4. Reconstruction and identification of physics objects

Events are required to have at least one reconstructed primary vertex with three or more associated tracks with $p_T > 0.4$ GeV in the inner detector. If more than one vertex is reconstructed, the primary vertex is chosen as the one with the highest sum of the squares of the transverse momenta of all its associated tracks.

Electron candidates are reconstructed from energy clusters in the electromagnetic calorimeter and are required to pass identification criteria based on the shower shape. Central electrons must have a matching track in the inner detector that is consistent with originating from the primary vertex and requirements are placed on track quality and track-cluster matching [39]. Further track and cluster related identification criteria are applied to electron candidates in order to reduce background from jets being misidentified as electrons. The criteria are tighter for W decays, where the background is larger. Muons are found offline by searching for tracks reconstructed in the muon spectrometer with $|\eta| < 2.7$.

The charged leptons that are used to reconstruct the vector boson candidate are required to satisfy $p_T > 20$ GeV in the $ZH \to \ell^+\ell^- b\bar{b}$ channel, while this cut is increased to $p_T > 25$ GeV in the $WH \to \ell\nu b\bar{b}$ channel in order to be above the trigger threshold, and maintain a high trigger efficiency. In both cases, the leptons must be central ($|\eta| < 2.47$ for electrons and $|\eta| < 2.5$ for muons) and have a matching track in the inner detector (with a coverage up to $|\eta| < 2.5$) that is consistent with originating from the primary vertex.

In order to suppress background from semileptonic heavy-flavour hadron decays, the leptons are required to be isolated. In the $ZH \to \ell^+\ell^- b\bar{b}$ and $WH \to \ell\nu b\bar{b}$ channels the sum of the transverse momenta of all charged tracks (other than those of the charged leptons) reconstructed in the inner detector within a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.2$ from each charged lepton is required to be less than 10% of the transverse momentum of the lepton itself. In the $WH \to \ell\nu b\bar{b}$ channel, the isolation requirement is strengthened by requiring in addition that the sum of all transverse energy deposits in the calorimeter within a cone of $\Delta R < 0.3$ from the charged lepton be less than 14% of the transverse energy of the lepton itself.

In order to suppress the top-quark background in the $ZH \to \nu\bar{\nu} b\bar{b}$ channel, events containing electrons with $|\eta| < 2.47$ and $p_T > 10$ GeV, or muons with $|\eta| < 2.7$ and $p_T > 10$ GeV are removed. Similar requirements are applied on any additional lepton reconstructed in the $WH \to \ell\nu b\bar{b}$ channel, but the minimum lepton p_T is increased to 20 GeV if the additional lepton has the same charge as, or a different flavour than the signal lepton. Events with forward electrons [39] ($2.47 < |\eta| < 4.5$) with $p_T > 20$ GeV are also removed in the $WH \to \ell\nu b\bar{b}$ channel.

Jets are reconstructed from energy clusters in the calorimeter using the anti-k_t algorithm [40] with a radius parameter of 0.4. Jet energies are calibrated using p_T- and η-dependent correction factors based on MC simulation and validated with data [41]. A further correction is applied when calculating the di-jet invariant mass, as described in Section 5 below. The contribution from jets originating from other collisions in the same bunch crossing is reduced by requiring that at least 75% of the summed transverse momentum of inner detector tracks (with $p_T > 0.4$ GeV) associated with the jet are compatible with originating from the primary vertex. Furthermore, a jet is required to have no identified electron within $\Delta R \leqslant 0.4$. Only jets with $p_T > 25$ GeV and within the acceptance of the inner detector ($|\eta| < 2.5$) are used to reconstruct Higgs boson candidates. Events containing additional jets are rejected in the $WH \to \ell\nu b\bar{b}$ analysis, to suppress backgrounds characterized by additional hadronic activity. To do this, jets are counted using the following criteria: $p_T > 20$ GeV and $|\eta| < 4.5$.

Jets which originate from b quarks can be distinguished from other jets by the relatively long lifetime of hadrons containing b quarks. Such jets are primarily identified ("b-tagged") by reconstructing one or more secondary decay vertices from tracks within the jet, using either an inclusive vertex reconstruction algorithm or a cascade $b \to c$-hadron decay chain vertex fit, or by combining the distances of closest approach to the primary event vertex (impact parameters) of tracks in the jet [42–45]. The information from the vertex and impact parameter based algorithms is combined into a single discriminant w by using an artificial neural network, which is trained based on a set of samples of simulated events, such that a jet with higher w is more likely to be a b jet. A selection cut on w is applied, resulting in an efficiency of about 70% for identifying true b jets, of about 20% for c jets and about 0.8% for light jets, as evaluated in simulated $t\bar{t}$ events. The b-tagging efficiency and rejection factors in the simulation are corrected to the respective measurements in data by the use of appropriate scale factors. These correspond to corrections of around 5 to 15% for b jets, 20% for c jets, and around 50% for light jets.

The E_T^{miss} magnitude and direction are measured from the vector sum of the transverse momentum vectors associated with clusters of energy reconstructed in the calorimeters with $|\eta| < 4.9$ [46]. A correction is applied to the energy of those clusters that are associated with a reconstructed physical object (jet, electron, τ-lepton, photon). Reconstructed muons are also included in the sum, and any calorimeter energy deposits associated with them are excluded. To supplement the calorimeter-based definition of E_T^{miss} in the $ZH \to \nu\bar{\nu}b\bar{b}$ channel, the track-based missing transverse momentum, p_T^{miss}, is calculated from the vector sum of the transverse momenta of inner detector tracks associated with the primary vertex [47].

5. Event selection

Events in the $ZH \to \ell^+\ell^- b\bar{b}$ channel are required to contain exactly two same-flavour leptons. The two leptons must be oppositely charged in the case of muons. This is not required for electrons since energy losses from showering in material in the inner detector lead to a higher charge misidentification probability. The invariant mass of the lepton pair must be in the range 83 GeV $< m_{\ell\ell} <$ 99 GeV. A requirement of $E_T^{miss} < 50$ GeV reduces the background from top-quark production.

Events in the $WH \to \ell\nu b\bar{b}$ channel are required to contain a single charged lepton and $E_T^{miss} > 25$ GeV. A requirement on the transverse mass[2] of $m_T > 40$ GeV is imposed to suppress the multijet background.

The $ZH \to \nu\bar{\nu}b\bar{b}$ selection requires $E_T^{miss} > 120$ GeV. Requirements of $p_T^{miss} > 30$ GeV and on the difference in azimuthal angle between the directions of E_T^{miss} and p_T^{miss}, $\Delta\phi(E_T^{miss}, p_T^{miss}) < \pi/2$, are imposed to suppress events with poorly measured E_T^{miss}. These help to suppress the multijet background, which is dominated by one or more jets being mismeasured by the calorimeter. A cut on the difference in azimuthal angle between E_T^{miss} and the nearest jet $\min(\Delta\phi(E_T^{miss}, \text{jet})) > 1.8$ is applied to further reduce the multijet background.

The transverse momentum of the vector boson, p_T^V, is reconstructed from the two leptons in the $ZH \to \ell^+\ell^- b\bar{b}$ channel, from the lepton and E_T^{miss} in the $WH \to \ell\nu b\bar{b}$ channel and from E_T^{miss} in the $ZH \to \nu\bar{\nu}b\bar{b}$ channel.

Events in all channels are required to contain exactly two b-tagged jets, of which one must have $p_T > 45$ GeV and the other $p_T > 25$ GeV. If p_T^V is less than 200 GeV the two b-tagged jets are required to have a separation of $\Delta R > 0.7$, to reduce W + jet and Z + jet backgrounds. Additionally, in the $ZH \to \nu\bar{\nu}b\bar{b}$ channel a cut on the separation between the two jets of $\Delta R < 2.0$ ($\Delta R < 1.7$) for $p_T^V < 160$ GeV ($p_T^V > 160$ GeV) is applied to reduce the multijet background. Events in the $ZH \to \ell^+\ell^- b\bar{b}$ channel may contain additional non-b-tagged jets, while in the $WH \to \ell\nu b\bar{b}$ and $ZH \to \nu\bar{\nu}b\bar{b}$ channels, events with additional jets are rejected to further suppress top-quark background. In the $WH \to \ell\nu b\bar{b}$ analysis, where the top-quark background is dominant, events containing additional jets with $|\eta| < 4.5$ and $p_T > 20$ GeV are rejected, while in the $ZH \to \nu\bar{\nu}b\bar{b}$ channel the selection is restricted to jets with $|\eta| < 2.5$ and $p_T > 25$ GeV.

In the $ZH \to \nu\bar{\nu}b\bar{b}$ analysis, further cuts are applied on the azimuthal angle between E_T^{miss} and the reconstructed transverse momentum of the $b\bar{b}$ system, $\Delta\phi(b\bar{b}, E_T^{miss})$, to further reject multijet background. The $ZH \to \nu\bar{\nu}b\bar{b}$ signal, where the Higgs and Z bosons recoil against each other, is characterized by large values of this angle. The cuts of $\Delta\phi(b\bar{b}, E_T^{miss}) > 2.7$ for $120 < p_T^V < 160$ GeV and $\Delta\phi(b\bar{b}, E_T^{miss}) > 2.9$ for $p_T^V \geqslant 160$ GeV were established from MC-based optimization studies.

A search for $H \to b\bar{b}$ decays is performed by looking for an excess of events above the background expectation in the invariant mass distribution of the b-jet pair ($m_{b\bar{b}}$). The value of the reconstructed $m_{b\bar{b}}$ is scaled by a factor of 1.05, obtained from MC-based studies, to account on average for e.g. losses due to soft muons and neutrinos from b and c hadron decays. To increase the sensitivity of the search, this distribution is examined in bins of p_T^V. As the expected signal is characterized by a relatively hard p_T^V spectrum, the signal to background ratio increases with p_T^V. The $ZH \to \ell^+\ell^- b\bar{b}$ and $WH \to \ell\nu b\bar{b}$ channels are examined in four bins of the transverse momentum of the reconstructed W or Z boson, given by: $p_T^V < 50$ GeV, $50 \leqslant p_T^V < 100$ GeV, $100 \leqslant p_T^V < 200$ GeV and $p_T^V \geqslant 200$ GeV. In the $ZH \to \nu\bar{\nu}b\bar{b}$ search three bins are defined: $120 < p_T^V < 160$ GeV, $160 \leqslant p_T^V < 200$ GeV and $p_T^V \geqslant 200$ GeV. The expected signal to background ratios for a Higgs boson signal with $m_H = 120$ GeV vary from about 1% in the lowest p_T^V bins to about 10–15% in the highest p_T^V bins. For this Higgs boson mass, 5.0% and 2.4% of the $ZH \to \ell^+\ell^- b\bar{b}$ and $WH \to \ell\nu b\bar{b}$ events are expected to pass the respective analysis selections, with negligible contributions from other final states. On the other hand, the $ZH \to \nu\bar{\nu}b\bar{b}$ analysis has a non-negligible contribution from $WH \to \ell\nu b\bar{b}$: 2.1% of the $ZH \to \nu\bar{\nu}b\bar{b}$ signal and 0.2% of the $WH \to \ell\nu b\bar{b}$ signal are expected to pass the analysis selection.

6. Background estimation

Backgrounds are estimated using a combination of data-driven and MC-based techniques. Significant sources of background include top, W + jet, Z + jet, diboson and multijet production. The dominant background in the $ZH \to \ell^+\ell^- b\bar{b}$ channel is Z + jet production. In the $WH \to \ell\nu b\bar{b}$ channel both the top-quark and

[2] The transverse mass (m_T) is defined from the transverse momenta and the azimuthal angles of the charged lepton (p_T^ℓ and ϕ^ℓ) and neutrino (p_T^ν and ϕ^ν): $m_T = \sqrt{2p_T^\ell p_T^\nu(1-\cos(\phi^\ell - \phi^\nu))}$, where $p_T^\nu = E_T^{miss}$.

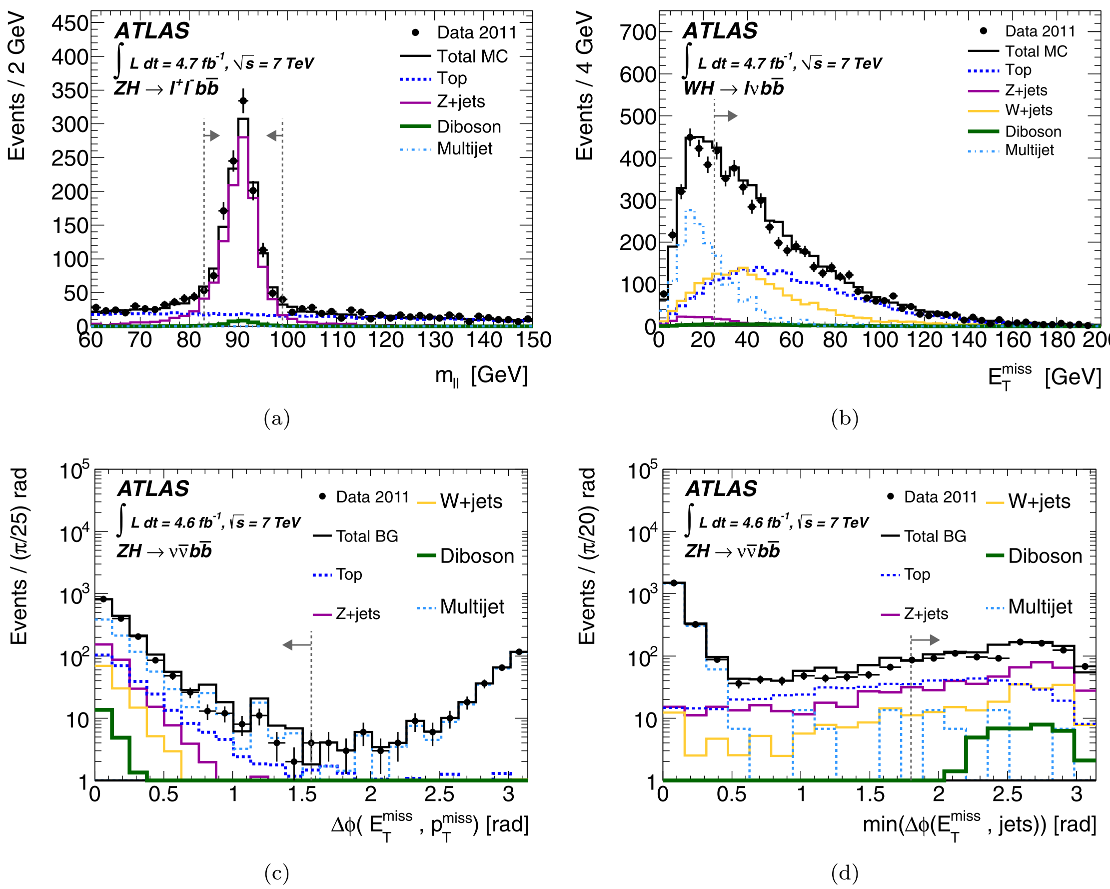

Fig. 1. (a) The dilepton invariant mass distribution in the $ZH \to \ell^+\ell^- b\bar{b}$ channel, (b) the missing transverse energy without the m_T requirement in the $WH \to \ell\nu b\bar{b}$ channel, (c) the azimuthal angle separation between E_T^{miss} and p_T^{miss} and (d) the minimum azimuthal separation between E_T^{miss} and any jet in the $ZH \to \nu\bar{\nu}b\bar{b}$ channel. All distributions are shown for events containing two b-tagged jets. The various Monte Carlo background distributions are normalized to data sidebands and control distributions and the multijet background is entirely estimated from data as described in the text. The vertical dashed lines correspond to the values of the cuts applied in each analysis, and the horizontal arrows indicate the events selected by each cut.

$W+$jet production are important. In the $ZH \to \nu\bar{\nu}b\bar{b}$ channel, there is a significant contribution from top, $W+$jet, $Z+$jet and diboson production. Multijet production is a negligible background, except for the $WH \to \ell\nu b\bar{b}$ channel.

The flavour composition of the $W+$jet and $Z+$jet backgrounds is determined partially from data.

The shapes of the $m_{b\bar{b}}$ distribution of the top, $W+$jet and $Z+$jet backgrounds are taken from MC simulation, with the respective normalizations being determined from data. The ratio of single-top to top-pair production is taken from NLO QCD computations [48].

The flavour composition of the $W+$jet and $Z+$jet samples is determined using templates produced from three exclusive MC samples containing at least one true b jet, at least one true c jet, or only light jets. The relative normalizations of the three components are adjusted by fitting the distribution of the b-tagging discriminating variable w found in MC simulation to the distribution found in control data samples dominated by $W+$jet and $Z+$jet events. For the $Z+$jet sample this is a Z reconstructed from 2 electrons or muons and 2 jets. The $W+$jet sample is a W and 2 jets with an additional cut on the invariant mass of the 2 jets of less than 80 GeV to reduce top background. Once the relative normalizations of the flavour components have been fixed, the overall normalizations are determined from data in a separate step.

Sidebands in the $m_{b\bar{b}}$ distribution, defined by selecting events with $m_{b\bar{b}} < 80$ GeV or 150 GeV $< m_{b\bar{b}} < 250$ GeV along with the standard event selection, are used to normalize the $Z+$jet, $W+$jet and top backgrounds.

In addition, two control regions which are dominated by top-quark production are used to further constrain the normalization of the top background. The ZH top control region selects events from the sidebands of the Z boson mass peak: $m_{\ell\ell} \in [60\text{ GeV}, 76\text{ GeV}] \cup [106\text{ GeV}, 150\text{ GeV}]$ with $E_T^{miss} > 50$ GeV, while the WH top control region selects $W+3$ jet events with two b-tagged jets.

The normalizations of the $Z+$jet, $W+$jet and top-quark backgrounds are determined in the $ZH \to \ell^+\ell^- b\bar{b}$ or $WH \to \ell\nu b\bar{b}$ channels, by simultaneous fits to the sidebands of the $m_{b\bar{b}}$ distributions, and either the ZH or WH top control regions defined above. In the WH sideband fit, the normalizations of the top-quark, the $W+2$ jet and the $W+3$ jet distributions are varied. In the ZH sideband fit, the normalizations of the top-quark and $Z+$jet backgrounds are left floating. The normalizations of the remaining sub-leading backgrounds are left fixed in the fit at their expectation values from Monte Carlo predictions, except for multijet production which is estimated from data. The relative data to MC normalization factors for top-quark background agree with unity to within 20% in both the $ZH \to \ell^+\ell^- b\bar{b}$ or $WH \to \ell\nu b\bar{b}$ sideband fits. The normalization of the top-quark background in the $ZH \to \ell^+\ell^- b\bar{b}$ signal region is based on the ZH sideband and control region fit result. The normalization of the top-quark background in the $WH \to \ell\nu b\bar{b}$ and $ZH \to \nu\bar{\nu}b\bar{b}$ signal regions is based on the WH sideband and control region fit result. Monte Carlo simulation is used to estimate the shape of the $Z+$jet ($W+$jet) background, while its normalization is determined in the

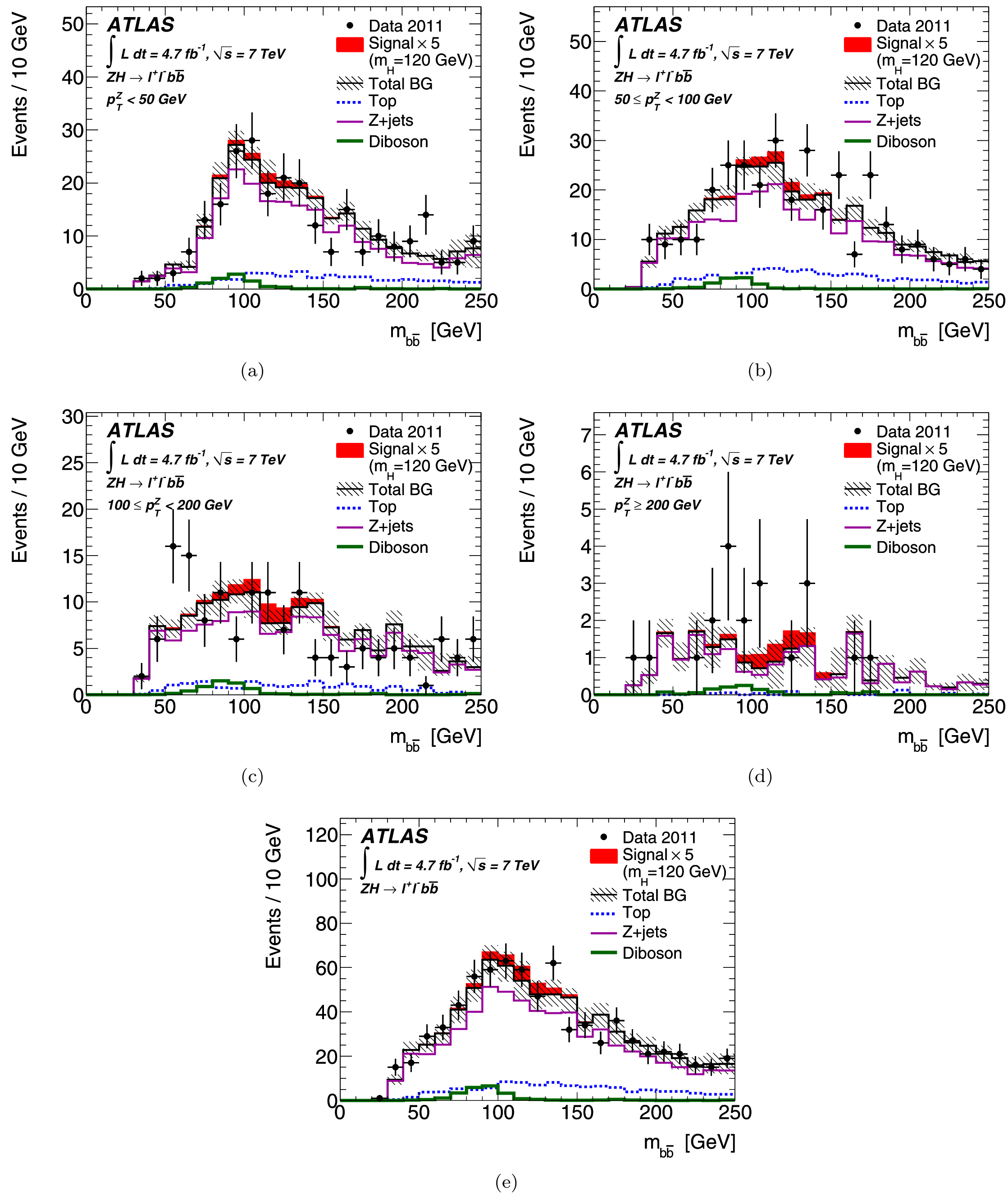

Fig. 2. The invariant mass $m_{b\bar{b}}$ for $ZH \to \ell^+\ell^-b\bar{b}$ shown for the different p_T^Z bins: (a) $0 < p_T^Z < 50$ GeV, (b) $50 \leqslant p_T^Z < 100$ GeV, (c) $100 \leqslant p_T^Z < 200$ GeV, (d) $p_T^Z \geqslant 200$ GeV and (e) for the combination of all p_T^Z bins. The signal distributions are shown for $m_H = 120$ GeV and are enhanced by a factor of five for visibility. The shaded area indicates the total uncertainty on the background prediction. For better visibility, the signal histogram is stacked onto the total background, unlike the various background components which are simply overlaid in the distribution.

$ZH \to \ell^+\ell^-b\bar{b}$ ($WH \to \ell\nu b\bar{b}$) sidebands to the signal regions of all three channels. The MC to data normalization factors for $W+$jet and $Z+$jet range from 0.8 to 2.4 depending on jet flavour and multiplicity. The normalization factors are applied to the MC in several additional control samples with selections to enhance the Z, W or top-quark contributions. After these corrections are applied, good agreement is found with the data in both shape and normalization within the statistical and systematic uncertainties.

The backgrounds from multijet events are estimated entirely from collision data. For the $ZH \to \ell^+\ell^-b\bar{b}$ channel, the multijet background normalization is determined from the sidebands of the $m_{\ell\ell}$ distribution in events containing at least two jets, and is found to contribute less than 1% and is therefore neglected. Multijet E_T^{miss} templates for the $WH \to \ell\nu b\bar{b}$ channel are obtained by selecting events with lepton candidates failing the charged lepton analysis selection, but satisfying looser lepton selections. The normalization is determined by fitting these templates to the E_T^{miss} distribution. A 30% uncertainty is determined from a comparison between the normalized templates and the data in a multijet-dominated control region, defined by requiring $E_T^{miss} < 25$ GeV and $m_T < 40$ GeV.

In the $ZH \to \nu\bar{\nu}b\bar{b}$ channel, the multijet background is estimated using three control regions defined using two variables, $\Delta\phi(E_T^{miss}, p_T^{miss})$ and $\min(\Delta\phi(E_T^{miss}, \text{jets}))$, which showed no appreciable correlation. The ratio of events with $\Delta\phi(E_T^{miss}, \text{jet}) > 1.8$

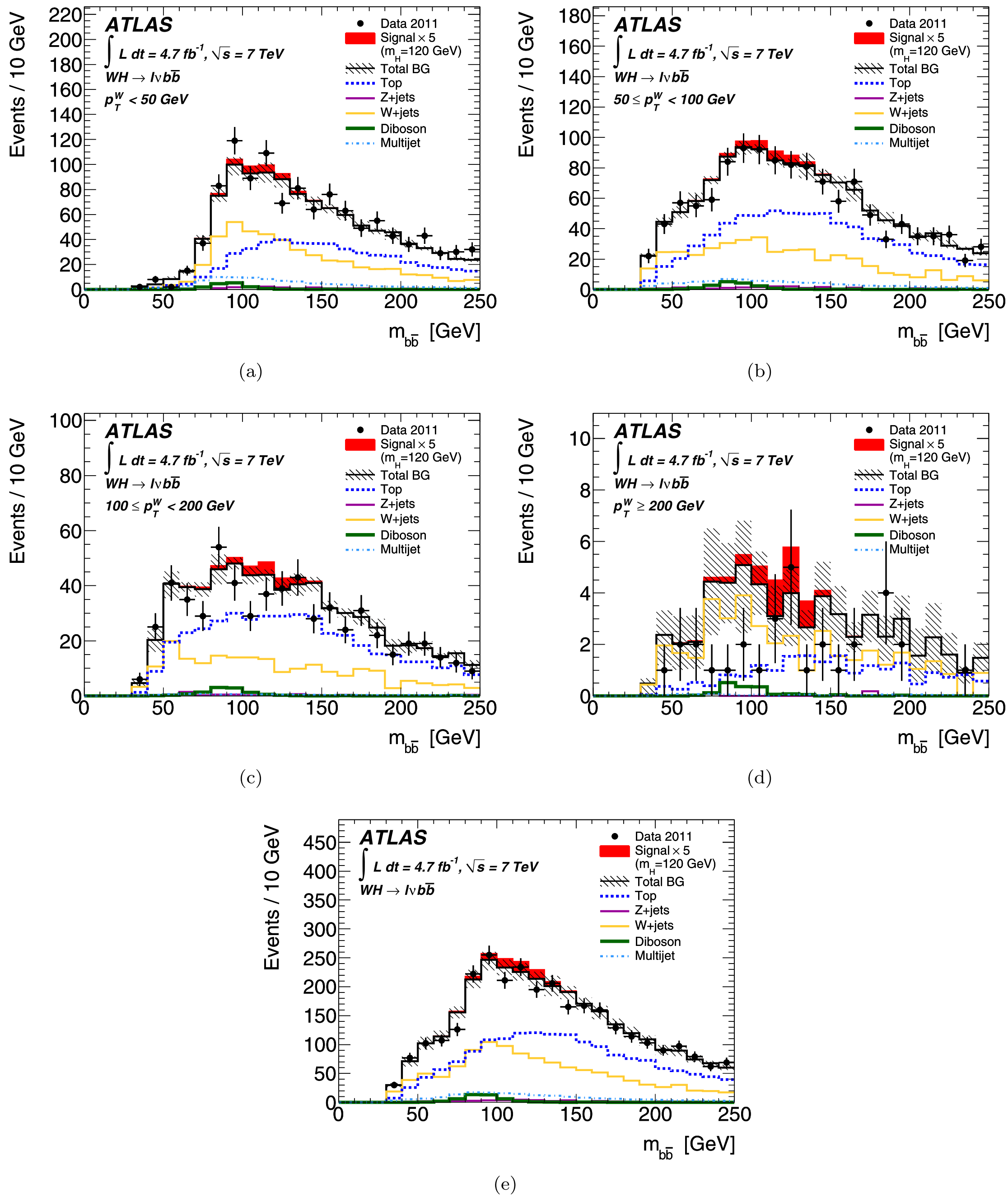

Fig. 3. The invariant mass $m_{b\bar{b}}$ for $WH \to \ell\nu b\bar{b}$ shown for the different p_T^W bins: (a) $0 < p_T^W < 50$ GeV, (b) $50 \leqslant p_T^W < 100$ GeV, (c) $100 \leqslant p_T^W < 200$ GeV, (d) $p_T^W \geqslant 200$ GeV and (e) for the combination of all p_T^W bins. The signal distributions are shown for $m_H = 120$ GeV and are enhanced by a factor of five for visibility. The shaded area indicates the total uncertainty on the background prediction. For better visibility, the signal histogram is stacked onto the total background, unlike the various background components which are simply overlaid in the distribution.

to those with $\min(\Delta\phi(E_T^{miss}, \text{jet})) < 1.8$ is determined for events with $\Delta\phi(E_T^{miss}, p_T^{miss}) > \pi/2$. This ratio is then applied to events with $\Delta\phi(E_T^{miss}, p_T^{miss}) < \pi/2$ to estimate the multijet background in the signal region. Upper estimates of the multijet contamination in the signal region are found to be 0.85, 0.04 and 0.26 events for $120 < p_T^V < 160$ GeV, $160 \leqslant p_T^V < 200$ GeV and $p_T^V \geqslant 200$ GeV, respectively. The accuracy of the estimate is limited by the number of events in the control regions.

The distribution of $m_{\ell\ell}$ in the $ZH \to \ell^+\ell^- b\bar{b}$ channel is shown in Fig. 1(a) after all analysis requirements have been applied (except for the di-lepton mass cut), including the requirement of two b-tagged jets. The signal region is seen to be dominated by Z + jet with smaller contributions from top-quark and diboson production. The E_T^{miss} distribution in the $WH \to \ell\nu b\bar{b}$ channel is shown in Fig. 1(b) after all requirements, except for the m_T and E_T^{miss} cuts. The signal region is seen to have large contributions from top-quark production and W + jet, with smaller contributions from the multijet background, Z + jet and diboson production. Figs. 1(c) and 1(d) show the $\Delta\phi(E_T^{miss}, p_T^{miss})$ and $\min(\Delta\phi(E_T^{miss}, \text{jet}))$ distributions for the $ZH \to \nu\bar{\nu}b\bar{b}$ channel, after all requirements except for those applied to these variables. The multijet background shape in Fig. 1(c) is obtained from data events with $\min(\Delta\phi(E_T^{miss}, \text{jet})) < 0.4$, after subtracting the remaining backgrounds, and normalized to the data in the region

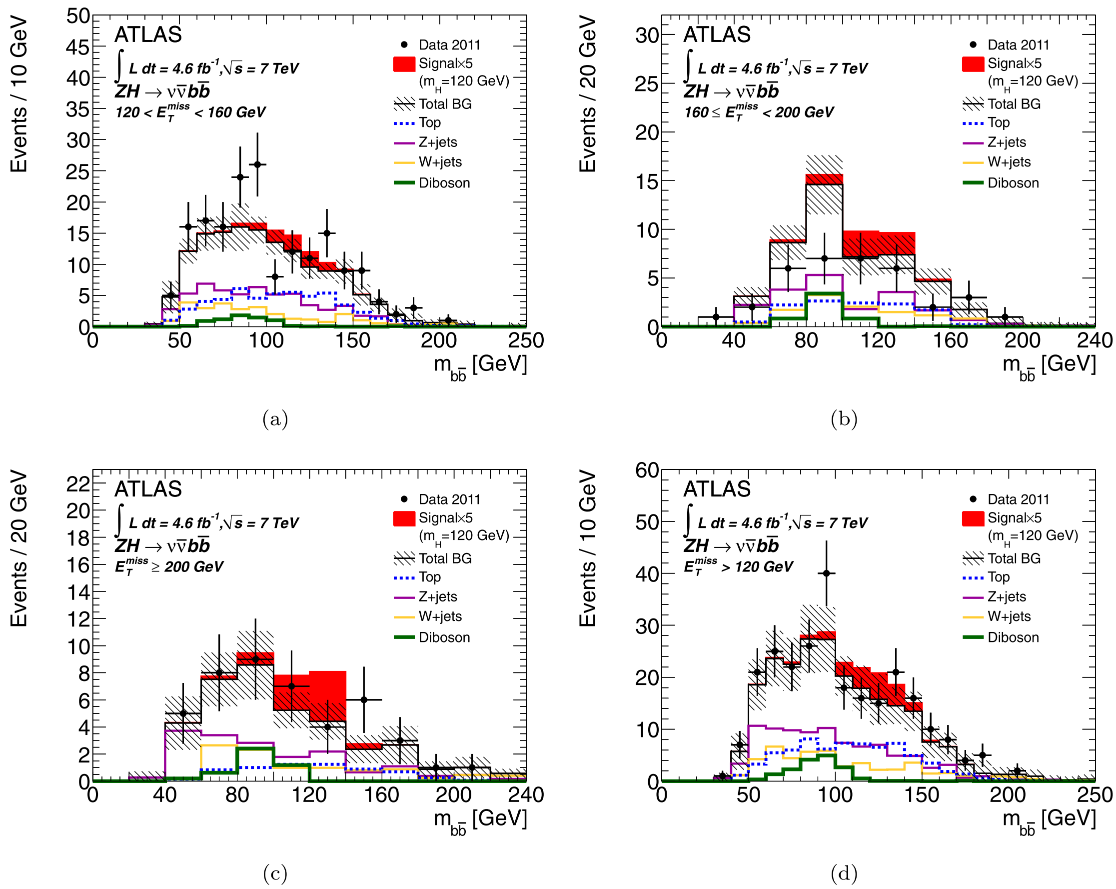

Fig. 4. The invariant mass $m_{b\bar{b}}$ for $ZH \to \nu\bar{\nu}b\bar{b}$ shown for the different p_T^Z bins: (a) $120 < p_T^Z < 160$ GeV, (b) $160 \leqslant p_T^Z < 200$ GeV, (c) $p_T^Z \geqslant 200$ GeV and (d) for the combination of all p_T^Z bins. The signal distributions are shown for $m_H = 120$ GeV and are enhanced by a factor of five for visibility. The shaded area indicates the total uncertainty on the background prediction. For better visibility, the signal histogram is stacked onto the total background, unlike the various background components which are simply overlaid in the distribution.

defined by $\Delta\phi(E_T^{\text{miss}}, p_T^{\text{miss}}) > \pi/2$. In Fig. 1(d), the multijet shape is obtained from events with $\Delta\phi(E_T^{\text{miss}}, p_T^{\text{miss}}) > \pi/2$ and normalized to data events with $\min(\Delta\phi(E_T^{\text{miss}}, \text{jet})) < 0.4$.

It can be seen that the requirements on these variables effectively reduce the multijet background. The signal region has large contributions from $Z+$jet and top, with smaller contributions from the $W+$jet, diboson production and multijet backgrounds. For all distributions, the data are reasonably well described by MC simulation and the multijet background, which was determined from data.

7. Systematic uncertainties

The sources of systematic uncertainty considered are those affecting the various efficiencies (reconstruction, identification, selection), as well as the momentum or energy of physics objects, the normalization and shape of the $m_{b\bar{b}}$ distribution of the signal and background processes, and the integrated luminosity. Among these, the leading instrumental uncertainties for all channels are related to the uncertainty on the b-tagging efficiency, which varies between 5% and 19% depending on the b-tagged jet p_T [44], and the jet energy scale (JES) for b-tagged jets which varies between 3% and 14% depending on the jet p_T and η [49]. The p_T dependence of the b-tagging efficiency has been considered, based on the full covariance matrix of the measured b-tagging efficiency in jet p_T intervals [44]. The uncertainty on the flavour composition of the $Z+$jet and $W+$jet background is estimated by varying the relative fraction of $Z+c$-jets and $W+c$-jets derived from the fit described in Section 6 by 30%.

The uncertainties on the SM Higgs boson inclusive cross sections are evaluated by varying the factorization and renormalization scales, and by taking into account the uncertainties on the PDFs, on the strong coupling constant and on the $H \to b\bar{b}$ branching fraction. These uncertainties are estimated to be ≈ 4% for both WH and ZH production and are treated according to the recommendations given in Refs. [21,50,51]. Additional uncertainties are considered, as a function of the transverse momentum of the W and Z bosons, which range from ≈ 4% to ≈ 8%, depending on channel and on the p_T^W or p_T^Z interval. These correspond to the difference between the inclusive and differential electroweak corrections [22,12], and to differences in acceptance between the Pythia and Powheg + Herwig generators. The latter arise mainly from the perturbative QCD model uncertainty caused by rejecting events with three or more jets in the $WH \to \ell\nu b\bar{b}$ and $ZH \to \nu\bar{\nu}b\bar{b}$ analyses.

The uncertainties on the normalizations of the $Z+$jet, $W+$jet and top-quark backgrounds are taken from the statistical uncertainties on the fits to control regions and $m_{b\bar{b}}$ sidebands (see Section 6) and from variations of the nominal fit result induced by the remaining sources of systematic uncertainty. The resulting normalization uncertainties are applied to the $ZH \to \nu\bar{\nu}b\bar{b}$ channel. A correlation between the normalizations of the $W+$jet and top-quark backgrounds is introduced by the simultaneous fit to the $m_{b\bar{b}}$ sidebands and the WH top control region in the $WH \to \ell\nu b\bar{b}$ channel. This correlation is taken into account when transferring

Table 1
Number of data, simulated signal, and estimated background events in each bin of p_T^V for the $WH \to \ell\nu b\bar{b}$, $ZH \to \ell^+\ell^- b\bar{b}$ and $ZH \to \nu\bar{\nu}b\bar{b}$ channels. The signal corresponds to a Higgs boson mass of $m_H = 120$ GeV. The number of events is shown for the full signal region ($m_{b\bar{b}} \in [80$ GeV, 150 GeV$]$). Background sources found to be negligible are signalled with "–". Relative systematic uncertainties on the hypothesized signal and estimated total background are shown.

bin	$ZH \to \ell^+\ell^- b\bar{b}$ p_T^V [GeV]				$WH \to \ell\nu b\bar{b}$ p_T^V [GeV]				$ZH \to \nu\bar{\nu}b\bar{b}$ p_T^V [GeV]		
	0–50	50–100	100–200	>200	0–50	50–100	100–200	>200	120–160	160–200	>200
Number of events for $80 < m_{b\bar{b}} < 150$ GeV											
Signal	1.3 ± 0.1	1.8 ± 0.2	1.6 ± 0.2	0.4 ± 0.1	5.0 ± 0.6	5.1 ± 0.6	3.7 ± 0.4	1.2 ± 0.2	2.0 ± 0.2	1.2 ± 0.1	1.5 ± 0.2
Top	17.4	24.1	7.3	0.2	229.9	342.7	201.3	8.2	35.2	8.3	4.1
W + jets	–	–	–	–	285.9	193.6	85.8	17.5	13.2	7.8	4.8
Z + jets	123.2	119.9	55.9	6.1	11.1	10.5	2.8	0.0	31.5	11.9	7.1
Diboson	7.2	5.6	3.6	0.7	12.6	11.9	7.8	1.4	4.6	4.3	3.6
Multijet	–	–	–	–	55.5	38.2	3.6	0.2	–	–	–
Total BG	148 ± 10	150 ± 6	67 ± 4	6.9 ± 1.2	596 ± 23	598 ± 16	302 ± 10	27 ± 5	85 ± 8	32 ± 3	20 ± 3
Data	141	163	61	13	614	588	271	15	105	22	25
Components of the relative systematic uncertainties of the background [%]											
b-tag eff	1.4	1.0	0.3	4.8	0.9	1.3	0.9	7.2	4.1	4.2	5.5
BG norm	3.6	3.4	3.6	3.8	2.7	1.8	1.8	4.5	2.7	2.2	3.2
Jets/E_T^{miss}	2.1	1.2	2.7	5.1	1.5	1.4	2.1	9.5	7.7	8.2	12.1
Leptons	0.2	0.3	1.1	3.4	0.1	0.2	0.2	1.7	0.0	0.0	0.0
Luminosity	0.2	0.1	0.2	0.4	0.1	0.1	0.1	0.2	0.2	0.5	0.7
Pileup	0.9	1.6	0.5	1.3	0.1	0.2	0.8	0.5	1.6	2.5	3.0
Theory	5.2	1.3	4.7	14.9	2.2	0.3	1.6	14.8	2.9	4.0	7.7
Total BG	6.9	4.3	6.6	17.3	3.9	2.7	3.4	19.6	9.7	10.6	16.0
Components of the relative systematic uncertainties of the signal [%]											
b-tag eff	6.4	6.4	7.0	13.7	6.4	6.4	7.0	12.1	7.1	8.2	9.2
Jets/E_T^{miss}	4.9	3.2	3.5	5.5	5.8	4.6	3.7	3.3	7.3	5.1	6.3
Leptons	0.9	1.2	1.7	2.6	3.0	3.0	3.0	3.2	0.0	0.0	0.0
Luminosity	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
Pileup	0.5	1.1	1.8	2.2	1.2	0.3	0.3	1.6	0.2	0.2	0.0
Theory	4.6	3.6	3.3	5.3	4.4	4.7	5.0	8.0	3.3	3.3	5.6
Total signal	10.1	9.1	9.6	16.5	11.4	10.8	11.0	16.0	11.8	11.4	13.4

Table 2
The observed and expected 95% CL exclusion limits on the Higgs boson cross section for each channel, expressed in multiples of the SM cross section as a function of the hypothesized Higgs boson mass. The last two columns show the combined exclusion limits for the three channels.

Mass [GeV]	$ZH \to \ell^+\ell^- b\bar{b}$		$WH \to \ell\nu b\bar{b}$		$ZH \to \nu\bar{\nu}b\bar{b}$		Combined	
	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.
110	7.7	6.0	3.3	4.2	3.7	4.0	2.5	2.5
115	7.7	6.2	4.0	4.9	3.6	4.2	2.6	2.7
120	10.4	8.0	4.9	5.9	4.8	5.0	3.4	3.3
125	11.6	9.1	5.5	7.5	7.3	6.0	4.6	4.0
130	14.4	11.6	5.9	9.2	10.3	7.6	5.5	4.9

to the $ZH \to \nu\bar{\nu}b\bar{b}$ channel the uncertainties on the normalization of these backgrounds.

The background normalization corrections are determined in an inclusive way, using all selected events in the $ZH \to \ell^+\ell^- b\bar{b}$ and $WH \to \ell\nu b\bar{b}$ channels, and the shape of the $m_{b\bar{b}}$ and p_T^V distributions are in each case taken from the MC simulation. Therefore, a possible mismodelling of the underlying $m_{b\bar{b}}$ and p_T^V distributions, as predicted by the MC generators, is also considered. An uncertainty due to the shape of the p_T^Z distribution for the Z + jet background in the $ZH \to \ell^+\ell^- b\bar{b}$ channel is estimated by finding variations of the MC p_T^Z distribution in the $m_{b\bar{b}}$ sidebands which cover any differences between MC simulation and data. The $m_{b\bar{b}}$ distribution of simulated Z + jet events is then reweighted according to these variations, to estimate the effect on the final results. An uncertainty due to the modelling of W + jet in the $WH \to \ell\nu b\bar{b}$ channel is estimated by reweighting the p_T^W and $m_{b\bar{b}}$ distributions of simulated W + jet events by variations motivated by a comparison of different theoretical models (Powheg + Pythia, Powheg + Herwig, aMC@NLO + Herwig [52] and Alpgen + Herwig). Theoretical uncertainties of 11% and 15% are applied to the normalization of the diboson samples and the single-top sample, respectively. The normalization uncertainty for the multijet background is taken to be 30% for $WH \to \ell\nu b\bar{b}$, as described in Section 6. For $ZH \to \ell^+\ell^- b\bar{b}$ and $ZH \to \nu\bar{\nu}b\bar{b}$ this background is found to be negligible. The uncertainty in the integrated luminosity has been estimated to be 3.9% [15,16]. This uncertainty is applied only to the simulated signal and to the diboson background, which are not normalized to the data. Where it is applied, this systematic uncertainty is assumed to be correlated among the different samples.

8. Results

The analysis is performed for five Higgs boson mass hypotheses between 110 GeV and 130 GeV and the signal hypothesis is tested based on a fit to the invariant mass distribution of the b-jet pair, $m_{b\bar{b}}$, in the signal region ($80 < m_{b\bar{b}} < 150$ GeV). The $m_{b\bar{b}}$ distribution is shown in Figs. 2–4 for each channel, separately for different ranges of p_T^V. The data distributions are overlaid with the expectations from the MC simulation and data-driven backgrounds.

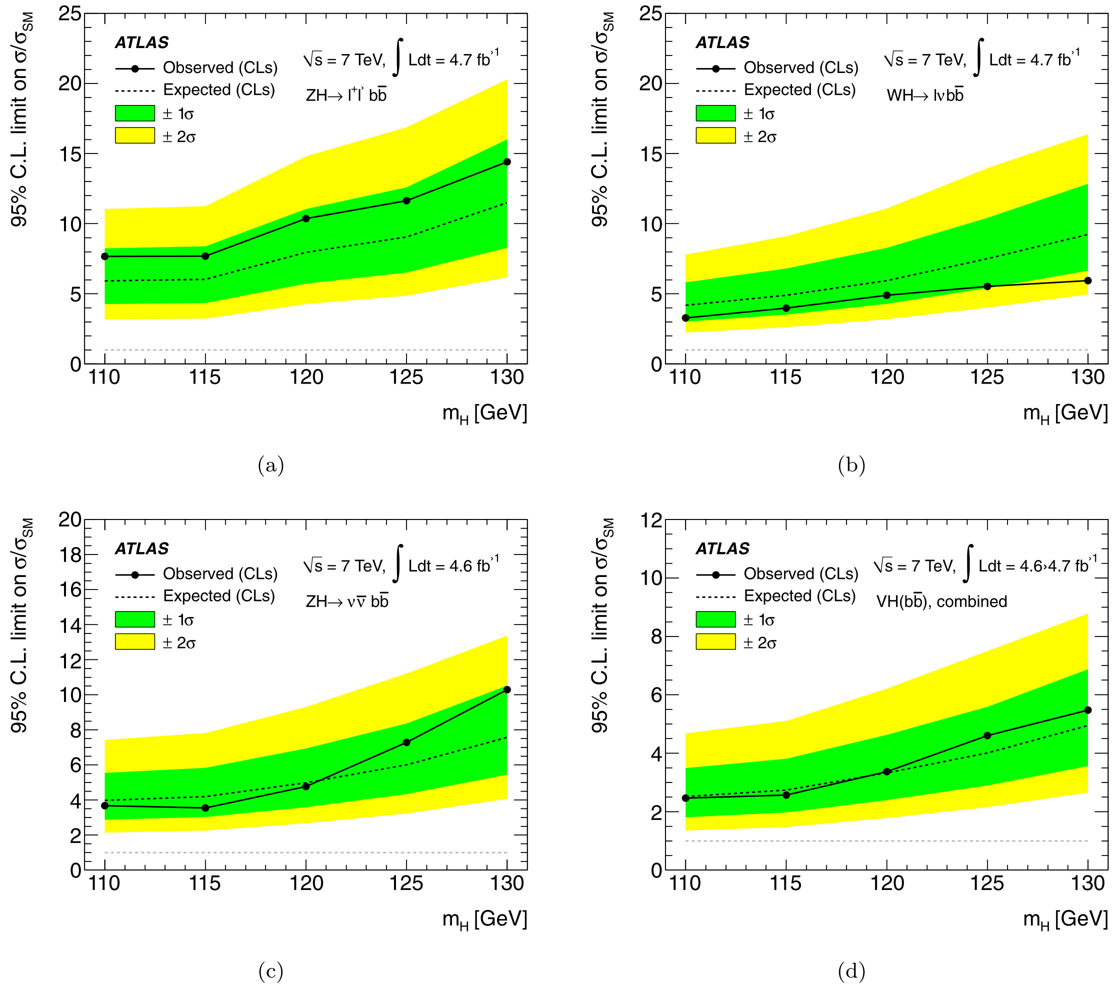

Fig. 5. Expected (dashed) and observed (solid line) exclusion limits for (a) the $ZH \to \ell^+\ell^- b\bar{b}$, (b) $WH \to \ell\nu b\bar{b}$ and (c) $ZH \to \nu\bar{\nu}b\bar{b}$ channels expressed as the ratio to the SM Higgs boson cross section, using the profile-likelihood method with CL_s. The dark (green in the web version) and light (yellow in the web version) areas represent the $\pm 1\sigma$ and $\pm 2\sigma$ ranges of the expectation in the absence of a signal. (d) shows the 95% CL exclusion limits obtained from the combination of the three channels.

Within the experimental uncertainty, the data show no excess over the background expectation. The signal shape is dominated by the experimental resolution on the jet energy measurement. The $m_{b\bar{b}}$ resolution for signal events is about 16 GeV on average.

The number of events in the signal region selected in data is shown in Table 1 for each channel. The expected number of signal events for $m_H = 120$ GeV is also shown, along with the corresponding estimated number of background events. Also shown are the relative systematic uncertainties on the signal and total background yields arising from the following sources: b-tagging efficiency and mis-tag rate, background normalization, jet and $E_{\mathrm{T}}^{\mathrm{miss}}$ uncertainties, lepton reconstruction and identification, integrated luminosity, overlaid collision events (pileup), and uncertainties on the MC predictions (theory). Uncertainties on the shape of the $m_{b\bar{b}}$ distribution are also taken into account in the fit.

For each Higgs boson mass hypothesis, a one-sided upper limit is placed on the ratio of the Higgs boson production cross section to its SM value, $\mu = \sigma/\sigma_{\mathrm{SM}}$, at the 95% CL. The exclusion limits are derived from the CL_s [53] treatment of the p-values computed with the profile likelihood ratio test statistic [54], as implemented in the RooStats program [55], using the binned distribution of $m_{b\bar{b}}$. The systematic uncertainties are treated by making the expected $m_{b\bar{b}}$ templates and sample normalizations dependent on additional fit parameters ("nuisance parameters"), one for each systematic uncertainty, which are then constrained with Gaussian terms within their expected uncertainties. The dependence of the $m_{b\bar{b}}$ shapes on the nuisance parameters is described with bin-by-bin linear interpolation between the corresponding $+1\sigma$ or -1σ variations and the nominal case.

The resulting exclusion limits are listed in Table 2 for each channel and for the statistical combination of the three channels. They are also plotted in Fig. 5. The limits are expressed as the multiple of the SM Higgs boson production cross section which is excluded at 95% CL for each value of the Higgs boson mass. The observed upper limits range between 7.7 and 14.4 for the $ZH \to \ell^+\ell^- b\bar{b}$ channel, between 3.3 and 5.9 for the $WH \to \ell\nu b\bar{b}$ channel and between 3.7 and 10.3 for the $ZH \to \nu\bar{\nu}b\bar{b}$ channel, depending on the Higgs boson mass. The combined exclusion limit for the three channels together ranges from 2.5 to 5.5 times the SM cross section, depending on the Higgs boson mass. The limits include systematic uncertainties, the largest of which arise from the top, Z + jet, and W + jet background estimates, the b-tagging efficiency, and the jet energy scale. The systematic uncertainties weaken the limits by 25–40% depending on the search channel.

9. Summary

This Letter presents the results of a direct search by ATLAS for the SM Higgs boson produced in association with a W or Z boson. The following decay channels are considered: $ZH \to \ell^+\ell^- b\bar{b}$,

$WH \rightarrow \ell\nu b\bar{b}$ and $ZH \rightarrow \nu\bar{\nu}b\bar{b}$, where ℓ corresponds to an electron or a muon. The mass range $110 < m_H < 130$ GeV is examined for five Higgs boson mass hypotheses separated by 5 GeV steps. The three channels use datasets corresponding to 4.6–4.7 fb^{-1} of pp collisions at $\sqrt{s} = 7$ TeV. No significant excess of events above the estimated backgrounds is observed. Upper limits on Higgs boson production, at the 95% CL, of 2.5 to 5.5 times the SM cross section are obtained in the mass range 110–130 GeV. The expected exclusion limits range between 2.5 and 4.9 for the same mass interval.

Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; EPLANET and ERC, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNAS, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

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