



# Measurement of the production cross section for a Higgs boson in association with a vector boson in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ channel in $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

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## ABSTRACT

A measurement of the Higgs boson production cross sections via associated  $WH$  and  $ZH$  production using  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  decays, where  $\ell$  stands for either an electron or a muon, is presented. Results for combined  $WH$  and  $ZH$  production are also presented. The analysis uses events produced in proton–proton collisions collected with the ATLAS detector at the Large Hadron Collider in 2015 and 2016. The data correspond to an integrated luminosity of  $36.1 \text{ fb}^{-1}$  recorded at a centre-of-mass energy of 13 TeV. The products of the  $H \rightarrow WW^*$  branching fraction times the  $WH$  and  $ZH$  cross sections are measured to be  $0.67_{-0.27}^{+0.31}(\text{stat.})_{-0.14}^{+0.18}(\text{syst.}) \text{ pb}$  and  $0.54_{-0.07}^{+0.31}(\text{stat.})_{-0.07}^{+0.15}(\text{syst.}) \text{ pb}$  respectively, in agreement with the Standard Model predictions.

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## 1. Introduction

Higgs boson production in association with a  $W$  or  $Z$  boson, which is respectively denoted by  $WH$  and  $ZH$ , and collectively referred to as  $VH$  associated production in the following, provides direct access to the Higgs boson couplings to weak bosons. In particular, in the  $WH$  mode with subsequent  $H \rightarrow WW^*$  decay, the Higgs boson couples only to  $W$  bosons, at both the production and decay vertices.

This paper presents a measurement of the corresponding production cross sections through the decay  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ , using proton–proton collisions at a centre-of-mass energy of  $\sqrt{s} = 13$  TeV. The data correspond to an integrated luminosity of  $36.1 \text{ fb}^{-1}$  and were recorded by the ATLAS detector at the Large Hadron Collider (LHC). Previous measurements at  $\sqrt{s} = 8$  TeV were performed by the ATLAS [1] and CMS [2] Collaborations and recently at  $\sqrt{s} = 13$  TeV with  $35.9 \text{ fb}^{-1}$  of data by the CMS Collaboration [3]. Recent results at  $\sqrt{s} = 13$  TeV on  $VH$  production in other decay modes can be found in Refs. [4–9].

The analysis is performed using events with three ( $3\ell$ ) or four ( $4\ell$ ) charged leptons (electrons or muons) in the final state, targeting the  $WH$  and  $ZH$  channels respectively. Leptonic decays of  $\tau$  leptons, from  $H \rightarrow WW^* \rightarrow \tau\nu\tau\nu$  or  $H \rightarrow WW^* \rightarrow \tau\nu\ell\nu$  or from the associated vector bosons, are considered as signal, while no specific selection is performed for events with hadronically decaying  $\tau$  leptons in the final state. Events from  $VH$  production with

$H \rightarrow \tau\tau$  are considered as background. The leading-order Feynman diagrams for the  $WH$  and  $ZH$  production processes are depicted in Fig. 1.

In the  $WH$  channel, multivariate discriminants are used to maximise the sensitivity to the Higgs boson signal, while in the  $ZH$  channel the analysis is performed through selection requirements. The distribution of these  $WH$  discriminants, together with event counts in background control regions and the signal regions in the  $ZH$  channel, are combined in a binned maximum-likelihood fit to extract the signal yield and the background normalisations. The maximum-likelihood fit provides results for the  $WH$  and the  $ZH$  channels separately and for their combination  $VH$ , assuming the Standard Model (SM) prediction for the relative cross sections of the two production processes.

## 2. ATLAS detector

The ATLAS experiment [10–12] is a multi-purpose particle detector with a forward–backward symmetric cylindrical geometry and a near  $4\pi$  coverage in solid angle.<sup>1</sup> It consists of an in-

<sup>1</sup> 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 pipe. The  $x$ -axis points from the IP to the centre of the LHC ring, and the  $y$ -axis points upwards. Cylindrical coordinates  $(r, \phi)$  are used in the transverse plane,  $\phi$  being the azimuthal angle around the  $z$ -axis. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln \tan(\theta/2)$ . Angular distance is measured in units of  $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ . Transverse momentum and energy are defined as  $p_T = p \sin \theta$  and  $E_T = E \sin \theta$  respectively.

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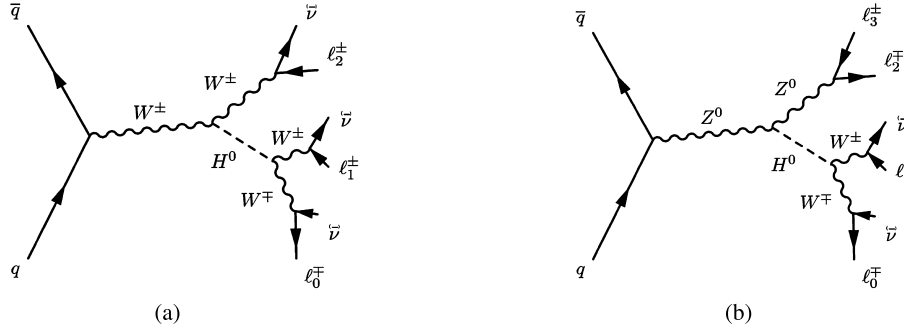


Fig. 1. Tree-level Feynman diagrams for the  $VH(H \rightarrow WW^*)$  topologies considered in this paper: (a)  $3\ell$  channel and (b)  $4\ell$  channel.

Table 1

Monte Carlo generators used to model the signal and background processes. Alternative generators, underlying event and parton-showering models, used to estimate systematic uncertainties, are shown in parentheses. In the last column the prediction order for the total cross section is shown. “PYTHIA6” refers to version 6.428, “PYTHIA8” refers to versions 8.210 or 8.186.

Process	Generator (alternative)	UEPS model (alternative)	Prediction order for total cross section
$q\bar{q} \rightarrow WH$	POWHEG-Box v2 MiNLO	PYTHIA8 (HERWIG 7)	NNLO QCD + NLO EW [16–18]
$q\bar{q} \rightarrow ZH$	POWHEG-Box v2 MiNLO	PYTHIA8 (HERWIG 7)	NNLO QCD + NLO EW [16–18]
$gg \rightarrow ZH$	POWHEG-Box v2	PYTHIA8 (HERWIG 7)	NLO + NLL [19]
ggF $H$	POWHEG-Box v2 NNLOPS	PYTHIA8	NNNLO QCD + NLO EW [20]
VBF $H$	POWHEG-Box v2	PYTHIA8	NNLO QCD + NLO EW [21]
$t\bar{t}$	POWHEG-Box v2	PYTHIA8 (HERWIG 7)	NNLO+NNLL [22]
$Wt$	(SHERPA 2.2.1) POWHEG-Box v1	(SHERPA 2.2.1) PYTHIA6	NLO [23]
$t\bar{t}W/Z$	MG5_AMC@LO	PYTHIA8	NLO [24,25]
$tZ$	MG5_AMC@LO	PYTHIA6	LO [26]
$q\bar{q}/qg \rightarrow \ell\nu\ell\ell$	SHERPA 2.2.2 (POWHEG-Box v2)	SHERPA 2.2.2 (HERWIG++)	NLO [27]
$q\bar{q}/qg \rightarrow \ell\ell\ell\ell$	SHERPA 2.1/2.2.2 (POWHEG-Box v2)	SHERPA 2.1/2.2.2 (HERWIG++)	NLO [27]
$gg \rightarrow \ell\ell\ell\ell$	SHERPA 2.1.1	SHERPA 2.1.1	NLO [28]
$VVV$	SHERPA 2.2.2 (MG5_AMC@NLO)	SHERPA 2.2.2 (PYTHIA8)	NLO [29]

ner tracking detector (ID) surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic (EM) and hadronic calorimeters, and a muon spectrometer (MS). The inner tracking detector covers the pseudorapidity range  $|\eta| < 2.5$ . It consists of silicon pixel, silicon micro-strip, and transition-radiation tracking detectors. Lead/liquid-argon (LAR) sampling calorimeters provide electromagnetic energy measurements with high granularity. A hadronic (steel/scintillator-tile) calorimeter covers the central pseudorapidity range ( $|\eta| < 1.7$ ). The endcap and forward regions are instrumented with LAR calorimeters for both EM and hadronic energy measurements up to  $|\eta| = 4.9$ . The muon spectrometer surrounds the calorimeters and is based on three large air-core toroidal superconducting magnet systems that provide a field integral between 2.0 and 6.0 Tm across most of the detector. The muon spectrometer includes a system of precision tracking chambers covering the region  $|\eta| < 2.7$  and fast detectors for triggering within the range  $|\eta| < 2.4$ . A two-level trigger system is used to select events [13].

### 3. Signal and background Monte Carlo simulation

Monte Carlo (MC) event generators are used to model signal and background processes. All signal samples were generated with a Higgs boson mass of 125 GeV [14,15]. For most processes, sep-

arate programs were used to generate the hard scattering process and to model the underlying event and the parton showering (UEPS). A description of the MC samples is given in Table 1. They are normalised to cross-section predictions calculated with the QCD and electroweak (EW) orders specified in the last column of Table 1.

The  $q\bar{q} \rightarrow WH$  and  $q\bar{q} \rightarrow ZH$  processes were generated with POWHEG-Box v2 [30] MiNLO interfaced to PYTHIA8 [31], with the AZNLO set of tuned parameters (tune) [32] for underlying event, showering and hadronisation. The  $gg \rightarrow ZH$  process was simulated with POWHEG-Box v2 + PYTHIA8 with the AZNLO tune for underlying event, showering and hadronisation. For the  $VH$  samples, the PDF4LHC15 parton distribution function (PDF) set [33] was used for the hard scattering process in POWHEG-Box v2 and the CTEQ6L1 PDF set [34] was used for the parton showering in PYTHIA8. HERWIG 7 [35], with the MMHT2014lo68cl PDF set [36], was used as an alternative parton-showering model for  $VH$ . The uncertainty due to the PDF choice is smaller than the uncertainty obtained by using HERWIG as an alternative parton shower model (Section 7).

The gluon-gluon fusion (ggF) events were generated with POWHEG-Box v2 NNLOPS [37] interfaced to PYTHIA8 with the AZNLO tune. The vector-boson fusion (VBF) events were generated with POWHEG-Box v2, interfaced to PYTHIA8. For the ggF and

VBF samples, the PDF4LHC15 PDF set was used for the hard scattering process in POWHEG-Box v2 and the CTEQ6L1 PDF set was used for the parton showering in PYTHIA8. The contribution from the  $t\bar{t}H$  and  $tH$  production modes is negligible.

The top-quark pair production ( $t\bar{t}$ ) was simulated with POWHEG-Box v2 [38] using the NNPDF 3.0 NNLO PDF set [39] and interfaced to PYTHIA8 using the NNPDF 2.3 PDF set [40] for parton showering, with the A14 tune [41]. For  $t\bar{t}$  production, SHERPA [42] 2.2.1, with the NNPDF 3.0 PDF set, was used as an alternative generator while HERWIG 7, with the MMHT2014lo68cl PDF set, was used as an alternative UEPS model. The single-top-quark production  $Wt$  was generated with POWHEG-Box v1 [23] interfaced to PYTHIA6 [43] for parton showering with the PERUGIA2012 tune [44]. EVTGEN 1.2.0 [45] was used for the simulation of  $b$ -quark and  $c$ -quark decays. The  $t\bar{t}W/Z$  and  $tZ$  processes were generated at leading order (LO) with MG5\_AMC@LO [25] version 2.2.2 ( $t\bar{t}W/Z$ ) and 2.2.1 ( $tZ$ ) interfaced to PYTHIA8 ( $t\bar{t}W/Z$ ) and PYTHIA6 ( $tZ$ ), using the NNPDF2.3 LO PDF set.

The  $q\bar{q}/gg \rightarrow VV^*$  samples with final states  $l\nu ll$  and  $llll$  [46] were generated with SHERPA 2.2.2, with the exception of the  $ZZ^*$  sample in the  $WH$  analysis for which SHERPA 2.1 was used; the CT10 PDF set [47] and the NNPDF 3.0 PDF set were used for versions 2.1 and 2.2.2, respectively. POWHEG-Box v2 [48] was used as an alternative generator for  $VV^*$ , with HERWIG++, using the CTEQ6L1 PDF set, for parton showering. Among the loop-induced  $gg$ -initiated diboson processes, the only relevant process in this analysis is  $gg \rightarrow ZZ^*$ , for which a  $K$ -factor of 1.55 was used [28]. This process was simulated with SHERPA 2.1.1, using the CT10 PDF set.

The triboson  $VVV$  samples were generated with SHERPA 2.2.2 and the NNPDF 3.0 PDF set. MG5\_AMC@NLO was used as an alternative generator for  $VVV$ , with PYTHIA8, using the NNPDF2.3 LO PDF set. The same PDF sets were used for the hard scattering and the parton showering in all the SHERPA samples described above.

All simulated samples include the effect of pile-up from multiple interactions in the same and neighbouring bunch crossings. This was achieved by overlaying minimum-bias events, simulated using PYTHIA8 with the A2 tune [49] and MSTW2008LO PDF set [50]. All samples were processed through the GEANT 4 [51] ATLAS detector simulation [52].

#### 4. Event reconstruction

Candidate signal events are selected using triggers that require a single isolated lepton with minimum transverse momentum ( $p_T$ ) thresholds between 24 GeV and 26 GeV for electrons and between 20 GeV and 26 GeV for muons, depending on the data-taking period. At least one of the leptons reconstructed offline is required to have triggered the event and to have a  $p_T$  higher than the nominal trigger threshold by at least 1 GeV. The single-lepton trigger efficiencies on the plateau are approximately 70% for single muons with  $|\eta| < 1.05$ , 90% for single muons in the range  $1.05 < |\eta| < 2.40$  and greater than 90% for single electrons in the range  $|\eta| < 2.47$ . The trigger efficiency for the signal events, estimated after the preselection, is 94% for  $WH$  and 98.5% for  $ZH$ .

Selected events are required to have at least one primary vertex reconstructed from at least two associated tracks, each with transverse momentum  $p_T > 400$  MeV, as described in Ref. [53]. If an event has more than one reconstructed primary vertex, the vertex with the largest track  $\sum p_T^2$  is selected for the analysis.

Electrons are reconstructed from clusters of energy deposits in the EM calorimeter matched to ID tracks, and are identified using criteria based on the calorimeter shower shape, the quality of the match between the track and the cluster and the amount of transition radiation emitted in the ID, as described in Ref. [54]. Electrons

are required to satisfy  $|\eta| < 2.47$ , excluding  $1.37 < |\eta| < 1.52$ , which corresponds to the transition region between the barrel and the endcap EM calorimeters. The efficiency for electron identification ranges from 88% to 94%, depending on electron  $p_T$  and  $\eta$ . Muons are reconstructed by combining ID and MS tracks with consistent trajectories and curvatures. An overall fit of hits from the ID track, energy loss in the calorimeter and the hits of the track in the muon system is used to form muon candidates, as described in Ref. [55]. The efficiency for muon identification is close to 95% over the full instrumented  $\eta$  range. To suppress particles misidentified as leptons, several identification requirements as well as impact parameter, calorimeter and track isolation criteria [54,55] are applied.

Jets are reconstructed using the anti- $k_t$  algorithm with radius parameter  $R = 0.4$  [56,57]. The four-momenta of jets are corrected for the effects of calorimeter non-compensation, energy loss in non-instrumented regions, and contributions from pile-up [58]. Jets are required to have  $|\eta| < 4.5$ , with  $p_T > 25$  GeV for the region  $|\eta| < 2.5$  and  $p_T > 30$  GeV for the region  $2.5 < |\eta| < 4.5$ . A multivariate selection [59] is used to suppress jets with  $p_T < 60$  GeV and  $|\eta| < 2.4$  originated from pile-up. Furthermore, to suppress pile-up jets in the forward region, jet shapes and topological jet correlations in pile-up interactions are exploited [60]. Jets with  $p_T > 20$  GeV and  $|\eta| < 2.5$  containing  $b$ -hadrons ( $b$ -jets) are identified using a multivariate technique [61] with an efficiency of 85%, estimated from simulated  $t\bar{t}$  events. The multivariate technique gives rejection factors against jets originating from a light quark or gluon and jets containing  $c$ -hadrons of 33 and 3, respectively.

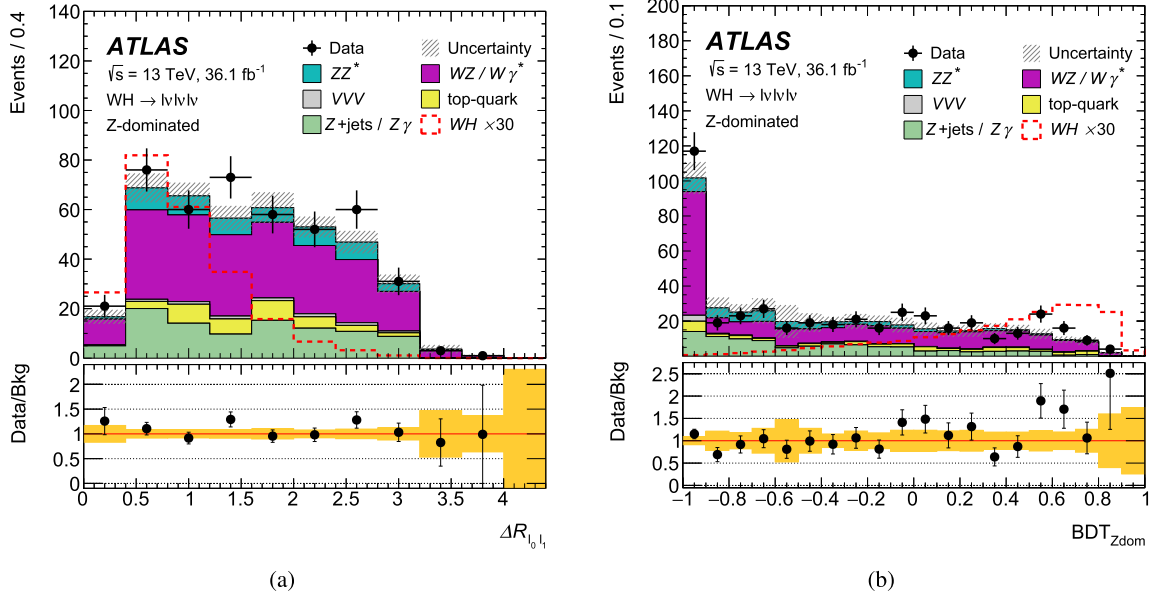
The missing transverse momentum  $\vec{p}_T^{\text{miss}}$  with magnitude  $E_T^{\text{miss}}$  in each event is calculated from the negative vectorial sum of the transverse momenta of electrons, muons, and jets. It uses both track-based and calorimeter-based measurements [62].

#### 5. Event selection

In the  $WH$  channel, exactly three isolated leptons with  $p_T > 15$  GeV are required with a total charge of  $\pm 1$ . The lepton with unique charge is labelled  $\ell_0$ , the lepton closest to  $\ell_0$  in angular distance  $\Delta R$  is labelled  $\ell_1$ , and the remaining lepton is labelled  $\ell_2$ . In signal events leptons  $\ell_0$  and  $\ell_1$  are most likely to originate from the  $H \rightarrow WW^*$  decay, with probabilities of 99% and 85% respectively.

The most prominent background processes to the  $WH$  channel are  $WZ/W\gamma^*$  production and top-quark processes with either three prompt leptons, e.g.  $t\bar{t}V$ , or two prompt leptons and one non-prompt lepton from a  $b$ -hadron decay, e.g.  $t\bar{t}$ . Other important background processes are  $ZZ^*$  (including  $Z\gamma^*$ ),  $Z\gamma$  and  $Z$ +jets production; they may satisfy the signal selection requirements if a lepton is undetected, in the case of  $ZZ^*$ , or if they contain a misidentified or non-prompt lepton, in the case of  $Z\gamma$  and  $Z$ +jets production. Processes with three prompt leptons in the final state such as tribosons, in particular  $WWW$ , also contribute to the background. Contributions from background processes that include more than one misidentified lepton, such as  $W$ +jets production and inclusive  $b\bar{b}$  pair production, are negligible. The background from top-quark production is suppressed by vetoing events if they contain any  $b$ -tagged jet.

The analysis of the  $WH$  channel separates events with at least one same-flavour opposite-sign charge (SFOS) lepton pair from events with zero SFOS lepton pairs, which have different signal-to-background ratios. Due to the presence of  $Z \rightarrow \ell\ell$  decays as a dominant background, the former is hereafter referred to as the  $Z$ -dominated category, while the latter is referred to as the  $Z$ -depleted category. In the  $Z$ -dominated category, the major background processes are those involving  $Z$  bosons. Events are ve-



**Fig. 2.** Distribution of (a) angular separation  $\Delta R_{\ell_0\ell_1}$  and (b)  $\text{BDT}_{\text{Zdom}}$  distribution in the Z-dominated category. The dashed line shows the  $WH$  signal scaled by a factor of 30. The hatched band in the upper panel and the shaded band in the lower panel show the total statistical and experimental systematic uncertainty in background predictions. The  $WZ/W\gamma^*$  and top-quark background processes are normalised with the normalisation factors from the control region analysis (Table 4). The  $Z$ +jets and  $Z\gamma$  background processes are estimated with the data-driven technique described in Section 6.

toed if they contain more than one jet. This requirement further suppresses top-quark events with an additional non-prompt lepton from  $b$ -hadron decays. In order to select final states with neutrinos,  $E_T^{\text{miss}}$  is required to be above 30 GeV. The invariant masses  $m_{\ell\ell}$  of all SFOS pairs are required to satisfy a Z-veto selection:  $|m_{\ell\ell} - m_Z| > 25$  GeV. The last two requirements suppress  $WZ/W\gamma^*$  and  $ZZ^*$  events, and improve the  $Z$ +jets rejection. In order to suppress background events from heavy-flavour quarkonia, the smallest invariant mass of SFOS pairs is required to be greater than 12 GeV. The signal efficiency of this selection with respect to the preselection is 34.6%. A discriminant based on a boosted decision tree (BDT) [63,64] is used to achieve a further separation between signal and background processes. The main purpose of the multivariate classifier, named  $\text{BDT}_{\text{Zdom}}$ , is to distinguish between signal and the dominant  $WZ/W\gamma^*$  and  $ZZ^*$  background processes, and hence it is trained against these two background processes. The  $\text{BDT}_{\text{Zdom}}$  uses seven input variables. They are the magnitude of the vectorial sum of lepton transverse momenta ( $|\Sigma p_T^{\ell_i}|$ ), the invariant masses of the first lepton pair ( $m_{\ell_0\ell_1}$ ) and of the three leptons ( $m_{\ell\ell\ell}$ ), the angular distance  $\Delta R_{\ell_0\ell_1}$ ,  $E_T^{\text{miss}}$  and the pseudorapidity separation between the leptons with the same charge ( $\Delta\eta_{\ell_1\ell_2}$ ). Moreover the BDT uses the transverse mass of the  $W$  boson,  $m_T^W = \sqrt{2 p_T^{\ell_W} \cdot E_T^{\text{miss}} \cdot (1 - \cos \Delta\phi(\ell_W, \vec{p}_T^{\text{miss}}))}$ , built from the  $\vec{p}_T^{\text{miss}}$  and the lepton  $\ell_W$  which is the lepton not belonging to the SFOS lepton pair with invariant mass closer to the  $Z$  boson mass, and could be either  $\ell_1$  or  $\ell_2$ . Fig. 2 shows the distribution of  $\Delta R_{\ell_0\ell_1}$ , which is the most powerful variable in the  $\text{BDT}_{\text{Zdom}}$  training, and the  $\text{BDT}_{\text{Zdom}}$  distribution in the Z-dominated category, before applying any selection requirement on the  $\text{BDT}_{\text{Zdom}}$  score.

The Z-dominated signal region (SR), defined as the events with high-ranking  $\text{BDT}_{\text{Zdom}}$  score ( $\text{BDT}_{\text{Zdom}} > 0.3$ ), is divided into three bins with increasing sensitivity:  $0.3 \leq \text{BDT}_{\text{Zdom}} < 0.5$ ,  $0.5 \leq \text{BDT}_{\text{Zdom}} < 0.7$  and  $0.7 \leq \text{BDT}_{\text{Zdom}} < 1.0$ . This binning is the result of an optimisation to find the minimal number of BDT bins that gives the highest sensitivity. The expected signal-to-background ra-

tio in these bins is about 0.05, 0.09 and 0.19, respectively. The full Z-dominated event selection is summarised in Table 2.

In the Z-depleted category, the two major background processes are  $WZ/W\gamma^*$  with  $Z/\gamma^* \rightarrow \tau\bar{\tau}$  and  $t\bar{t}$ , where  $WZ/W\gamma^*$  has the same signature of the signal, namely three prompt leptons, while  $t\bar{t}$  contains a misidentified or non-prompt lepton from a jet. Two separate BDTs, named  $\text{BDT}_{WZ}$  and  $\text{BDT}_{t\bar{t}}$ , are trained to allow an optimal background rejection. The  $\text{BDT}_{WZ}$  uses 11 input variables, of which three common to the  $\text{BDT}_{\text{Zdom}}$  are  $m_{\ell_0\ell_1}$ ,  $E_T^{\text{miss}}$  and  $\Delta\eta_{\ell_1\ell_2}$ ; the other variables are the transverse momenta of the three leptons ( $p_T^{\ell_0}$ ,  $p_T^{\ell_1}$ ,  $p_T^{\ell_2}$ ), the transverse mass ( $m_{\ell_0\ell_1}^T$ ) built from  $\ell_0$ ,  $\ell_1$  and  $\vec{p}_T^{\text{miss}}$ , the invariant mass of the electrons with same-sign charge ( $m_{ee}$ ), the transverse impact parameter significances of the lepton with lowest  $p_T$  ( $|d_{0,\text{sig},\text{min}}|$ ), the transverse impact parameter significances of the lepton with second-lowest  $p_T$  and opposite charge with respect to the lepton with lowest  $p_T$  ( $|d_{0,\text{sig},\text{mid}}|$ ) and the compatibility of the event with the  $WZ$  hypothesis  $F_\alpha$ .<sup>2</sup>

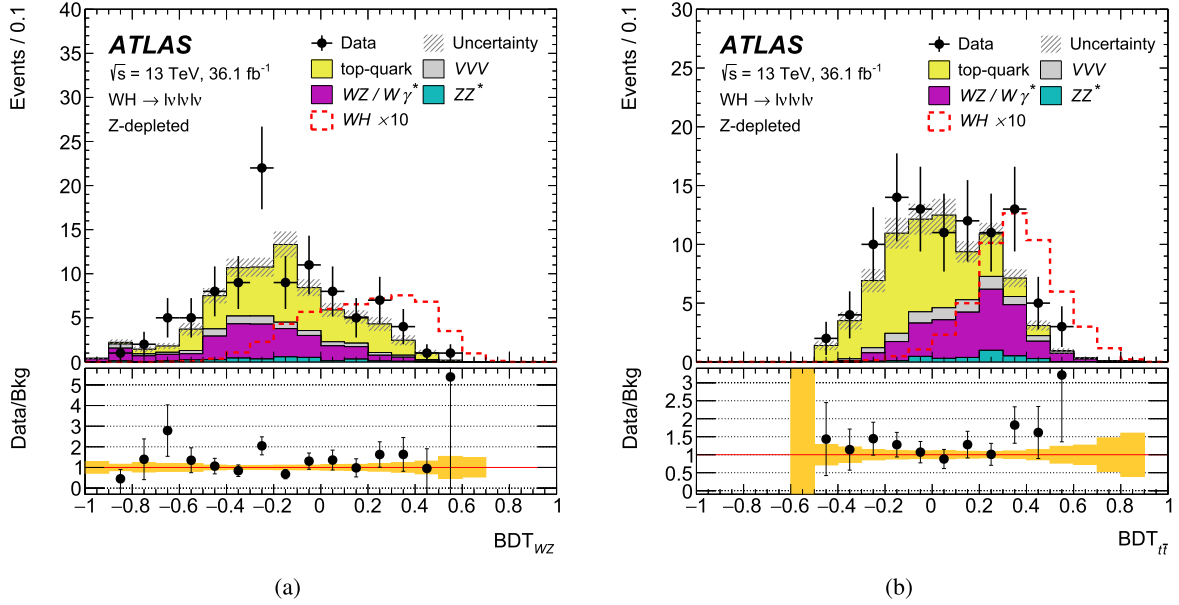
A definition of the most likely lepton from heavy-flavour decays ( $\ell_{\text{HFL}}$ ) is crucial for an optimal performance of the  $\text{BDT}_{t\bar{t}}$ . For this purpose, a  $\text{BDT}_{\text{HFL}}$  is trained purely on data using track and calorimeter isolation as well as impact-parameter variables as input. The lepton with the minimal  $\text{BDT}_{\text{HFL}}$  output is selected as  $\ell_{\text{HFL}}$ . The  $\text{BDT}_{t\bar{t}}$  uses nine input variables, of which two common to the  $\text{BDT}_{\text{Zdom}}$  and  $\text{BDT}_{WZ}$  are  $m_{\ell_0\ell_1}$  and  $\Delta\eta_{\ell_1\ell_2}$ , one common to the  $\text{BDT}_{\text{Zdom}}$  is  $\Delta R_{\ell_0\ell_1}$ , and the other input variables are the number of jets ( $N_{\text{jet}}$ ), the transverse momentum of the leading jet ( $p_T^{\text{lead}}$ ), the invariant mass of the leptons with same-sign charge ( $m_{\ell_1\ell_2}$ ), and three  $\ell_{\text{HFL}}$ -related variables: its  $\text{BDT}_{\text{HFL}}$  output, its transverse momentum,  $p_T^{\ell_{\text{HFL}}}$ , and the invariant mass built from it together

<sup>2</sup> Given the reconstructed charged-lepton momenta and the  $\vec{p}_T^{\text{miss}}$ , the event kinematics can be calculated under the  $WZ$  with  $Z \rightarrow \tau\tau$  hypothesis and using the collinear approximation for the  $\tau$  decays with one remaining unknown, e.g. the ratio of one  $\tau$  energy to the energy of the lepton from this  $\tau$  decay. This unknown is varied and the number of physical kinematic solutions is taken as a measure of the compatibility with the  $WZ$  hypothesis.

**Table 2**

Event selection criteria used to define the signal regions in the  $WH$  and  $ZH$  analyses. The symbols are defined in the text.

Category	$WH$		$ZH$	
	Z-dominated	Z-depleted	2-SFOS	1-SFOS
Preselection	3 isolated leptons ( $p_T > 15$ GeV) total lepton charge $\pm 1$		4 isolated leptons ( $p_T > 10$ GeV) total lepton charge 0	
Number of SFOS	2 or 1	0	2	1
Number of jets	$\leq 1$	—	$\leq 1$	$\leq 2$
Number of $b$ -jets	0	0	0	0
$E_T^{\text{miss}}$ [GeV]	$> 30$	—	$> 45$	—
$p_T^{A\ell}$ [GeV]	—	—	$> 45$	—
$m_{\ell\ell}$ [GeV]	$> 12$ (min. SFOS)	—	$> 10$	$> 10$
$ m_{\ell\ell} - m_Z $ [GeV]	$> 25$ (SFOS)	—	$< 10$ ( $m_{\ell_2\ell_3}$ )	$< 10$ ( $m_{\ell_2\ell_3}$ )
$m_{\ell_0\ell_1}$ [GeV]	—	—	$< 55$	$< 60$
$\Delta\phi_{\ell_0\ell_1}^{\text{boost}}$	—	—	$< 2.3$	$< 1.9$
$m_{\tau\tau}$ [GeV]	—	—	—	$< 50$
$\Delta\phi_{\ell_0\ell_1, \vec{p}_T^{\text{miss}}}$ [rad]	—	—	—	$> 0.4$
$m_{4\ell}$ [GeV]	—	—	$> 140$	—
BDT	$\text{BDT}_{\text{Zdom}} > 0.3$	$\text{BDT}_{\ell\bar{\ell}} > 0.2 \& \text{BDT}_{WZ} > 0.15$	—	—



**Fig. 3.** Distribution of (a)  $\text{BDT}_{WZ}$  and (b)  $\text{BDT}_{\ell\bar{\ell}}$  in the Z-depleted category. The dashed line shows the  $WH$  signal scaled by a factor of 10. The hatched band in the upper panel and the shaded band in the lower panel show the total statistical and experimental systematic uncertainty in background predictions. The  $WZ/W\gamma^*$  and top-quark background processes are normalised with the normalisation factors from the control region analysis (Table 4).

**Table 3**

Summary of the Z-depleted fit regions.

Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6
$0.2 \leq \text{BDT}_{\ell\bar{\ell}} < 0.3$		$0.3 \leq \text{BDT}_{\ell\bar{\ell}} < 0.45$		$0.45 \leq \text{BDT}_{\ell\bar{\ell}}$	
$0.15 \leq \text{BDT}_{WZ} < 0.35$	$0.35 \leq \text{BDT}_{WZ}$	$0.15 \leq \text{BDT}_{WZ} < 0.35$	$0.35 \leq \text{BDT}_{WZ}$	$0.15 \leq \text{BDT}_{WZ} < 0.35$	$0.35 \leq \text{BDT}_{WZ}$

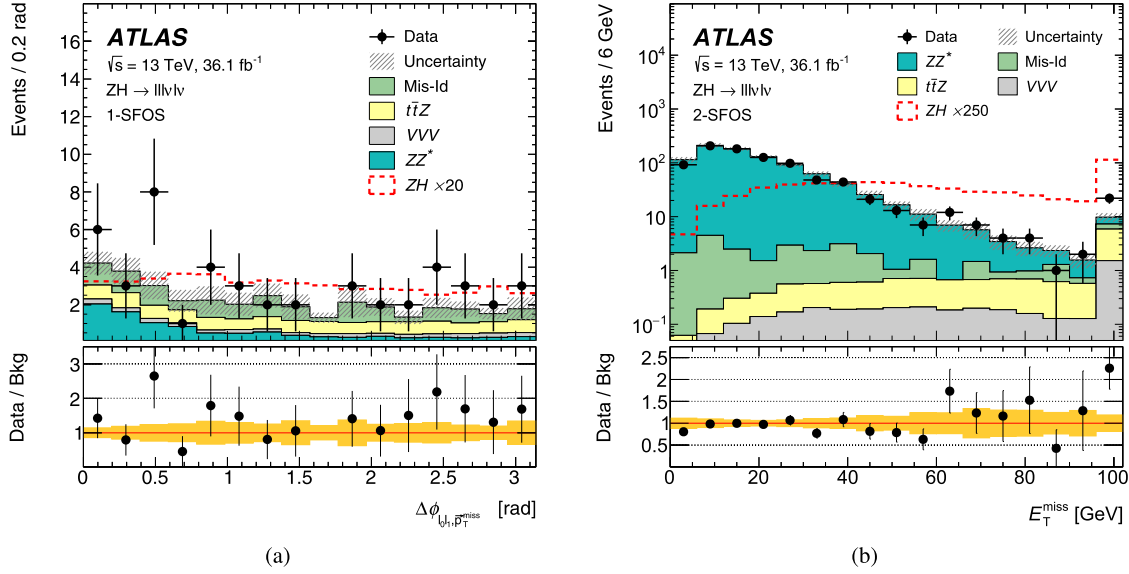
with the closest opposite-charge lepton ( $m_{\ell_{\text{HFL}}\ell_{\text{cloc}}}$ ). Fig. 3 shows the outputs of  $\text{BDT}_{WZ}$  and  $\text{BDT}_{\ell\bar{\ell}}$  in the Z-depleted category, before applying any selection requirements on the BDT scores.

The choice of input variables for the different BDTs was the result of an optimisation study where several thousand different BDTs using different set of input variables have been compared and the best performing BDTs have been selected for the final analysis.

The full Z-depleted event selection is summarised in Table 2. The events with high-ranking BDT scores ( $\text{BDT}_{\ell\bar{\ell}} > 0.2$  and  $\text{BDT}_{WZ} > 0.15$ ) are used to define the Z-depleted SR. In this region, the BDT scores are used as discriminant variables in the statistical analysis, with three bins in  $\text{BDT}_{\ell\bar{\ell}}$ , each being subdivided into

two bins in  $\text{BDT}_{WZ}$  as shown in Table 3. The expected signal-to-background ratio in these bins ranges from about 0.07 in the first bin up to about 3.6 in the last bin. The signal efficiency with respect to the preselection, before any cut on the BDT scores, is 23.5%.

The  $ZH$  channel requires events to contain four isolated leptons with  $p_T > 10$  GeV and total electric charge of zero. Events that contain a SFOS lepton pair with  $m_{\ell\ell} < 10$  GeV are rejected to suppress the contamination from heavy-flavour quarkonia. Following this preselection, events are classified according to the number of SFOS lepton pairs: 1-SFOS and 2-SFOS. Events with no SFOS lepton pairs are not considered.



**Fig. 4.** Distributions of (a) the azimuthal separation between the Higgs-candidate lepton pair and the missing transverse momentum  $\Delta\phi_{\ell_0\ell_1, \vec{p}_T^{\text{miss}}}$  in 1-SFOS events and (b) the missing transverse momentum  $E_T^{\text{miss}}$  in 2-SFOS events, after preselection. For the latter the last bin contains overflow events. The dashed line shows the  $ZH$  signal scaled by a factor 20 (left) and by a factor 250 (right). The hatched band in the upper panel and the shaded band in the lower panel show the total statistical and experimental systematic uncertainty in background predictions. The  $ZZ^*$  background process is normalised in the 2-SFOS case with the normalisation factor from the control region analysis (Table 4). The Mis-Id background is estimated with the data-driven technique described in Section 6.

The reconstruction of the  $ZH$  process proceeds through the identification of the leptons from the  $Z$  boson, called  $\ell_2$  and  $\ell_3$ , as the SFOS lepton pair with invariant mass closest to the  $Z$  boson mass,  $m_Z$ . Then, the remaining two leptons, labelled  $\ell_0$  and  $\ell_1$ , are candidates for originating from the Higgs boson decay. The background in the  $ZH$  channel is almost exclusively due to  $ZZ^*$  production. This constitutes  $\sim 92\%$  of the total background after the preselection is applied. Processes with four prompt leptons in the final state such as triboson production, in particular  $ZWW$ , which has the same signature as the signal, and  $t\bar{t}Z$  also contribute to the background. Other background processes such as  $WZ/W\gamma^*$ ,  $Z$ +jets and  $tV$  may contribute when at least one jet, hadron or a converted photon is misidentified as a lepton.

In order to suppress the  $t\bar{t}Z$  process, events containing  $b$ -tagged jets are rejected and at most one and two jets are allowed in 2-SFOS and 1-SFOS classes, respectively. To reduce the  $ZZ^*$  background process in events with two SFOS lepton pairs, a threshold of 45 GeV is applied to the  $E_T^{\text{miss}}$  and to the vector sum of the lepton transverse momenta,  $p_T^{4\ell}$ . The invariant mass of  $\ell_2$  and  $\ell_3$ ,  $m_{\ell_2\ell_3}$ , is required to satisfy  $|m_{\ell_2\ell_3} - m_Z| < 10$  GeV, and the invariant mass of  $\ell_0$  and  $\ell_1$ ,  $m_{\ell_0\ell_1}$ , is required to be between 10 GeV and 60 GeV (55 GeV) in 1-SFOS (2-SFOS) events. The variable  $\Delta\phi_{\ell_0\ell_1}^{\text{boost}}$  denotes the difference in azimuthal angle between the leptons from the Higgs boson candidate in the frame where the Higgs boson  $p_T$  is zero. The Higgs boson transverse momentum is approximated with  $\vec{p}_T^H \approx -\vec{p}_T^Z$ , or  $\vec{p}_T^H \approx -\vec{p}_T^Z - \sum \vec{p}_T^{\text{jet}}$  if at least one jet is present in the event. Events are required to satisfy  $\Delta\phi_{\ell_0\ell_1}^{\text{boost}} < 1.9$  (2.3) rad in the 1-SFOS (2-SFOS) class. In 1-SFOS events the  $ZZ^*$  process contributes through the  $Z \rightarrow \tau\tau$  decay, therefore the reconstructed mass of the  $\tau$  pair,  $m_{\tau\tau}$  is required to be below 50 GeV;  $m_{\tau\tau}$  is computed using the collinear approximation method [65]. In addition, the azimuthal separation between the Higgs-candidate lepton pair and the  $\vec{p}_T^{\text{miss}}$ ,  $\Delta\phi_{\ell_0\ell_1, \vec{p}_T^{\text{miss}}}$ , is required to be above 0.4 rad. The final selection of these variables is optimised in order to maximise the signal significance. Fig. 4(a) illustrates the discriminating power of the  $\Delta\phi_{\ell_0\ell_1, \vec{p}_T^{\text{miss}}}$  variable for 1-SFOS events after the preselection. This variable reduces the  $ZZ^*$

contribution which becomes the dominant background source after the  $b$ -tagged jet veto and  $m_{\ell_0\ell_1}$  selection are applied. Fig. 4(b) shows the  $E_T^{\text{miss}}$  distribution for 2-SFOS events after the preselection. In order to be orthogonal to the  $H \rightarrow ZZ^*$  analysis of Ref. [66], 2-SFOS events are required to have an invariant mass of the four-lepton system,  $m_{4\ell}$ , above 140 GeV. The full event selection for  $ZH$  is summarised in Table 2.

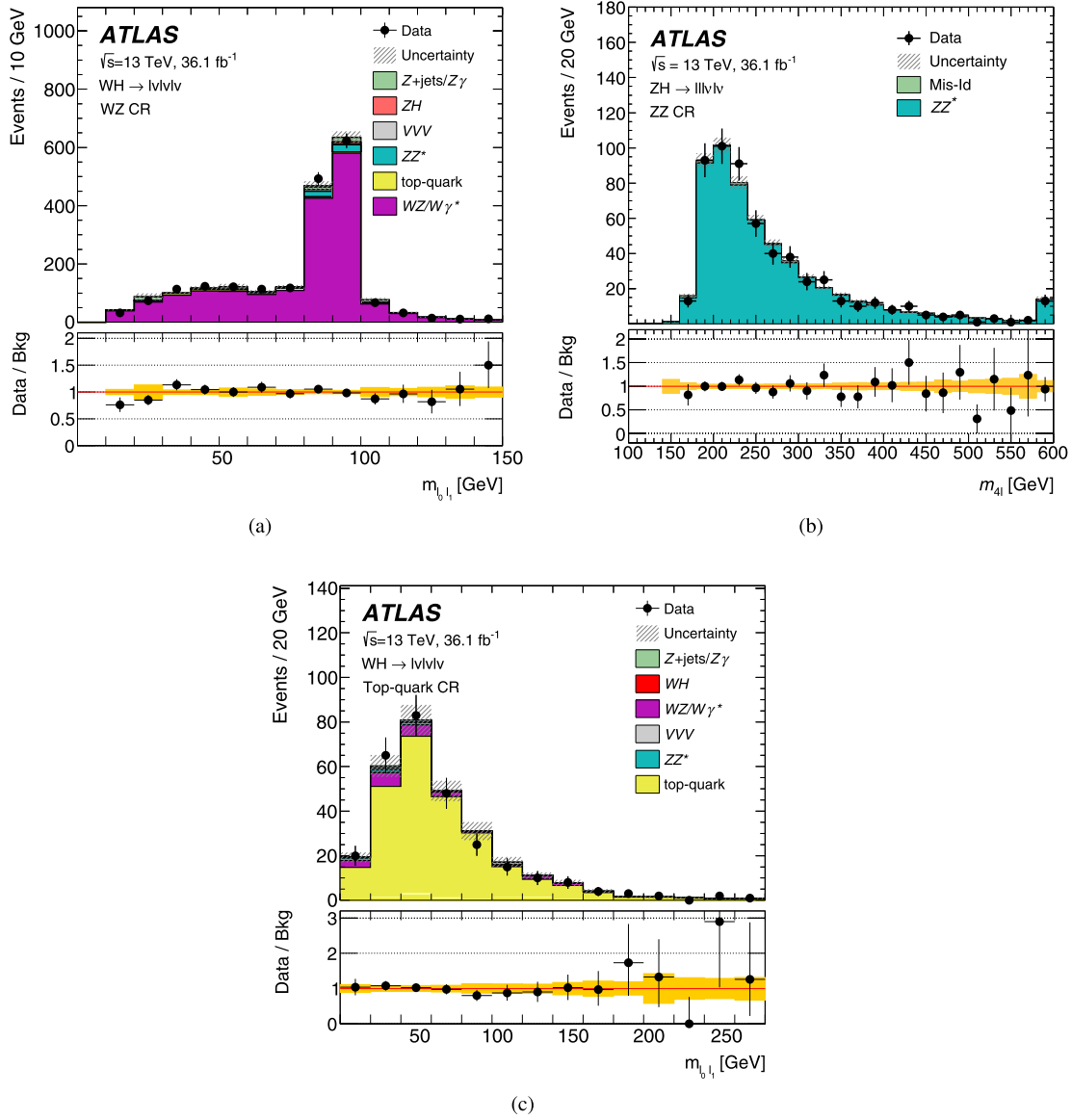
The total efficiency times acceptance of this selection for the process  $WH$  with subsequent  $H \rightarrow WW^*$  decay is about 0.073% while for  $ZH$  it is about 0.026%. These numbers are given with respect to all  $W$  and  $Z$  decays.

## 6. Background estimation

The main background contamination originates from processes with the same final state as the signal, namely diboson production ( $WZ/W\gamma^*$ ,  $ZZ^*$ ), top-quark processes with three or four prompt leptons such as  $t\bar{t}V$ , and triboson production. Other relevant background contributions arise from processes, such as  $t\bar{t}$  or  $Z$ +jets, where the reconstructed leptons either originate from non-prompt decays of heavy-flavour hadrons or from jets misidentified as leptons.

Two dedicated regions, hereafter named control regions (CRs), are used to estimate the normalisation factors (NFs) of the main prompt background processes by fitting the expected yields from simulation to data:  $WZ/W\gamma^*$  for the  $WH$  channel and  $ZZ^*$  for the  $ZH$  channel in the 2-SFOS SR. In the 1-SFOS SR,  $ZZ^*$  is estimated purely from simulation.

The CRs are made orthogonal to the corresponding SRs by inverting various selection criteria with respect to the SR definitions. The  $WZ$  CR is defined by reversing the  $Z$ -veto in the  $Z$ -dominated  $WH$  signal region. To improve the purity of the  $WZ$  CR, the minimum  $E_T^{\text{miss}}$  is increased from 30 GeV to 50 GeV. The  $ZZ$  CR is defined by inverting the  $m_{\ell_0\ell_1}$  requirement defined in the  $ZH$  2-SFOS SR. In order to increase the number of events, the  $E_T^{\text{miss}}$ ,  $\Delta\phi_{\ell_0\ell_1}^{\text{boost}}$ ,  $p_T^{4\ell}$ , and  $m_{4\ell}$  requirements are removed. Table 4 summarises the event selection for the  $WZ$  and  $ZZ$  CRs and the NFs for the background processes, obtained from the fit described in



**Fig. 5.** Post-fit distributions of the dilepton invariant mass  $m_{l_0 l_1}$  in the WZ CR (a) and of the four-lepton invariant mass  $m_{4l}$  in the ZZ CR (b). For the latter the last bin contains overflow events. Post-fit distributions of the dilepton invariant mass  $m_{l_0 l_1}$  is shown also in the top-quark CR (c). The hatched band in the upper panel and the shaded band in the lower panel show the total statistical and experimental systematic uncertainty in background predictions. The Mis-Id background is estimated with the data-driven technique described in Section 6.

**Table 4**

Definition of control regions in the  $WH$  and  $ZH$  analyses. Selections indicated in boldface font are designed to ensure the control region (CR) is orthogonal to the relevant SR. In the last line normalisation factors which scale the corresponding yields in the signal region are shown with their uncertainties, including both the statistic and the systematic uncertainties.

Channel (Category)	$WH$ (Z-dominated and Z-depleted)		$ZH$ (2-SFOS)
	WZ	Top-quark	ZZ
Number of leptons	3	3	4
Total lepton charge	$\pm 1$	$\pm 1$	0
Number of SFOS	2 or 1	$\leq 2$	2
Number of jets	$\leq 1$	$\geq 1$	$\leq 1$
Number of $b$ -jets	0	$\geq 1$	0
$E_T^{\text{miss}}$ [GeV]	$> 50$	$> 50$ (2 or 1 SFOS)	—
$ m_{\ell\ell} - m_Z $ [GeV]	$< \mathbf{25}$	$> 25$ (2 or 1 SFOS)	$< 10$ ( $m_{\ell_2 \ell_3}$ )
$m_{l_0 l_1}$ [GeV]	—	—	$> \mathbf{55}$
$m_{\ell\ell}$ (min. SFOS) [GeV]	$> 12$	$> 12$ (2 or 1 SFOS)	—
Normalisation factors	$0.99 \pm 0.05$	$0.97 \pm 0.08$	$1.13 \pm 0.06$

Section 8. The NFs are hereby completely dominated by the CR statistics and their values do not change when only the control regions are used in the fit. Figs. 5(a) and 5(b) show the distributions of  $m_{l_0 l_1}$  in the WZ CR and the invariant mass of the four leptons in the ZZ CR, as obtained from the final fit in the statistical analysis (post-fit) described in Section 8.

The background contributions with misidentified leptons are estimated using different techniques. The top-quark background in the  $WH$  channels is normalised using a CR (top-quark CR) defined by requiring at least one  $b$ -tagged jet. To improve the purity of the top-quark CR, the minimum  $E_T^{\text{miss}}$  is increased from 30 GeV to 50 GeV if at least one SFOS pair is present in the event. Processes with one misidentified lepton ( $t\bar{t}$  and  $Wt$ ) constitute 94% of the top-quark CR, the remaining events contain three prompt leptons from  $t\bar{t}W$  decays. The full selection requirements applied to define the top-quark CR and the measured NF are also summarised in Table 4. Fig. 5(c) shows the  $m_{l_0 l_1}$  distribution in the top-quark CR as obtained from the final fit.

**Table 5**

Post-fit predictions and data yields in the four SRs. The uncertainties include those from the sample statistics, and the theoretical and experimental systematic uncertainties. The sum of the single contributions may differ from the total value due to rounding. Moreover, the total uncertainty differs from the sum in quadrature of the single-process uncertainties due to the correlations. “Other Higgs” contains Higgs production mechanisms and decay processes different from  $VH$  and  $H \rightarrow WW^*$  respectively, except for the  $H \rightarrow ZZ^*$  contribution which is included in the “ $ZZ^*$ ” row. The corresponding pre-fit predictions for the background processes differ only by the normalization factors listed in Table 4.

Process	$WH$		$ZH$	
	Z-dominated	Z-depleted	1-SFOS	2-SFOS
$WH$	$11 \pm 6$	$5.8 \pm 2.8$	–	–
$ZH$	$1.1 \pm 0.6$	$0.61 \pm 0.34$	$3.3 \pm 1.7$	$1.8 \pm 0.9$
$WZ/W\gamma^*$	$40.1 \pm 2.8$	$1.7 \pm 0.5$	–	–
$ZZ^*$	$2.4 \pm 1.1$	$0.27 \pm 0.09$	$0.14 \pm 0.14$	$1.2 \pm 0.3$
$VVV$	$1.5 \pm 0.1$	$0.71 \pm 0.11$	$0.32 \pm 0.05$	$0.20 \pm 0.03$
$tV/t\bar{t}V$	$0.14 \pm 0.03$	$0.13 \pm 0.03$	$0.04 \pm 0.02$	$0.03 \pm 0.01$
Other top-quark	$8.4 \pm 2.6$	$1.9 \pm 0.8$	–	–
Other Higgs	$0.31 \pm 0.03$	$0.06 \pm 0.01$	$< 0.01$	$0.04 \pm 0.01$
Misid. leptons	$9.7 \pm 3.4$	$< 0.1$	$0.19 \pm 0.08$	$0.36 \pm 0.12$
Total background	$62 \pm 5$	$4.7 \pm 1.0$	$0.65 \pm 0.17$	$1.8 \pm 0.3$
Observed	76	10	5	2

A data-driven technique is used to estimate the  $Z$ +jets and  $Z\gamma$  contribution in both the  $WH$  and  $ZH$  channels and the contributions from  $WZ/W\gamma^*$  and top-quark processes in the  $ZH$  channel. These contributions typically have one misidentified lepton ( $Z$ +jets and  $Z\gamma$  in the  $WH$  channel, and  $WZ/W\gamma^*$  and  $tZ/t\bar{t}W$  in the  $ZH$  channel) or two misidentified leptons ( $Z$ +jets and  $tW/t\bar{t}$  in the  $ZH$  channel). A control sample where one or two of the lepton candidates fail to meet the nominal identification or isolation criteria but satisfy looser identification criteria, referred to as anti-identified leptons, is used. The contribution from misidentified leptons in the SR is then obtained by scaling the number of events in the control sample by extrapolation factors measured in a data sample enriched in  $Z$ +jets events. The latter is obtained by selecting events with two prompt leptons from a  $Z$  boson decay and a loosely identified lepton considered to be the misidentified lepton candidate. The extrapolation factors are defined as the ratio of the number of misidentified lepton candidates that pass the nominal identification criteria to the number that pass the anti-identification criteria. In both the control sample and the data samples enriched in  $Z$ +jets events, the contribution from background events not estimated with this method is subtracted using MC expectations. Details of this method can be found in Ref. [67]. The uncertainty in the data-driven background processes described in this section includes the statistical uncertainty in the  $Z$ +jets enriched sample, the uncertainty from  $Z$ +jets MC modelling, and the theory uncertainty from the subtraction of other processes. For the  $ZH$  channel, which can have events with two prompt leptons and two misidentified leptons, the uncertainty in the extrapolation from the control sample to the SRs is also included.

## 7. Systematic uncertainties

The systematic uncertainties can be categorised into those arising from experimental sources and those from theoretical sources. The dominant experimental uncertainties come from the misidentification of leptons (see Section 6), the mismodelling of the impact-parameter significance, the  $b$ -tagging efficiency [61] and the jet energy scale and resolution [58]. Other sources of uncertainty are due to the modelling of pile-up, the calibration of the missing transverse momentum measurement [62], and the luminosity measurement. The uncertainty in the combined 2015+2016 integrated luminosity is 2.1%. It is derived from the calibration of

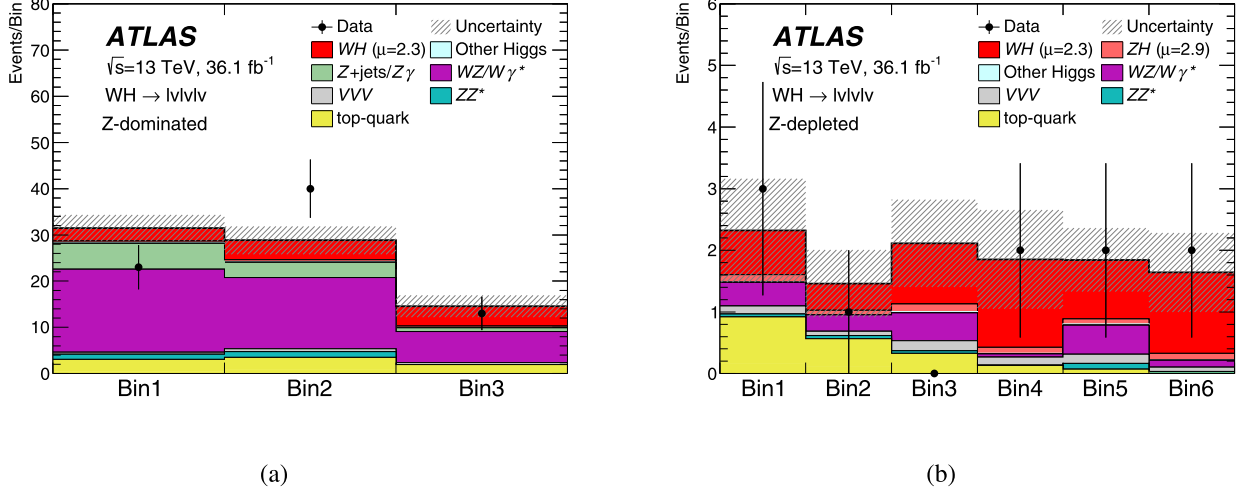
the luminosity scale using  $x$ - $y$  beam-separation scans, following a methodology similar to that detailed in Ref. [68], and using the LUCID-2 detector for the baseline luminosity measurements [69].

The impact of the uncertainties on lepton energy (momentum) scale and resolution, and identification and isolation criteria [54, 55, 70] is negligible. The experimental uncertainties are varied in a correlated way across all background processes and all signal- and control-region bins, so that uncertainties in the extrapolation from control to signal regions are correctly propagated. The luminosity uncertainty is only applied to background processes that are normalised to theoretical predictions, and to the Higgs boson signal. The theoretical uncertainties are evaluated by comparing nominal and alternative event generators and UEPS models as described in Section 3 and by varying PDF sets and the QCD renormalisation and factorisation scales. The uncertainty due to the PDF choice for the signal process is 1% while the uncertainty obtained by using HERWIG as an alternative parton shower model is 3–10%, depending on the signal region. All uncertainties are propagated through the full analysis chain and treated as being bin-dependent and region-dependent, i.e. potentially modifying not only the normalisation but also the shape of the BDT output distributions. Whenever the influence on the shape is found to be negligible, as in the case of the PDF and scale variations, only the normalisation uncertainties are used. A list of the systematic uncertainty sources and their impact on the cross-section measurement are shown later in Section 8.

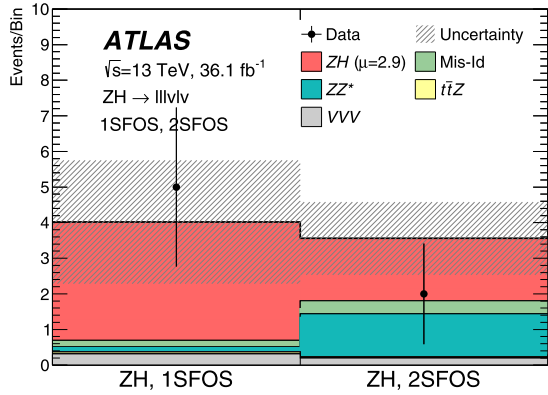
## 8. Results

A binned likelihood function is constructed as a product of Poisson probability terms over the eleven bins of the different SRs defined in Section 5. The function has two independent scaling parameters: the signal strength parameter  $\mu$ , defined as the ratio of the measured signal yield to that predicted by the SM, for each of the  $WH$  and the  $ZH$  processes. Additionally, one Poisson probability term is added for each CR to determine simultaneously the normalisation of the corresponding background processes. Systematic uncertainties enter as nuisance parameters in the likelihood function and their correlations are taken into account. The final results are obtained using the profile likelihood method [71]. The resulting post-fit prediction and data yields in the four SRs are shown in Table 5.





**Fig. 6.** Post-fit BDT-score distributions (a) in the  $WH$  Z-dominated SR and (b) for the two-dimensional grid in  $BDT_{\tilde{t}}$  and  $BDT_{WZ}$  in the  $WH$  Z-depleted SR. The shaded band includes statistical and systematic uncertainties on both signal and background as estimated by the fit.



**Fig. 7.** Post-fit event yields in the  $ZH$  1-SFOS and 2-SFOS SRs. The shaded band includes statistical and systematic uncertainties on both signal and background as estimated by the fit.

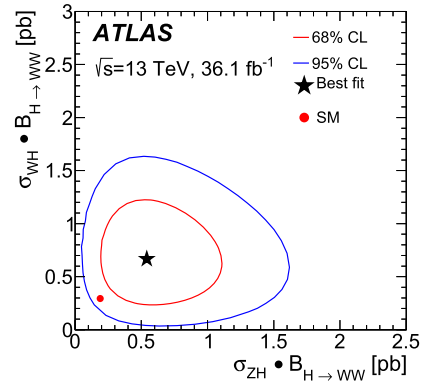
Fig. 6 shows the post-fit distribution of BDT scores in the  $WH$  Z-dominated and Z-depleted SRs. The post-fit event yields in the  $ZH$  1-SFOS and 2-SFOS SRs are shown in Fig. 7.

The measured signal strengths for the  $WH$  and  $ZH$  production modes in the  $H \rightarrow WW^*$  decay channel are simultaneously determined to be

$$\mu_{WH} = 2.3^{+1.1}_{-0.9}(\text{stat.})^{+0.49}_{-0.36}(\text{exp syst.})^{+0.41}_{-0.33}(\text{theo syst.}) = 2.3^{+1.2}_{-1.0},$$

$$\mu_{ZH} = 2.9^{+1.7}_{-1.3}(\text{stat.})^{+0.54}_{-0.28}(\text{exp syst.})^{+0.66}_{-0.27}(\text{theo syst.}) = 2.9^{+1.9}_{-1.3},$$

compared to the expected results of  $\mu_{WH} = 1.0^{+0.86}_{-0.69}(\text{stat.})^{+0.40}_{-0.30}(\text{exp syst.})^{+0.32}_{-0.26}(\text{theo syst.}) = 1.0^{+1.0}_{-0.8}$  and  $\mu_{ZH} = 1.0^{+1.3}_{-0.9}(\text{stat.})^{+0.41}_{-0.20}(\text{exp syst.})^{+0.32}_{-0.16}(\text{theo syst.}) = 1.0^{+1.4}_{-0.9}$ . The observed (expected) significances of  $WH$  and  $ZH$  production modes are 2.6 (1.3) standard deviations and 2.8 (1.2) standard deviations above the SM background, including other Higgs-boson processes, respectively. When determining the significance for  $WH$  production, the  $ZH$  signal-strength parameter is left floating in the fit, and vice versa. The combination of the  $WH$  and  $ZH$  channels leads to an observed (expected) significance for the combined  $VH$  production mode of 4.1 (1.9) standard deviations above the SM background, including other Higgs-boson processes. The  $p$ -value with respect to the value predicted by the SM corresponds to about two stan-



**Fig. 8.** Two-dimensional likelihood contours of  $\sigma_{WH} \cdot \mathcal{B}_{H \rightarrow WW^*}$  vs.  $\sigma_{ZH} \cdot \mathcal{B}_{H \rightarrow WW^*}$  for 68% and 95% confidence level (CL) compared with the prediction from the Standard Model.

dard deviations. The validity of the asymptotic approximation used in deriving these results was tested using pseudo-experiments. The combined signal strength for  $VH$  is measured to be

$$\mu_{VH} = 2.5^{+0.8}_{-0.7}(\text{stat.})^{+0.30}_{-0.23}(\text{exp syst.})^{+0.37}_{-0.26}(\text{theo syst.}) = 2.5^{+0.9}_{-0.8}$$

with an expected signal strength of  $\mu_{VH} = 1.0^{+0.66}_{-0.54}(\text{stat.})^{+0.26}_{-0.17}(\text{exp syst.})^{+0.22}_{-0.17}(\text{theo syst.}) = 1.0^{+0.7}_{-0.6}$ .

The cross-section times branching-fraction values,  $\sigma_{WH} \cdot \mathcal{B}_{H \rightarrow WW^*}$  and  $\sigma_{ZH} \cdot \mathcal{B}_{H \rightarrow WW^*}$ , are simultaneously determined to be:

$$\sigma_{WH} \cdot \mathcal{B}_{H \rightarrow WW^*} = 0.67^{+0.31}_{-0.27}(\text{stat.})^{+0.14}_{-0.11}(\text{exp syst.})^{+0.11}_{-0.09}(\text{theo syst.}) \text{ pb},$$

$$\sigma_{ZH} \cdot \mathcal{B}_{H \rightarrow WW^*} = 0.54^{+0.31}_{-0.24}(\text{stat.})^{+0.10}_{-0.05}(\text{exp syst.})^{+0.11}_{-0.05}(\text{theo syst.}) \text{ pb}.$$

The main contributions to the uncertainties in  $\sigma_{WH} \cdot \mathcal{B}_{H \rightarrow WW^*}$  and  $\sigma_{ZH} \cdot \mathcal{B}_{H \rightarrow WW^*}$  are summarised in Table 6. The predicted cross-section times branching-fraction values are  $0.293 \pm 0.007$  pb and  $0.189 \pm 0.007$  pb for  $WH$  and  $ZH$  [72], respectively. The 68% and 95% confidence level two-dimensional contours of  $\sigma_{WH} \cdot \mathcal{B}_{H \rightarrow WW^*}$  and  $\sigma_{ZH} \cdot \mathcal{B}_{H \rightarrow WW^*}$  are shown in Fig. 8. The corresponding one-dimensional results, where the other parameter is left

**Table 6**

Breakdown of the main contributions to the total uncertainty in  $\sigma_{WH} \cdot \mathcal{B}_{H \rightarrow WW^*}$  (left) and  $\sigma_{ZH} \cdot \mathcal{B}_{H \rightarrow WW^*}$  (right). The individual sources of systematic uncertainties are grouped together. The sum in quadrature of the individual components differs from the total uncertainty due to correlations between the components. Systematic uncertainties that affect the shape of the fitted distribution are indicated by an asterisk.

Source	$\Delta\sigma_{WH} \cdot \mathcal{B}_{H \rightarrow WW^*}$ [%]	Source	$\Delta\sigma_{ZH} \cdot \mathcal{B}_{H \rightarrow WW^*}$ [%]
Data statistics in SR	43	Data statistics in SR	50
Data statistics in CR	6	Data statistics in CR	< 1
Theoretical uncertainties	16	Theoretical uncertainties	15
$WZ/W\gamma^{* (*)}$	12	$ZH$ signal	14
Top-quark <sup>(*)</sup>	8	Top-quark	1
$WH$ signal <sup>(*)</sup>	4	$WZ/W\gamma^{* (*)}$	< 1
$ZZ^{* (*)}$	2	$ZZ^{* (*)}$	< 1
Experimental uncertainties	12	Experimental uncertainties	7
Impact parameter mismodelling	8	Misidentified leptons	3
Misidentified leptons	8	$b$ -tagging	1
$b$ -tagging	1	MC statistics	11
MC statistics	9	Luminosity	2
Luminosity	3	TOTAL	54
TOTAL	49		

floating in the fit, are consistent with the SM predictions within  $1.3\sigma$  for  $WH$  and  $1.5\sigma$  for  $ZH$ .

## 9. Conclusion

Measurements of the inclusive production of a Higgs boson in association with a  $W$  or  $Z$  boson are presented. Results of the  $WH$  and  $ZH$  production cross section times branching fraction for  $H \rightarrow WW^*$  are obtained selecting the leptonic decays  $W \rightarrow \ell\nu$  and  $Z \rightarrow \ell\ell$ , with  $\ell = e, \mu$ , in  $\sqrt{s} = 13$  TeV proton–proton collisions recorded with the ATLAS detector at the LHC in a data sample corresponding to an integrated luminosity of  $36.1 \text{ fb}^{-1}$ . The products of the  $H \rightarrow WW^*$  branching fraction times the  $WH$  and  $ZH$  cross sections are measured to be  $0.67^{+0.31}_{-0.27}(\text{stat.})^{+0.18}_{-0.14}(\text{syst.}) \text{ pb}$  and  $0.54^{+0.31}_{-0.24}(\text{stat.})^{+0.15}_{-0.07}(\text{syst.}) \text{ pb}$ , respectively, compatible with the Standard Model predictions of  $0.293 \pm 0.007 \text{ pb}$  for  $WH$  and  $0.189 \pm 0.007 \text{ pb}$  for  $ZH$  within up to  $1.5\sigma$ . The  $WH$  channel with  $H \rightarrow WW^*$  is purely sensitive to the  $HW$  coupling and this measurement is to date the most precise measurement of this channel.

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