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# Search for a heavy charged Higgs boson decaying into a $W$ boson and a Higgs boson in final states with leptons and $b$ -jets in $\sqrt{s} = 13$ TeV $pp$ collisions with the ATLAS detector

The ATLAS Collaboration

This article presents a search for a heavy charged Higgs boson produced in association with a top quark and a bottom quark, and decaying into a  $W$  boson and a 125 GeV Higgs boson  $h$ . The search is performed in final states with one charged lepton, missing transverse momentum, and jets using proton–proton collision data at  $\sqrt{s} = 13$  TeV recorded with the ATLAS detector during Run 2 of the LHC at CERN. This data set corresponds to a total integrated luminosity of  $140 \text{ fb}^{-1}$ . The search is conducted by examining the reconstructed invariant mass distribution of the  $Wh$  candidates for evidence of a localised excess in the charged Higgs boson mass range from 250 GeV to 3 TeV. No significant excess is observed and 95% confidence-level upper limits between 2.8 pb and 1.2 fb are placed on the production cross-section times branching ratio for charged Higgs bosons decaying into  $Wh$ .

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## 1 Introduction

The Higgs boson discovery at the Large Hadron Collider (LHC) was a great success of the ATLAS and CMS collaborations [1, 2]. Following its discovery, numerous studies have been performed to establish whether it is a Standard Model (SM) particle or rather the first observed physical state of an extended scalar sector.

Searches for an extended scalar sector are crucial as numerous models of new physics beyond the SM require additional scalar states. For example, two Higgs doublets [3, 4] are required in the minimal supersymmetric extension of the SM, while Higgs triplets [5–9] are required in models with a type-II seesaw mechanism. In addition, an extended scalar sector can modify the electroweak phase transition and facilitate baryogenesis, enhance vacuum stability, provide a dark matter candidate or provide a solution to the strong CP problem (i.e. predict axions). In short, extending the scalar sector provides solutions to some of the open questions in the SM.

Various theories predicting an extended scalar sector postulate also the existence of at least one set of charged Higgs bosons in addition to the discovered neutral one, such as models that add a second doublet or one or more triplets to the scalar sector. The main production and decay modes of these new particles are strongly model dependent. For example, in the alignment limit of the two-Higgs-doublet model (2HDM) [10], the dominant production mode, for charged Higgs boson masses larger than the sum of the top and the bottom quark masses, is expected to be in association with a top quark and a bottom quark

$(tbH^\pm)$ ,<sup>1</sup> while the dominant charged Higgs boson decay modes are via  $H^\pm \rightarrow tb$  or  $H^\pm \rightarrow \tau^\pm \nu$ . However, there are also several models such as the next-to-minimal two-Higgs-doublet model (N2HDM) [11, 12], the three-Higgs-doublet Model (3HDM) [13] or the Georgi-Machacek model [14] in which other decay and production modes become important. The studies presented in this article search for charged Higgs bosons decaying via  $H^\pm \rightarrow W^\pm h$ , where  $h$  is a Higgs boson with mass  $m_h = 125$  GeV. This decay mode is predicted to have significant branching ratios by various extended scalar sector models [15–18].

The ATLAS and CMS collaborations searched for charged Higgs bosons in proton–proton ( $pp$ ) collisions at  $\sqrt{s} = 7, 8$  and 13 TeV with data samples corresponding to integrated luminosities ranging from 2.9 up to 140 fb<sup>-1</sup>, probing the mass range below the top-quark mass in the  $\tau^\pm \nu$  [19–24],  $cs$  [25, 26], and  $cb$  [27, 28] decay modes, as well as above the top-quark mass in the  $\tau^\pm \nu$  [29] and  $tb$  [30–32] decay modes. Searches for  $H^\pm \rightarrow W^\pm Z$  decays have been performed in the vector-boson-fusion (VBF) production mode [33–35]. Searches for doubly-charged Higgs bosons have also been performed [35–38]. Charged Higgs boson decays via  $H^\pm \rightarrow W^\pm h$  have been so far not yet searched for by either the ATLAS or CMS collaborations.

This article describes a first search for a charged Higgs boson produced in association with a top quark and a bottom quark with subsequent decays of the charged Higgs boson via  $H^\pm \rightarrow W^\pm h \rightarrow \ell^\pm \nu b \bar{b}$  or  $H^\pm \rightarrow W^\pm h \rightarrow q \bar{q} b \bar{b}$ . The search is performed in events that are consistent with the final state  $\ell^\pm \nu b \bar{b} b \bar{b} q \bar{q}$  (with  $\ell = e, \mu$ ), where the charged lepton can originate either from the decay chain of the charged Higgs boson or of the associated top quark. Representative lowest-order Feynman diagrams of these processes are shown in Figure 1.

To ensure high sensitivity to both low- and high-mass resonances, two different analysis techniques are used. At low charged Higgs boson masses, when the final state particles have a relatively low Lorentz-boost, the decay products of neutral Higgs boson and hadronically decaying  $W$  boson are reconstructed via individual small-radius jets (such decays are referred to as ‘resolved’). At high charged Higgs boson masses, when the final state particles have a relatively large Lorentz-boost, the neutral Higgs boson and the hadronically decaying  $W$  boson are reconstructed as single large-radius jets (such decays are referred to as ‘merged’).

The search for charged Higgs bosons is performed by probing for a localised excess in the invariant mass distribution of the reconstructed  $\ell^\pm \nu b \bar{b}$  and  $q \bar{q} b \bar{b}$  systems. This is achieved through a simultaneous profile likelihood fit on the invariant mass distribution obtained in selected signal and control regions. The signal and control regions are defined based on requirements on kinematic properties of the final-state particles and event-level quantities. Multivariate analysis techniques are used to improve the background rejection and to reconstruct the decays of the charged Higgs boson candidates. The major backgrounds are modelled using simulation and their normalisations are determined by a profile-likelihood fit to data. The results are presented as upper limits at 95% confidence level (CL) on the production cross-section times branching ratio  $\sigma(pp \rightarrow tbH^\pm) \times \mathcal{B}(H^\pm \rightarrow W^\pm h) \times \mathcal{B}(h \rightarrow b \bar{b})$  of the signal process. In this article, charged Higgs boson mass hypotheses are probed in a range from 250 GeV to 3 TeV.

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<sup>1</sup> The notation  $tbH^\pm$  is used to represent the  $\bar{t}bH^+$  and  $t\bar{b}H^-$  processes. In general, the difference between particles and antiparticles is to be understood from the context.

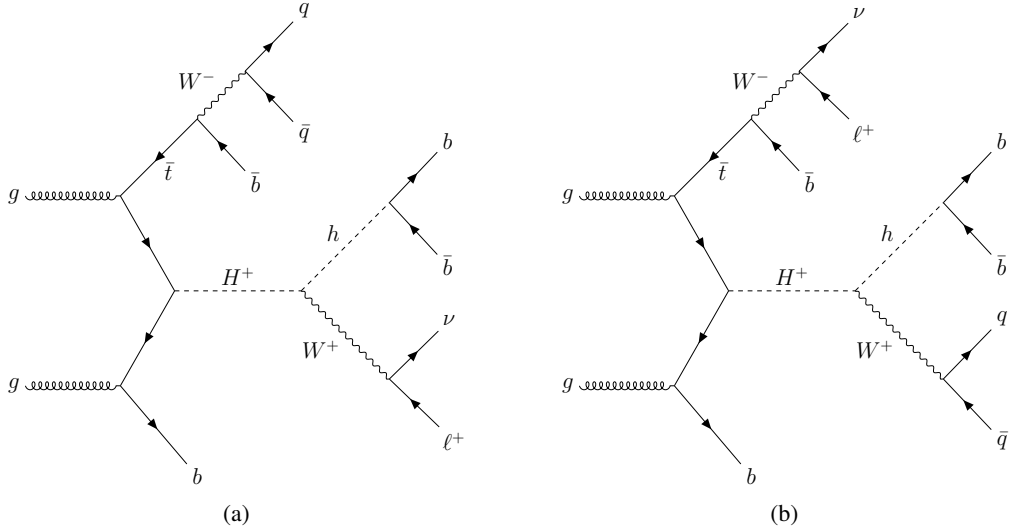


Figure 1: Representative lowest-order Feynman diagrams of  $pp \rightarrow \bar{t}bH^+$  production and subsequent decays via (a)  $H^+ \rightarrow W^+h \rightarrow \ell^+\nu b\bar{b}$  and (b)  $H^+ \rightarrow W^+h \rightarrow q\bar{q}b\bar{b}$ .

## 2 ATLAS detector

The ATLAS detector [39] at the LHC covers nearly the entire solid angle around the collision point.<sup>2</sup> It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three large superconducting air-core toroidal magnets.

The inner-detector system (ID) is immersed in a 2 T axial magnetic field and provides charged-particle tracking in the range  $|\eta| < 2.5$ . The high-granularity silicon pixel detector typically provides four measurements per track, the first hit generally being in the insertable B-layer (IBL) installed before Run 2 [40, 41]. It is followed by the SemiConductor Tracker (SCT), which usually provides eight measurements per track. These silicon detectors are complemented by the transition radiation tracker (TRT), which enables radially extended track reconstruction up to  $|\eta| = 2.0$ . The TRT also provides electron identification information based on the fraction of hits (typically 30 in total) above a higher energy-deposit threshold corresponding to transition radiation.

The calorimeter system covers the pseudorapidity range  $|\eta| < 4.9$ . Within the region  $|\eta| < 3.2$ , electromagnetic calorimetry is provided by barrel and endcap high-granularity lead/liquid-argon (LAr) calorimeters, with an additional thin LAr presampler covering  $|\eta| < 1.8$  to correct for energy loss in material upstream of the calorimeters. Hadronic calorimetry is provided by the steel/scintillator-tile calorimeter, segmented into three barrel structures within  $|\eta| < 1.7$ , and two copper/LAr hadronic endcap calorimeters. The solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules optimised for electromagnetic and hadronic energy measurements respectively.

<sup>2</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. Polar 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  $\eta = -\ln \tan(\theta/2)$  and is equal to the rapidity  $y = \frac{1}{2} \ln \left( \frac{E+p_z}{E-p_z} \right)$  in the relativistic limit. Angular distance is measured in units of  $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$ .

The muon spectrometer (MS) comprises separate trigger and high-precision tracking chambers measuring the deflection of muons in a magnetic field generated by the superconducting air-core toroidal magnets. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. Three layers of precision chambers, each consisting of layers of monitored drift tubes, cover the region  $|\eta| < 2.7$ , complemented by cathode-strip chambers in the forward region, where the background is highest. The muon trigger system covers the range  $|\eta| < 2.4$  with resistive-plate chambers in the barrel, and thin-gap chambers in the endcap regions.

The luminosity is measured mainly by the LUCID-2 [42] detector that records Cherenkov light produced in the quartz windows of photomultipliers located close to the beam pipe.

Events are selected by the first-level trigger system implemented in custom hardware, followed by selections made by algorithms implemented in software in the high-level trigger [43]. The first-level trigger accepts events from the 40 MHz bunch crossings at a rate below 100 kHz, which the high-level trigger further reduces in order to record complete events to disk at about 1 kHz.

A software suite [44] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

### 3 Data and simulated event samples

The  $pp$  collision data at  $\sqrt{s} = 13$  TeV used in the analysis were recorded with the ATLAS detector between 2015 and 2018, and correspond to a total integrated luminosity of  $140.0 \pm 1.2 \text{ fb}^{-1}$  [45]. The data are required to satisfy criteria that ensure that the detector was in good operating condition [46]. Monte Carlo (MC) simulation samples were used to model the background and signal processes, as well as to derive modelling uncertainties. The MC simulation samples were processed using either the GEANT4-based simulation of the ATLAS detector geometry and response [47, 48] or fast simulation [49], where the GEANT4 simulation of the calorimeter response is replaced by a detailed parameterisation of shower shapes. The simulated events were reconstructed using the same algorithms as were used for the data events.

The signal process, i.e. the associated production of a charged Higgs boson, a bottom quark and a top quark, was simulated using the matrix element (ME) generator MADGRAPH5\_AMC@NLO 2.7.3 [50] in the 4-flavour scheme (4FS) at next-to-leading-order (NLO) accuracy in QCD and the NNPDF3.0NLO [51] set of parton distribution functions (PDFs). PYTHIA 8.244 [52] with the A14 set [53] of tuned parameters is used to decay the charged Higgs boson and to model the parton shower (PS), hadronisation, and underlying event. The renormalisation and factorisation scales  $\mu_R$  and  $\mu_F$  were set to  $\frac{1}{3} \sum_i \sqrt{m_i^2 + p_{T,i}^2}$ , where  $i$  runs over all final state particles used in the matrix element calculation. The signal process is simulated using the FeynRules [54] model 2HDMtypeII [55] using a narrow-width approximation. The choice of model is expected to have only small impact on the results of this search as long as the narrow-width approximation is valid. While specific models may alter the cross-section times branching ratio values, they typically do not affect the event kinematics of the  $tbH^\pm$  process. Seventeen signal samples were generated covering a mass range between 250 GeV and 3 TeV.<sup>3</sup> Fast detector simulation was employed for mass points below

<sup>3</sup> In the mass range between 250 GeV and 400 GeV, the signal samples are produced in 50 GeV steps, while in the ranges from 400 GeV to 1000 GeV and 1000 GeV to 2000 GeV step sizes of 100 GeV and 200 GeV were chosen. In addition, signal masses of 2500 GeV and 3000 GeV are considered.

500 GeV and the GEANT4-based simulation of the ATLAS detector was used otherwise.<sup>4</sup> In the simulation of the signal processes, only the  $H^+$  decay into  $W^+h$  and Higgs boson decaying to pairs of  $b$ -quarks were considered assuming a Higgs boson mass of  $m_h = 125$  GeV. Other decay modes of the 125 GeV Higgs boson were neglected, as their contributions to the signal and control regions (cf. Section 5) were an order of magnitude lower than those for the  $h \rightarrow b\bar{b}$  decay.

The production of top-quark pair ( $t\bar{t}$ ) events was modelled using the POWHEG BOX v2 [56–59] generator in the five-flavour scheme (5FS) to calculate the ME at NLO accuracy in QCD, and the NNPDF3.0<sub>NLO</sub> PDF set. The  $h_{\text{damp}}$  parameter<sup>5</sup> was set to  $1.5 m_t$  [60], where  $m_t$  is the top-quark mass. The top-quark decays are modelled using MADSPIN [61, 62]. The PS, hadronisation, and underlying event were modelled with the PYTHIA 8.230 generator using the A14 set of tuned parameters and the NNPDF2.3<sub>LO</sub> [63] PDF set. The top-quark pair events are normalised to the state-of-the-art cross-section prediction calculated with TOP++ 2.0 [64–70] at next-to-next-to-leading order (NNLO) in QCD, including the resummation of next-to-next-to-leading logarithmic (NNLL) soft-gluon terms.

The  $t\bar{t} + h$  sample was generated at NLO accuracy in QCD using the POWHEG BOX v2 generator in the 5FS, and the NNPDF3.0<sub>NLO</sub> PDF set. The  $h_{\text{damp}}$  parameter was set to  $\frac{3}{4} \cdot (2m_t + m_h) = 352.5$  GeV and the events were showered with PYTHIA 8.230, which used the A14 set of tuned parameters and the NNPDF2.3<sub>LO</sub> PDF set. The  $t\bar{t} + h$  production cross-section is calculated at NLO accuracy in both QCD and electroweak (EW) using MADGRAPH5\_AMC@NLO, as reported in Ref. [71]. The production of  $t\bar{t} + V$  (with  $V = W^\pm$  or  $Z$ ) events was modelled using the MADGRAPH5\_AMC@NLO 2.3.3 generator, which provides MEs at NLO in QCD with the NNPDF3.0<sub>NLO</sub> PDF set. The events were interfaced to PYTHIA 8.210 using the A14 set of tuned parameters and the NNPDF2.3<sub>LO</sub> PDF set.

The associated production of a top quark and  $W$  boson ( $Wt$ ), and the  $s$ - and  $t$ -channel single-top-quark production were modelled with the POWHEG BOX v2 generator at NLO in QCD using the 5FS and the NNPDF3.0<sub>NLO</sub> set of PDFs. The diagram-removal (DR) scheme [72] was used to remove interference and overlap with the production of top-quark pairs. The events were interfaced to PYTHIA 8.230, which used the A14 set of tuned parameters and the NNPDF2.3<sub>LO</sub> set of PDFs.

Rare processes including top-quarks, such as  $tZq$ ,  $tWZ$ ,  $thjb$ ,  $tWh$ , and  $t\bar{t}\bar{t}$ , were also simulated and accounted for, even though their contribution to any analysis region is lower than 1% of the total background yields. The MADGRAPH5\_AMC@NLO generator and the NNPDF PDF set were used to calculate the MEs for these processes. The events were interfaced to PYTHIA 8.2 using the A14 set of tuned parameters and the NNPDF2.3<sub>LO</sub> set of PDFs. The MEs of the  $tZq$  process was calculated at leading-order (LO) accuracy in QCD, while the MEs of the other four processes were calculated at NLO accuracy in QCD.

A sample of  $V$ +jets events was simulated using SHERPA 2.2.11 [73] with the NNPDF3.0<sub>NNLO</sub> [51] PDF set. The ME was calculated based on the COMIX [74] and OPENLOOPS [75–77] libraries at NLO accuracy in QCD for diagrams with up to two additional parton emissions, and LO accuracy in QCD for diagrams with three, four or five additional parton emissions. The MEPS@NLO prescription [78–81] was used to merge the ME and the SHERPA PS [82], which is based on a set of tuned parameters developed by the SHERPA authors. The  $V$ +jets event sample was normalised to match cross-section predictions at NNLO accuracy in QCD calculated with FEWZ [83].

<sup>4</sup> The decision to employ GEANT4-based simulation for masses above 500 GeV was motivated by the onset of the merged analysis at this mass point and the limitations of the fast detector simulation to accurately describe the properties of large-radius jets, which are essential to the merged analysis.

<sup>5</sup> The  $h_{\text{damp}}$  parameter is a resummation damping factor and one of the parameters that control the matching of POWHEG MEs to the parton shower, effectively regulating the high- $p_T$  radiation against which the  $t\bar{t}$  system recoils.

Diboson ( $VV$ ) events with decays into semileptonic final states were simulated using SHERPA 2.2.1, while events with decays into fully leptonic final states were simulated using SHERPA 2.2.2. Both samples include off-shell effects and Higgs boson contributions where appropriate. Diagrams with up to one additional emission were calculated at NLO accuracy in QCD, while diagrams with two or three parton emissions were described at LO accuracy. The ME calculations were matched and merged with the SHERPA PS using the MEPS@NLO prescription. Virtual QCD corrections for the ME at NLO accuracy were provided by the OPENLOOPS library. Loop-induced diboson processes initiated via the  $gg$  production mode were simulated at LO in QCD for diagrams with up to one additional parton emission in the ME using OPENLOOPS in SHERPA 2.2.2. For electroweak  $VVjj$  production, the calculation of the ME was performed in the  $G_\mu$ -scheme [84] to describe the pure electroweak interactions at the electroweak scale. All diboson events were generated using the NNPDF3.0NNLO PDF set, along with the SHERPA PS.

Finally, the production of a SM Higgs boson in association with a vector boson ( $Vh$ ) was simulated using POWHEG BOX v2, interfaced with PYTHIA 8.212 for PS and non-perturbative effects. The POWHEG prediction is accurate to NLO in QCD for the production of  $Vh$  plus one jet. The loop-induced  $gg \rightarrow Zh$  process was generated separately at LO. The PDF4LHC15 PDF set [85] and the AZNLO set of tuned parameters [86] of PYTHIA 8.212 were used. The  $gg \rightarrow Zh$  production cross-section was calculated at NLO accuracy in QCD, including the resummation of next-to-leading logarithmic (NLL) soft-gluon terms [87]. For the generation of  $Vh$  events, the Higgs boson mass was set to 125 GeV.

All simulated event samples include the effect of multiple  $pp$  interactions in the same and neighbouring bunch crossings (pile-up) by overlaying simulated minimum-bias events on each generated signal and background event. The minimum-bias events were simulated with the single-, double- and non-diffractive  $pp$  processes of PYTHIA 8.186 using the A3 set of tuned parameters [88] and the NNPDF2.3LO PDF set. GEANT4-based simulations of the ATLAS detector were used for the production of the background samples (unless otherwise stated). For all samples produced with MADGRAPH and POWHEG BOX, the EVTGEN 1.6.0 programme [89] was used to model the decays of bottom and charm hadrons. Simulated events were corrected to compensate for differences between data and simulations regarding the energy (or momentum) scale and resolution of leptons and jets, the efficiencies for the reconstruction, identification, isolation and triggering of leptons, and the tagging efficiency for heavy-flavour jets.

A summary of MC generators and programs used to model the signal and background processes is provided in Table 1.

## 4 Event reconstruction

Charged-particle tracks are reconstructed in the ID. They are required to have a transverse momentum ( $p_T$ ) larger than 500 MeV,  $|\eta| < 2.5$ , and at least seven hits in the pixel and SCT detectors. A maximum of one (two) of the expected hits may be missing from the pixel (SCT) detector sensors, and no more than one hit may be shared with other tracks [90]. Collision vertices are reconstructed from at least two ID tracks [91]. Among all vertices, the one with the highest  $p_T^2$  sum of associated tracks is chosen to be the primary vertex (PV) of the event. The properties of ID tracks are calculated relative to the PV.

Electrons are reconstructed from ID tracks originating from the PV that are matched to clusters of energy deposits in the electromagnetic calorimeter [92]. The compatibility of the track and the PV is satisfied by a requirement on the transverse impact parameter significance  $|d_0|/\sigma_{d_0} < 5$ , and on the longitudinal impact parameter  $|z_0 \sin \theta| < 0.5$  mm. Electron candidates must satisfy requirements on the electromagnetic



Table 1: Overview of the simulation tools used to generate signal and background processes, and to model the underlying event and parton shower (UEPS). The PDF sets are also summarised. The perturbative accuracy (in QCD and if relevant in EW corrections) of the total cross-section is stated for each process. Alternative event generators and configurations used to estimate systematic uncertainties are discussed in Section 7.

Process	Matrix element	UEPS	PDF set	Perturbative accuracy of total cross-section
$tbH^\pm(\rightarrow W^\pm h \rightarrow \ell^\pm \nu b\bar{b}, q\bar{q}b\bar{b})$	MADGRAPH5_AMC@NLO 2.7.3	PYTHIA 8.244	NNPDF3.0NLO	NLO (QCD)
$t\bar{t}$ + jets	POWHEG Box v2	PYTHIA 8.230	NNPDF3.0NLO	NNLO+NNLL (QCD)
$t\bar{t} + W^\pm$	MADGRAPH5_AMC@NLO 2.3.3	PYTHIA 8.210	NNPDF3.0NLO	NNLO (QCD) and NLO (EW)
$t\bar{t} + Z$	MADGRAPH5_AMC@NLO 2.3.3	PYTHIA 8.210	NNPDF3.0NLO	NLO+NNLL (QCD)
$t\bar{t} + h$	POWHEG Box v2	PYTHIA 8.230	NNPDF3.0NLO	NLO (QCD) and NLO (EW)
single top quark ( $s$ - and $t$ -channels)	POWHEG Box v2	PYTHIA 8.230	NNPDF3.0NLO	NLO (QCD)
single top quark ( $Wt$ -channel)	POWHEG Box v2	PYTHIA 8.230	NNPDF3.0NLO	approx. NNLO (QCD)
$tZq$	MADGRAPH5_AMC@NLO 2.3.3	PYTHIA 8.210	NNPDF3.0LO	NLO (QCD)
$tWZ$	MADGRAPH5_AMC@NLO 2.3.3	PYTHIA 8.212	NNPDF3.0NLO	NLO (QCD)
$t\bar{t}\bar{t}$	MADGRAPH5_AMC@NLO 2.6.2	PYTHIA 8.230	NNPDF3.1NLO	NLO (QCD)
$thj\bar{b}$	MADGRAPH5_AMC@NLO 2.6.2	PYTHIA 8.230	NNPDF3.0NLO	NLO (QCD)
$tWh$	MADGRAPH5_AMC@NLO 2.6.2	PYTHIA 8.235	NNPDF3.0NLO	NLO (QCD)
$q\bar{q} \rightarrow Wh$	POWHEG Box v2	PYTHIA 8.212	PDF4LHC15	NNLO (QCD) and NLO (EW)
$q\bar{q} \rightarrow Zh$	POWHEG Box v2	PYTHIA 8.212	PDF4LHC15	NNLO (QCD) and NLO (EW)
$gg \rightarrow Zh$	POWHEG Box v2	PYTHIA 8.212	PDF4LHC15	NLO + NLL (QCD)
$W^\pm \rightarrow \ell^\pm \nu, Z \rightarrow \ell^\pm \ell^\mp$	SHERPA 2.2.11		NNPDF3.0NNLO	NNLO (QCD)
$qg/q\bar{q} \rightarrow VV \rightarrow \ell^\pm \ell^\mp / \ell^\pm \nu / \nu \nu + q\bar{q}$	SHERPA 2.2.1		NNPDF3.0NNLO	NLO (QCD)
$qg/q\bar{q} \rightarrow VV \rightarrow \ell^\pm \ell^\mp \ell^\pm \ell^\mp / \ell^\pm \nu \ell^\pm \ell^\mp / \ell^\pm \ell^\mp \nu \nu / \ell^\pm \nu \nu$	SHERPA 2.2.2		NNPDF3.0NNLO	NLO (QCD)
$gg \rightarrow VV$	SHERPA 2.2.2		NNPDF3.0NNLO	NLO (QCD)
$VVjj$	SHERPA 2.2.2		NNPDF3.0NNLO	LO (QCD)

shower shapes, track quality, and track-cluster matching, using a likelihood-based approach [92], where the *Tight* operating point is used for this study. Electrons are also required to have a  $p_T$  larger than 27 GeV and  $|\eta| < 2.47$ , with the transition region between the barrel and endcap electromagnetic calorimeters,  $1.37 < |\eta| < 1.52$ , being excluded. Finally, to reduce contributions from hadrons mimicking electron signatures or non-prompt electrons from heavy-flavour decays or photon conversions, a multivariate classifier is used. This classifier considers the energy deposits and charged-particle tracks in a cone around the electron direction and information from secondary vertices [93].

Muon reconstruction [94] is based on matching MS tracks to ID tracks. A combined fit is then performed incorporating the information from the ID, MS and the energy deposits in the calorimeter system. Similar to electrons, muon candidates have to satisfy selection requirements on the impact parameters:  $|d_0|/\sigma_{d_0} < 3$  and  $|z_0| < 0.5$  mm. Muon candidates are required to have a minimum  $p_T$  of 27 GeV and lie within  $|\eta| < 2.5$ . Furthermore, they are required to satisfy the *Medium* identification operating point. However, candidates with  $p_T > 300$  GeV must satisfy tighter identification requirements in the MS to improve the  $p_T$  resolution [94]. To reduce contributions from non-prompt muons from heavy-flavour decays, muon candidates are required to be isolated in the ID system using the *TightTrackOnly* operating point [94]. A muon is considered to be isolated if the  $p_T$  sum within a cone around the combined track is smaller than 0.06 times the muon's transverse momentum,  $p_T^\mu$ . The size of the isolation cone is  $\Delta R = \min(0.3, 10 \text{ GeV}/p_T^\mu)$  for  $p_T^\mu < 50$  GeV, and remains constant at  $\Delta R = 0.2$  for  $p_T^\mu > 50$  GeV.

Three jet types are reconstructed, using the anti- $k_t$  [95] algorithm as implemented in the FASTJET package [96]: small-radius (denoted small- $R$ ) jets, large-radius (denoted large- $R$ ) jets, and variable-radius jets. The small- $R$  jets are built using a radius parameter of  $R = 0.4$  and particle-flow objects as input [97]. They are required to have  $p_T > 25$  GeV and  $|\eta| < 2.5$ . To reduce the contamination from jets originating from pile-up interactions, a selection requirement on a multivariate classifier is applied to the selected jets. This classifier is based on calorimeter and tracking information and is applied to jets with  $p_T < 60$  GeV



and  $|\eta| < 2.4$  [98]. Large- $R$  jets are used to reconstruct high-momentum Higgs or  $W$ -boson candidates, for which the hadronic decay products are emitted with small angular separation. These jets are built using a radius parameter of  $R = 1.0$  and topological calorimeter clusters with noise suppression as input [99]. The clusters are locally calibrated [100] before being combined into jets. Trimming [101] is used to minimise contributions from initial-state radiation, pile-up interactions or the underlying event. This is done by reclustering the constituents of the initial jet, using the  $k_t$  algorithm [102, 103], into subjets with a radius parameter of  $R^{\text{sub}} = 0.2$  and then removing any subjet with a  $p_T$  less than 5% of the  $p_T$  of the parent jet [104]. The trimmed large- $R$  jets are required to have  $p_T > 250$  GeV and  $|\eta| < 2.0$ . The momenta of both the small- $R$  and large- $R$  jets are corrected for energy losses in passive material and for the non-compensating response of the calorimeter. Small- $R$  jets are also corrected for the average additional energy due to pile-up interactions [105, 106]. A third type of jets is clustered from ID tracks using a variable radius (VR) parameter that shrinks with increasing  $p_T$  of the studied proto-jet [107]. VR track-jets are used in this analysis to identify decays of boosted Higgs bosons into a pair of bottom quarks. The VR track-jets must contain at least two ID tracks compatible with the PV and must have  $p_T > 7$  GeV as well as  $|\eta| < 2.5$ .

Small- $R$  jets containing  $b$ -hadrons are identified ( $b$ -tagged) using the DL1r  $b$ -tagging algorithm [108] based on a deep neural network that combines information from displaced tracks and reconstructed secondary and tertiary vertices inside jets. A jet is  $b$ -tagged if the response value of the DL1r algorithm exceeds a predefined threshold. Four operating points are defined with efficiencies of 60%, 70%, 77%, and 85% for  $b$ -jets, as measured in simulated  $t\bar{t}$  events. These operating points divide the DL1r response score distribution into five intervals. The lower edge of the lowest interval corresponds to a  $b$ -tagging efficiency of 100%, and the upper edge of the highest interval corresponds to an efficiency of 0%. These intervals are referred to as pseudo-continuous operating points. The number of  $b$ -tagged jets per event is evaluated at a fixed  $b$ -tagging efficiency of 77%. Applying the  $b$ -tagging algorithm at this operating point reduces the number of light-flavour and gluon jets, and jets containing  $c$ -hadrons, by a factor of 192 and 5.6, respectively [108]. The pseudo-continuous operating points are used as input to the machine learning algorithms that are designed to reconstruct the charged Higgs boson's decay chain. For this purpose, a score,  $w_{\text{DL1r}}$ , is defined for each jet as the number of pseudo-continuous operating points the jet satisfies, where zero corresponds to failing and four to satisfying all operating points.

Boosted  $h \rightarrow b\bar{b}$  decays are identified exploiting the kinematics of the large- $R$  jet as well as the flavour-tagging information of up to three VR track-jets that are spatially matched via ghost-association [109] to the reconstructed large- $R$  jet [110]. The identification algorithm is based on a feed-forward neural network which is trained using the probabilities of the  $b$ -,  $c$ - and light-flavour hypotheses of the three leading VR track-jets<sup>6</sup> and the  $p_T$  and  $\eta$  of the large- $R$  jet. The neural network is trained to separate boosted  $h \rightarrow b\bar{b}$  jets from boosted top-quark jets and jets arising from multijet processes. The network maps the input vector to a three-dimensional output layer. The three output nodes quantify the probabilities for a large- $R$  jet to correspond to the signal class, and to either of the two background classes. The three output nodes of the neural network are combined into a single discriminant:

$$D_{\text{Xbb}} = \ln \frac{p_{\text{Higgs}}}{f_{\text{top}} \cdot p_{\text{top}} + (1 - f_{\text{top}}) \cdot p_{\text{multijet}}},$$

where  $f_{\text{top}}$  determines the fraction of top-quark jets, which is set to  $f_{\text{top}} = 0.25$ . Furthermore,  $p_{\text{Higgs}}$ ,  $p_{\text{top}}$ , and  $p_{\text{multijet}}$  are the probabilities for the Higgs boson jet, top-quark jet, and multijet hypotheses. An

<sup>6</sup> If there are fewer than three associated track-jets with  $p_T > 7$  GeV, the inputs corresponding to any missing subjets are replaced with the mean input values.

operating point that corresponds to a selection efficiency of 60% for large- $R$  jets containing  $h \rightarrow b\bar{b}$  decays is chosen for this analysis. The  $h \rightarrow b\bar{b}$  tagging algorithm reduces contributions from QCD jets and boosted top-quark jets by a factor of 92 and 31, respectively [110], as measured in simulated  $t\bar{t}$  events.

Electrons, muons, and jets are reconstructed and identified independently. This can lead to ambiguous identifications when these objects are spatially close to each other. Therefore, an overlap removal procedure is applied to uniquely identify these objects. First, the closest small- $R$  jet within a cone of size  $\Delta R = 0.2$  around an electron is removed. Furthermore, a small- $R$  jet with fewer than three associated tracks is removed if the jet is within a cone of  $\Delta R = 0.2$  around a selected muon. Finally, electrons and muons are discarded if they are within a cone of size  $\Delta R = \min(0.4, 0.04 + 10 \text{ GeV}/p_T^\ell)$  around the axis of any surviving jet, where  $p_T^\ell$  is the transverse momentum of the electron or muon. The latter requirement reduces the background contribution from semileptonic decays of heavy-flavour hadrons.

The missing transverse momentum (with magnitude  $E_T^{\text{miss}}$ ) is computed as the negative vector sum of the  $p_T$  of selected electrons, muons and jets, plus a track-based soft term, i.e. all tracks compatible with the PV and not associated with any lepton or jet used in the  $E_T^{\text{miss}}$  calculation [111].

## 5 Analysis strategy and event selection

This analysis selects events consistent with the  $\ell^\pm \nu b\bar{b} b\bar{b} q\bar{q}$  final state. The  $pp$  collision events are retained for further analysis using single-lepton triggers [112, 113]. The transverse momentum thresholds range from 24 GeV to 26 GeV for single-electron triggers and from 20 GeV to 26 GeV for single-muon triggers, depending on the data-taking period. The trigger-level lepton is required to match within  $\Delta R = 0.07$  (0.1) a reconstructed electron (muon) with  $p_T > 27$  GeV.

Two different analysis strategies are applied to ensure high sensitivity to both low- and high-mass resonances. One analysis strategy targets the ‘resolved’ event topology, in which the final state objects are well separated from each other. The second analysis strategy targets the ‘merged’ event topology, in particular events containing hadronic decays of strongly boosted Higgs and  $W$  bosons. These decays are reconstructed using large- $R$  jets.

Events are required to contain exactly one prompt electron or muon and a missing transverse momentum of  $E_T^{\text{miss}} > 30$  GeV. In addition, events for the resolved categories are required to contain at least five small- $R$  jets of which at least two have to be  $b$ -tagged. For the merged categories, events are required to contain at least one large- $R$  jet. Among all large- $R$  jets in the event, exactly one has to be identified as a  $h \rightarrow b\bar{b}$  candidate using the boosted  $h \rightarrow b\bar{b}$  identification technique described previously.

This analysis targets two charged Higgs boson decay channels:  $H^\pm \rightarrow W^\pm h \rightarrow \ell^\pm \nu b\bar{b}$  (referred to as the  $\ell^\pm \nu b\bar{b}$  channel) and  $H^\pm \rightarrow W^\pm h \rightarrow q\bar{q} b\bar{b}$  (referred to as the  $q\bar{q} b\bar{b}$  channel). Leptons from charged Higgs boson decays generally tend to have higher momenta and are more centrally located in the detector compared with those from top-quark decays. This allows to exploit the differences in the event kinematics to separate the two decay channels. The  $\ell^\pm \nu b\bar{b}$  and  $q\bar{q} b\bar{b}$  channels are created to be mutually exclusive using distinct selection criteria. Dedicated analysis techniques including machine learning are employed to reconstruct the targeted charged Higgs boson decay modes. These techniques are detailed in Sections 5.1 and 5.2 for the resolved and merged analyses, respectively.

To fully reconstruct the  $H^\pm \rightarrow W^\pm h \rightarrow \ell^\pm \nu b\bar{b}$  decay chain, the four-vector of the neutrino has to be determined. The  $p_x$  and  $p_y$  components of the neutrino momentum are directly obtained by the  $p_x^{\text{miss}}$  and

$p_y^{\text{miss}}$ , while the longitudinal component of the neutrino momentum is calculated by applying an on-shell  $W$ -boson mass constraint to the charged lepton plus neutrino system. This approach leads to a quadratic equation, which provides either two, one, or zero real solutions. If it does not have an existing real solution, the missing momentum vector  $\vec{p}_T^{\text{miss}}$  is rotated until a real solution is found. If this procedure leads to ambiguities, the rotation which provides the minimal change in the  $\vec{p}_T^{\text{miss}}$  is chosen. If two real solutions are obtained, the solution with the smallest  $|p_z^{\nu}|$  is used [114].

Both the resolved and merged analyses are applied to all events, and the same events can be selected by either analysis. Hence, the final search result is reported using the analysis that is most sensitive to the specific mass hypothesis being tested (cf. Section 8).

## 5.1 Reconstruction and classification of resolved charged Higgs boson decays

For low charged Higgs boson masses, the  $\ell^\pm \nu b \bar{b}$  and  $q \bar{q} b \bar{b}$  decay channels produce identical detector signatures, as indicated in Figure 1. To differentiate between them, events are classified based on a requirement on the reconstructed leptonic top-quark mass,  $m_{\text{top}}^{\text{lep}}$ . This observable is calculated from the four-vector sum of a selected  $b$ -tagged jet, the charged lepton, and the neutrino candidate. Since several  $b$ -tagged jets are present in the event, the selected  $b$ -tagged jet is chosen to minimise  $|m_{\ell\nu j} - 172.5 \text{ GeV}|$ , where  $m_{\ell\nu j}$  is the invariant mass of the combined  $b$ -tagged jet, charged lepton, and neutrino system. While  $m_{\text{top}}^{\text{lep}}$  is distributed around the top-quark pole mass for events containing a leptonically decaying top quark (as in the  $q \bar{q} b \bar{b}$  channel), it exhibits broader distributions at higher values for true  $\ell^\pm \nu b \bar{b}$  events. Consequently, events with  $m_{\text{top}}^{\text{lep}} > 225 \text{ GeV}$  are classified into the  $\ell^\pm \nu b \bar{b}$  analysis channel, while those with  $m_{\text{top}}^{\text{lep}} \leq 225 \text{ GeV}$  are classified as  $q \bar{q} b \bar{b}$  candidates. Distributions of the  $m_{\text{top}}^{\text{lep}}$  observable are presented in Figure 2 for a representative charged Higgs boson mass.

The accuracy of the classification requirement on  $m_{\text{top}}^{\text{lep}}$  varies as a function of the charged Higgs boson mass. For a mass of 250 GeV, around 40% (45%) of the signal events are correctly classified into the  $q \bar{q} b \bar{b}$  ( $\ell^\pm \nu b \bar{b}$ ) analysis channel. The success rates increase with increasing charged Higgs boson mass, reaching values around 75% (90%) for the  $q \bar{q} b \bar{b}$  ( $\ell^\pm \nu b \bar{b}$ ) analysis channel.

The charged Higgs boson decays are reconstructed either via a charged lepton, a neutrino candidate, and two small- $R$  jets (for the  $\ell^\pm \nu b \bar{b}$  decay mode) or via four small- $R$  jets (for the  $q \bar{q} b \bar{b}$  decay mode). Reconstructing the decay of the charged Higgs boson is challenging due to the large number of objects produced in association with it. To address this challenge, sets of boosted decision trees (BDTs) are used to identify the correct decay products of the charged Higgs boson. This allows the four-momentum, and thus the invariant mass, of the heavy scalar to be reconstructed. One set of BDTs is applied to events in the  $\ell^\pm \nu b \bar{b}$  category, and another set of BDTs is applied to events in the  $q \bar{q} b \bar{b}$  category. The BDTs are trained to distinguish between the correct pairings of the final state objects, i.e. leptons and jets, labelled as signal, and the incorrect pairings labelled as background.<sup>7</sup> All available signal samples are used to train the BDTs. However, the BDT performance remains stable when adding or removing individual mass points.

<sup>7</sup> To determine whether a pairing is correct, generator-level particles (i.e. the decay products of the Higgs and  $W$  bosons) are spatially matched to the reconstructed objects. A dijet system is considered correctly associated with the generator-level Higgs or  $W$  boson if its angular distance to the combined four-vectors of the decay products of the Higgs or  $W$  boson is smaller than 0.3. The matching between the charged lepton + neutrino system and the corresponding generator-level particles is based on the same criteria.

The BDTs are implemented into the analysis using the TMVA package [115]. Both sets of BDTs contain a total of 400 decision trees, using the Gradient Boost algorithm with a learning rate of 0.1 and a maximum depth of five.

The BDTs dedicated to reconstruct the charged Higgs boson in the resolved  $\ell^\pm \nu b \bar{b}$  category are trained on seven input features built from the four-vectors of the charged lepton, the neutrino candidate and the two jets used to construct the  $W$  and Higgs boson candidates. These features are the invariant mass of the Higgs boson candidate ( $m_{j_1 j_2}$ ), the azimuthal angular difference and the pseudorapidity difference between the Higgs boson candidate and the  $W$ -boson candidate ( $\Delta\Phi(\ell\nu, j_1 j_2)$  and  $|\Delta\eta(\ell\nu, j_1 j_2)|$ ), the ratio of the Higgs boson transverse momentum to the invariant mass of the reconstructed charged Higgs boson candidate ( $p_T^{j_1 j_2}/m_{\ell\nu j_1 j_2}$ ), the ratio of the  $W$ -boson transverse momentum to the invariant mass of the reconstructed charged Higgs boson candidate ( $p_T^{\ell\nu}/m_{\ell\nu j_1 j_2}$ ), and the pseudo-continuous  $b$ -tagging intervals of the two jets used to build the Higgs boson candidate ( $w_{DL1r}^{j_1}$  and  $w_{DL1r}^{j_2}$ ).

These BDTs are iteratively applied to all possible lepton, neutrino, and dijet pairings of events in the resolved  $\ell^\pm \nu b \bar{b}$  category. The pairing with the largest BDT score,  $w_{\text{BDT}}^{\text{max}}$ , is used to construct the four-momentum vector (and hence the invariant mass) of the charged Higgs boson candidate. Furthermore, the  $w_{\text{BDT}}^{\text{max}}$  distribution is used to define signal and control regions, motivated by the fact that the dominant backgrounds tend to have lower  $w_{\text{BDT}}^{\text{max}}$  values than the signal process.

The BDTs dedicated to the resolved  $H^\pm \rightarrow W^\pm h \rightarrow q\bar{q}b\bar{b}$  decay are trained on ten input features built from the four-vectors of the four jets used to construct the  $W$  and Higgs boson candidates. These features are the invariant mass of the Higgs boson and  $W$ -boson candidates ( $m_{j_1 j_2}$  and  $m_{j_3 j_4}$ ), the azimuthal angular difference and the pseudorapidity difference between the Higgs boson candidate and the  $W$ -boson candidate ( $\Delta\Phi(j_1 j_2, j_3 j_4)$  and  $|\Delta\eta(j_1 j_2, j_3 j_4)|$ ), the ratio of the Higgs boson candidate's transverse momentum to the invariant mass of the reconstructed charged Higgs boson candidate ( $p_T^{j_1 j_2}/m_{j_1 j_2 j_3 j_4}$ ), the ratio of the  $W$ -boson transverse momentum to the invariant mass of the reconstructed charged Higgs boson candidate ( $p_T^{j_3 j_4}/m_{j_1 j_2 j_3 j_4}$ ), and the pseudo-continuous  $b$ -tagging intervals of the four jets ( $w_{DL1r}^{j_1}$ ,  $w_{DL1r}^{j_2}$ ,  $w_{DL1r}^{j_3}$ , and  $w_{DL1r}^{j_4}$ ).

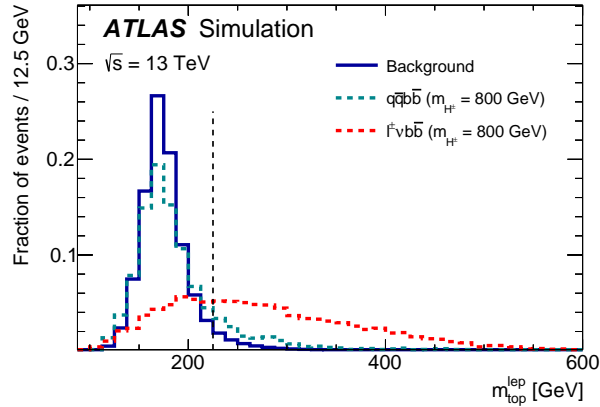


Figure 2: Distributions of the  $m_{\text{top}}^{\text{lep}}$  observable for  $H^\pm \rightarrow W^\pm h \rightarrow \ell^\pm \nu b \bar{b}$  and  $H^\pm \rightarrow W^\pm h \rightarrow q\bar{q}b\bar{b}$  decays as well as the sum of backgrounds after the preselection requirements of the resolved analysis. The distributions are presented for a representative charged Higgs boson mass of  $m_{H^\pm} = 800$  GeV. All distributions are normalised to unit area. The dashed vertical line indicates the threshold of the selection requirement on  $m_{\text{top}}^{\text{lep}}$  used to define the  $\ell^\pm \nu b \bar{b}$  and  $q\bar{q}b\bar{b}$  analysis regions.

These BDTs are iteratively applied to all possible four-jet pairings of events in the resolved  $q\bar{q}b\bar{b}$  category. The pairing with the largest  $w_{\text{BDT}}^{\text{max}}$  value is used to construct the four-momentum vector and the invariant mass of the charged Higgs boson candidate. Again, selection requirements on the  $w_{\text{BDT}}^{\text{max}}$  observable are used to define signal and control regions.

To protect against potential biases due to overtraining, a two-fold cross-validation is employed. Events are randomly divided into two equal-sized subsamples,  $A$  and  $B$ . Two independent boosted decision trees are trained on the two subsamples. The BDTs trained on sample  $A$  are evaluated with sample  $B$  and vice versa. Half of the data are analysed with the BDTs trained on sample  $A$ , and the other half with the BDTs trained on sample  $B$ . Finally, the output distributions from both BDTs are merged for both simulated and collision data. This approach results in four sets of BDTs: two for the  $\ell^\pm\nu b\bar{b}$  channel and two for the  $q\bar{q}b\bar{b}$  channel.

The sets of BDTs perform well in reconstructing the targeted final states. At a charged Higgs boson pole mass of 500 GeV, the final state is reconstructed correctly in about 55% (45%) of the time for the  $H^\pm \rightarrow W^\pm h \rightarrow \ell^\pm\nu b\bar{b}$  ( $H^\pm \rightarrow W^\pm h \rightarrow q\bar{q}b\bar{b}$ ) decay mode<sup>8</sup>. The success rates increase with increasing charged Higgs boson mass values, reaching around 90% for both decay modes at masses above 1 TeV. The reconstruction efficiency drops to around 12% for the lowest considered Higgs boson masses, as the decay products tend to fail the kinematic selection requirements and the charged Higgs boson decay cannot be fully reconstructed.

The invariant masses of the reconstructed charged Higgs bosons are determined with a resolution<sup>9</sup> below 10% for both decay chains and all event categories. The corresponding invariant mass distributions of the reconstructed final states are shown in Figure 3, separated by decay mode and for different signal mass hypotheses.

Finally, events are further categorised according to the overall number of jets ( $j$ ), and the number of  $b$ -tagged jets ( $b$ ) in the event. In this context, four exclusive categories are defined:  $5j3b$ ,  $5j \geq 4b$ ,  $\geq 6j3b$ , and  $\geq 6j \geq 4b$ .

## 5.2 Reconstruction and classification of merged charged Higgs boson decays

For sufficiently high charged Higgs boson masses, the ambiguities between the  $\ell^\pm\nu b\bar{b}$  and  $q\bar{q}b\bar{b}$  decay channels are largely reduced due to their distinct detector signatures. Thus, the events in the merged analysis are classified based on the number and properties of selected large- $R$  jets. The  $q\bar{q}b\bar{b}$  category requires one large- $R$  jet tagged as a  $h \rightarrow b\bar{b}$  candidate and another large- $R$  jet with a mass  $m_J$  within the  $W$ -boson mass window,  $50 \text{ GeV} < m_J < 110 \text{ GeV}$  ( $N^{W\text{-tags}} = 1$ ). Events lacking a second large- $R$  jet with mass around the  $W$  boson pole mass ( $N^{W\text{-tags}} = 0$ ) are classified as  $\ell^\pm\nu b\bar{b}$ . Consequently, the charged Higgs boson decays are reconstructed using a charged lepton, a neutrino candidate, and one large- $R$  jet (for the  $\ell^\pm\nu b\bar{b}$  channel) or two large- $R$  jets (for the  $q\bar{q}b\bar{b}$  channel). Events are further categorised based on the number of additional  $b$ -tagged jets ( $b$ ), considering only small- $R$  jets that are spatially separated from any

<sup>8</sup> This reconstruction efficiency is defined as the ratio of the number of correctly reconstructed  $\ell^\pm\nu b\bar{b}$  ( $q\bar{q}b\bar{b}$ ) decays to the number of true  $\ell^\pm\nu b\bar{b}$  ( $q\bar{q}b\bar{b}$ ) events satisfying the preselection and classification requirements.

<sup>9</sup> The mass resolution is determined by fitting the convolution of a Gaussian and an exponential function (i.e. a Bukin function) through the distributions of  $(m_{W^\pm h} - m_{W^\pm h}^{\text{truth}})/m_{W^\pm h}^{\text{truth}}$ , where  $m_{W^\pm h}$  and  $m_{W^\pm h}^{\text{truth}}$  represent the reconstructed and generator-level invariant masses of the  $W^\pm h$  system, respectively. The extracted mass resolution values are given by one standard deviation of the Gaussian component.

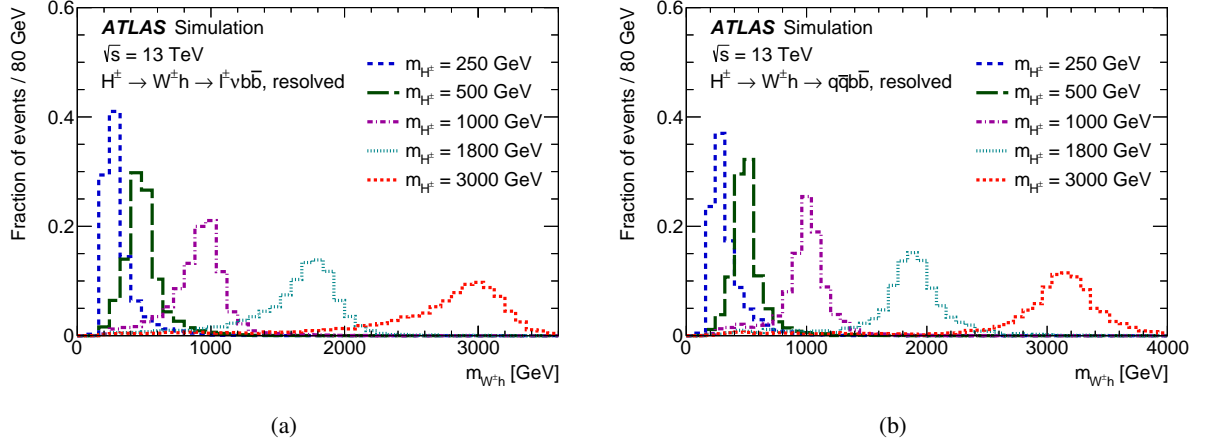


Figure 3: Distributions of the invariant mass of the (a)  $H^\pm \rightarrow W^\pm h \rightarrow \ell^\pm \nu b \bar{b}$  and (b)  $H^\pm \rightarrow W^\pm h \rightarrow q \bar{q} b \bar{b}$  signal hypotheses presented for a selection of different charged Higgs boson pole masses. The final states are reconstructed by applying boosted decision trees to events satisfying the resolved preselection requirements. All distributions are normalised to unit area.

large- $R$  jet used in the analysis. Two exclusive categories are defined,  $0b$  and  $\geq 1b$ , based on the number of  $b$ -tagged small- $R$  jets.

A neural network (NN) algorithm is used to further distinguish between the signal and background processes. Its architecture is sequential with three (two) fully connected dense layers of 128 nodes for the merged  $\ell^\pm \nu b \bar{b}$  ( $q \bar{q} b \bar{b}$ ) category. The NNs are implemented with the PYTHON-based deep learning library, KERAS [116]. The networks are trained and optimised separately for the  $\ell^\pm \nu b \bar{b}$  and  $q \bar{q} b \bar{b}$  decay modes, due to differences in the event kinematics. Both networks use the ADAM optimiser [117] to minimise a Binary Cross Entropy loss function and seven input features. All signal samples with charged Higgs boson masses greater than or equal to 1200 GeV are used to train the NNs. Lower mass hypotheses were excluded from the training to optimise the NN performance for the high-mass hypotheses. Consequently, the NNs tend to assign lower scores to lower mass hypotheses due to their inherent mass dependence.

The NN for the merged  $\ell^\pm \nu b \bar{b}$  category is trained on input features built from the leptonically decaying  $W$  boson ( $W^{\text{lep}}$ ) obtained from the four-vector sum of the charged lepton and the neutrino candidates and the large- $R$  jet used to construct the boosted Higgs boson candidate. These features are the angular separation between the charged lepton and the Higgs boson candidate ( $\Delta R(\ell, h)$ ), the azimuthal angular difference and the pseudorapidity difference between the Higgs boson candidate and the reconstructed  $W$  boson ( $\Delta\phi(W^{\text{lep}}, h)$  and  $|\Delta\eta(W^{\text{lep}}, h)|$ ), the ratio of the Higgs boson transverse momentum to the invariant mass of the reconstructed charged Higgs boson candidate ( $p_{T,h}/m_{W_h}$ ), the ratio of the  $W$ -boson transverse momentum to the invariant mass of the reconstructed charged Higgs boson candidate ( $p_{T,W^{\text{lep}}}/m_{W_h}$ ), the reconstructed leptonic top-quark mass ( $m_{\text{top}}^{\text{lep}}$ ), which is calculated in the same way as for the resolved analysis, and the ratio of the  $W$ -boson transverse momentum to the transverse momentum sum of all the decay products of the charged Higgs boson candidate ( $p_{T,W^{\text{lep}}}/(p_{T,W^{\text{lep}}} + p_{T,h})$ ).

The NN for the merged  $q \bar{q} b \bar{b}$  category is trained on input features built from the charged lepton and neutrino candidates and the two large- $R$  jets used to reconstruct the hadronically decaying  $W$ -boson ( $W^{\text{had}}$ ) and the Higgs boson candidates. Similar to the NN trained for the merged  $\ell^\pm \nu b \bar{b}$  category, the  $\Delta R(\ell, h)$ ,  $\Delta\phi(W^{\text{had}}, h)$ ,  $|\Delta\eta(W^{\text{had}}, h)|$ ,  $p_{T,h}/m_{W_h}$ , and  $p_{T,W}/m_{W_h}$  observables are used in the training. In addition,



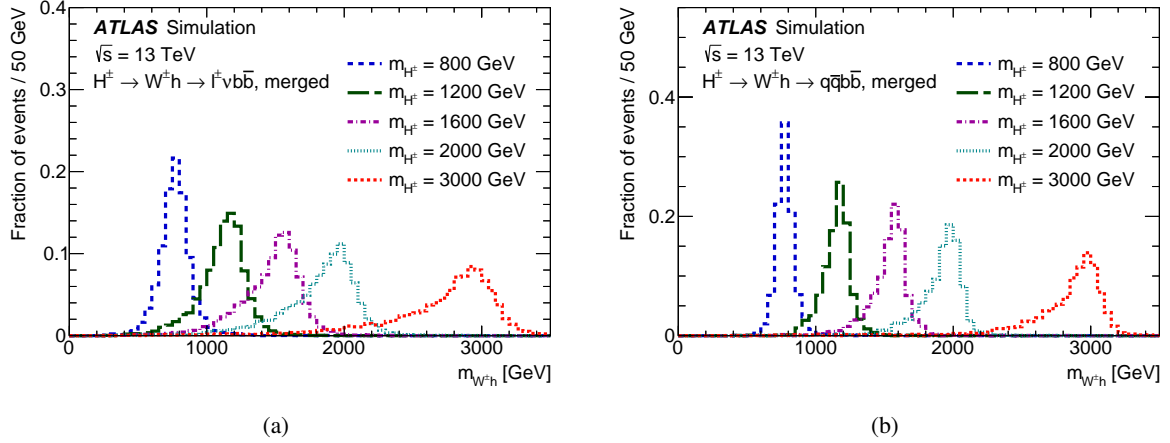


Figure 4: Distributions of the invariant mass of the (a)  $H^\pm \rightarrow W^\pm h \rightarrow \ell^\pm \nu b\bar{b}$  and (b)  $H^\pm \rightarrow W^\pm h \rightarrow q\bar{q}b\bar{b}$  signal hypotheses presented for a selection of different charged Higgs boson pole masses. The final states are reconstructed using either a charged lepton, a neutrino candidate, and one large- $R$  jet (for the  $\ell^\pm \nu b\bar{b}$  channel) or via two large- $R$  jets (for the  $q\bar{q}b\bar{b}$  channel) for events entering the merged analysis regions. All distributions are normalised to unit area.

the angular separation between the charged lepton and the hadronically decaying  $W$ -boson candidate ( $\Delta R(\ell, W^{\text{had}})$ ), and the ratio of the transverse momentum of the leptonically decaying  $W$ -boson candidate to the transverse momentum sum of the leptonically decaying  $W$ -boson candidate, the hadronically decaying  $W$ -boson candidate and the Higgs boson candidate ( $p_{T,W^{\text{lep}}} / (p_{T,W^{\text{lep}}} + p_{T,W^{\text{had}}} + p_{T,h})$ ), are used as input features.

The same two-folded cross-validation approach as used in the BDT training is employed in the NN training to mitigate any bias due to overtraining.

The invariant mass of the charged Higgs boson candidates is reconstructed in all event categories with a resolution below 9% for the  $\ell^\pm \nu b\bar{b}$  category and below 6% for the  $q\bar{q}b\bar{b}$  category. The corresponding charged Higgs boson invariant mass distributions are shown in Figure 4, separated by decay mode and for various signal mass hypotheses.

### 5.3 Definition of signal and control regions

The topological and kinematic preselection requirements of the resolved and merged event categories and the classification requirements used to distinguish the  $\ell^\pm \nu b\bar{b}$  and  $q\bar{q}b\bar{b}$  decay chains are summarised in Table 2. The signal and control regions are finally defined by applying additional selection criteria on top of the preselection and event classification requirements.

The signal and control regions of the resolved analysis are obtained based on selection requirements on the  $w_{\text{BDT}}^{\text{max}}$  observable. A dedicated signal and control region is defined for each of the four  $5j3b$ ,  $5j \geq 4b$ ,  $\geq 6j3b$ , and  $\geq 6j \geq 4b$  categories. Hence, eight regions are used in the resolved  $\ell^\pm \nu b\bar{b}$  channel:

- *Signal regions (SRs)* are defined by  $w_{\text{BDT}}^{\text{max}} \geq 0.7$ ,
- *Control regions (CRs)* are defined in the range of  $-0.5 \leq w_{\text{BDT}}^{\text{max}} < 0.5$ .

Twelve regions are used in the resolved  $q\bar{q}b\bar{b}$  channel:

- *High-purity signal regions* are defined by  $w_{\text{BDT}}^{\text{max}} \geq 0.9$ ,
- *Low-purity signal regions* are defined by  $0.0 \leq w_{\text{BDT}}^{\text{max}} < 0.9$  for events with exactly three  $b$ -tagged jets and by  $0.6 \leq w_{\text{BDT}}^{\text{max}} < 0.9$  for events with at least four  $b$ -tagged jets,
- *Control regions* are defined in the range of  $-0.5 \leq w_{\text{BDT}}^{\text{max}} < 0.0$  for events with exactly three  $b$ -tagged jets and by  $-0.5 \leq w_{\text{BDT}}^{\text{max}} < 0.6$  for events with at least four  $b$ -tagged jets.

Events enter the signal regions of the merged analysis, if the mass of the  $h \rightarrow b\bar{b}$  tagged large- $R$  jet ( $m_h$ ) is in a window around the Higgs boson pole mass,  $95 \text{ GeV} \leq m_h < 140 \text{ GeV}$ . The signal regions are further split based on the NN output score. A dedicated signal region is defined for each of the  $0b$  and  $\geq 1b$  categories. Hence, six regions are used for the merged  $\ell^\pm \nu b\bar{b}$  channel:

- *High-NN-score signal regions* are defined by  $w_{\text{NN}} \geq 0.83$ ,
- *Medium-NN-score signal regions* are defined by  $0.4 \leq w_{\text{NN}} < 0.83$ ,
- *Low-NN-score signal regions* are defined by  $w_{\text{NN}} < 0.4$ .

In the merged  $q\bar{q}b\bar{b}$  channel four regions are used:

- *High-NN-score signal regions* are defined by  $w_{\text{NN}} \geq 0.2$  ( $w_{\text{NN}} \geq 0.1$ ) for events with (without) additional  $b$ -tagged jets,
- *Low-NN-score signal regions* are defined by  $w_{\text{NN}} < 0.2$  ( $w_{\text{NN}} < 0.1$ ) for events with (without) additional  $b$ -tagged jets.

Furthermore, two sets of sideband control regions are defined in the merged event categories by inverting the selection requirement on  $m_h$ . *Low-mass sidebands* ( $50 \text{ GeV} \leq m_h < 95 \text{ GeV}$ ) are defined to constrain the  $W$ +jets background, while *high-mass sidebands* ( $140 \text{ GeV} \leq m_h < 250 \text{ GeV}$ ) are defined to target backgrounds containing boosted top quarks. Again, a dedicated region is defined per  $0b$  and  $\geq 1b$  category. The various signal and control regions are summarised in Table 3.

Table 2: Topological and kinematic selections for each channel and category as described in the text. Events are further classified according to the number of  $b$ -tagged jets in the events.

Decay channel	Resolved analysis		Merged analysis	
	$\ell^\pm \nu b\bar{b}$	$q\bar{q}b\bar{b}$	$\ell^\pm \nu b\bar{b}$	$q\bar{q}b\bar{b}$
Preselection	$N^\ell = 1$ $E_T^{\text{miss}} > 30 \text{ GeV}$ $N^{\text{small-}R \text{ jets}} \geq 5$ $N^{b\text{-tags}} \geq 2$		$N^{\text{large-}R \text{ jets}} \geq 1$ $N^{h\text{-tags}} = 1$	
Classification requirement	$m_{\text{top}} > 225 \text{ GeV}$	$m_{\text{top}} < 225 \text{ GeV}$	$N^{W\text{-tags}} = 0$	$N^{W\text{-tags}} = 1$
	$5j3b, 5j \geq 4b, \geq 6j3b, \text{ and } \geq 6j \geq 4b$		$0b \text{ and } \geq 1b$	

Table 3: Summary of signal and control regions considered in the statistical analysis for the resolved and merged channels.

Region	Requirement	$\ell^\pm \nu b\bar{b}$ channel	$q\bar{q}b\bar{b}$ channel
Resolved			
Signal regions	Jet & $b$ -tag multiplicity	$w_{\text{BDT}}^{\text{max}} \geq 0.7$	$5j3b, 5j \geq 4b, \geq 6j3b, \geq 6j \geq 4b$
	BDT score		$w_{\text{BDT}}^{\text{max}} \geq 0.9$
Low-purity signal regions	Jet & $b$ -tag multiplicity	-	$5j3b, 5j \geq 4b, \geq 6j3b, \geq 6j \geq 4b$
	BDT score		$0.0 \leq w_{\text{BDT}}^{\text{max}} < 0.9$ (for events with $5j3b$ or $\geq 6j3b$ ) $0.6 \leq w_{\text{BDT}}^{\text{max}} < 0.9$ (for events with $5j \geq 4b$ or $\geq 6j \geq 4b$ )
Control regions	Jet & $b$ -tag multiplicity	$-0.5 \leq w_{\text{BDT}}^{\text{max}} < 0.5$	$5j3b, 5j \geq 4b, \geq 6j3b, \geq 6j \geq 4b$
	BDT score		$-0.5 \leq w_{\text{BDT}}^{\text{max}} < 0.0$ (for events with $5j3b$ or $\geq 6j3b$ ) $-0.5 \leq w_{\text{BDT}}^{\text{max}} < 0.6$ (for events with $5j \geq 4b$ or $\geq 6j \geq 4b$ )
Merged			
High-NN score signal region	$b$ -tag multiplicity	$w_{\text{NN}} \geq 0.83$	$0b, \geq 1b$
	Mass window		$95 \text{ GeV} \leq m_J < 140 \text{ GeV}$
	NN score		$w_{\text{NN}} \geq 0.2$ (for events with $0b$ ) $w_{\text{NN}} \geq 0.1$ (for events with $\geq 1b$ )
Medium-NN score signal region	$b$ -tag multiplicity	$0.4 \leq w_{\text{NN}} < 0.83$	$0b, \geq 1b$
	Mass window		$95 \text{ GeV} \leq m_J < 140 \text{ GeV}$
	NN score		-
Low-NN score signal region	$b$ -tag multiplicity	$w_{\text{NN}} < 0.4$	$0b, \geq 1b$
	Mass window		$95 \text{ GeV} \leq m_J < 140 \text{ GeV}$
	NN score		$w_{\text{NN}} < 0.2$ (for events with $0b$ ) $w_{\text{NN}} < 0.1$ (for events with $\geq 1b$ )
Low-mass control region	$b$ -tag multiplicity		$0b, \geq 1b$
	Mass window		$m_J < 95 \text{ GeV}$
	NN score		-
High-mass control region	$b$ -tag multiplicity		$0b, \geq 1b$
	Mass window		$m_J \geq 140 \text{ GeV}$
	NN score		-

The products of kinematic acceptance and reconstruction efficiency for  $pp \rightarrow tbH^\pm (\rightarrow W^\pm h)$  is presented in Figure 5 and Figure 6 separately for all signal regions of the resolved and merged  $\ell^\pm \nu b\bar{b}$  and  $q\bar{q}b\bar{b}$  decay channels. In this context, the acceptance is defined as the fraction of simulated signal events for which the expected final state particles satisfy all relevant object definition requirements. The denominator of the acceptance is calculated considering simulated signal events with inclusive decays of the  $W$  boson, and  $h \rightarrow b\bar{b}$  decays of the 125 GeV Higgs boson. The reconstruction efficiency is defined as the ratio of simulated signal events that satisfy all selection criteria for a given signal region to the total number of simulated signal events that satisfy the acceptance requirements.

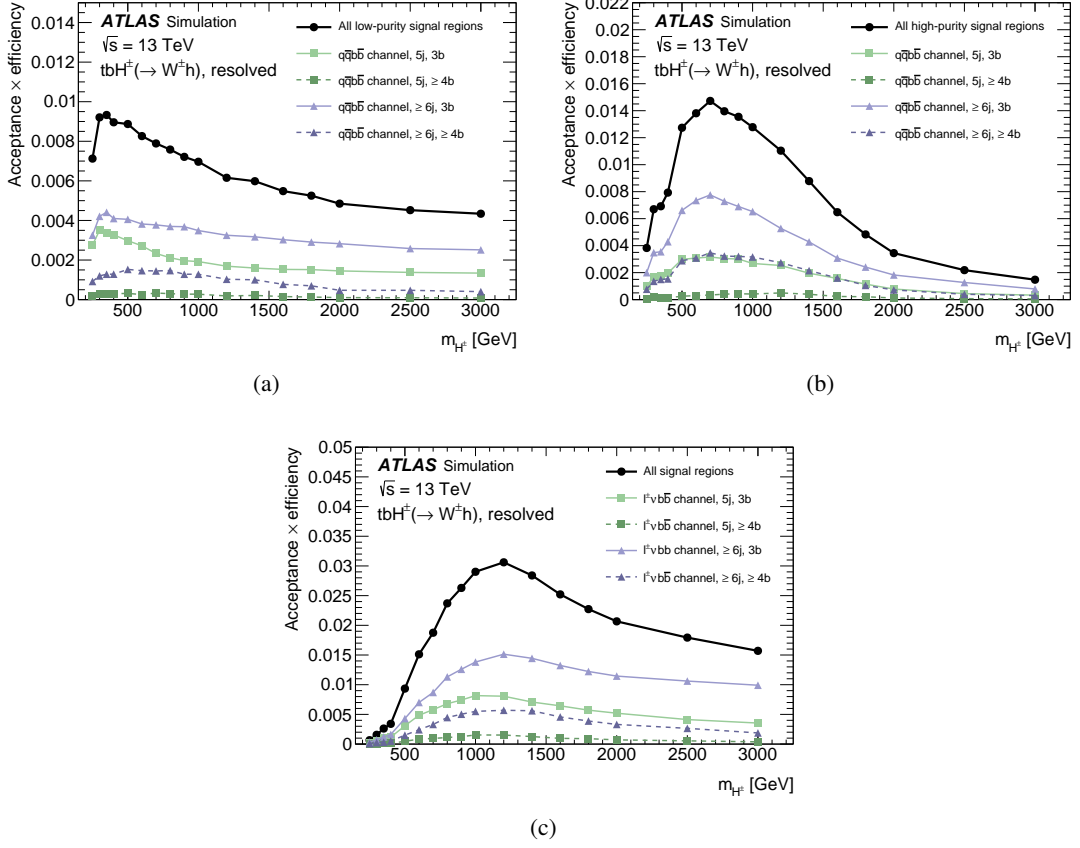


Figure 5: Product of acceptance and efficiency for  $pp \rightarrow tbH^\pm (\rightarrow W^\pm h)$  as a function of the charged Higgs boson mass for (a) the resolved  $q\bar{q}b\bar{b}$  low-purity signal regions, (b) the resolved  $q\bar{q}b\bar{b}$  high-purity signal regions, and (c) the resolved  $l^\pm v b\bar{b}$  signal regions.

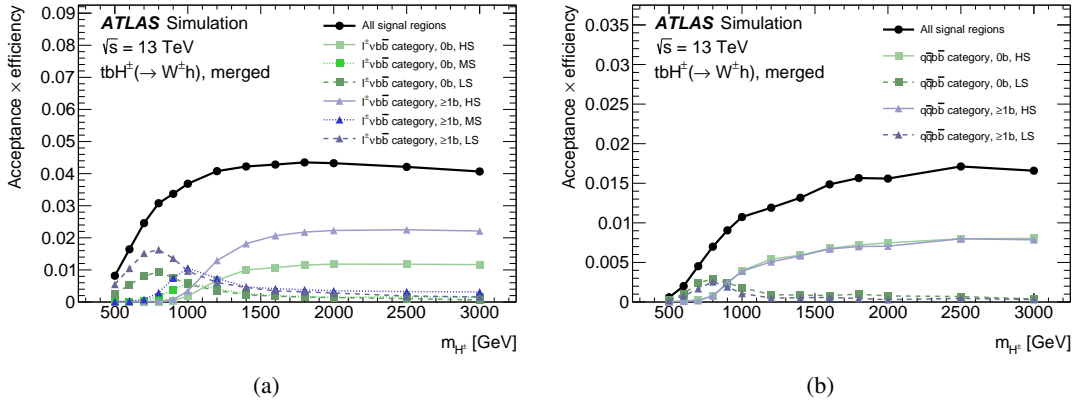


Figure 6: Product of acceptance and efficiency for  $pp \rightarrow tbH^\pm (\rightarrow W^\pm h)$  as a function of the charged Higgs boson mass for (a) the merged  $l^\pm v b\bar{b}$  high-NN score (HS), medium-NN score (MS) and low-NN score (LS) signal regions, and (b) the merged  $q\bar{q}b\bar{b}$  high-NN score and low-NN score signal regions.

## 6 Background modelling

The background composition in the signal and control regions depends on the event categories and  $b$ -jet multiplicities. In the resolved analysis categories, the dominant background source is  $t\bar{t}$  + jets production, contributing between 81% and 95% of the total background. Other backgrounds such as  $W/Z$  + jets or  $Wt$  production are significantly smaller. In the merged categories, the most significant background contributions stem from  $t\bar{t}$  + jets and  $W$  + jets production. Contributions from diboson, SM  $Vh$ ,  $t\bar{t} + h$ ,  $t\bar{t} + V$ , and from the rare top-quark processes (i.e.  $tZq$ ,  $tWZ$ ,  $tHjb$ ,  $tWh$ , and  $t\bar{t}t\bar{t}$ ) are small in all channels. Background contributions from events containing non-prompt leptons are found to be negligible. These findings are consistent with previous studies in the same and similar final states [30, 118].

Backgrounds are estimated from samples of simulated events, where the normalisation of the dominant backgrounds is obtained from data. In addition, shape corrections are derived for the  $t\bar{t}$  + jets production process. These corrections are necessary because the additional jets in the  $t\bar{t}$  + jets events are produced by the parton shower, which leads to a mis-modelling of high jet multiplicities and the hardness of additional jet emissions. Hence, in the resolved analysis channels, the simulated  $t\bar{t}$  + jets events are reweighted as a function of the  $H_T^{\text{all}}$  observable.<sup>10</sup> The reweighting function is obtained from fits to the data-to-simulation ratio in events with one charged lepton,  $E_T^{\text{miss}} > 30$  GeV, and at least five jets of which exactly two are  $b$ -tagged ( $\geq 5j2b$ ) following the approach detailed in Ref. [30] This reweighting procedure is performed separately for different jet multiplicity intervals, distinguishing events with five, six, seven, or at least eight jets. The reweighting factors are expressed as a function of the  $H_T^{\text{all}}$  observable:

$$r_i(H_T^{\text{all}}) = \frac{N_i^{\text{Data}}(H_T^{\text{all}}) - N_i^{\text{MC,non-}t\bar{t}}(H_T^{\text{all}})}{N_i^{\text{MC},t\bar{t}}(H_T^{\text{all}})},$$

where  $N_i$  is the number of events in a  $H_T^{\text{all}}$  interval and the  $i$ -th jet bin. The ensemble of  $r_i(H_T^{\text{all}})$  is fitted per jet bin with an exponential plus sigmoid functional form,<sup>11</sup> which is then used as a correction function applied to the  $5j3b$ ,  $5j \geq 4b$ ,  $\geq 6j3b$  and  $\geq 6j \geq 4b$  regions of the  $\ell^\pm \nu b\bar{b}$  and  $q\bar{q}b\bar{b}$  analysis channels. In contrast, the merged analysis channels are more inclusive in jet multiplicity, making them less dependent on the modelling of the additional jet activity. While a similar correction procedure was tested for the merged analysis, it did not significantly improve the modelling of relevant observables. Thus, no such correction procedure is applied in the merged analysis.

Events containing top-quark pairs are categorised according to the flavour of jets produced in association with the  $t\bar{t}$  system. This categorisation procedure is based on generator-level information, where jets are reconstructed from stable particles (i.e. particles with a mean lifetime  $\tau > 3 \times 10^{-11}$  s) using the anti- $k_t$  algorithm with the radius parameter set to  $R = 0.4$ . These jets are required to have  $p_T > 15$  GeV and  $|\eta| < 2.5$ , and their flavour is determined by counting  $b$ - or  $c$ -hadrons with  $p_T$  larger than 5 GeV within a cone of  $\Delta R = 0.4$  around the jet axis. Jets including  $b$ -hadrons are labelled as  $b$ -jets, while jets that do not include any  $b$ -hadron, but do include one or more  $c$ -hadrons are labelled as  $c$ -jets. Events that include at least one  $b$ - or  $c$ -jet, not considering heavy-flavour jets from top-quark,  $W$ -boson,  $Z$ -boson or Higgs-boson decays, are labelled as  $t\bar{t}$  + HF (with HF denoting ‘heavy flavour’). Events not containing any heavy-flavour

<sup>10</sup> The  $H_T^{\text{all}}$  observable is defined as the scalar sum of the transverse momenta of all jets and the charged lepton in the event.

<sup>11</sup> In addition a hyperbola plus sigmoid functional form and a 2nd order polynomial plus first order exponential functional form were tested. However, the exponential plus sigmoid functional form was found to fit the data best.

jets, aside from those from top-quark or  $W$ -boson decays, are labelled as  $t\bar{t} + \text{LF}$  (with LF denoting ‘light flavour’).

The subdominant background processes are grouped into four components: single-top-quark production (including  $s$ - and  $t$ -channels,  $Wt$  production,  $tZq$ , and  $tWZ$ ),  $VV$  &  $V + \text{jets}$  (including  $W/Z + \text{jets}$ ,  $WW$ ,  $ZZ$ , and  $WZ$ ),  $t\bar{t} + X$  (including  $t\bar{t} + h$ ,  $t\bar{t} + W$ , and  $t\bar{t} + Z$ ), and the remaining backgrounds referred to as ‘Others’ (including  $tHjb$ ,  $tWh$ ,  $t\bar{t}\bar{t}$ , and SM  $Vh$ ).

## 7 Systematic uncertainties

The distributions of the  $m_{W\pm h}$  observable and the event yields in the signal and control regions are affected by both experimental and modelling uncertainties, which enter the final fits as nuisance parameters (NPs). Uncertainties in the modelling of physics objects are correlated between signal and background processes, channels, kinematic regions and distributions of observables. The modelling uncertainties are evaluated separately for the signal and all relevant background processes.

### 7.1 Experimental systematic uncertainties

All experimental uncertainties, except for the luminosity uncertainty, impact both the normalisation and shape of the simulated distributions. The dominant experimental uncertainties are uncertainties in the flavour-tagging performance, in the jet energy scale and resolution calibration, and in the modelling of the pile-up activity.

Uncertainties in the trigger selection, the charged lepton reconstruction, identification and isolation criteria, as well as the lepton momentum scale and resolution are measured in data applying tag-and-probe techniques to  $Z \rightarrow \ell^+\ell^-$  events [92, 94]. These uncertainties have only a small impact on the charged Higgs boson search.

The uncertainties in the small- $R$  jet energy scale and resolution have contributions from *in situ* calibration measurements, from the dependency on the pile-up activity and from the flavour composition of the jets [105]. The uncertainty in the scale and resolution of the large- $R$  jet energy and mass is derived by comparing the ratio of calorimeter-based to track-based measurements in dijet data and simulation, as described in Ref. [106].

Dedicated measurements are performed to calibrate the jet flavour-tagging efficiency for  $b$ -jets and the mis-tagging rates for  $c$ - and light-flavour jets to the performance in data. The results of these measurements are expressed as  $p_T$  dependent correction factors that are derived for  $b$ -jets in  $t\bar{t}$  events with dilepton final states [119], for  $c$ -jets in  $t\bar{t}$  events with single-lepton final states [120] and in  $Z$ +jets events for light-flavour jets [121]. Uncertainties in these correction factors are decomposed into uncorrelated components and then propagated to the charged Higgs boson search. Additional uncertainties are considered to extrapolate the measured efficiencies to high jet  $p_T$  [122]. These terms are calculated from simulated events by considering variations of the quantities affecting the  $b$ -tagging performance, such as the impact parameter resolution, percentage of tracks from random combinations of measurements in the ID, description of the detector material, and track multiplicity per jet.

The  $h \rightarrow b\bar{b}$  identification efficiencies and the corresponding mis-identification rates for boosted top-quark jets are corrected to data using dedicated measurements. Correction factors and their corresponding



uncertainties in the  $h \rightarrow b\bar{b}$  identification efficiencies are obtained from events containing  $Z \rightarrow b\bar{b}$  decays [123]. The correction factors are dependent on the large- $R$  jet  $p_T$  and vary from approximately 0.96 to 1.34 with uncertainties ranging from around 30% to 35%. The mis-identification efficiency scale factors for boosted top quarks are measured in top-quark pair events. They vary from  $1.10 \pm 0.12$  at low  $p_T$  to  $1.00 \pm 0.16$  at high  $p_T$ . Mis-identification efficiency uncertainties for QCD jets were estimated in the sideband control regions of the merged analysis by performing a three-component fit to data: one component describing events in which the  $h \rightarrow b\bar{b}$  tagged jet originates from the decay of a boosted top quark, one component describing events in which the  $h \rightarrow b\bar{b}$  tagged jet originates from a QCD jet, and a third component describing events in which the tagged jet stems from a boosted  $Z$ ,  $W$ , or Higgs boson. The large- $R$  mass distributions of these three components are fitted to data across different jet  $p_T$  intervals, excluding the Higgs boson mass region. In these fits, the normalisation factors of the top-quark jet and QCD jet components were allowed to vary freely, while the third component was fixed to the SM prediction. The final uncertainties are determined by summing the deviation of the central value from unity and the uncertainty of a given normalisation factor. These uncertainties range from 7% at low large- $R$  jet  $p_T$  to 41% for jets with  $p_T$  exceeding 500 GeV.

The uncertainties in the energy scale and resolution of the small- $R$  jets and leptons are propagated to the calculation of  $E_T^{\text{miss}}$ , which also has additional uncertainties from the modelling of the underlying event and the momentum scale, momentum resolution and reconstruction efficiency of the tracks used to compute the soft-term [111].

Finally, a global luminosity uncertainty of 0.83% is applied to the normalisation of the simulated signal and background samples [42, 45].

## 7.2 Modelling systematic uncertainties

Modelling uncertainties are taken into account for all simulated signal and relevant background processes and cover three areas: shape uncertainties that account for uncertainties in the  $m_{W^\pm h}$  template shapes used for the statistical analysis; absolute normalisation uncertainties; and relative acceptance uncertainties (referred to as extrapolation uncertainties), that account for differences in the acceptance between regions with a common floating normalisation factor, e.g. migration effects between the signal and control regions, the  $\ell^\pm \nu b\bar{b}$  and  $q\bar{q}b\bar{b}$  channels, and the different jet multiplicity regions. While normalisation and shape uncertainties may be described by a common nuisance parameter, extrapolation uncertainties are always described by separate nuisance parameters. The modelling uncertainties are assessed by comparing nominal and alternative event generators and the underlying event and parton shower models. In general, the perturbative accuracy and the PDF sets used in these alternative configurations match those of the nominal generators (unless explicitly stated). Uncertainties due to the modelling of PDF sets are evaluated following the PDF4LHC recommendations [85], and uncertainties due to missing higher orders are evaluated by varying the renormalisation and factorisation scales,  $\mu_R$  and  $\mu_F$ , as described below.

For the signal processes, uncertainties in the acceptance are derived by comparing the predictions of the nominal PDF set with those from the CT14 [124] and MMHT2014 [125] PDF sets and then comparing the larger variation with the difference from the root-mean-square spread of the nominal replica sets. The variation with the largest impact on the results is taken as the final uncertainty. Further uncertainties are obtained by replacing PYTHIA 8.244 by HERWIG 7.2.2 for the showering and hadronisation, and by varying the renormalisation and factorisation scales. The total acceptance uncertainties show substantial variation across different charged Higgs boson masses, decay channels, and event categories.

The modelling uncertainties of the top-quark pair production processes are derived as follows. To assess the uncertainties in the matching of the matrix element to the parton shower, the nominal  $t\bar{t}$  + HF and  $t\bar{t}$  + LF samples are compared with samples where POWHEG BOX is replaced by MADGRAPH5\_AMC@NLO. The parton shower modelling uncertainties are determined by replacing PYTHIA 8.230 by HERWIG 7.0.4 and switching to the H7UE set of tuned parameters [126]. The uncertainties in the modelling of the initial-state radiation (ISR) and the final-state radiation (FSR) are addressed by varying the strong coupling constant  $\alpha_S$  independently at the matrix element and the parton shower generation stage. In the matrix element, the parameter  $\alpha_S$  is increased (decreased) to 0.140 (0.115) instead of the nominal value 0.127, while in the parton shower  $\alpha_S$  is increased (decreased) to 0.142 (0.115) instead of the nominal value. Uncertainties related to missing higher-order terms in the perturbative expansion are estimated by scaling  $\mu_R$  and  $\mu_F$  independently up and down by a factor of two. Additional uncertainties in the associated production of top-quark pairs and  $b$ -quarks are estimated by comparing the predictions of the nominal POWHEG BOX + PYTHIA sample, in which the extra  $b$ -quarks arise from the PS, to the predictions of an alternative POWHEG BOX + PYTHIA sample simulated using the four-flavour scheme. In the latter sample, an additional  $b$ -quark pair is produced in association with the top-quark pair ( $t\bar{t}b\bar{b}$ ) in the matrix element, which is calculated at NLO accuracy in QCD. Furthermore, an uncertainty in the relative composition of the additional  $c$ - and  $b$ -jet contributions in the  $t\bar{t}$  + HF sample is taken into account. This uncertainty is evaluated by varying the relative normalisations of the  $t\bar{t} + \geq 1b$  and  $t\bar{t} + \geq 1c$  contributions according to the predictions of the alternative MC generators relative to the predictions of the nominal MC generator configuration. These variations range from 10% to 30% in the regions of the resolved analysis and from 3% to 30% in the regions of the merged analysis. While varying the  $t\bar{t} + \geq 1b$  and  $t\bar{t} + \geq 1c$  contributions, the overall normalisation of the  $t\bar{t}$  + HF background is kept constant. When calculating the modelling uncertainties for the  $t\bar{t}$  + HF and  $t\bar{t}$  + LF processes, the same  $H_T$  reweighting is applied to the nominal and alternative models.

A 5% uncertainty is considered on the cross-section of the  $Wt$  production mode and the  $s$ - and  $t$ -channel production of single top quarks [127]. Uncertainties associated with the matching of the matrix element and the parton shower and the choice of the parton shower and hadronisation models, are estimated by comparing, for each of these three processes, the nominal POWHEG BOX + PYTHIA 8.230 sample with alternative samples produced using MADGRAPH5\_AMC@NLO 2.62 + PYTHIA 8.140 and POWHEG BOX + HERWIG 7.0.4, respectively. Uncertainties associated with the interference between top-quark pair and  $Wt$  production at NLO are evaluated by comparing the predictions of the nominal  $Wt$  sample with those from an alternative sample generated with POWHEG BOX and PYTHIA 8.230 using the diagram subtraction (DS) scheme [128] instead of the diagram removal scheme. Finally, an 8% uncertainty is considered on the cross-section of the  $tZq$  process, and a 50% uncertainty is considered on the  $tWZ$  cross-section [30].

An uncertainty of  $^{+9\%}_{-12\%}$  in the  $t\bar{t} + h$  production cross-section is considered, including effects from varying the factorisation and renormalisation scales, the PDF set, and  $\alpha_S$  [71, 129]. The nominal POWHEG BOX + PYTHIA 8.230 sample is compared with a sample produced with MADGRAPH5\_AMC@NLO 2.60 + PYTHIA 8.230 to assess the uncertainty associated with the matching of the matrix element and the parton shower, and to a sample generated with POWHEG BOX + HERWIG 7.0.4 for the uncertainty in the modelling of the parton shower.

The uncertainties in the normalisation of the  $t\bar{t} + Z$  and  $t\bar{t} + W^\pm$  backgrounds are  $^{+10.4\%}_{-12.0\%}$  and  $^{+13.4\%}_{-12.0\%}$ , respectively and include effects from varying the factorisation and renormalisation scales and the PDF set [130]. In addition, uncertainties in the choice of the parton shower and hadronisation models and matching scheme for the  $t\bar{t} + Z$  and  $t\bar{t} + W^\pm$  processes are estimated by comparing the nominal MADGRAPH5\_AMC@NLO 2.33 + PYTHIA 8.210 samples to alternative samples simulated using SHERPA 2.2.1 with the NNPDF3.0NNLO

PDF set. For the alternative  $t\bar{t} + W^\pm$  event samples, diagrams with up to one additional parton emission are generated at NLO accuracy in QCD, and diagrams with two, three or four additional parton emissions are generated at LO accuracy in QCD. For the production of  $t\bar{t} + Z$  events, diagrams with up to four additional parton emission are generated at LO accuracy in QCD. In both samples, the CKKW matching scale of the additional emissions was set to 30 GeV.

An overall 50% uncertainty is considered in the normalisation of the four-top-quarks background [50, 131], while uncertainties of  $^{+7.5\%}_{-15.4\%}$  and  $^{+9.1\%}_{-9.2\%}$  are assigned to the  $thjb$  and  $thW$  backgrounds [50]. These uncertainties cover effects from varying the renormalisation and factorisation scales, the PDF set and  $\alpha_S$ .

In the merged event categories, the modelling uncertainties in the  $W$ +jets background are determined as follows: uncertainties related to missing higher order terms in the perturbative expansion are estimated by individually varying  $\mu_R$  and  $\mu_F$  by a factor of 2 or 0.5. Six combinations are considered:  $(\mu_R, \mu_F) = (0.5, 0.5), (0.5, 1.0), (1.0, 0.5), (1.0, 2.0), (2.0, 1.0),$  and  $(2.0, 2.0)$  times their nominal value. The final uncertainty is derived as the variation of  $\mu_R$  and  $\mu_F$  that has the largest impact on the results. Additionally, variations of the SHERPA merging scale are taken into account, where the nominal value, 20 GeV, is changed to 30 GeV and 15 GeV. Furthermore, uncertainties in the parton shower evolution's upper cutoff scale are assessed by varying the resummation scale by factors of  $1/\sqrt{2}$  and  $\sqrt{2}$  from its nominal value. Additional modelling uncertainties are derived by comparing the nominal  $W$ +jets sample to an alternative sample simulated using MADGRAPH5\_AMC@NLO 2.6.5 with the NNPDF3.1NNLO PDF set. The alternative sample includes vector bosons with up to three additional partons at NLO accuracy in QCD. PYTHIA 8.240 with the A14 set of tuned parameters is used for showering and hadronisation, and the different jet multiplicities were merged using the FxFx procedure [132]. In the resolved event categories, where the  $W$ +jets background is nearly negligible, a flat 40% uncertainty is considered on the normalisation of the  $W$ +jets background.

Both the resolved and merged analyses assign an uncertainty of 35% to the  $Z$ +jets background normalisation, and a 50% uncertainty in the normalisation of the diboson backgrounds. These normalisation uncertainties account for effects from varying the renormalisation and factorisation scales, the merging scale and the PDF set and  $\alpha_S$ .

Additional uncertainties in the  $H_T$  reweighting of the  $t\bar{t} +$  jets background in the resolved analysis regions (cf. Section 6) are evaluated by independently varying the fitted parameters of the exponential plus sigmoid functional form within their uncertainties and reapplying the reweighting procedure. The resulting differences in the normalisation and  $m_{W^\pm h}$  shape of the  $t\bar{t} +$  jets background compared with the nominal reweighting are assigned as a systematic uncertainty. These uncertainties are evaluated separately for each jet multiplicity bin. In addition to the nominal reweighting function, two other functional forms (cf. Section 6) were considered for the reweighting procedure. The differences in results between the nominal and alternative functions are negligible compared to the MC statistical uncertainties of the  $t\bar{t} +$  jets sample. Therefore, no additional uncertainty due to the choice of the reweighting function is assigned.

Residual mismodelling (i.e. non-closure in the comparison between data and simulation) of the transverse  $W$ -boson momentum,  $p_{T,W}$ , distribution in the resolved analysis regions and the  $p_{T,W}/m_{Wh}$ ,  $\Delta\Phi(W, h)$  and  $E_T^{\text{miss}}$  distributions in the merged analysis regions are observed in the respective control regions. The non-closure uncertainties are derived by parameterising the data-to-simulation ratios of mis-modelled observables. These parametric functions are then used to reweight the observables and assess the impact on the shape of the  $m_{W^\pm h}$  distribution. The magnitude of the  $m_{W^\pm h}$  shape differences reach up to 30% in the tails of the distributions. The final uncertainty is quantified as the variation between the reweighted

and nominal  $m_{W\neq h}$  distributions, and is incorporated as an additional nuisance parameter affecting all processes.

The relative modelling systematic uncertainties (at the pre-fit stage), impacting the normalisation, cross-region extrapolation, and shape of the signal and background processes are summarised in Table 4.

## 8 Results

To test for the presence of a massive charged Higgs boson in data, the  $m_{Wh}$  templates obtained from the simulated signal and background event samples are fitted to data using a binned maximum-likelihood approach based on the RooFIT/RooSTATS framework [133–135]. Fits are simultaneously performed on the signal and control regions defined in Section 5.3 to constrain the normalisation of the main backgrounds and the nuisance parameters describing the systematic uncertainties detailed in Section 7. Each systematic variation is incorporated in the fit as an individual nuisance parameter using a Gaussian constraint, while nuisance parameters describing statistical uncertainties are incorporated using a Poisson constraint. Systematic variations that are impacted by large statistical fluctuations are smoothed, while systematic variations with negligible impact on the final results are pruned away. Asimov data sets [136] are used to evaluate the expected performance of each fit.

As no significant excess over the SM expectations is found, the results of this search are expressed as upper limits at the 95% confidence level on the production cross-section times branching ratio of charged Higgs bosons for a wide range of resonance masses. The largest deviation from the SM expectations is found for a charged Higgs boson mass of 900 GeV and corresponds to a local significance of about 0.9 standard deviations (and a  $p$ -value, i.e. the probability that the background can produce a fluctuation greater than the excess observed in data, of 0.184). The limits are evaluated using the CL<sub>s</sub> method [137] and the profile-likelihood-ratio test statistic in the asymptotic approximation [136].

Two separate likelihood fits are performed to search for charged Higgs bosons: one for the resolved analysis and the other for the merged analysis. Each fit includes dedicated SRs and CRs for  $q\bar{q}b\bar{b}$  and  $\ell^\pm\nu b\bar{b}$  decays (cf. Section 5.3) and the fit models differ between the analyses. The resolved fit has the signal cross-section and the global normalisation factor of the  $t\bar{t}$  + HF background as free parameters, while the merged fit has the signal cross-section and the global normalisation factors of the  $t\bar{t}$  + HF,  $t\bar{t}$  + LF, and  $VV$  &  $V$  + jets backgrounds as free parameters. Common normalisation factors are applied across all regions used in a fit. However, dedicated nuisance parameters address extrapolation uncertainties between the signal and control regions, decay channels, and the different jet multiplicity regions. The corresponding extrapolation uncertainties are detailed in Table 4. Normalisation factors and uncertainties from background-only fits<sup>12</sup> in the resolved and merged analysis categories are summarised in Table 5. The normalisation factors for the  $t\bar{t}$  + HF background exceed unity in both resolved and merged analyses. The normalisation factors are consistent within about one standard deviation across the two analyses. Furthermore, the normalisation factor for the  $t\bar{t}$  + LF background component in the merged analysis is below unity, consistent with the corrections obtained from the  $H_T^{\text{all}}$  reweighting in the resolved analysis.

In addition to constraining the normalisation of the dominant backgrounds, the fit also constrains several modelling uncertainties. Significant constraints are observed in the resolved analysis for nuisance parameters

<sup>12</sup> When performing signal-plus-background fits, the corresponding normalisation factors show minor deviations from those obtained in the background-only fits. However, these differences are insignificant in comparison to the uncertainties in the normalisation factors.

Table 4: Relative modelling systematic uncertainties (at the pre-fit stage) in the normalisation, cross-region extrapolation, and shape of signal and the background processes included in the fits described in the text. An ‘S’ indicates that a shape variation is included for the listed sources. ‘ $A \leftrightarrow B$ ’ indicates relative acceptance uncertainties that account for the relative normalisation differences between two regions,  $A$  and  $B$ , with a common floating normalisation factor (i.e. these are extrapolation uncertainties). Furthermore, ‘norm.’ is the product of cross-section and acceptance variations, and a value of ‘float’ indicates that the parameter is not constrained in the fit. A range of values means that the size of the uncertainties vary between the regions included in the fit, where the minimum and maximum relative uncertainties in the predicted yields are stated. No dedicated normalisation uncertainty is taken into account for the  $t\bar{t}$  + LF background given that the normalisation of this process is fixed by the  $H_T$  reweighting. Each of the listed uncertainties is treated as uncorrelated in the fits. The uncertainties are listed separately for (a) the resolved analysis channels and (b) the merged analysis channels.

(a) Relative acceptance and normalisation uncertainties for the resolved analysis channels

	$t\bar{t}$ + HF	$t\bar{t}$ + LF	$t\bar{t}$ + X	Single Top	VV & V + jets	Others	Signal
Norm.	float	fixed	0.8%–12%	1.1%–4.7%	2%–34%	2.9%–47%	float
PDF	S	0.2%–0.5%, S	–	–	–	–	0.5%–6%
ISR	S	0.7%–5%, S	–	–	–	–	–
FSR	S	1.3%–19%, S	–	–	–	–	–
ME-PS matching	S	2.0%–40%, S	0.6%–7%, S	0.6%–53%, S	–	–	–
Parton shower	S	3.3%–22%, S	1.7%–13%, S	2.2%–61%, S	–	–	1.0%–50%, S
4FS vs. 5FS	S	–	–	–	–	–	–
Heavy-flavour composition	S	–	–	–	–	–	–
DS vs. DR scheme ( $Wt$ )	–	–	–	3.3%–68%, S	–	–	–
Renormalisation/factorisation scales	S	0.5%–3.0%, S	–	–	–	–	1.0%–13%, S
$H_T$ reweighting	S	0.5%–6%, S	–	–	–	–	–
$p_{T,W}$ non-closure	S	0.5%–0.9%, S	0.7%–1.6%, S	2.7%–4%, S	1.8%–3.3%, S	1.1%–2.0%, S	3.0%–30%, S
$5j \leftrightarrow \geq 6j$	17%–34%	–	–	–	–	–	–
SRs $\leftrightarrow$ CRs	11%–33%	–	–	–	–	–	–
SRs $\leftrightarrow$ low-purity SRs	6.8%–17%	–	–	–	–	–	–
Low-purity SRs $\leftrightarrow$ CRs	5.2%–12%	–	–	–	–	–	–
$\ell^\pm v b \bar{b} \leftrightarrow q \bar{q} b \bar{b}$	5.1%–17%	–	–	–	–	–	–

(b) Relative acceptance and normalisation uncertainties for the merged analysis channels

	$t\bar{t}$ + HF	$t\bar{t}$ + LF	$t\bar{t}$ + X	Single Top	VV & V + jets	Others	Signal
Norm.	float	float	0.5%–11%	5%–50%	float	0.5%–50%	float
PDF	S	S	–	–	–	–	<0.5%
ISR	S	S	–	–	–	–	–
FSR	S	S	–	–	–	–	–
ME-PS matching	S	S	0.5%–28%, S	0.5%–26%, S	S	–	–
Parton shower	S	S	0.5%–18%, S	0.5%–60%, S	S	–	0.8%–60%, S
4FS vs. 5FS	S	–	–	–	–	–	–
Heavy-flavour composition	S	–	–	–	–	–	–
DS vs. DR scheme ( $Wt$ )	–	–	–	13%–86%, S	–	–	–
Renormalisation/factorisation scales	S	S	–	–	S	–	0.5%–11%, S
$p_{T,W}/m_{Wh}$ non-closure	S	S	1.0%–4%, S	0.8%–9%, S	S	0.7%–9%, S	0.5%–21%, S
$\Delta\Phi(W, h)$ non-closure	S	S	0.6%–1.2%, S	0.5%–1.2%, S	S	0.5%–0.6%, S	0.5%–3.2%, S
$E_T^{\text{miss}}$ non-closure	S	S	0.8%–8%, S	0.6%–8%, S	S	4%–10%, S	0.5%–12%, S
$0b \leftrightarrow \geq 1b$	4%–24%	11%–18%	–	–	8%–70%	–	–
$\ell^\pm v b \bar{b} \leftrightarrow q \bar{q} b \bar{b}$	18%–35%	18%–50%	–	–	16%–60%	–	–
High-mass CRs $\leftrightarrow$ low-mass CRs	3.4%–19%	3.7%–16%	–	–	10%–32%	–	–
CRs $\leftrightarrow$ high-score SR	13.1%–22%	6%–30%	–	–	4%–28%	–	–
CRs $\leftrightarrow$ medium-score SR	11%–17%	6%–22%	–	–	4%–12%	–	–
CRs $\leftrightarrow$ low-score SR	6%–13%	2.7%–23%	–	–	6%–40%	–	–
Low-score SR $\leftrightarrow$ high-score SR	17%–27%	7%–30%	–	–	11%–35%	–	–
Low-score SR $\leftrightarrow$ medium-score SR	13%–19%	7%–23%	–	–	11%–14%	–	–
Medium-score SR $\leftrightarrow$ high-score SR	7%–34%	11%–26%	–	–	14%–20%	–	–

associated with the flavour composition, parton shower modelling and matrix element to parton shower matching of the  $t\bar{t}$  + HF background. Furthermore, nuisance parameters associated with the parton shower

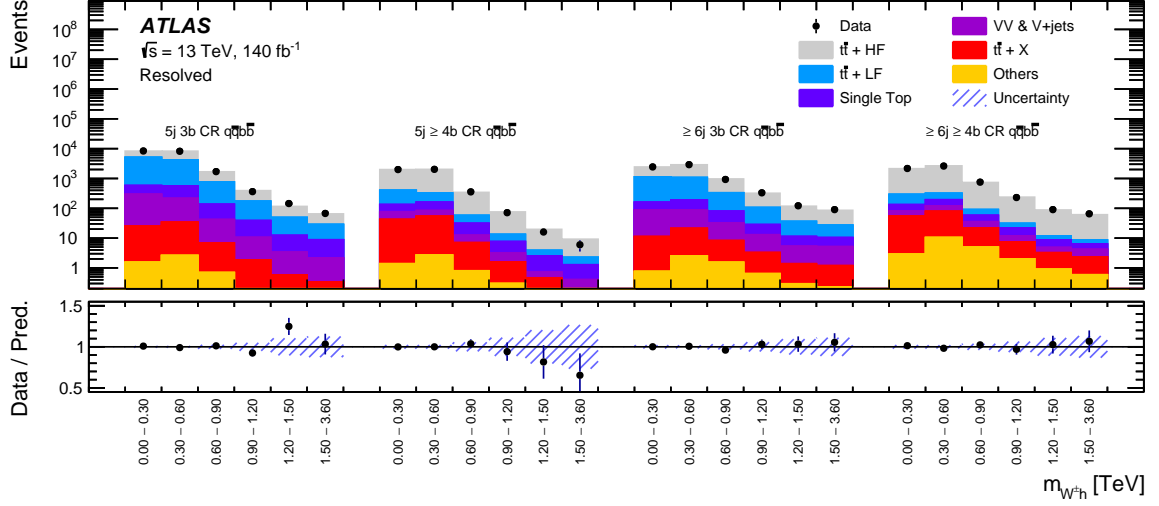
Table 5: Post-fit normalisation factors and their uncertainties obtained from a combined background-only fit to the various signal and control regions of the resolved and merged analyses. Numbers are presented for the background components that are allowed to float in the likelihood fit. Uncertainties in the cross-section times branching ratio and the overall acceptance are not considered in the denominators of these normalisation factors.

Background	Resolved analysis	Merged analysis
$t\bar{t} + \text{HF}$	$1.39 \pm 0.18$	$1.20 \pm 0.17$
$t\bar{t} + \text{LF}$	–	$0.75 \pm 0.08$
$VV \& V + \text{jets}$	–	$1.17 \pm 0.13$

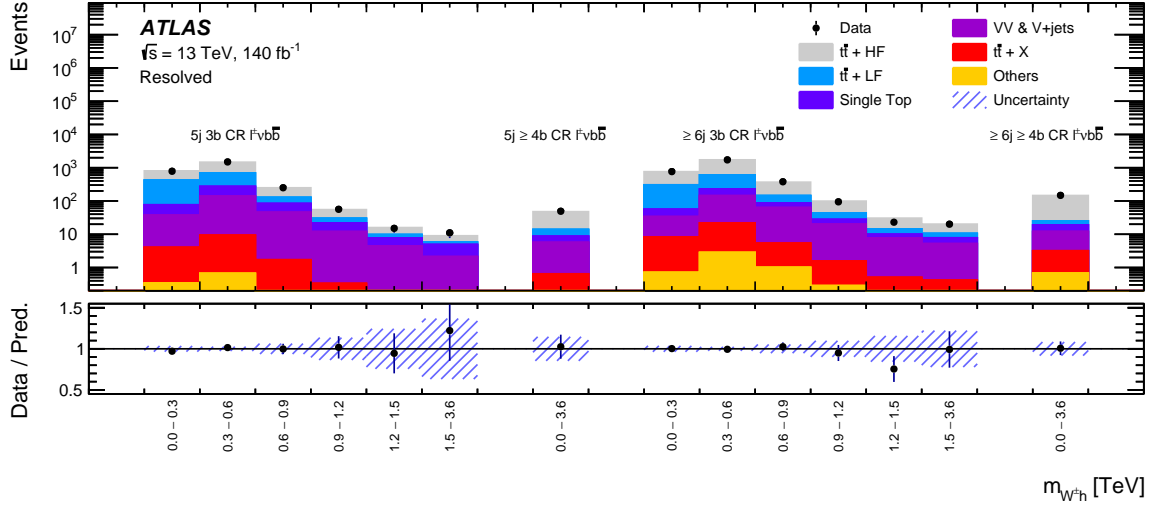
modelling of the  $t\bar{t} + \text{LF}$  background and the comparison between the DS and DR schemes of the  $Wt$  background are constrained substantially. The nuisance parameter corresponding to the flavour composition of the  $t\bar{t} + \text{HF}$  background is constrained to 20% of its initial value, while the other nuisance parameters listed above are constrained to about 40%-60% of their initial values. In addition to the constraints, a few significantly pulled nuisance parameters are observed in both analyses. In the resolved analysis, the nuisance parameter associated with the  $p_{T,W}$  non-closure uncertainty is pulled by about one standard deviation. In the merged analyses, the nuisance parameters associated with the  $E_T^{\text{miss}}$  non-closure uncertainty, the uncertainties related to missing higher order terms in the perturbative expansion of the  $W + \text{jets}$  background, and the matrix element to parton shower matching of the  $t\bar{t} + \text{LF}$  background are each pulled by around 0.7 to 0.8 standard deviations.

The  $m_{W\pm h}$  distributions after a background-only fit to data are shown in Figures 7 to 8 for the control regions of the resolved and merged analyses. The corresponding signal region distributions are shown in Figures 9 to 11 for the signal regions of the resolved analysis and in Figures 12 to 14 for the signal regions of the merged analysis. Additionally, the expected and observed event yields after fits of the backgrounds to data performed under the background-only hypothesis are shown in Table 6.



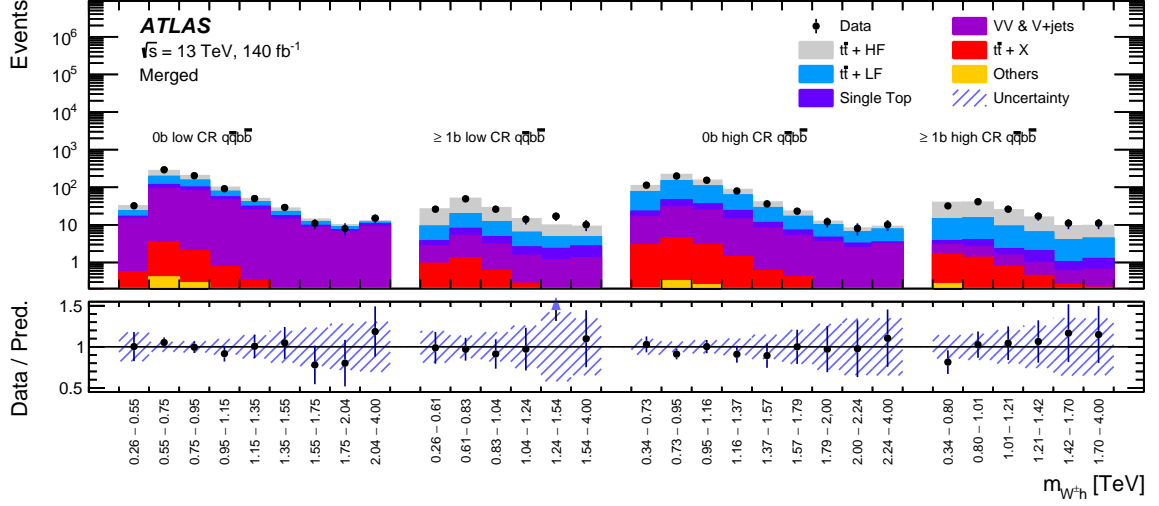


(a)

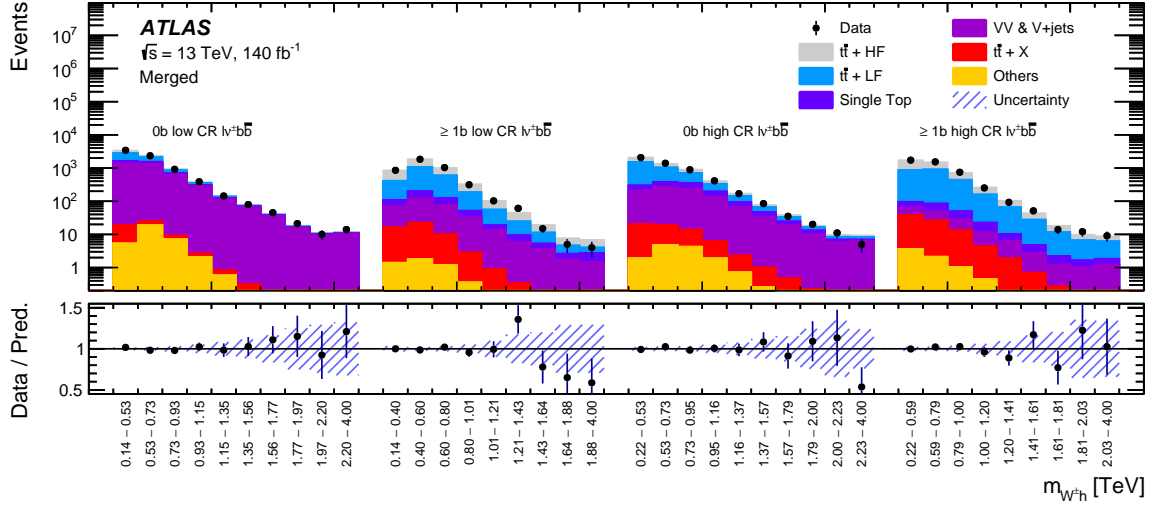


(b)

Figure 7: Distributions of the  $m_{W^{\pm}h}$  observable in the control regions of the resolved (a)  $q\bar{q}b\bar{b}$  and (b)  $\ell^{\pm}vb\bar{b}$  event categories. The term ‘Others’ summarises events from  $tHj\bar{b}$ ,  $tWh$ ,  $t\bar{t}t\bar{t}$ , and SM  $Vh$  production. The distributions are presented after a background-only maximum-likelihood fit to data. The lower panels show the ratio of the observed to the estimated SM background. The shaded bands show the total post-fit uncertainty in the background.



(a)



(b)

Figure 8: Distributions of the  $m_{W^\pm h}$  observable in the control regions of the merged (a)  $q\bar{q}b\bar{b}$  and (b)  $\ell^\pm v b\bar{b}$  event categories. The term ‘Others’ summarises events from  $tHj b$ ,  $tWh$ ,  $t\bar{t}t$ , and SM  $Vh$  production. The distributions are presented after a background-only maximum-likelihood fit to data. The lower panels show the ratio of the observed to the estimated SM background. The shaded bands show the total post-fit uncertainty in the background.

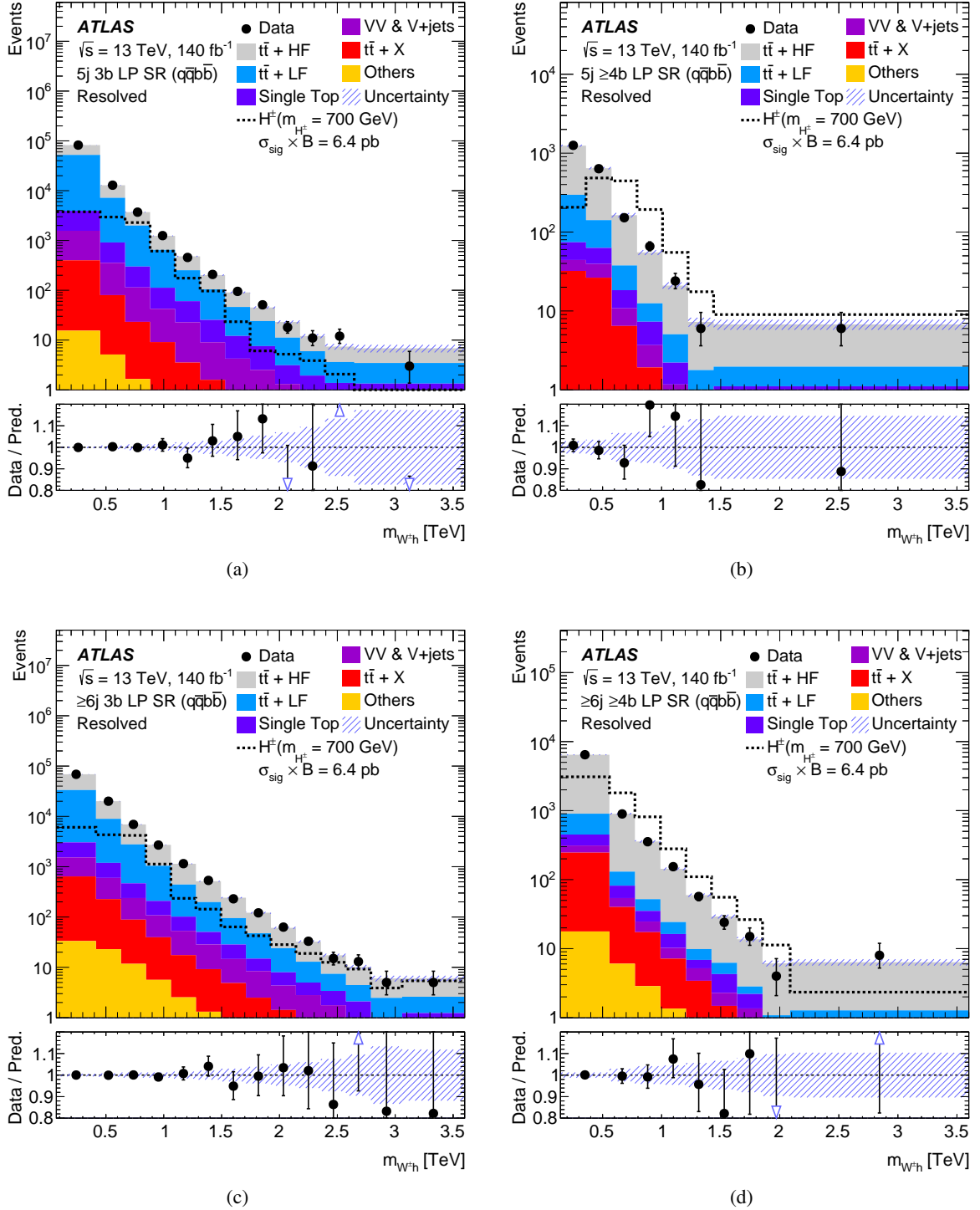


Figure 9: The  $m_{W^{\pm}h}$  distributions in the low-purity signal regions (LP SR) of the resolved  $q\bar{q}b\bar{b}$  event categories. The term ‘Others’ summarises events from  $tHj b$ ,  $tWh$ ,  $t\bar{t}t\bar{t}$ , and SM  $Vh$  production. The background prediction is shown after a background-only maximum-likelihood fit to data. The lower panels show the ratio of the observed to the estimated SM background. The shaded bands show the total post-fit uncertainty in the background. The expected signal contribution assuming  $m_{H^{\pm}} = 700\text{ GeV}$ , normalised to a cross-section times branching ratio ( $\sigma_{\text{sig}} \times B$ ) of  $6.4\text{ pb}$ , is shown as a dashed histogram.

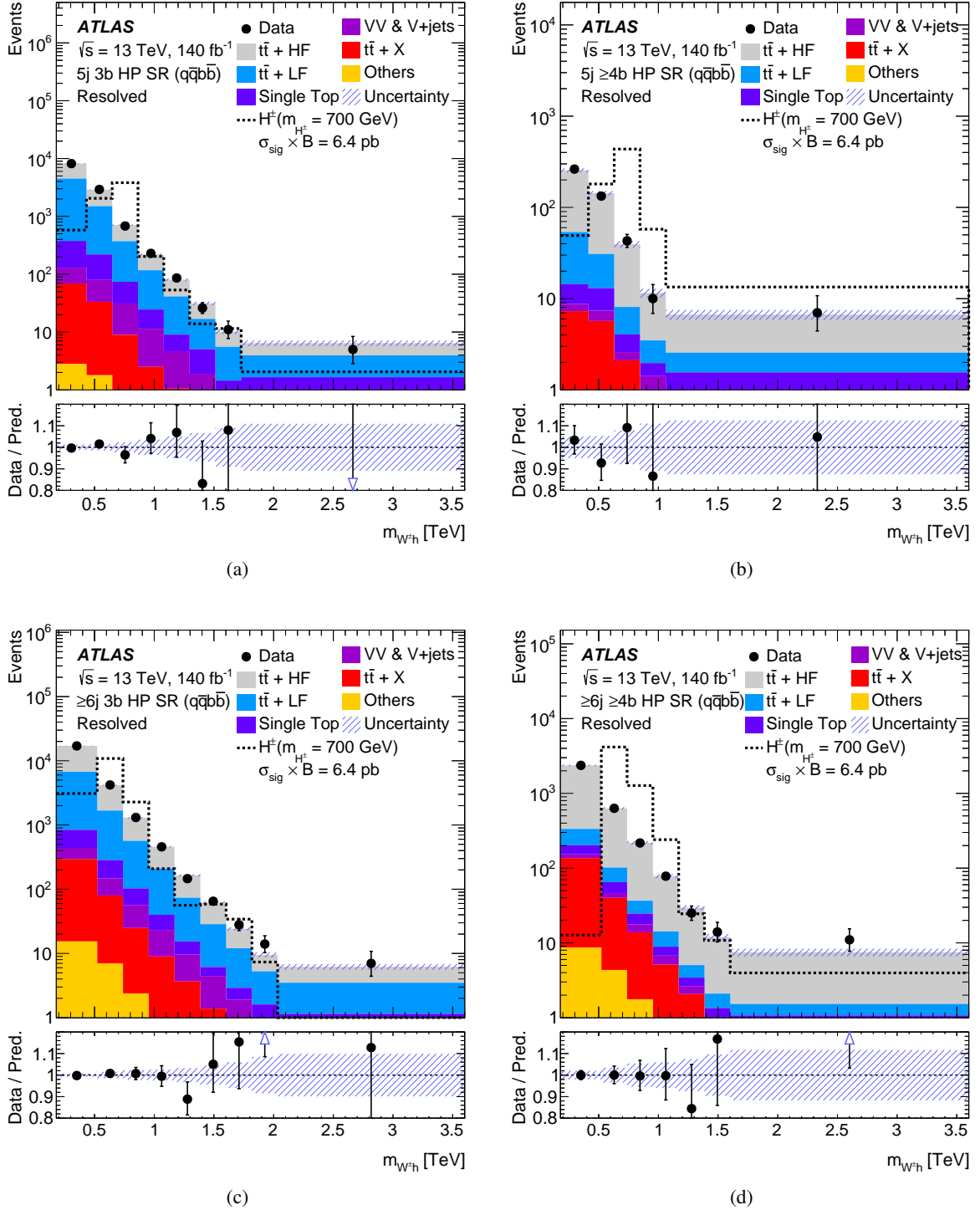


Figure 10: The  $m_{W^{\pm}h}$  distributions in the high-purity signal regions (HP SR) of the resolved  $q\bar{q}b\bar{b}$  event categories. The term ‘Others’ summarises events from  $tHj b$ ,  $tWh$ ,  $t\bar{t}t\bar{t}$ , and SM  $Vh$  production. The background prediction is shown after a background-only maximum-likelihood fit to data. The lower panels show the ratio of the observed to the estimated SM background. The shaded bands show the total post-fit uncertainty in the background. The expected signal contribution assuming  $m_{H^{\pm}} = 700$  GeV, normalised to a cross-section times branching ratio ( $\sigma_{\text{sig}} \times B$ ) of 6.4 pb, is shown as a dashed histogram.

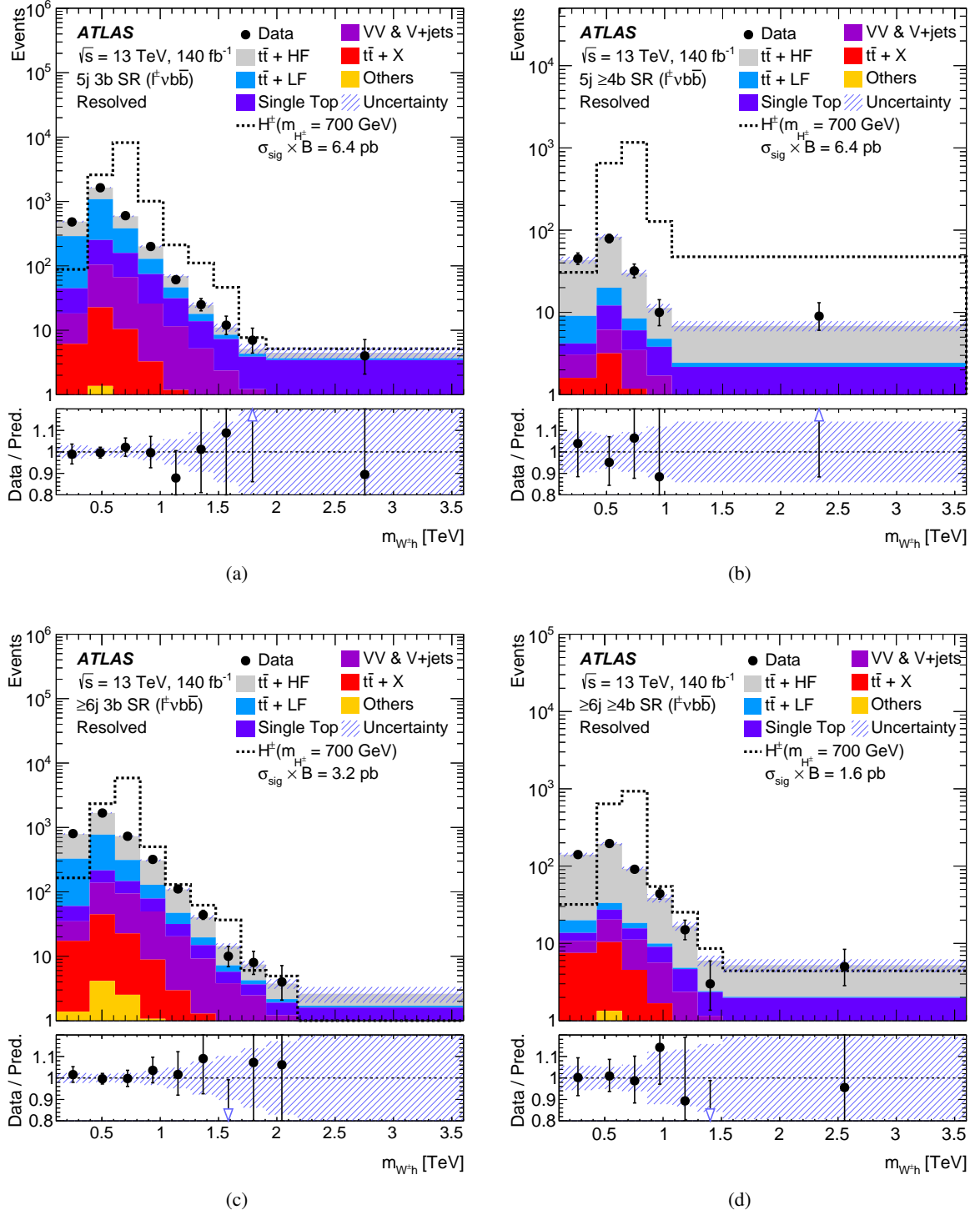


Figure 11: The  $m_{W^{\pm}h}$  distributions in the signal regions of the resolved  $\ell^{\pm} \nu b \bar{b}$  event categories. The term ‘Others’ summarises events from  $tHjb$ ,  $tWh$ ,  $t\bar{t}\bar{t}$ , and SM  $Vh$  production. The background prediction is shown after a background-only maximum-likelihood fit to data. The lower panels show the ratio of the observed to the estimated SM background. The shaded bands show the total post-fit uncertainty in the background. The expected signal contribution assuming  $m_{H^{\pm}} = 700$  GeV, normalised to different values of the cross-section times branching ratio ( $\sigma_{\text{sig}} \times B$ ), is shown as a dashed histogram.

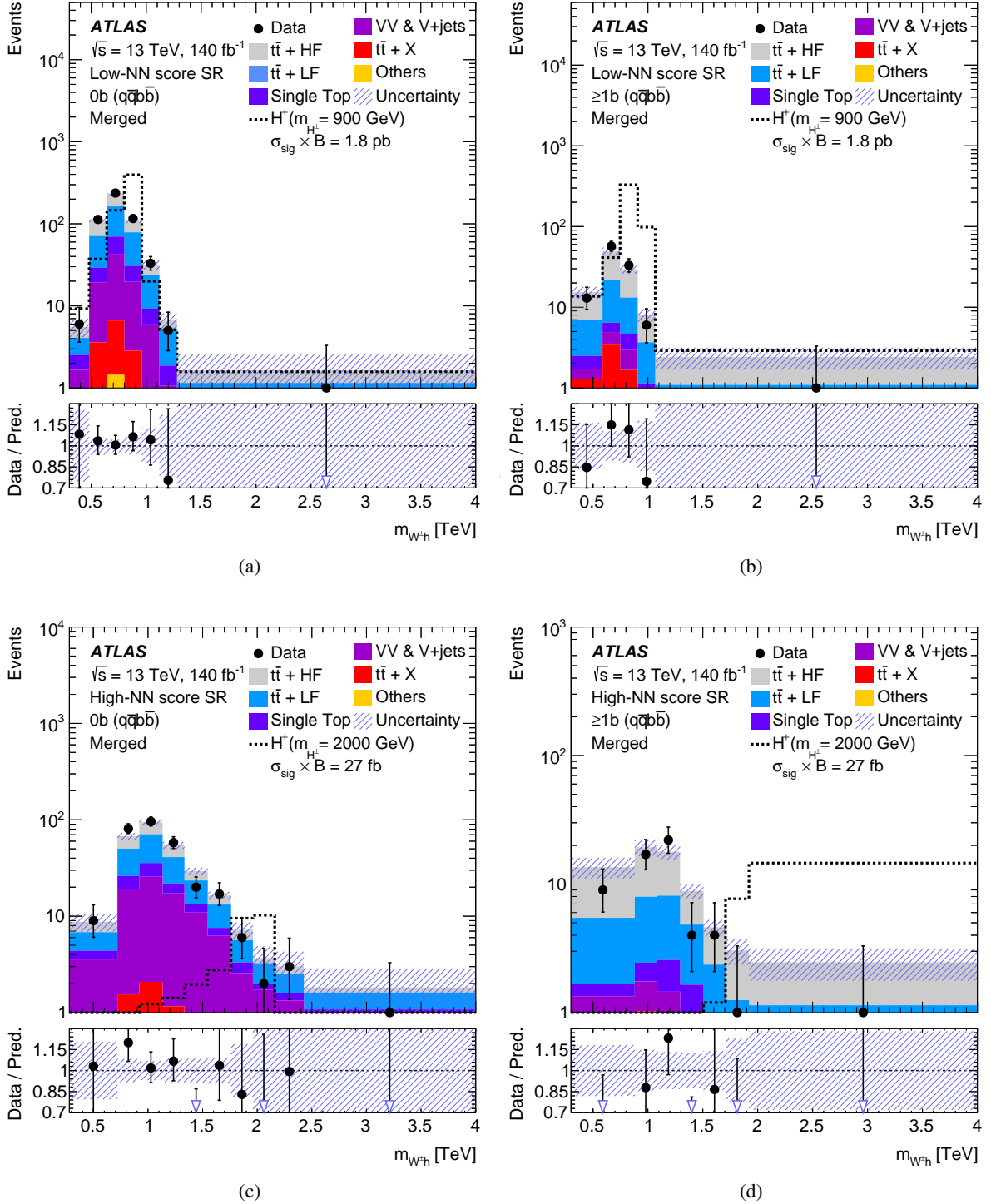


Figure 12: The  $m_{W^{\pm}h}$  distributions in the low-NN-score SRs (top) and high-NN-score SRs (bottom) of the merged  $q\bar{q}b\bar{b}$  event categories. The term ‘Others’ summarises events from  $tHjb$ ,  $tWh$ ,  $t\bar{t}t\bar{t}$ , and SM  $Vh$  production. The background prediction is shown after a background-only maximum-likelihood fit to data. The lower panels show the ratio of the observed to the estimated SM background. The shaded bands show the total post-fit uncertainty in the background. The expected signal contributions assuming  $m_{H^{\pm}} = 900$  GeV and  $m_{H^{\pm}} = 2000$  GeV, normalised to cross-section times branching ratio ( $\sigma_{\text{sig}} \times B$ ) values of 1.8 pb and 27 fb respectively, are shown as dashed histograms.

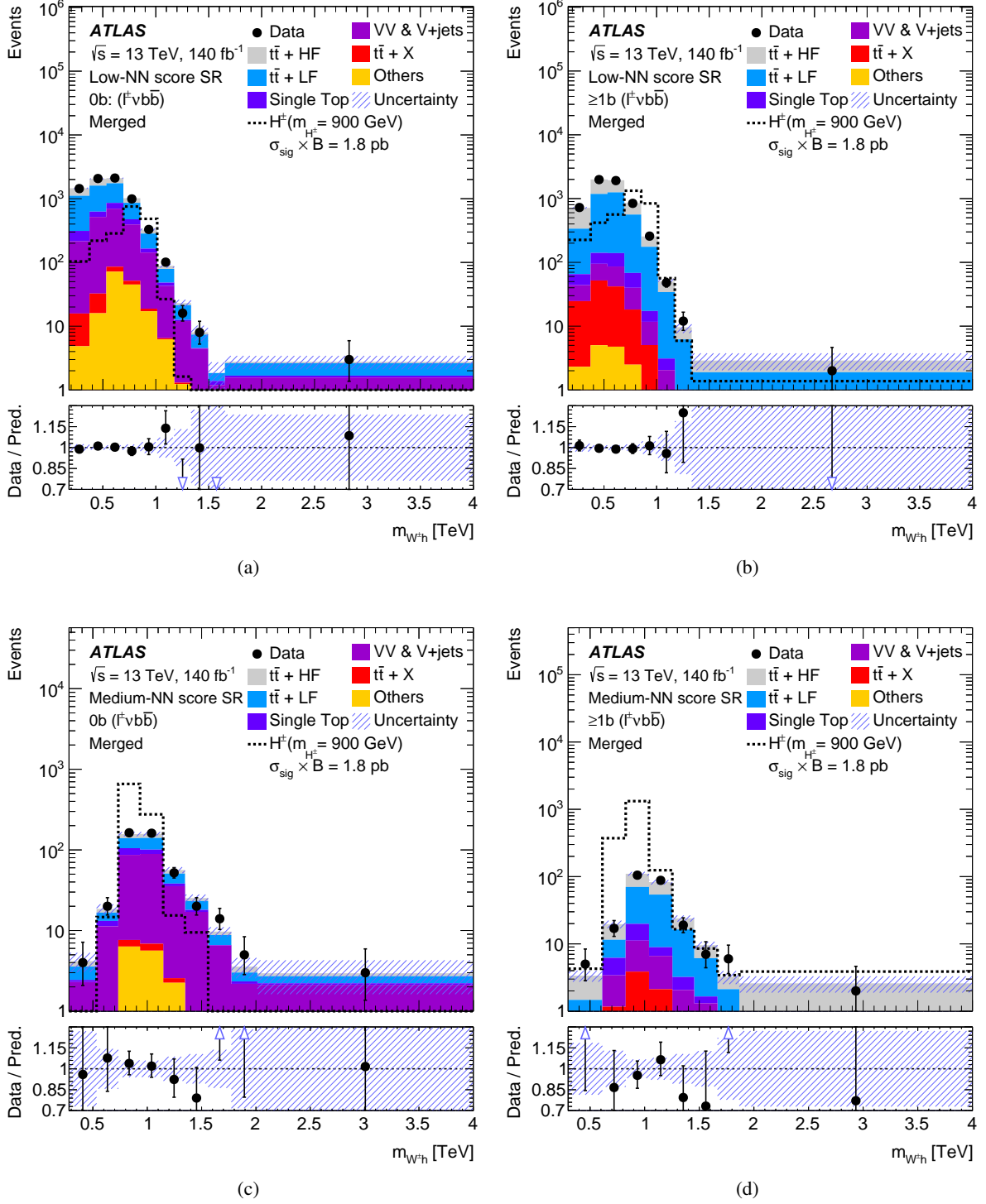


Figure 13: The  $m_{W\neq h}$  distributions in the low-NN-score SRs (top) and medium-NN-score SRs (bottom) of the merged  $\ell^{\pm}\nu b\bar{b}$  event categories. The term ‘Others’ summarises events from  $tHjb$ ,  $tWh$ ,  $t\bar{t}t\bar{t}$ , and SM  $Vh$  production. The background prediction is shown after a background-only maximum-likelihood fit to data. The lower panels show the ratio of the observed to the estimated SM background. The shaded bands show the total post-fit uncertainty in the background. The expected signal contribution assuming  $m_{H^{\pm}} = 900$  GeV, normalised to a cross-section times branching ratio ( $\sigma_{\text{sig}} \times B$ ) values of 1.8 pb, is shown as a dashed histogram.



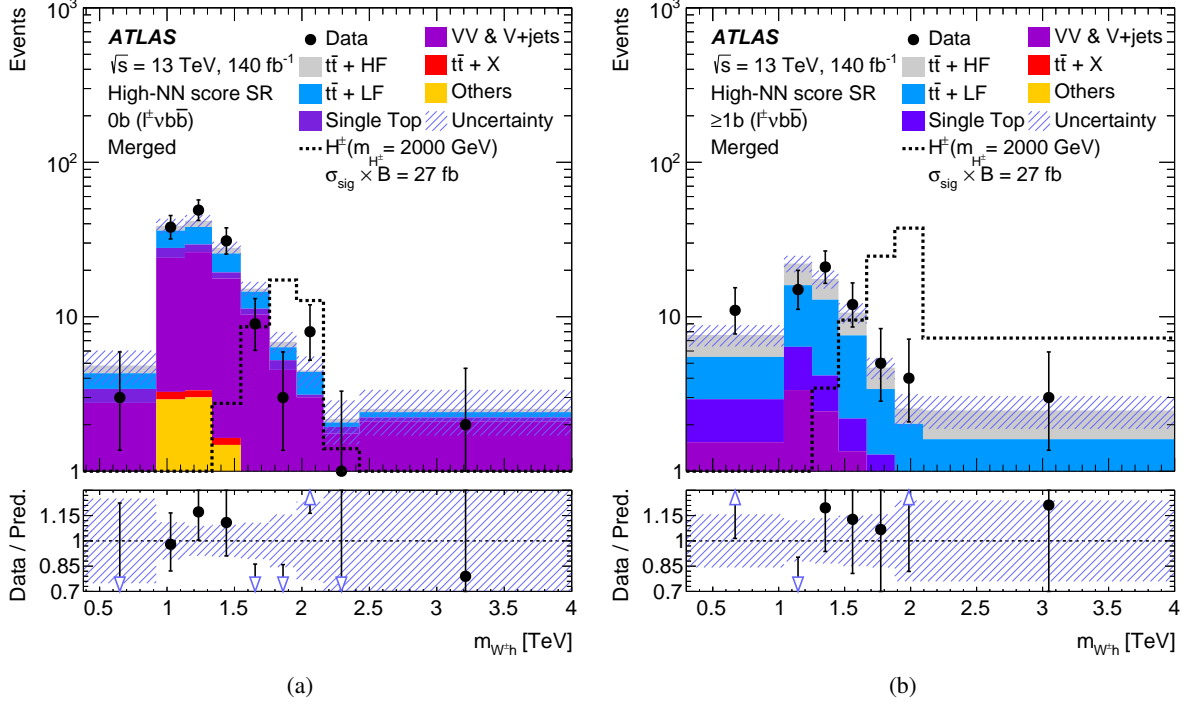


Figure 14: The  $m_{W^{\pm}h}$  distributions in the high-NN-score SRs of the merged  $\ell^{\pm}vbb\bar{b}$  event categories. The term ‘Others’ summarises events from  $tHjb$ ,  $tWh$ ,  $t\bar{t}t\bar{t}$ , and SM  $Vh$  production. The background prediction is shown after a background-only maximum-likelihood fit to data. The lower panels show the ratio of the observed to the estimated SM background. The shaded bands show the total post-fit uncertainty in the background. The expected signal contribution assuming  $m_{H^{\pm}} = 2000$  GeV, normalised to a cross-section times branching ratio ( $\sigma_{\text{sig}} \times B$ ) of 27 fb, is shown as a dashed histogram.

This search probes for charged Higgs bosons in the mass range from 250 GeV to 3 TeV. In total, 17 signal mass hypotheses are tested. The resolved and merged analyses show complementary sensitivities to different charged Higgs boson mass regions. The resolved analysis is more sensitive for masses up to (and including) 900 GeV, while the merged analysis dominates at higher masses. Instead of performing a statistical combination of the two analyses, the analysis with the more stringent expected upper limit on the production cross-section times branching ratio is used at each mass point.

The 95% CL upper limits on the production cross-section times branching ratio for a charged Higgs boson decaying via  $H^{\pm} \rightarrow W^{\pm}h$  are presented in Figure 15 as a function of the charged Higgs boson mass. The observed limits range from 2.8 pb for a mass value of 250 GeV to 1.2 fb for a mass of 3 TeV. The limits on the signal hypotheses with  $m_{H^{\pm}} \geq 0.7$  TeV were also calculated using pseudo-experiments to validate the asymptotic approximation approach in a phase-space region strongly limited by a low number of data events. It was found that the asymptotic approximation is valid within 10%.

The expected exclusion limits are dominated by the  $\ell^{\pm}vbb\bar{b}$  channel except for the 250 GeV mass hypothesis, where the  $q\bar{q}b\bar{b}$  channel is stronger. In the resolved analysis, the  $\ell^{\pm}vbb\bar{b}$  channel provides a cross-section times branching ratio limit that is 1.1 times lower at 350 GeV and 2.5 times lower at 800 GeV. In the merged analysis, the  $\ell^{\pm}vbb\bar{b}$  channel provides a limit that is 1.4 times lower at 900 GeV and 2.5 times lower at 3000 GeV.

Table 6: Event yields in the various signal and control regions of the (a) resolved and (b) merged analyses after a background-only fit to data. The quoted uncertainties are the total post-fit uncertainties. The uncertainties in the individual background predictions are larger than the total background uncertainty due to correlations resulting from the fit to data.

(a) Post-fit event yields of the resolved event categories

	$t\bar{t}$ + LF	$t\bar{t}$ + HF	Single top	VV & V + jets	$t\bar{t}$ + X	Others	Total bkg.	Data
$5j3b$ CR ( $q\bar{q}b\bar{b}$ )	9000 ± 500	8400 ± 600	770 ± 190	500 ± 150	64 ± 11	5.0 ± 0.6	18720 ± 150	18737
$5j \geq 4b$ CR ( $q\bar{q}b\bar{b}$ )	470 ± 80	3640 ± 130	160 ± 50	69 ± 20	100 ± 15	5.3 ± 0.6	4450 ± 70	4449
$\geq 6j3b$ CR ( $q\bar{q}b\bar{b}$ )	2200 ± 400	4100 ± 400	250 ± 80	180 ± 60	41 ± 8	6.0 ± 2.4	6790 ± 90	6788
$\geq 6j \geq 4b$ CR ( $q\bar{q}b\bar{b}$ )	330 ± 110	5140 ± 150	160 ± 60	87 ± 25	147 ± 18	22 ± 9	5890 ± 80	5889
$5j3b$ low-purity SR ( $q\bar{q}b\bar{b}$ )	57000 ± 4000	38000 ± 4000	3300 ± 900	1600 ± 500	500 ± 80	23.4 ± 1.4	100970 ± 330	100957
$5j \geq 4b$ low-purity SR ( $q\bar{q}b\bar{b}$ )	330 ± 60	1650 ± 90	67 ± 24	32 ± 9	66 ± 10	2.44 ± 0.22	2140 ± 50	2145
$\geq 6j3b$ low-purity SR ( $q\bar{q}b\bar{b}$ )	42000 ± 6000	53000 ± 6000	2500 ± 700	1600 ± 500	960 ± 160	79 ± 31	100500 ± 500	100485
$\geq 6j \geq 4b$ low-purity SR ( $q\bar{q}b\bar{b}$ )	530 ± 140	6830 ± 200	190 ± 80	94 ± 27	290 ± 40	29 ± 13	7960 ± 90	7963
$5j3b$ high-purity SR ( $q\bar{q}b\bar{b}$ )	5800 ± 700	5600 ± 700	450 ± 160	140 ± 40	110 ± 19	5.53 ± 0.29	12130 ± 140	12130
$5j \geq 4b$ high-purity SR ( $q\bar{q}b\bar{b}$ )	64 ± 16	357 ± 28	14 ± 11	4.5 ± 1.7	16.0 ± 2.9	0.58 ± 0.16	456 ± 21	456
$\geq 6j3b$ high-purity SR ( $q\bar{q}b\bar{b}$ )	8000 ± 1400	14000 ± 1400	610 ± 220	270 ± 80	390 ± 60	26 ± 10	23260 ± 160	23258
$\geq 6j \geq 4b$ high-purity SR ( $q\bar{q}b\bar{b}$ )	190 ± 60	2850 ± 100	80 ± 40	30 ± 10	182 ± 27	16 ± 7	3340 ± 60	3343
$5j3b$ CR ( $\ell^\pm v b \bar{b}$ )	820 ± 80	1310 ± 130	230 ± 90	220 ± 70	14 ± 4	1.22 ± 0.16	2600 ± 50	2599
$5j \geq 4b$ CR ( $\ell^\pm v b \bar{b}$ )	5.2 ± 2.2	34 ± 6	3.0 ± 1.9	5.0 ± 1.7	0.60 ± 0.15	0.05 ± 0.05	48 ± 6	49
$\geq 6j3b$ CR ( $\ell^\pm v b \bar{b}$ )	710 ± 120	1870 ± 180	140 ± 70	240 ± 70	33 ± 7	5.0 ± 2.2	3000 ± 50	2991
$\geq 6j \geq 4b$ CR ( $\ell^\pm v b \bar{b}$ )	6.2 ± 2.7	121 ± 14	7 ± 5	8.9 ± 2.7	2.5 ± 0.4	0.68 ± 0.32	146 ± 12	147
$5j3b$ SR ( $\ell^\pm v b \bar{b}$ )	1380 ± 140	1060 ± 180	350 ± 80	190 ± 60	42 ± 8	2.72 ± 0.24	3030 ± 50	3026
$5j \geq 4b$ SR ( $\ell^\pm v b \bar{b}$ )	16 ± 4	130 ± 15	13 ± 6	8.8 ± 2.7	6.2 ± 0.9	0.43 ± 0.08	175 ± 13	175
$\geq 6j3b$ SR ( $\ell^\pm v b \bar{b}$ )	1060 ± 170	2060 ± 220	210 ± 100	260 ± 80	89 ± 16	10 ± 4	3690 ± 60	3703
$\geq 6j \geq 4b$ SR ( $\ell^\pm v b \bar{b}$ )	16 ± 5	403 ± 32	23 ± 18	27 ± 8	21.7 ± 2.9	3.5 ± 1.7	494 ± 22	495

(b) Post-fit event yields of the merged event categories

	$t\bar{t}$ + LF	$t\bar{t}$ + HF	Single top	VV & V + jets	$t\bar{t}$ + X	Others	Total bkg.	Data
High- $m_h \geq 1b$ CR ( $q\bar{q}b\bar{b}$ )	39 ± 9	86 ± 14	5.0 ± 3.5	4.6 ± 0.8	4.0 ± 1.5	0.6 ± 0.3	139 ± 10	138
Low- $m_h \geq 1b$ CR ( $q\bar{q}b\bar{b}$ )	33 ± 7	82 ± 11	9 ± 5	11.4 ± 1.9	3.2 ± 0.9	0.24 ± 0.11	139 ± 9	142
High- $m_h$ 0b CR ( $q\bar{q}b\bar{b}$ )	300 ± 50	202 ± 35	50 ± 30	92 ± 16	12.0 ± 2.5	0.9 ± 0.3	659 ± 22	632
Low- $m_h$ 0b CR ( $q\bar{q}b\bar{b}$ )	180 ± 30	187 ± 28	70 ± 40	281 ± 42	6.4 ± 1.2	1.0 ± 0.4	724 ± 24	728
Low-NN-score 0b SR ( $q\bar{q}b\bar{b}$ )	203 ± 29	152 ± 24	53 ± 27	77 ± 16	11.1 ± 2.2	3.0 ± 1.2	499 ± 17	511
Low-NN-score $\geq 1b$ SR ( $q\bar{q}b\bar{b}$ )	32 ± 10	58 ± 11	4.6 ± 1.3	3.6 ± 1.8	6.2 ± 1.3	0.64 ± 0.20	105 ± 8	110
High-NN-score 0b SR ( $q\bar{q}b\bar{b}$ )	102 ± 16	68 ± 17	28 ± 17	83 ± 22	4.4 ± 0.9	1.8 ± 0.8	286 ± 14	293
High-NN-score $\geq 1b$ SR ( $q\bar{q}b\bar{b}$ )	21 ± 4	39 ± 7	3.5 ± 2.7	3.0 ± 0.8	2.9 ± 0.8	0.27 ± 0.08	70 ± 6	58
High- $m_h \geq 1b$ CR ( $\ell^\pm v b \bar{b}$ )	2230 ± 240	1870 ± 250	110 ± 40	78 ± 13	79 ± 16	7.6 ± 2.8	4380 ± 60	4414
Low- $m_h \geq 1b$ CR ( $\ell^\pm v b \bar{b}$ )	1840 ± 200	1860 ± 220	190 ± 60	278 ± 53	48 ± 9	5.0 ± 1.2	4220 ± 60	4202
High- $m_h$ 0b CR ( $\ell^\pm v b \bar{b}$ )	2480 ± 240	1160 ± 170	420 ± 160	940 ± 240	50 ± 9	14 ± 7	5060 ± 70	5063
Low- $m_h$ 0b CR ( $\ell^\pm v b \bar{b}$ )	1950 ± 250	930 ± 130	560 ± 160	3840 ± 280	23 ± 5	34 ± 17	7340 ± 80	7357
Low-NN-score 0b SR ( $\ell^\pm v b \bar{b}$ )	3210 ± 310	1360 ± 200	480 ± 130	1820 ± 250	50 ± 9	160 ± 80	7070 ± 80	7066
Low-NN-score $\geq 1b$ SR ( $\ell^\pm v b \bar{b}$ )	3120 ± 310	2260 ± 310	160 ± 50	137 ± 19	127 ± 25	15.3 ± 3.0	5810 ± 70	5785
Medium-NN-score 0b SR ( $\ell^\pm v b \bar{b}$ )	101 ± 28	46 ± 12	36 ± 22	230 ± 30	3.3 ± 0.7	16 ± 8	435 ± 20	442
Medium-NN-score $\geq 1b$ SR ( $\ell^\pm v b \bar{b}$ )	121 ± 16	92 ± 18	16 ± 8	18 ± 6	6.9 ± 1.4	1.2 ± 0.4	255 ± 14	249
High-NN-score 0b SR ( $\ell^\pm v b \bar{b}$ )	30 ± 12	11 ± 5	11 ± 11	82 ± 18	1.1 ± 0.2	9 ± 5	145 ± 11	144
High-NN-score $\geq 1b$ SR ( $\ell^\pm v b \bar{b}$ )	30 ± 13	19 ± 6	8 ± 7	8 ± 6	2.1 ± 0.3	0.62 ± 0.25	68 ± 8	71

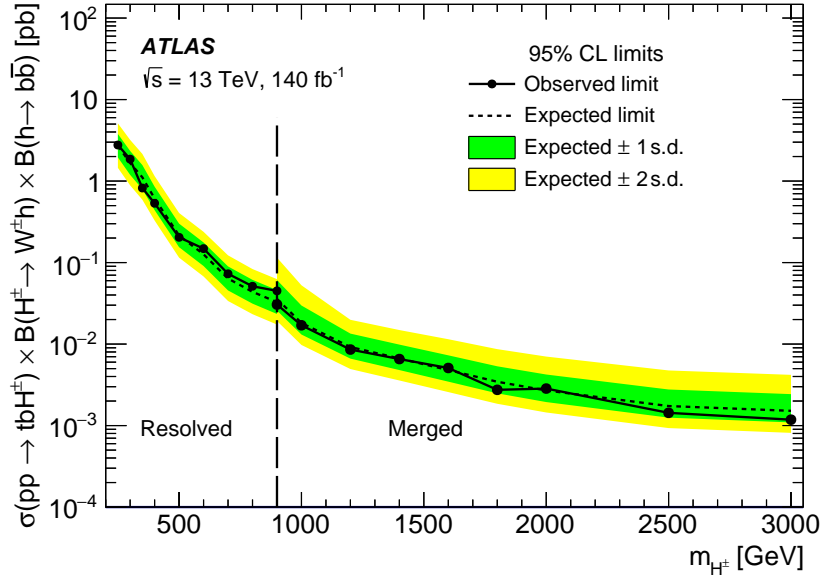


Figure 15: Upper limits at 95% CL on the product of the cross-section for  $pp \rightarrow tbH^\pm$  and the branching ratio  $\mathcal{B}(W^\pm h) \times \mathcal{B}(h \rightarrow b\bar{b})$  from the combined fit to all signal and control regions of the resolved and merged analyses. The bands surrounding the expected limit correspond to the  $\pm 1$  and  $\pm 2$  standard deviation (s.d.) intervals around the expected limit. The results of the resolved analysis are used up to a mass of 900 GeV and those of the merged analysis are used at higher masses.

The dominant uncertainties for low charged Higgs boson masses (e.g.  $m_{H^\pm} = 0.4$  TeV) are related to the modelling of the  $t\bar{t} + \text{HF}$  and  $t\bar{t} + \text{LF}$  backgrounds, while at high charged Higgs boson masses (e.g.  $m_{H^\pm} = 2.0$  TeV) the dominant uncertainties are related to the data statistical uncertainty. The relative impact of the dominant uncertainties on the best-fit signal-strength parameter  $\mu$ , i.e. the ratio of the extracted to injected signal cross-section times branching ratio, are detailed in Table 7.

Table 7: Breakdown of the relative contributions to the uncertainty in the best-fit signal-strength parameter  $\mu$  of the hypothesised production of a charged Higgs boson for two signal mass hypotheses:  $m_{H^\pm} = 0.4$  TeV and  $m_{H^\pm} = 2.0$  TeV. The contributions are obtained by fixing the relevant nuisance parameters to their post-fit values in the likelihood fit to data. The relative impact is determined as the square-root of the difference of the squares of the nominal uncertainty and the varied uncertainty, divided by the nominal uncertainty. The sum in quadrature of the individual components differs from the total uncertainty due to correlations between uncertainties in the different groups. The uncertainty from data statistical uncertainties is determined from fits with all nuisance parameters fixed to their post-fit values. The breakdown of uncertainties for the  $m_{H^\pm} = 0.4$  TeV mass point corresponds to the resolved analysis, while for the  $m_{H^\pm} = 2.0$  TeV mass point, the breakdown of uncertainties corresponds to the merged analysis. The signal cross-section times branching ratio is assumed to be 0.6 pb at 400 GeV and 2.7 fb at 2 TeV, corresponding to the expected upper limits for these two mass hypotheses.

$m_{H^\pm} = 0.4$ TeV		$m_{H^\pm} = 2$ TeV	
Category	Relative contribution	Category	Relative contribution
Modelling uncertainties			
$t\bar{t}$ + HF modelling	74%	Extrapolation/migration	25%
$t\bar{t}$ + LF modelling	34%	$t\bar{t}$ + LF modelling	17%
Extrapolation/migration	20%	Non- $t\bar{t}$ modelling	16%
Non- $t\bar{t}$ modelling	9%	MC statistical uncertainty	12%
Signal modelling	5%	$t\bar{t}$ + HF normalisation	10%
$t\bar{t}$ + HF normalisation	5%	Non-closure	7%
Non-closure	5%	$t\bar{t}$ + LF normalisation	6%
MC statistical uncertainty	4%	$t\bar{t}$ + HF modelling	6%
		VV modelling	4%
		Signal modelling	3%
		VV normalisation	1%
Experimental uncertainties			
Small- $R$ jets	15%	$h \rightarrow b\bar{b}$ tagging	12%
Flavour tagging	14%	Larger- $R$ -jets	4%
Pile-up	7%	Small- $R$ jets	4%
Electrons	4%	Flavour tagging	3%
Luminosity	3%	Pile-up	1%
Muons	1%	Electrons	1%
Missing transverse momentum	<0.1%	Missing transverse momentum	0.1%
		Muons	<0.1%
		Luminosity	<0.1%
Total systematic uncertainty	93%	Total systematic uncertainty	49%
Data statistical uncertainty	37%	Data statistical uncertainty	87%

## 9 Conclusion

A search for a heavy charged Higgs boson produced in association with a top quark and a bottom quark and decaying into a  $W$  boson and a 125 GeV Higgs boson is performed in the mass range from 250 GeV to 3000 GeV. This search uses  $pp$  collision data at  $\sqrt{s} = 13$  TeV collected with the ATLAS detector at the LHC from 2015 to 2018, corresponding to an integrated luminosity of  $140 \text{ fb}^{-1}$ .

Two different analysis strategies are applied to ensure high sensitivity to both low- and high-mass charged Higgs bosons. The mass range up to 900 GeV is probed in final states with exactly one charged electron or muon, missing transverse momentum and at least five small- $R$  jets. Events are classified based on kinematic requirements and the multiplicity of  $b$ -tagged jets per event. Finally, two sets of boosted decision trees are used to reconstruct the four-momentum of the charged Higgs boson candidate. The mass range above 900 GeV is probed in final states with exactly one charged electron or muon, missing transverse momentum and at least one large- $R$  jet. A recently developed boosted  $h \rightarrow b\bar{b}$  tagging technique is used to identify the decay of boosted Higgs bosons and sets of neural networks are employed to further separate between the signal and the background processes.

Both analyses search for a localised excess in the distribution of the reconstructed invariant mass of the charged Higgs boson. Neither analyses observe a significant excess of events above the SM prediction and upper limits at 95% CL are set on the production cross-section times branching ratio. The upper limits range from 2.8 pb for  $m_{H^\pm} = 250$  GeV to 1.2 fb for  $m_{H^\pm} = 3000$  GeV.

This search is performed for the first time at the LHC, complementing previous searches for  $H^\pm \rightarrow tb$  and  $H^\pm \rightarrow \tau^\pm \nu$  decays by the ATLAS and CMS collaborations. While the  $H^\pm \rightarrow W^\pm h$  decay mode is predicted to be subdominant in common two-Higgs-doublet models, its branching ratio is predicted to be significant in other extended scalar sector models such as the Georgi-Machacek model, or the three-Higgs-doublet model.

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