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### Search for new resonances decaying to a $W$ or $Z$ boson and a Higgs boson in the $\ell\ell^+\ell\ell^-b\bar{b}$ , $\ell\ell b\bar{b}$ , and $b\bar{b}b$ channels with $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

ATLAS Collaboration; Newman, Paul

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**Search for new resonances decaying to a  $W$  or  $Z$  boson and a Higgs boson in the  $\ell^+\ell^-b\bar{b}$ ,  $\ell\nu b\bar{b}$ , and  $\nu\bar{\nu}b\bar{b}$  channels with  $pp$  collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector**

The ATLAS Collaboration

**Abstract**

A search is presented for new resonances decaying to a  $W$  or  $Z$  boson and a Higgs boson in the  $\ell^+\ell^-b\bar{b}$ ,  $\ell\nu b\bar{b}$ , and  $\nu\bar{\nu}b\bar{b}$  channels in  $pp$  collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector at the Large Hadron Collider using a total integrated luminosity of  $3.2 \text{ fb}^{-1}$ . The search is conducted by looking for a localized excess in the  $WH/ZH$  invariant or transverse mass distribution. No significant excess is observed, and the results are interpreted in terms of constraints on a simplified model based on a phenomenological Lagrangian of heavy vector triplets.

# 1 Introduction

The Higgs boson discovery by the ATLAS [1] and CMS [2] collaborations imposes constraints on theories beyond the Standard Model (SM). Nevertheless, quadratically divergent radiative corrections to the Higgs boson mass make it unnatural for the SM to be valid beyond a scale of a few TeV. Various dynamical electroweak symmetry-breaking scenarios attempt to solve the naturalness problem by assuming a new strong interaction at a higher scale. These models generically predict the existence of new resonances decaying to a vector boson plus the Higgs boson, as for example in Minimal Walking Technicolour [3–5], Little Higgs [6], or composite Higgs models [7, 8].

This Letter describes a search for new heavy vector bosons decaying to a SM vector boson and a SM Higgs boson, denoted hereafter by  $W'$  and  $Z'$  ( $pp \rightarrow W' \rightarrow WH$  and  $pp \rightarrow Z' \rightarrow ZH$ ) and together as  $V'$ . The analyses described here only consider leptonic decays of the vector bosons ( $W \rightarrow \ell\nu$ ,  $Z \rightarrow \ell^+\ell^-$ ,  $Z \rightarrow \nu\bar{\nu}$ ;  $\ell = e, \mu$ ) and decays of the Higgs boson to bottom-quark pairs ( $H \rightarrow b\bar{b}$ ). This results in three search channels:  $W' \rightarrow WH \rightarrow \ell\nu b\bar{b}$ ,  $Z' \rightarrow ZH \rightarrow \ell^+\ell^- b\bar{b}$ , and  $Z' \rightarrow ZH \rightarrow \nu\bar{\nu} b\bar{b}$ .

For the interpretation of the results in terms of a search for heavy vector bosons, a simplified model [9] based on a phenomenological Lagrangian is used as a benchmark. This simplified model incorporates heavy vector triplets (HVT) and allows for the interpretation of the results in a large class of models. Here, the new heavy vector bosons couple to the Higgs boson and SM gauge bosons via a combination of parameters  $g_V c_H$  and to the fermions via the combination  $(g^2/g_V)c_F$ , where  $g$  is the weak SU(2) coupling constant. The parameter  $g_V$  represents the strength of the new vector boson’s interaction, and  $c_H$  and  $c_F$  are multiplicative factors to modify the couplings to the Higgs boson and the fermions, and are expected to be of order unity in most models. Two benchmark models [9] are used here. In the first, referred to as *Model A*, the branching fractions to fermions and gauge bosons are comparable, as in some extensions of the SM gauge group [10]. For *Model B*, fermionic couplings are suppressed, for example in a composite Higgs model [11]. The regions of HVT parameter space probed in this Letter correspond to the production of resonances with an intrinsic width that is narrow relative to the experimental resolution, which is roughly 10% of the resonance mass.

Previous searches in the same final states have been performed by both the ATLAS and CMS collaborations using data at  $\sqrt{s} = 8$  TeV. The ATLAS searches for  $V' \rightarrow VH$  set a lower limit at the 95% confidence level (CL) on the  $W'$  ( $Z'$ ) mass at 1.47 (1.36) TeV, assuming the HVT benchmark *Model A* with  $g_V = 1$  [12]. Searches by the CMS Collaboration for  $V' \rightarrow VH$ , based on HVT benchmark *Model B* with  $g_V = 3$ , similarly exclude heavy resonance masses up to 1.1 TeV ( $Z' \rightarrow ZH$ ), 1.5 TeV ( $W' \rightarrow WH$ ), yielding a combined limit of 1.7 TeV ( $V' \rightarrow VH$ ) in the fully hadronic final state [13], and masses up to 1.5 TeV for the  $W' \rightarrow WH \rightarrow \ell\nu b\bar{b}$  final state [14]. A search by the CMS Collaboration has been carried out for a narrow resonance decaying to  $ZH$  in the  $\tau^+\tau^- b\bar{b}$  final state, setting limits on the production cross-section of  $Z'$  assuming the HVT benchmark *Model B* with  $g_V = 3$  [15]. The ATLAS Collaboration has also performed a search for narrow resonances decaying to  $VV$  final states [16].

The search presented here has been optimized to be sensitive to resonances of mass larger than 1 TeV, hence decaying to highly boosted final-state particles. As a consequence, the Higgs boson decay to bottom quarks is less likely to be observed as two separate jets than as a single wide jet where the two  $b$ -jets are “merged” (the Higgs boson candidate). Bottom-quark tagging is used as a means to further purify the event selection. Decays of the Higgs boson to charm quarks are included in the signal Monte Carlo simulation to properly account for the small contribution of  $b$ -tagged charm quarks. Together, the reconstructed mass of the Higgs boson candidate jet and the results of the bottom-quark tagging are used

to identify likely Higgs boson candidates. The search is performed by examining the distribution of the reconstructed  $VH$  mass ( $m_{VH}$ ) or transverse mass ( $m_{T,VH}$ ) for a localized excess. The signal strength and background normalization are determined from a binned maximum-likelihood fit to the data distribution in each channel and are used to evaluate bounds on the production cross-section times decay branching fraction for  $V'$  bosons.

## 2 ATLAS detector

The ATLAS detector [17] is a general-purpose particle detector used to investigate a broad range of physics processes. It includes inner tracking devices surrounded by a superconducting solenoid, electromagnetic and hadronic calorimeters and a muon spectrometer with a toroidal magnetic field. The inner detector consists of a high-granularity silicon pixel detector, including the insertable B-layer [18] installed after Run 1 of the LHC, a silicon strip detector, and a straw-tube tracker; it is situated inside a 2 T axial field and provides precision tracking of charged particles with pseudorapidity  $|\eta| < 2.5$ , where the pseudorapidity is defined in terms of the polar angle<sup>1</sup>  $\theta$  as  $\eta = -\ln \tan(\theta/2)$ . The straw-tube tracker also provides transition radiation measurements for electron identification up to  $|\eta| = 2.0$ . The calorimeter system covers the pseudorapidity range  $|\eta| < 4.9$ . It is composed of sampling calorimeters with either liquid argon or scintillator tiles as the active media. The muon spectrometer provides muon identification and measurement for  $|\eta| < 2.7$ . The ATLAS detector has a two-level trigger system to select events for offline analysis [19].

## 3 Data and simulated samples

The data used in this analysis were recorded with the ATLAS detector during the 2015  $pp$  collisions run and correspond to a total integrated luminosity of  $3.2 \text{ fb}^{-1}$  [20] at  $\sqrt{s} = 13 \text{ TeV}$ . Collision events satisfy a number of requirements ensuring that the ATLAS detector was operating in stable conditions while the data were recorded.

Simulated Monte Carlo (MC) samples for the HVT are generated with MadGraph5\_aMC@NLO 2.2.2 [21] using the NNPDF2.3LO [22] parton distribution functions (PDFs). For all signal events, parton showering and hadronization are performed with PYTHIA 8.186 [23] using the A14 set of tuned parameters (tune) [24]. The Higgs boson has its mass set to 125.5 GeV, and it is allowed to decay to  $b\bar{b}$  and  $c\bar{c}$  pairs, with relative branching fractions  $\text{BR}(H \rightarrow c\bar{c})/\text{BR}(H \rightarrow b\bar{b}) = 0.05$  fixed to the Standard Model prediction [25]. Signal samples are generated for a range of resonance masses from 0.7 to 5 TeV in steps of 100 GeV up to 2 TeV and in wider steps for higher masses.

Monte Carlo samples are used to model the shape and normalization of most SM background processes. Diboson events ( $WW$ ,  $WZ$ ,  $ZZ$ ) and events containing a  $W$  or  $Z$  boson with associated jets ( $W$ +jets,  $Z$ +jets) are simulated using the SHERPA 2.1.1 [26] generator. Matrix elements are calculated using the COMIX [27] and OPENLOOPS [28] matrix element generators and merged with the SHERPA parton shower using the ME+PS@NLO prescription [29]. For  $W$ +jets and  $Z$ +jets events these are calculated for up to two additional partons at next-to-leading order (NLO) and four partons at leading order (LO); they are

<sup>1</sup> ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the  $z$ -axis along the beam axis. The  $x$ -axis points from the IP to the centre of the LHC ring, and the  $y$ -axis points upward. Cylindrical coordinates  $(r, \phi)$  are used in the transverse plane,  $\phi$  being the azimuthal angle around the  $z$ -axis.

calculated for up to one (ZZ) or no (WW, WZ) additional partons at NLO and up to three additional partons at LO. The CT10 PDF set [30] is used in conjunction with dedicated parton shower tuning developed by the authors of SHERPA.

The  $W/Z$ +jets simulated samples are split into different components according to the true flavour of the jets, i.e.  $W/Z + q$ , where  $q$  denotes a light quark ( $u, d, s$ ) or a gluon,  $W/Z + c$  and  $W/Z + b$ . Each event is categorized based on the hadrons associated to the track jets matched to the highest- $p_T$  (leading) large- $R$  jet in the event; these jet collections are introduced in Section 4. If there is an associated bottom (charm) hadron, then the event is given a  $b$  ( $c$ ) label; otherwise it is labelled  $W/Z + q$ .

For the generation of  $t\bar{t}$  and single top quarks in the  $Wt$ - and  $s$ -channels the POWHEG-BOX v2 [31–33] generator with the CT10 PDF sets is used. Electroweak  $t$ -channel single-top-quark events are generated using the POWHEG-BOX v1 generator. This generator uses the four-flavour scheme for the NLO matrix elements calculations together with the four-flavour PDF set [30]. For all top processes, top-quark spin correlations are preserved (for the  $t$ -channel, top quarks are decayed using MADSPIN [34]). The parton shower, fragmentation, and the underlying event are simulated using PYTHIA 6.428 [35] with the CTEQ6L1 [36] PDF sets and the corresponding Perugia 2012 tune (P2012) [37]. The top quark mass is set to 172.5 GeV. The EVTGEN v1.2.0 program [38] is used for the bottom and charm hadron decays.

Finally, SM Higgs boson production in association with a  $W/Z$  boson is simulated using PYTHIA 8.186 and POWHEG with showering by PYTHIA 8.186 for the gluon-induced associated production; the CT10 PDFs and the AZNLO tune is used in both cases [39]. SM Higgs boson production is considered as a background in this search.

All simulated MC 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 or background event. Simulated events are reconstructed with the standard ATLAS reconstruction software used for collision data.

## 4 Object selection

Collision vertices are reconstructed from tracks with transverse momentum  $p_T > 400$  MeV. If an event contains more than one vertex candidate, the one with the highest  $\sum p_T^2$  calculated considering all the associated tracks is selected as the primary vertex.

Electrons are reconstructed from inner-detector tracks that are matched to energy clusters in the electromagnetic calorimeter obtained using the standard ATLAS sliding-window algorithm [40]. Electron candidates satisfy criteria for the electromagnetic shower shape, track quality and track-cluster matching. These requirements are applied using a likelihood-based approach, and two different working points are used: “loose” and “tight” with increasing purity [41]. Muons are identified by matching tracks found in the inner detector to either full tracks or track segments reconstructed in the muon spectrometer [42]. Muons are required to pass identification requirements based on quality criteria imposed on the inner detector and muon spectrometer tracks, and, as for electrons, both “loose” and “tight” operating points are used. Both the electrons and muons are required to have a minimum  $p_T$  of 7 GeV and to lie within a region with a good reconstruction and identification efficiency ( $|\eta| < 2.7$  for muons and  $|\eta| < 2.47$  for electrons). They are required to be isolated using requirements on the sum of the  $p_T$  of the tracks lying in a cone around the lepton direction whose radius,  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ , decreases as a function of the lepton  $p_T$ . They are also required to originate from the primary vertex [41, 42].

Three types of jets are used to characterize the hadronic activity of events: large- $R$  jets, small- $R$  jets and track jets. All three jet collections are reconstructed using the anti- $k_t$  algorithm but with different radius parameters,  $R$  [43]. Large- and small- $R$  jets are built from noise-suppressed topological clusters [44] in the calorimeter, while track jets are constructed from inner-detector tracks.

Large- $R$  jets are constructed with a radius parameter  $R = 1.0$ . They are required to have  $p_T > 250$  GeV and  $|\eta| < 2.0$ . These jets are trimmed [45] to suppress the energy of clusters which originate from initial-state radiation, pile-up vertices or the underlying event. This is done by reclustering the constituents of the initial jet using the  $k_t$  algorithm [46] into subjets of radius  $R_{\text{sub}}$ ; the constituents of any subjet with transverse momentum less than  $f_{\text{cut}}$  times the transverse momentum of the initial jet are removed. The  $R_{\text{sub}}$  and  $f_{\text{cut}}$  parameter values found to be optimal in identifying hadronic  $W/Z$  boson decays [47] are  $R_{\text{sub}} = 0.2$  and  $f_{\text{cut}} = 5\%$ . Large- $R$  jets are required to be separated by  $\Delta R > 1.0$  to the nearest electron candidate.

Small- $R$  jets are reconstructed with a radius parameter  $R = 0.4$  and are required to have  $p_T > 20$  GeV and  $|\eta| < 2.4$  or  $p_T > 30$  GeV and  $2.4 < |\eta| < 4.5$ . If an electron candidate has an angular separation  $\Delta R < 0.2$  to a small- $R$  jet, the small- $R$  jet is discarded; however, if an electron candidate and small- $R$  jet are separated by  $0.2 < \Delta R < 0.4$ , the electron candidate is removed. Similarly, if a small- $R$  jet is separated by  $\Delta R < 0.4$  to the nearest muon candidate, the small- $R$  jet is discarded if it has fewer than three associated inner-detector tracks; otherwise the muon candidate is removed. The jet-vertex-tagger discriminant is used to reject small- $R$  jets originating from pile-up based on vertex information of each of the jet's associated tracks [48]. Small- $R$  jets with  $p_T < 50$  GeV and  $|\eta| < 2.4$  must have a discriminant greater than 0.64. The energies of both the large- $R$  and small- $R$  jets and the mass of the large- $R$  jets are corrected for energy losses in passive material, for the non-compensating response of the calorimeter, and for any additional energy due to multiple  $pp$  interactions [49].

The third type of jet used in this analysis, track jets, are built from inner-detector tracks with  $p_T > 400$  MeV associated with the primary vertex using the anti- $k_t$  algorithm with  $R = 0.2$  and are required to have  $p_T > 10$  GeV and  $|\eta| < 2.5$ . Track jets containing  $b$ -hadrons are identified using the MV2c20  $b$ -tagging algorithm [50, 51] with 70% efficiency and a rejection factor of about 5.6 (180) for jets containing  $c$ -hadrons (not containing  $b$ - or  $c$ -hadrons) in a simulated sample of  $t\bar{t}$  events and are matched to the large- $R$  jets via ghost-association [43].

Hadronically decaying  $\tau$ -lepton candidates, which are used to veto background events, are reconstructed from noise-suppressed topological clusters in the calorimeter using the anti- $k_t$  algorithm with  $R = 0.4$ . They are required to have  $p_T > 20$  GeV,  $|\eta| < 2.5$  and to be outside the transition region between the barrel and end-cap calorimeters ( $1.37 < |\eta| < 1.52$ ); to have either one or three associated tracks; and to satisfy the “medium” working point criteria [52]. The leptonic decays of  $\tau$  leptons are simulated and included in the acceptance if the final-state electron or muon passes lepton selections.

The presence of one or more neutrinos in collision events can be inferred from an observed momentum imbalance in the transverse plane. The missing transverse momentum ( $\vec{E}_T^{\text{miss}}$ ) is calculated as the negative vectorial sum of the transverse momenta of all the muons, electrons, small- $R$  jets, and any inner-detector tracks from the primary vertex not matched to any of these objects [53]. The magnitude of the  $\vec{E}_T^{\text{miss}}$  is denoted by  $E_T^{\text{miss}}$ . For multi-jet background rejection, a similar quantity,  $\vec{p}_T^{\text{miss}}$ , is computed using only charged-particle tracks originating from the nominal hard-scatter vertex, and its magnitude is denoted by  $p_T^{\text{miss}}$ .

## 5 Event selection

This analysis is performed for events containing zero, one, or two charged leptons (electrons or muons), targeting the  $Z' \rightarrow ZH \rightarrow \nu\bar{\nu}b\bar{b}$ ,  $W' \rightarrow WH \rightarrow \ell\nu b\bar{b}$  and  $Z' \rightarrow ZH \rightarrow \ell^+\ell^-b\bar{b}$  decay modes, respectively; the “loose” lepton identification working points are used to categorize events by their charged-lepton number. While the 1-lepton channel has some acceptance for the  $Z' \rightarrow ZH \rightarrow \ell\ell b\bar{b}$  signal, it has significantly larger backgrounds than the 2-lepton channel; the 1-lepton channel is therefore not included in the  $Z'$  search. The 0-lepton channel has a non-negligible acceptance for the  $W' \rightarrow WH \rightarrow \ell\nu b\bar{b}$  signal in events in which the lepton is not detected or is a hadronically decaying  $\tau$ -lepton; it also has smaller predicted backgrounds than the 1-lepton channel. For this reason, the 0-lepton channel and the 1-lepton channel are combined in the  $W'$  search.

In the 0-lepton channel events are recorded using an  $E_T^{\text{miss}}$  trigger with an online threshold of 70 GeV, while in the 2-lepton channel, events are recorded using a combination of single-lepton triggers, with the lowest  $p_T$  threshold being 24 GeV for isolated electrons and 20 GeV for isolated muons. These triggers are complemented with non-isolated ones with higher  $p_T$  thresholds. The 1-lepton channel uses the single-electron triggers for the electron channel and a combination of the  $E_T^{\text{miss}}$  trigger and single-muon trigger for the muon channel, where the  $E_T^{\text{miss}}$  trigger considers only the energy of objects in the calorimeter, and thus muons are seen as a source of  $E_T^{\text{miss}}$ . For events selected by lepton triggers, the object that satisfied the trigger is required to be matched geometrically to the offline-reconstructed lepton.

Events containing no loose lepton are assigned to the 0-lepton channel. The multi-jet and non-collision backgrounds in the 0-lepton channel are suppressed by imposing requirements on  $p_T^{\text{miss}}$  ( $p_T^{\text{miss}} > 30$  GeV),  $E_T^{\text{miss}}$  ( $E_T^{\text{miss}} > 200$  GeV), the azimuthal angle between  $\vec{E}_T^{\text{miss}}$  and  $\vec{p}_T^{\text{miss}}$  ( $\Delta\phi(\vec{E}_T^{\text{miss}}, \vec{p}_T^{\text{miss}}) < \pi/2$ ), and the azimuthal angle between  $\vec{E}_T^{\text{miss}}$  and the leading large- $R$  jet ( $\Delta\phi(\vec{E}_T^{\text{miss}}, \text{large-}R \text{ jet}) > 2\pi/3$ ). An additional requirement is imposed on the azimuthal angle between  $\vec{E}_T^{\text{miss}}$  and the nearest small- $R$  jet that is not identified as a  $\tau$ -lepton ( $\min[\Delta\phi(\vec{E}_T^{\text{miss}}, \text{small-}R \text{ jet})] > \pi/9$ ). Finally, only in the search for  $Z' \rightarrow ZH$ , events containing one or more identified hadronically decaying  $\tau$ -lepton candidates are rejected; this veto reduces the  $W$ +jets and  $t\bar{t}$  contributions and has a negligible impact on the  $Z'$  acceptance. Since it is not possible to fully reconstruct the invariant mass of the  $ZH \rightarrow \nu\bar{\nu}b\bar{b}$  system due to the neutrinos present in the final state, the transverse mass is used as the final discriminant:  $m_{T,VH} = \sqrt{(E_T^{\text{jet}} + E_T^{\text{miss}})^2 - (\vec{p}_T^{\text{jet}} + \vec{E}_T^{\text{miss}})^2}$ , where  $p_T^{\text{jet}}$  ( $E_T^{\text{jet}}$ ) is the transverse momentum (energy) of the leading large- $R$  jet.

Events containing exactly one lepton with  $p_T > 25$  GeV (and with  $|\eta| < 2.5$  for muons) are assigned to the 1-lepton channel. To reduce the multi-jet background from non-prompt leptons or from jets faking leptons, the lepton must satisfy the tight quality criteria. Moreover, isolation requirements based on the sum of the calorimeter energy deposits and track transverse momentum in a cone around the lepton direction are applied. In addition, the event must have significant missing transverse momentum:  $E_T^{\text{miss}} > 100$  GeV. To reconstruct the invariant mass of the  $WH \rightarrow \ell\nu b\bar{b}$  system in the 1-lepton channel, the momentum of the neutrino in the  $z$ -direction,  $p_z$ , is obtained by imposing the  $W$  boson mass constraint on the lepton–neutrino system. In the resulting quadratic equation,  $p_z$  is taken as either the real component in the case of complex solutions or the smaller of the two solutions if both solutions are real.

Events containing exactly two loose leptons of the same flavour with  $p_T > 25$  GeV (and with  $|\eta| < 2.5$  for muons) are assigned to the 2-lepton channel. Only loose track isolation requirements are applied since this channel has negligible background from fake and non-prompt leptons. The invariant mass of the two leptons,  $m_{\ell\ell}$ , must be in the range 70–110 GeV for the dielectron selection. This range is widened to



55–125 GeV for the dimuon selection due to the poorer momentum resolution at high  $p_T$ . To improve the  $m_{VH}$  resolution of  $ZH \rightarrow \mu\mu b\bar{b}$  events, the four-momentum of the dimuon system is scaled by  $m_Z/m_{\mu\mu}$ , where  $m_Z = 91.2$  GeV and  $m_{\mu\mu}$  is the invariant mass of the dimuon system.

All three channels require at least one large- $R$  jet with  $p_T > 250$  GeV and  $|\eta| < 2.0$ . The leading large- $R$  jet is considered to be the  $H \rightarrow b\bar{b}$  candidate. To enhance the sensitivity to a  $VH$  signal, the leading large- $R$  jet is required to have at least one associated track jet, and at least one of the associated track jets must be  $b$ -tagged [54]. If more than two track jets are matched to the  $H \rightarrow b\bar{b}$  candidate, only the two with the highest  $p_T$  are considered for the  $b$ -tagging requirement. In all the three channels, events are vetoed if they have at least one  $b$ -tagged track jet not matched to the leading large- $R$  jet. This veto is particularly effective in suppressing the  $t\bar{t}$  background in the 0- and 1-lepton channels. The events fulfilling these requirements are divided into 1- and 2  $b$ -tag categories depending on whether one or both of the two leading track jets matched to the leading large- $R$  jet are  $b$ -tagged.

The four-momentum of the large- $R$  jet is corrected by adding the four-momentum of the muon closest in  $\Delta R$  to the jet axis provided it is within the jet radius. The distribution of the mass of the leading large- $R$  jet ( $m_{\text{jet}}$ ) in events passing the selection described so far is shown in Figure 1. The mass of the leading large- $R$  jet (jet) is required to be consistent with the Higgs boson mass of 125.5 GeV. A 90% efficient mass requirement, corresponding to a window of  $75 \text{ GeV} < m_{\text{jet}} < 145 \text{ GeV}$ , is applied. This is particularly effective for discriminating the signal from  $t\bar{t}$  and  $V + b\bar{b}$  backgrounds.

The events passing this selection, and categorized into 0-, 1-, and 2-lepton channels by 1- and 2- $b$ -tags (six categories in total), define the signal regions of this analysis. The efficiencies of selecting events in the 2- $b$ -tag (1- $b$ -tag) signal region for an HVT resonance of mass of 1.5 TeV are 24% (34%), 16% (25%) and 15% (22%) for the  $Z' \rightarrow ZH \rightarrow \nu\bar{\nu}b\bar{b}$ ,  $W' \rightarrow WH \rightarrow \ell\nu b\bar{b}$  and  $Z' \rightarrow ZH \rightarrow \ell^+\ell^-b\bar{b}$  processes respectively.

## 6 Background estimation

The background contamination in the signal regions is different for each of the three channels. In the 0-lepton analysis the dominant background is  $Z$ +jets production with significant contributions from  $W$ +jets and  $t\bar{t}$  production. In the 1-lepton channel the dominant backgrounds are  $W$ +jets and  $t\bar{t}$  production. In the 2-lepton channel, where two same-flavour leptons with an invariant mass near the  $Z$  mass are selected,  $Z$ +jets production is by far the dominant background. All three channels also have small contributions from single-top-quark, diboson and SM Higgs production. The multi-jet background, which enters the signal regions through semileptonic hadron decays and through misidentified or mismeasured jets, is found to be negligibly small in all three channels.

The background modelling is studied using control regions with low signal contamination, chosen to not overlap with the signal regions. These control regions are used both to evaluate the background predictions outside the signal-rich regions and to establish the normalization and  $m_{VH}$  shape of the dominant backgrounds through their inclusion as nuisance parameters in the likelihood fit described in Section 8.

Sideband regions of the  $m_{\text{jet}}$  distribution, defined as  $m_{\text{jet}} < 75$  GeV (low- $m_{\text{jet}}$ ) or  $m_{\text{jet}} > 145$  GeV (high- $m_{\text{jet}}$ ) are used as control regions for the  $W/Z$ +jets backgrounds. Furthermore, the events are divided into categories corresponding to the number of  $b$ -tagged track jets matched to the large- $R$  jet to test the different flavour compositions. The 1- and 2- $b$ -tag low- $m_{\text{jet}}$  control regions mainly test the  $W/Z + c$  and  $W/Z + b$  contributions, respectively.



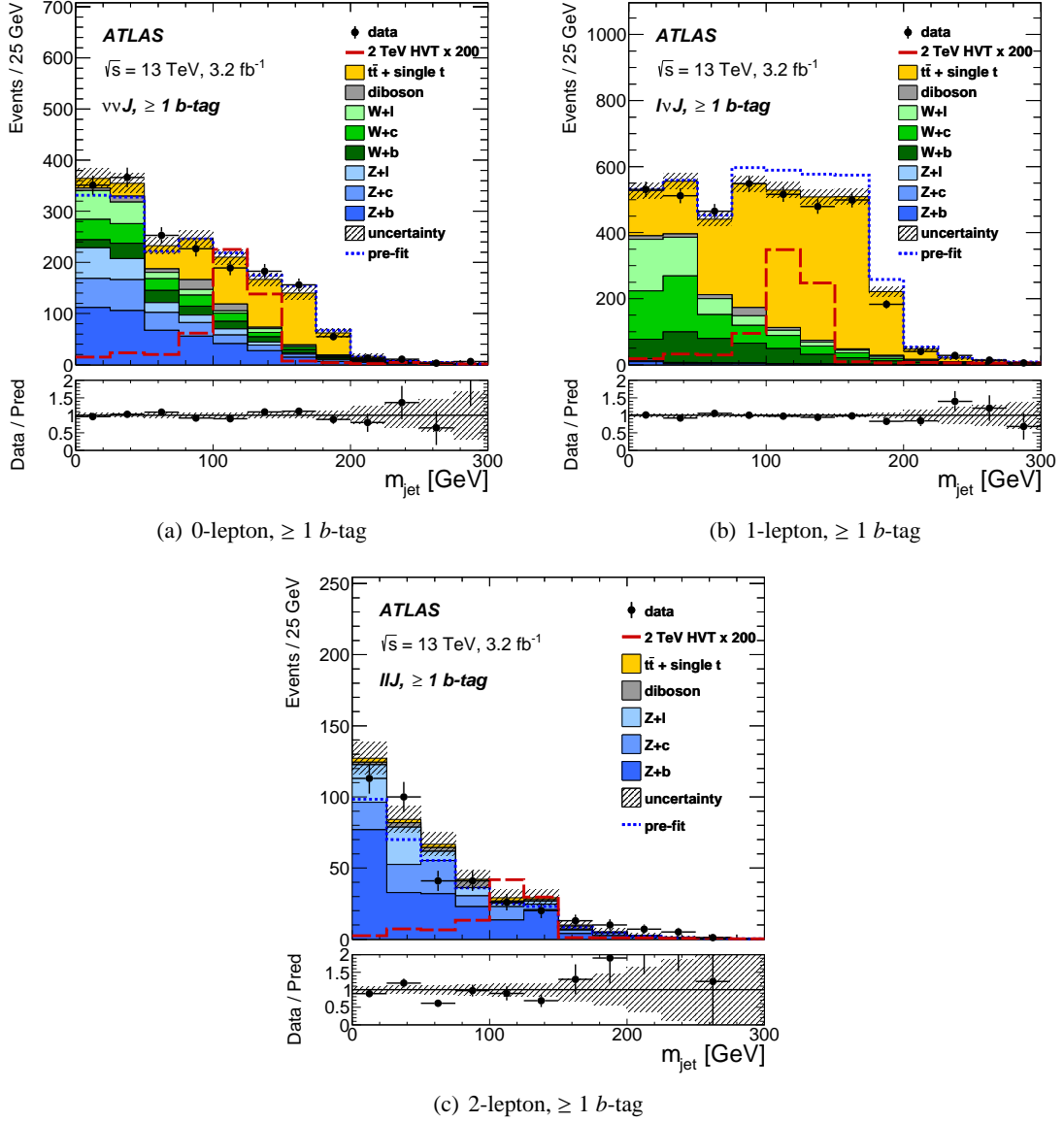


Figure 1: Distributions of the mass of the leading large- $R$  jet,  $m_{\text{jet}}$ , for the (a) 0-lepton, (b) 1-lepton, and (c) 2-lepton channels. The background prediction is shown after the maximum-likelihood fits to the data described in Section 8; the total background prediction before the fit is shown by the dotted blue line. The signal for the benchmark HVT *Model A* with  $m_{\nu'} = 2$  TeV is shown as a dotted red line and normalized to 200 times the theoretical cross-section.

Control regions for the  $t\bar{t}$  background prediction are also defined. For the 0- and 1-lepton channels, the  $t\bar{t}$  control regions are defined by requiring at least one additional  $b$ -tagged track jet that is not matched to the large- $R$  jet; no Higgs boson candidate mass window requirement is imposed in the 0- and 1-lepton  $t\bar{t}$  control regions. The  $t\bar{t}$  control region for the 2-lepton channel is defined by requiring exactly one electron, exactly one muon and at least one  $b$ -tagged track jet matched to the leading large- $R$  jet; there is no requirement on additional  $b$ -tagged track jets in the 2-lepton channel.

## 7 Systematic uncertainties

The most important experimental systematic uncertainties are associated with the measurement of the scale and resolution of the large- $R$  jet energy and mass, as well as with the determination of the track jet  $b$ -tagging efficiency and mistag rate. The uncertainties in the scale and resolution of large- $R$  jet energy and mass are evaluated by comparing the ratio of calorimeter-based to track-based measurements in multi-jet data and simulation [47]. The uncertainty in the track-jet  $b$ -tagging efficiency arises mainly from uncertainty in the measurement of the  $b$ -tagging efficiency in  $t\bar{t}$  events, while the mistag rate and uncertainty are determined using dijet events [50]. These uncertainties have an impact on the normalization and differential distribution of events, and have typical sizes of 2–20% for the large- $R$  jet energy/mass scales and 5–15% for the  $b$ -tagging efficiency.

Other experimental systematic uncertainties with a smaller impact are those associated with the lepton energy and momentum scales, lepton identification efficiency, the efficiency of the triggers, the small- $R$  jet energy scale and the  $E_T^{\text{miss}}$  measurement.

Uncertainties are taken into account for possible differences between data and the simulation model that is used for each process. In addition to the 5% uncertainty in the integrated luminosity, the following normalization uncertainties are assigned to particular processes: 30% for  $t\bar{t}$  and single top quarks [55], 11% for dibosons [56], 10% for  $W/Z$ +light jets [57], and 30% for  $W/Z+c$  and  $W/Z+b$ . Uncertainties in the modelling of the  $m_{VH}$  and  $m_{T,VH}$  distributions are assigned to the  $Z$ +jets and  $W$ +jets backgrounds. These uncertainties are estimated by comparing predictions from SHERPA 2.1.1 and MadGraph5\_aMC@NLO-2.2.2 at leading order with showering by PYTHIA 8.186 using the A14 tune. An uncertainty in the shape of the  $m_{VH}$  or  $m_{T,VH}$  distribution for the  $t\bar{t}$  background is derived by comparing a POWHEG sample with the distribution obtained using MadGraph5\_aMC@NLO 2.2.2. Additional systematic uncertainties are evaluated by comparing the nominal sample showered with PYTHIA 6.428 using the P2012 tune to one showered with HERWIG++ 2.7.1 [58] and using the UEEE5 underlying-event tune. Samples of  $t\bar{t}$  events with the factorization and renormalization scale doubled or halved are compared to the nominal, and differences observed are taken as an additional uncertainty.

The dominant uncertainties in the signal acceptance arise from the choice of PDF and from uncertainty in the amount of initial- and final-state radiation present in simulated signal events. The PDF uncertainties are estimated by taking the acceptance difference between the NNPDF2.3LO and MSTW2008LO PDF and adding it in quadrature with the differences in acceptance found between the NNPDF2.3LO error sets. Typical values for the signal acceptance uncertainties are 2–3% per source of uncertainty.

All uncertainties are evaluated in an identical way for all signal and background sources and are thus treated as fully correlated across sources. For all simulated samples, the statistical uncertainty arising from the limited number of simulated events is taken into account.

## 8 Results

To determine how well the observed data agrees with the predicted backgrounds and to test for an HVT signal, a maximum-likelihood fit is performed over the binned  $m_{VH}$  or  $m_{T,VH}$  mass distributions, including all control regions described in Section 6. The maximum-likelihood fit parameters are the systematic uncertainties in each background and signal contribution, which can vary the normalizations and differential distributions. The systematic uncertainties are given log-normal priors in the likelihood, with

Table 1: The predicted and observed number events for the three final states considered in this analysis. The predicted number of events is shown after a maximum-likelihood fit to the data, performed simultaneously across the three lepton channels. The quoted uncertainties are the combined systematic and statistical uncertainties after the fit. Uncertainties in the normalization of individual backgrounds may be larger than the uncertainty on the total background due to correlations.

	Two $b$ -tags		
	$\nu\nu b\bar{b}$	$\ell\nu b\bar{b}$	$\ell\ell b\bar{b}$
$t\bar{t}$	9.6 $\pm$ 1.4	50 $\pm$ 7	0.54 $\pm$ 0.36
Single top	2.0 $\pm$ 0.6	11.4 $\pm$ 3.0	0.20 $\pm$ 0.10
$W + b$	5.2 $\pm$ 1.3	18 $\pm$ 5	
$W + c$	0.64 $\pm$ 0.18	2.0 $\pm$ 0.7	
$W + q$	0.06 $\pm$ 0.03	2.0 $\pm$ 0.8	
Diboson	4.2 $\pm$ 1.8	4.6 $\pm$ 0.8	1.28 $\pm$ 0.27
SM $VH$	1.43 $\pm$ 0.57	0.03 $\pm$ 0.01	0.45 $\pm$ 0.19
$Z + b$	12.3 $\pm$ 2.4	1.0 $\pm$ 0.4	3.4 $\pm$ 0.8
$Z + c$	1.46 $\pm$ 0.43	0.05 $\pm$ 0.02	0.31 $\pm$ 0.10
$Z + q$	0.13 $\pm$ 0.05		0.04 $\pm$ 0.04
Backgrounds	36.9 $\pm$ 3.5	90 $\pm$ 6	6.2 $\pm$ 1.0
Data	37	96	8

	One $b$ -tag		
	$\nu\nu b\bar{b}$	$\ell\nu b\bar{b}$	$\ell\ell b\bar{b}$
$t\bar{t}$	216 $\pm$ 17	969 $\pm$ 50	3.8 $\pm$ 0.8
Single top	26 $\pm$ 7	112 $\pm$ 30	0.58 $\pm$ 0.19
$W + b$	33 $\pm$ 8	100 $\pm$ 24	
$W + c$	41 $\pm$ 10	109 $\pm$ 31	
$W + q$	20 $\pm$ 5	1.5 $\pm$ 0.6	
Diboson	28 $\pm$ 5	32 $\pm$ 5	6.4 $\pm$ 1.0
SM $VH$	1.6 $\pm$ 0.6	0.04 $\pm$ 0.01	0.30 $\pm$ 0.12
$Z + b$	99 $\pm$ 17	3.8 $\pm$ 1.0	36 $\pm$ 6
$Z + c$	51 $\pm$ 13	2.7 $\pm$ 1.6	19 $\pm$ 5
$Z + q$	32 $\pm$ 8	3.0 $\pm$ 1.0	9 $\pm$ 4
Backgrounds	548 $\pm$ 16	1385 $\pm$ 30	75 $\pm$ 7
Data	520	1364	75

scale parameters described in Section 7. High- and low- $m_{\text{jet}}$  sideband control regions are merged if fewer than 100 background events are expected with the full dataset; this is the case for the 0-lepton 2- $b$ -tag sidebands, the 1-lepton 2- $b$ -tag sidebands, and the 2-lepton 1- and 2- $b$ -tag sidebands. The HVT signal is included as a binned template with an unconstrained normalization.

Table 1 provides the predicted and observed number of events in each signal region, and the reconstructed mass distributions for events passing the selections are shown in Figure 2. The predicted background is shown after the binned maximum-likelihood fit to the data, performed simultaneously across lepton channels.

No significant excess of events is observed in the data compared to the prediction from SM background sources. Exclusion limits at the 95% confidence level are set on the production cross-section times the branching fraction for the HVT models. The limits for the charged resonance,  $W'$ , are obtained by performing the likelihood fit over the 0- and 1-lepton channels, while the 0- and 2-lepton channels are used for the neutral resonance,  $Z'$ . In the case of the  $W'$  search, the  $\tau$ -lepton veto is not imposed and

the search considers only the  $W' \rightarrow WH$  signal, while for the  $Z'$  search the  $\tau$  veto is imposed and only  $Z' \rightarrow ZH$  signal is considered.

The results for combined HVT production are evaluated without the  $\tau$  veto imposed, including both the  $W' \rightarrow WH$  and  $Z' \rightarrow ZH$  signals simultaneously. The combined HVT  $V'$  search is performed with maximum-likelihood fits that are independent from those of the  $W'$  and  $Z'$  searches, so there is no double-counting of 0-lepton events that are included in the individual fits.

The exclusion limits are calculated with a modified frequentist method [59], also known as  $CL_s$ , and the profile-likelihood-ratio test statistic [60] in the asymptotic approximation, using the binned  $m_{VH}$  or  $m_{T,VH}$  mass distributions for 0-, 1- and 2-lepton final states. Systematic uncertainties and their correlations are taken into account as nuisance parameters. None of the systematic uncertainties considered are significantly constrained or pulled in the likelihood fit. Figures 3(a) and 3(b) show the 95% CL upper limits on the production cross-section multiplied by the branching fraction into  $WH$  and  $ZH$  and the branching fraction  $\text{BR}(H \rightarrow b\bar{b}/c\bar{c})$  as a function of the resonance mass, separately for the charged  $W'$  and the neutral  $Z'$  bosons, respectively. The theoretical predictions for the HVT benchmark *Model A* with coupling constant  $g_V = 1$  allow exclusion of  $m_{Z'} < 1490$  GeV and  $m_{W'} < 1750$  GeV. For *Model B* with coupling constant  $g_V = 3$  the corresponding excluded masses are  $m_{Z'} < 1580$  GeV and  $m_{W'} < 2220$  GeV. In both theoretical predictions, the branching fraction  $\text{BR}(H \rightarrow b\bar{b}/c\bar{c})$  is fixed to the Standard Model prediction of 60.6% [25].

To study the scenario in which the masses of charged and neutral resonances are degenerate, a combined likelihood fit over all the signal regions and control regions is also performed. The 95% CL upper limits on the production cross-section of a  $V'$  decaying to  $WH/ZH$ , relative to the HVT model predictions, are shown in Figure 3(c). For *Model A* (*Model B*) with coupling constant  $g_V = 1$  ( $g_V = 3$ ),  $m_{V'^{\pm}} < 1730$  GeV (2310 GeV) is excluded.

The exclusion contours in the HVT parameter space  $\{g_V c_H, (g^2/g_V) c_F\}$  for resonances of mass 1.2 TeV, 2.0 TeV and 3.0 TeV are shown in Figure 4 where all three channels are combined, taking into account the branching fractions to  $WH$  and  $ZH$  from the HVT model parameterization. Here the parameter  $c_F$  is assumed to be the same for quarks and leptons, including third-generation fermions, and other parameters involving more than one heavy vector boson,  $g_V c_{VVV}$ ,  $g_V^2 c_{VVHH}$  and  $c_{VW}$ , have negligible contributions to the overall cross-sections for the processes of interest.

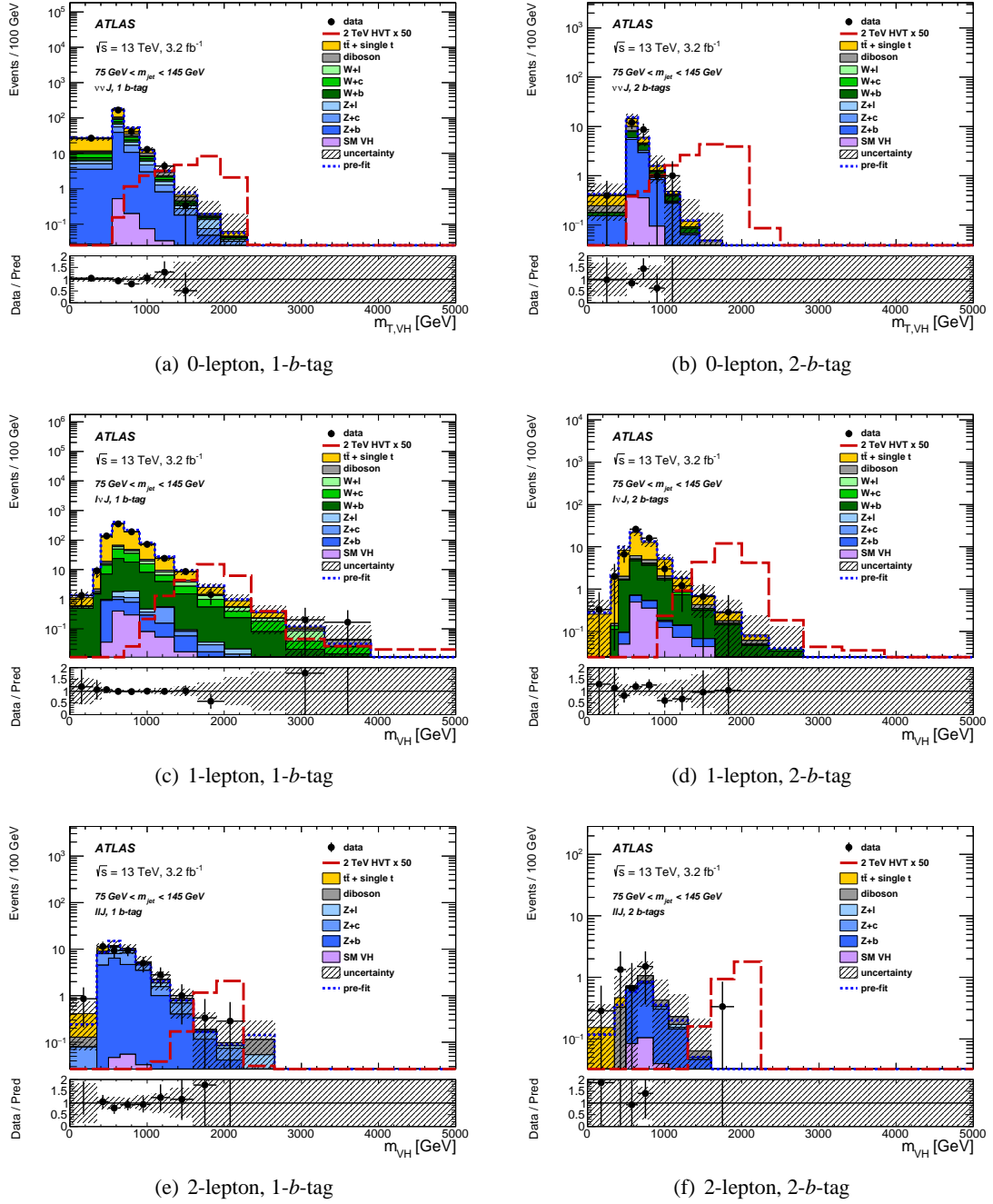


Figure 2: Distributions of reconstructed  $VH$  transverse mass,  $m_{T,VH}$ , and invariant mass,  $m_{VH}$ , for the 0-lepton (top), 1-lepton (middle), and 2-lepton (bottom) channels. The left (right) column corresponds to the 1- $b$ -tag (2- $b$ -tag) signal regions. The background prediction is shown after the maximum-likelihood fits to the data; the total background prediction before the fit is shown by the dotted blue line. The signal for the benchmark HVT *Model A* with  $m_{V'} = 2$  TeV is shown as a dotted red line and normalized to 50 times the theoretical cross-section.

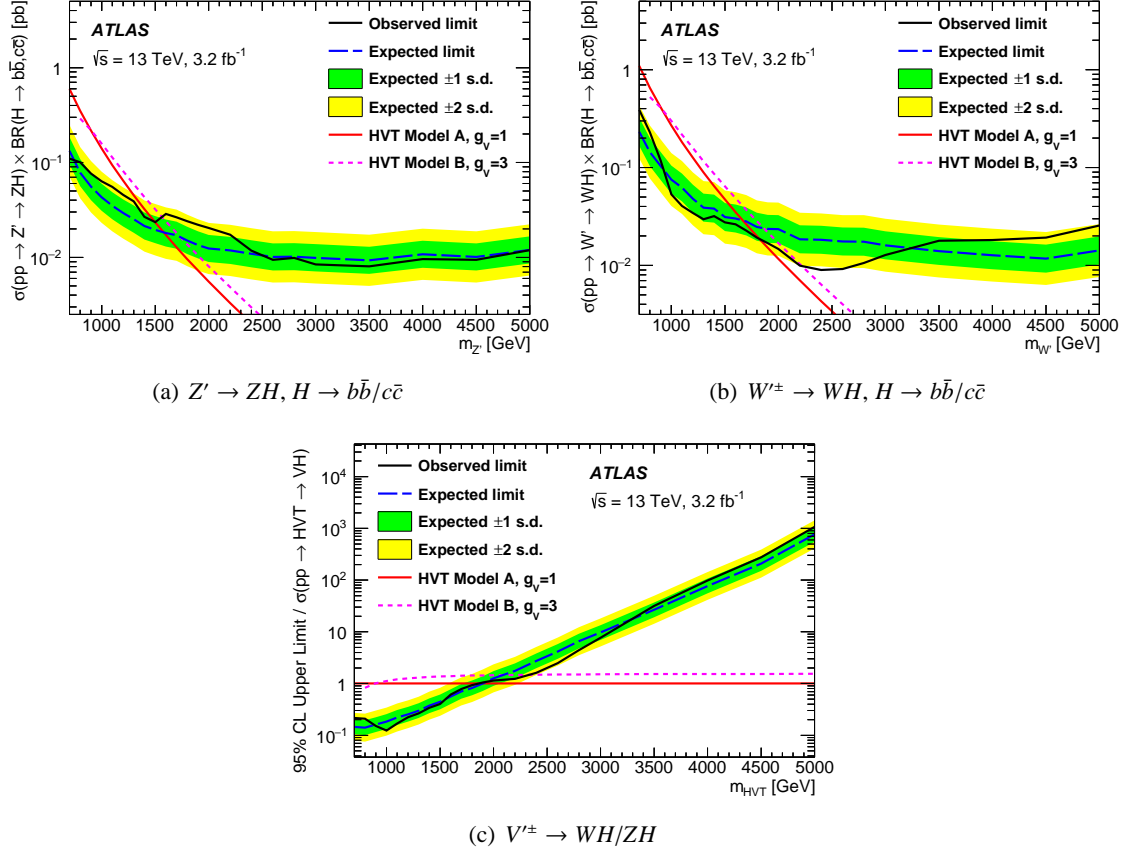


Figure 3: Upper limits at the 95% CL for (a) the production cross-section of  $Z'$  times its branching fraction to  $ZH$  and the branching ratio  $\text{BR}(H \rightarrow b\bar{b}/c\bar{c})$  and (b) the production cross-section of  $W'$  times its branching fraction to  $WH$  and the branching ratio  $\text{BR}(H \rightarrow b\bar{b}/c\bar{c})$ . Upper limits at the 95% CL for (c) the scaling factor of the production cross-section for  $V'$  times its branching fraction to  $WH/ZH$  in *Model A*. The production cross-sections predicted by *Model A* and *Model B* are shown for comparison.

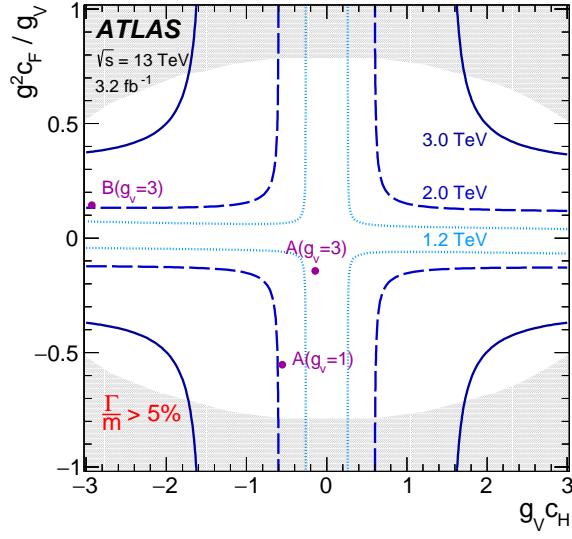


Figure 4: Observed 95% CL exclusion contours in the HVT parameter space  $\{g_V c_H, (g^2/g_V) c_F\}$  for resonances of mass 1.2 TeV, 2.0 TeV and 3.0 TeV. The areas outside the curves are excluded. Also shown are the benchmark model parameters  $A(g_V=1)$ ,  $A(g_V=3)$  and  $B(g_V=3)$ . The shaded region corresponds to the parameter values for which the resonance total width  $\Gamma$  is greater than 5% of its mass, in which case it is not negligible compared to the experimental resolution.



## 9 Conclusion

A search for a new, heavy resonance decaying to  $WH/ZH$  is presented. The search is performed using  $3.2 \pm 0.2 \text{ fb}^{-1}$  of  $pp$  collision data at a 13 TeV centre-of-mass energy collected by the ATLAS detector at the Large Hadron Collider. No significant deviations from the SM background predictions are observed in the three final states considered:  $\ell^+\ell^-b\bar{b}$ ,  $\ell\nu b\bar{b}$ ,  $\nu\bar{\nu}b\bar{b}$ . Upper limits are set at the 95% confidence level on the production cross-sections of  $V'$  in heavy vector triplet models with resonance masses above 700 GeV. HVT benchmark *Model A* with coupling constant  $g_V = 1$  is excluded for  $m_{Z'} < 1490$  GeV,  $m_{W'} < 1750$  GeV, and  $m_{V'} < 1730$  GeV; for *Model B* with coupling constant  $g_V = 3$ ,  $m_{Z'} < 1580$  GeV,  $m_{W'} < 2220$  GeV, and  $m_{V'} < 2310$  GeV are excluded.

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M. Aaboud<sup>135d</sup>, G. Aad<sup>86</sup>, B. Abbott<sup>113</sup>, J. Abdallah<sup>64</sup>, O. Abdinov<sup>12</sup>, B. Abeloos<sup>117</sup>, R. Aben<sup>107</sup>, O.S. AbouZeid<sup>137</sup>, N.L. Abraham<sup>149</sup>, H. Abramowicz<sup>153</sup>, H. Abreu<sup>152</sup>, R. Abreu<sup>116</sup>, Y. Abulaiti<sup>146a,146b</sup>, B.S. Acharya<sup>163a,163b,a</sup>, L. Adamczyk<sup>40a</sup>, D.L. Adams<sup>27</sup>, J. Adelman<sup>108</sup>, S. Adomeit<sup>100</sup>, T. Adye<sup>131</sup>, A.A. Affolder<sup>75</sup>, T. Agatonovic-Jovin<sup>14</sup>, J. Agricola<sup>56</sup>, J.A. Aguilar-Saavedra<sup>126a,126f</sup>, S.P. Ahlen<sup>24</sup>, F. Ahmadov<sup>66,b</sup>, G. Aielli<sup>133a,133b</sup>, H. Akerstedt<sup>146a,146b</sup>, T.P.A. Åkesson<sup>82</sup>, A.V. Akimov<sup>96</sup>, G.L. Alberghi<sup>22a,22b</sup>, J. Albert<sup>168</sup>, S. Albrand<sup>57</sup>, M.J. Alconada Verzini<sup>72</sup>, M. Aleksa<sup>32</sup>, I.N. Aleksandrov<sup>66</sup>, C. Alexa<sup>28b</sup>, G. Alexander<sup>153</sup>, T. Alexopoulos<sup>10</sup>, M. Alhroob<sup>113</sup>, B. Ali<sup>128</sup>, M. Aliev<sup>74a,74b</sup>, G. Alimonti<sup>92a</sup>, J. Alison<sup>33</sup>, S.P. Alkire<sup>37</sup>, B.M.M. Allbrooke<sup>149</sup>, B.W. Allen<sup>116</sup>, P.P. Allport<sup>19</sup>, A. Aloisio<sup>104a,104b</sup>, A. Alonso<sup>38</sup>, F. Alonso<sup>72</sup>, C. Alpigiani<sup>138</sup>, M. Alstady<sup>86</sup>, B. Alvarez Gonzalez<sup>32</sup>, D. Álvarez Piqueras<sup>166</sup>, M.G. Alviggi<sup>104a,104b</sup>, B.T. Amadio<sup>16</sup>, K. Amako<sup>67</sup>, Y. Amaral Coutinho<sup>26a</sup>, C. Amelung<sup>25</sup>, D. Amidei<sup>90</sup>, S.P. Amor Dos Santos<sup>126a,126c</sup>, A. Amorim<sup>126a,126b</sup>, S. Amoroso<sup>32</sup>, G. Amundsen<sup>25</sup>, C. Anastopoulos<sup>139</sup>, L.S. Ancu<sup>51</sup>, N. Andari<sup>19</sup>, T. Andeen<sup>11</sup>, C.F. Anders<sup>59b</sup>, G. Anders<sup>32</sup>, J.K. Anders<sup>75</sup>, K.J. Anderson<sup>33</sup>, A. Andreazza<sup>92a,92b</sup>, V. Andrei<sup>59a</sup>, S. Angelidakis<sup>9</sup>, I. Angelozzi<sup>107</sup>, P. Anger<sup>46</sup>, A. Angerami<sup>37</sup>, F. Anghinolfi<sup>32</sup>, A.V. Anisenkov<sup>109,c</sup>, N. Anjos<sup>13</sup>, A. Annovi<sup>124a,124b</sup>, C. Antel<sup>59a</sup>, M. Antonelli<sup>49</sup>, A. Antonov<sup>98,\*</sup>, F. Anulli<sup>132a</sup>, M. Aoki<sup>67</sup>, L. Aperio Bella<sup>19</sup>, G. Arabidze<sup>91</sup>, Y. Arai<sup>67</sup>, J.P. Araque<sup>126a</sup>, A.T.H. Arce<sup>47</sup>, F.A. Arduh<sup>72</sup>, J-F. Arguin<sup>95</sup>, S. Argyropoulos<sup>64</sup>, M. Arik<sup>20a</sup>, A.J. Armbruster<sup>143</sup>, L.J. Armitage<sup>77</sup>, O. Arnaez<sup>32</sup>, H. Arnold<sup>50</sup>, M. Arratia<sup>30</sup>, O. Arslan<sup>23</sup>, A. Artamonov<sup>97</sup>, G. Artoni<sup>120</sup>, S. Artz<sup>84</sup>, S. Asai<sup>155</sup>, N. Asbah<sup>44</sup>, A. Ashkenazi<sup>153</sup>, B. Åsman<sup>146a,146b</sup>, L. 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Barlow<sup>30</sup>, S.L. Barnes<sup>85</sup>, B.M. Barnett<sup>131</sup>, R.M. Barnett<sup>16</sup>, Z. Barnovska<sup>5</sup>, A. Baroncelli<sup>134a</sup>, G. Barone<sup>25</sup>, A.J. Barr<sup>120</sup>, L. Barranco Navarro<sup>166</sup>, F. Barreiro<sup>83</sup>, J. Barreiro Guimarães da Costa<sup>35a</sup>, R. Bartoldus<sup>143</sup>, A.E. Barton<sup>73</sup>, P. Bartos<sup>144a</sup>, A. Basalae<sup>123</sup>, A. Bassalat<sup>117</sup>, R.L. Bates<sup>55</sup>, S.J. Batista<sup>158</sup>, J.R. Batley<sup>30</sup>, M. Battaglia<sup>137</sup>, M. Baue<sup>132a,132b</sup>, F. Bauer<sup>136</sup>, H.S. Bawa<sup>143,f</sup>, J.B. Beacham<sup>111</sup>, M.D. Beattie<sup>73</sup>, T. Beau<sup>81</sup>, P.H. Beauchemin<sup>161</sup>, P. Bechtel<sup>23</sup>, H.P. Beck<sup>18,g</sup>, K. Becker<sup>120</sup>, M. Becker<sup>84</sup>, M. Beckingham<sup>169</sup>, C. Becot<sup>110</sup>, A.J. Beddall<sup>20e</sup>, A. Beddall<sup>20b</sup>, V.A. Bednyakov<sup>66</sup>, M. 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U. Blumenschein<sup>56</sup>, S. Blunier<sup>34a</sup>, G.J. Bobbink<sup>107</sup>, V.S. Bobrovnikov<sup>109,c</sup>, S.S. Bocchetta<sup>82</sup>, A. Bocci<sup>47</sup>, C. Bock<sup>100</sup>, M. Boehler<sup>50</sup>, D. Boerner<sup>174</sup>, J.A. Bogaerts<sup>32</sup>, D. Bogavac<sup>14</sup>, A.G. Bogdanchikov<sup>109</sup>, C. Bohm<sup>146a</sup>, V. Boisvert<sup>78</sup>, P. Bokan<sup>14</sup>, T. Bold<sup>40a</sup>, A.S. Boldyrev<sup>163a,163c</sup>, M. Bomben<sup>81</sup>, M. Bona<sup>77</sup>, M. Boonekamp<sup>136</sup>, A. Borisov<sup>130</sup>, G. Borissov<sup>73</sup>, J. Bortfeldt<sup>32</sup>, D. Bortoletto<sup>120</sup>, V. Bortolotto<sup>61a,61b,61c</sup>, K. Bos<sup>107</sup>, D. Boscherini<sup>22a</sup>, M. Bosman<sup>13</sup>, J.D. Bossio Sola<sup>29</sup>, J. Boudreau<sup>125</sup>, J. Bouffard<sup>2</sup>, E.V. Bouhova-Thacker<sup>73</sup>, D. Boumediene<sup>36</sup>, C. Bourdarios<sup>117</sup>, S.K. Boutle<sup>55</sup>, A. Boveia<sup>32</sup>, J. Boyd<sup>32</sup>, I.R. Boyko<sup>66</sup>, J. Bracinik<sup>19</sup>, A. Brandt<sup>8</sup>, G. Brandt<sup>56</sup>, O. Brandt<sup>59a</sup>, U. Bratzler<sup>156</sup>, B. Brau<sup>87</sup>, J.E. Brau<sup>116</sup>, H.M. Braun<sup>174,\*</sup>, W.D. Breaden Madden<sup>55</sup>, K. Brendlinger<sup>122</sup>, A.J. Brennan<sup>89</sup>, L. Brenner<sup>107</sup>, R. Brenner<sup>164</sup>, S. Bressler<sup>171</sup>, T.M. Bristow<sup>48</sup>, D. Britton<sup>55</sup>, D. Britzger<sup>44</sup>, F.M. Brochu<sup>30</sup>, I. Brock<sup>23</sup>, R. Brock<sup>91</sup>, G. Brooijmans<sup>37</sup>, T. Brooks<sup>78</sup>, W.K. Brooks<sup>34b</sup>, J. Brosamer<sup>16</sup>, E. Brost<sup>108</sup>, J.H. Broughton<sup>19</sup>, P.A. Bruckman de Renstrom<sup>41</sup>, D. Bruncko<sup>144b</sup>, R. Bruneliere<sup>50</sup>, A. Bruni<sup>22a</sup>, G. Bruni<sup>22a</sup>, L.S. Bruni<sup>107</sup>, B.H. Brunt<sup>30</sup>, M. Bruschi<sup>22a</sup>, N. Bruscino<sup>23</sup>, P. Bryant<sup>33</sup>, L. Bryngemark<sup>82</sup>, T. Buanes<sup>15</sup>, Q. Buat<sup>142</sup>, P. Buchholz<sup>141</sup>, A.G. Buckley<sup>55</sup>, I.A. Budagov<sup>66</sup>, F. Buehrer<sup>50</sup>, M.K. Bugge<sup>119</sup>, O. Bulekov<sup>98</sup>, D. Bullock<sup>8</sup>, H. Burckhart<sup>32</sup>, S. Burdin<sup>75</sup>, C.D. Burgard<sup>50</sup>, B. Burghgrave<sup>108</sup>, K. Burka<sup>41</sup>, S. Burke<sup>131</sup>, I. Burmeister<sup>45</sup>, J.T.P. Burr<sup>120</sup>, E. Busato<sup>36</sup>, D. Büscher<sup>50</sup>, V. Büscher<sup>84</sup>, P. Bussey<sup>55</sup>, J.M. Butler<sup>24</sup>, C.M. Buttar<sup>55</sup>, J.M. Butterworth<sup>79</sup>, P. Butti<sup>107</sup>, W. Buttinger<sup>27</sup>, A. Buzatu<sup>55</sup>, A.R. Buzykaev<sup>109,c</sup>, S. Cabrera Urbán<sup>166</sup>, D. Caforio<sup>128</sup>, V.M. Cairo<sup>39a,39b</sup>, O. Cakir<sup>4a</sup>, N. Calace<sup>51</sup>, P. Calafiura<sup>16</sup>, A. Calandri<sup>86</sup>, G. Calderini<sup>81</sup>, P. Calfayan<sup>100</sup>, G. 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<sup>1</sup> Department of Physics, University of Adelaide, Adelaide, Australia

<sup>2</sup> Physics Department, SUNY Albany, Albany NY, United States of America

- <sup>3</sup> Department of Physics, University of Alberta, Edmonton AB, Canada
- <sup>4</sup> <sup>(a)</sup> Department of Physics, Ankara University, Ankara; <sup>(b)</sup> Istanbul Aydin University, Istanbul; <sup>(c)</sup> Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
- <sup>5</sup> LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France
- <sup>6</sup> High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America
- <sup>7</sup> Department of Physics, University of Arizona, Tucson AZ, United States of America
- <sup>8</sup> Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America
- <sup>9</sup> Physics Department, University of Athens, Athens, Greece
- <sup>10</sup> Physics Department, National Technical University of Athens, Zografou, Greece
- <sup>11</sup> Department of Physics, The University of Texas at Austin, Austin TX, United States of America
- <sup>12</sup> Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- <sup>13</sup> Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain, Spain
- <sup>14</sup> Institute of Physics, University of Belgrade, Belgrade, Serbia
- <sup>15</sup> Department for Physics and Technology, University of Bergen, Bergen, Norway
- <sup>16</sup> Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
- <sup>17</sup> Department of Physics, Humboldt University, Berlin, Germany
- <sup>18</sup> Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
- <sup>19</sup> School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
- <sup>20</sup> <sup>(a)</sup> Department of Physics, Bogazici University, Istanbul; <sup>(b)</sup> Department of Physics Engineering, Gaziantep University, Gaziantep; <sup>(d)</sup> Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey; <sup>(e)</sup> Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey, Turkey
- <sup>21</sup> Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
- <sup>22</sup> <sup>(a)</sup> INFN Sezione di Bologna; <sup>(b)</sup> Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
- <sup>23</sup> Physikalisches Institut, University of Bonn, Bonn, Germany
- <sup>24</sup> Department of Physics, Boston University, Boston MA, United States of America
- <sup>25</sup> Department of Physics, Brandeis University, Waltham MA, United States of America
- <sup>26</sup> <sup>(a)</sup> Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; <sup>(b)</sup> Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; <sup>(c)</sup> Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; <sup>(d)</sup> Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
- <sup>27</sup> Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
- <sup>28</sup> <sup>(a)</sup> Transilvania University of Brasov, Brasov, Romania; <sup>(b)</sup> National Institute of Physics and Nuclear Engineering, Bucharest; <sup>(c)</sup> National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; <sup>(d)</sup> University Politehnica Bucharest, Bucharest; <sup>(e)</sup> West University in Timisoara, Timisoara, Romania
- <sup>29</sup> Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
- <sup>30</sup> Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- <sup>31</sup> Department of Physics, Carleton University, Ottawa ON, Canada
- <sup>32</sup> CERN, Geneva, Switzerland
- <sup>33</sup> Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
- <sup>34</sup> <sup>(a)</sup> Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; <sup>(b)</sup> Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- <sup>35</sup> <sup>(a)</sup> Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; <sup>(b)</sup> Department of

Modern Physics, University of Science and Technology of China, Anhui; <sup>(c)</sup> Department of Physics, Nanjing University, Jiangsu; <sup>(d)</sup> School of Physics, Shandong University, Shandong; <sup>(e)</sup> Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai; (also affiliated with PKU-CHEP); <sup>(f)</sup> Physics Department, Tsinghua University, Beijing 100084, China

<sup>36</sup> Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France

<sup>37</sup> Nevis Laboratory, Columbia University, Irvington NY, United States of America

<sup>38</sup> Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark

<sup>39</sup> <sup>(a)</sup> INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; <sup>(b)</sup> Dipartimento di Fisica, Università della Calabria, Rende, Italy

<sup>40</sup> <sup>(a)</sup> AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; <sup>(b)</sup> Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland

<sup>41</sup> Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland

<sup>42</sup> Physics Department, Southern Methodist University, Dallas TX, United States of America

<sup>43</sup> Physics Department, University of Texas at Dallas, Richardson TX, United States of America

<sup>44</sup> DESY, Hamburg and Zeuthen, Germany

<sup>45</sup> Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany

<sup>46</sup> Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany

<sup>47</sup> Department of Physics, Duke University, Durham NC, United States of America

<sup>48</sup> SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom

<sup>49</sup> INFN Laboratori Nazionali di Frascati, Frascati, Italy

<sup>50</sup> Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany

<sup>51</sup> Section de Physique, Université de Genève, Geneva, Switzerland

<sup>52</sup> <sup>(a)</sup> INFN Sezione di Genova; <sup>(b)</sup> Dipartimento di Fisica, Università di Genova, Genova, Italy

<sup>53</sup> <sup>(a)</sup> E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; <sup>(b)</sup> High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

<sup>54</sup> II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany

<sup>55</sup> SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom

<sup>56</sup> II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany

<sup>57</sup> Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France

<sup>58</sup> Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America

<sup>59</sup> <sup>(a)</sup> Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; <sup>(b)</sup> Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; <sup>(c)</sup> ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany

<sup>60</sup> Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan

<sup>61</sup> <sup>(a)</sup> Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; <sup>(b)</sup> Department of Physics, The University of Hong Kong, Hong Kong; <sup>(c)</sup> Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China

<sup>62</sup> Department of Physics, Indiana University, Bloomington IN, United States of America

<sup>63</sup> Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria

<sup>64</sup> University of Iowa, Iowa City IA, United States of America

<sup>65</sup> Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America

<sup>66</sup> Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia

<sup>67</sup> KEK, High Energy Accelerator Research Organization, Tsukuba, Japan

- <sup>68</sup> Graduate School of Science, Kobe University, Kobe, Japan
- <sup>69</sup> Faculty of Science, Kyoto University, Kyoto, Japan
- <sup>70</sup> Kyoto University of Education, Kyoto, Japan
- <sup>71</sup> Department of Physics, Kyushu University, Fukuoka, Japan
- <sup>72</sup> Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- <sup>73</sup> Physics Department, Lancaster University, Lancaster, United Kingdom
- <sup>74</sup> <sup>(a)</sup> INFN Sezione di Lecce; <sup>(b)</sup> Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- <sup>75</sup> Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- <sup>76</sup> Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- <sup>77</sup> School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- <sup>78</sup> Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- <sup>79</sup> Department of Physics and Astronomy, University College London, London, United Kingdom
- <sup>80</sup> Louisiana Tech University, Ruston LA, United States of America
- <sup>81</sup> Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- <sup>82</sup> Fysiska institutionen, Lunds universitet, Lund, Sweden
- <sup>83</sup> Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
- <sup>84</sup> Institut für Physik, Universität Mainz, Mainz, Germany
- <sup>85</sup> School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- <sup>86</sup> CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- <sup>87</sup> Department of Physics, University of Massachusetts, Amherst MA, United States of America
- <sup>88</sup> Department of Physics, McGill University, Montreal QC, Canada
- <sup>89</sup> School of Physics, University of Melbourne, Victoria, Australia
- <sup>90</sup> Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
- <sup>91</sup> Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
- <sup>92</sup> <sup>(a)</sup> INFN Sezione di Milano; <sup>(b)</sup> Dipartimento di Fisica, Università di Milano, Milano, Italy
- <sup>93</sup> B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
- <sup>94</sup> National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
- <sup>95</sup> Group of Particle Physics, University of Montreal, Montreal QC, Canada
- <sup>96</sup> P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
- <sup>97</sup> Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- <sup>98</sup> National Research Nuclear University MEPhI, Moscow, Russia
- <sup>99</sup> D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- <sup>100</sup> Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- <sup>101</sup> Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- <sup>102</sup> Nagasaki Institute of Applied Science, Nagasaki, Japan
- <sup>103</sup> Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- <sup>104</sup> <sup>(a)</sup> INFN Sezione di Napoli; <sup>(b)</sup> Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- <sup>105</sup> Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
- <sup>106</sup> Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands

- <sup>107</sup> Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- <sup>108</sup> Department of Physics, Northern Illinois University, DeKalb IL, United States of America
- <sup>109</sup> Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- <sup>110</sup> Department of Physics, New York University, New York NY, United States of America
- <sup>111</sup> Ohio State University, Columbus OH, United States of America
- <sup>112</sup> Faculty of Science, Okayama University, Okayama, Japan
- <sup>113</sup> Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
- <sup>114</sup> Department of Physics, Oklahoma State University, Stillwater OK, United States of America
- <sup>115</sup> Palacký University, RCPTM, Olomouc, Czech Republic
- <sup>116</sup> Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
- <sup>117</sup> LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
- <sup>118</sup> Graduate School of Science, Osaka University, Osaka, Japan
- <sup>119</sup> Department of Physics, University of Oslo, Oslo, Norway
- <sup>120</sup> Department of Physics, Oxford University, Oxford, United Kingdom
- <sup>121</sup> <sup>(a)</sup> INFN Sezione di Pavia; <sup>(b)</sup> Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- <sup>122</sup> Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
- <sup>123</sup> National Research Centre "Kurchatov Institute" B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
- <sup>124</sup> <sup>(a)</sup> INFN Sezione di Pisa; <sup>(b)</sup> Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- <sup>125</sup> Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
- <sup>126</sup> <sup>(a)</sup> Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa; <sup>(b)</sup> Faculdade de Ciências, Universidade de Lisboa, Lisboa; <sup>(c)</sup> Department of Physics, University of Coimbra, Coimbra; <sup>(d)</sup> Centro de Física Nuclear da Universidade de Lisboa, Lisboa; <sup>(e)</sup> Departamento de Física, Universidade do Minho, Braga; <sup>(f)</sup> Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); <sup>(g)</sup> Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- <sup>127</sup> Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
- <sup>128</sup> Czech Technical University in Prague, Praha, Czech Republic
- <sup>129</sup> Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
- <sup>130</sup> State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia
- <sup>131</sup> Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- <sup>132</sup> <sup>(a)</sup> INFN Sezione di Roma; <sup>(b)</sup> Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- <sup>133</sup> <sup>(a)</sup> INFN Sezione di Roma Tor Vergata; <sup>(b)</sup> Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- <sup>134</sup> <sup>(a)</sup> INFN Sezione di Roma Tre; <sup>(b)</sup> Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
- <sup>135</sup> <sup>(a)</sup> Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; <sup>(b)</sup> Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; <sup>(c)</sup> Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; <sup>(d)</sup> Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; <sup>(e)</sup> Faculté des sciences, Université Mohammed V, Rabat, Morocco
- <sup>136</sup> DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
- <sup>137</sup> Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America

States of America

- <sup>138</sup> Department of Physics, University of Washington, Seattle WA, United States of America
- <sup>139</sup> Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- <sup>140</sup> Department of Physics, Shinshu University, Nagano, Japan
- <sup>141</sup> Fachbereich Physik, Universität Siegen, Siegen, Germany
- <sup>142</sup> Department of Physics, Simon Fraser University, Burnaby BC, Canada
- <sup>143</sup> SLAC National Accelerator Laboratory, Stanford CA, United States of America
- <sup>144</sup> <sup>(a)</sup> Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; <sup>(b)</sup> Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- <sup>145</sup> <sup>(a)</sup> Department of Physics, University of Cape Town, Cape Town; <sup>(b)</sup> Department of Physics, University of Johannesburg, Johannesburg; <sup>(c)</sup> School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- <sup>146</sup> <sup>(a)</sup> Department of Physics, Stockholm University; <sup>(b)</sup> The Oskar Klein Centre, Stockholm, Sweden
- <sup>147</sup> Physics Department, Royal Institute of Technology, Stockholm, Sweden
- <sup>148</sup> Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
- <sup>149</sup> Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- <sup>150</sup> School of Physics, University of Sydney, Sydney, Australia
- <sup>151</sup> Institute of Physics, Academia Sinica, Taipei, Taiwan
- <sup>152</sup> Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
- <sup>153</sup> Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- <sup>154</sup> Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- <sup>155</sup> International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
- <sup>156</sup> Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
- <sup>157</sup> Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
- <sup>158</sup> Department of Physics, University of Toronto, Toronto ON, Canada
- <sup>159</sup> <sup>(a)</sup> TRIUMF, Vancouver BC; <sup>(b)</sup> Department of Physics and Astronomy, York University, Toronto ON, Canada
- <sup>160</sup> Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan
- <sup>161</sup> Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
- <sup>162</sup> Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
- <sup>163</sup> <sup>(a)</sup> INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; <sup>(b)</sup> ICTP, Trieste; <sup>(c)</sup> Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
- <sup>164</sup> Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
- <sup>165</sup> Department of Physics, University of Illinois, Urbana IL, United States of America
- <sup>166</sup> Instituto de Física Corpuscular (IFIC) and Departamento de Física Atomica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
- <sup>167</sup> Department of Physics, University of British Columbia, Vancouver BC, Canada
- <sup>168</sup> Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
- <sup>169</sup> Department of Physics, University of Warwick, Coventry, United Kingdom
- <sup>170</sup> Waseda University, Tokyo, Japan

- <sup>171</sup> Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
- <sup>172</sup> Department of Physics, University of Wisconsin, Madison WI, United States of America
- <sup>173</sup> Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
- <sup>174</sup> Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
- <sup>175</sup> Department of Physics, Yale University, New Haven CT, United States of America
- <sup>176</sup> Yerevan Physics Institute, Yerevan, Armenia
- <sup>177</sup> Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
- <sup>a</sup> Also at Department of Physics, King's College London, London, United Kingdom
- <sup>b</sup> Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- <sup>c</sup> Also at Novosibirsk State University, Novosibirsk, Russia
- <sup>d</sup> Also at TRIUMF, Vancouver BC, Canada
- <sup>e</sup> Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, United States of America
- <sup>f</sup> Also at Department of Physics, California State University, Fresno CA, United States of America
- <sup>g</sup> Also at Department of Physics, University of Fribourg, Fribourg, Switzerland
- <sup>h</sup> Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
- <sup>i</sup> Also at Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, Portugal
- <sup>j</sup> Also at Tomsk State University, Tomsk, Russia
- <sup>k</sup> Also at Università di Napoli Parthenope, Napoli, Italy
- <sup>l</sup> Also at Institute of Particle Physics (IPP), Canada
- <sup>m</sup> Also at National Institute of Physics and Nuclear Engineering, Bucharest, Romania
- <sup>n</sup> Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia
- <sup>o</sup> Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
- <sup>p</sup> Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa
- <sup>q</sup> Also at Louisiana Tech University, Ruston LA, United States of America
- <sup>r</sup> Also at Institució Catalana de Recerca i Estudis Avançats, ICREA, Barcelona, Spain
- <sup>s</sup> Also at Graduate School of Science, Osaka University, Osaka, Japan
- <sup>t</sup> Also at Department of Physics, National Tsing Hua University, Taiwan
- <sup>u</sup> Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- <sup>v</sup> Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America
- <sup>w</sup> Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia
- <sup>x</sup> Also at CERN, Geneva, Switzerland
- <sup>y</sup> Also at Georgian Technical University (GTU), Tbilisi, Georgia
- <sup>z</sup> Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan
- <sup>aa</sup> Also at Manhattan College, New York NY, United States of America
- <sup>ab</sup> Also at Hellenic Open University, Patras, Greece
- <sup>ac</sup> Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
- <sup>ad</sup> Also at School of Physics, Shandong University, Shandong, China
- <sup>ae</sup> Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
- <sup>af</sup> Also at Section de Physique, Université de Genève, Geneva, Switzerland
- <sup>ag</sup> Also at Eötvös Loránd University, Budapest, Hungary
- <sup>ah</sup> Also at Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
- <sup>ai</sup> Also at International School for Advanced Studies (SISSA), Trieste, Italy



<sup>aj</sup> Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America

<sup>ak</sup> Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China

<sup>al</sup> Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria

<sup>am</sup> Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia

<sup>an</sup> Also at Institute of Physics, Academia Sinica, Taipei, Taiwan

<sup>ao</sup> Also at National Research Nuclear University MEPhI, Moscow, Russia

<sup>ap</sup> Also at Department of Physics, Stanford University, Stanford CA, United States of America

<sup>aq</sup> Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary

<sup>ar</sup> Also at Flensburg University of Applied Sciences, Flensburg, Germany

<sup>as</sup> Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia

<sup>at</sup> Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France

\* Deceased