<table>
<thead>
<tr>
<th><strong>Title</strong></th>
<th>Search for new resonances decaying to a W or Z boson and a Higgs boson in the l+l-bb, lvbb, and vvbb channels with pp collisions at $\sqrt{s}=13$ TeV with the ATLAS detector</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Author(s)</strong></td>
<td>Tu, Y; Orlando, N</td>
</tr>
<tr>
<td><strong>Citation</strong></td>
<td>Physics Letters B, 2017, v. 765, p. 32-52</td>
</tr>
<tr>
<td><strong>Issued Date</strong></td>
<td>2017</td>
</tr>
<tr>
<td><strong>URL</strong></td>
<td><a href="http://hdl.handle.net/10722/240315">http://hdl.handle.net/10722/240315</a></td>
</tr>
<tr>
<td><strong>Rights</strong></td>
<td>Creative Commons: Attribution 3.0 Hong Kong License</td>
</tr>
</tbody>
</table>
Search for new resonances decaying to a $W$ or $Z$ boson and a Higgs boson in the $\ell^+\ell^-bb$, $\ell\nu b\bar{b}$, and $\nu\bar{\nu}bb$ channels with $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration*
The HVT benchmark Model B with \( g_V = 3 \) [17]. The ATLAS collaboration has also performed a search for narrow resonances decaying to \( VV \) final states [18].

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 [19] 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 [20] 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 \( \vartheta \) as \( \eta = -\ln(\tan(\vartheta/2)) \). 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 [21].

### 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 fb\(^{-1} \) [22] at \( \sqrt{s} = 13 \) 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 [23] using the NNPDF2.3LO [24] parton distribution functions (PDFs). For all signal events, parton showering and hadronization are performed with PYTHIA 8.186 [25] using the A14 set of tuned parameters (tune) [26]. The Higgs boson has its mass set to 125.5 GeV, and it is allowed to decay to \( bb \) and \( c\bar{c} \) pairs, with relative branching fractions \( BR(H \to c\bar{c})/BR(H \to bb) = 0.05 \) fixed to the Standard Model prediction [27]. The ratio of \( W' \) to \( Z' \) production is predicted by the model and depends on the masses of the \( W' \) and \( Z' \). 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 (\( W + \text{jets} \), \( Z + \text{jets} \)) are simulated using the SHERRA 2.1.1 [28] generator. Matrix elements are calculated using the COMIX [29] and OPENLOOPS [30] matrix element generators and merged with the SHERRA parton shower using the MELPS@NLO prescription [31]. For \( W + \text{jets} \) and \( Z + \text{jets} \) 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 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 [32] is used in conjunction with dedicated parton shower tuning developed by the authors of SHERRA.

The \( W'Z' + \text{jets} \) 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 each event’s Higgs boson candidate; the Higgs boson candidate is defined in Section 4. If there is an associated bottom (charm) hadron, then the event is given a \( b \) (c) label; if both bottom and charm hadrons are associated, the \( b \) label takes precedence. Otherwise it is labelled \( W'Z' + q \).

For the generation of \( \ell \ell \) and single top quarks in the \( W \)- and \( s \)-channels the POWHEG-BOX v2 [33-35] 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 [32]. For all top processes, top-quark spin correlations are preserved (for the \( t \)-channel, top quarks are decayed using MadSpin [36]). The parton shower, fragmentation, and the underlying event are simulated using PYTHIA 6.428 [37] with the CTEQ6L1 [38] PDF sets and the corresponding Perugia 2012 tune (P2012) [39]. The top quark mass is set to 172.5 GeV. The EVTGEN v1.2.0 program [40] 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 [41]. SM Higgs boson production is considered as a background in this search. Interference between the SM \( pp \to VH \) production and \( V' \to VH \) production is expected to be small for large resonance masses, and is not included here.

Multi-jet events are modelled using data and validated using a loosener event selection than required for the search. The rate of the multi-jet background has been shown to be negligible when the tight search selection is applied, and is thus not included in the presentation of results.

The effect of multiple \( pp \) interactions in the same and neighbouring bunch crossings (pile-up) is simulated by overlaying minimum-bias events generated with PYTHIA 8.186 on each generated signal or background event. Simulated events are reconstructed with the standard ATLAS reconstruction software used for collision data using the GEANT4 toolkit [42,43].

### 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 [44]. 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 [45]. Muons are identified by matching tracks found in the inner detector to either full tracks or track segments reconstructed in the muon spectrometer [46]. 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 $p_T$, so-called “mini-isolation” [47]. Leptons must also originate from the primary vertex [45,46]. The identification efficiencies, including isolation efficiencies, of both electrons and muons are calibrated using tag-and-probe methods in $Z \rightarrow \ell \ell$ data events.

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, $R$ [48]. Large- and small-$R$ jets are built from noise-suppressed topological clusters [49] 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 [50] 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 [51] into subsets of radius $R_{sub}$, the constituents of any subset with transverse momentum less than $f_{cut}$ times the transverse momentum of the initial jet are removed. The $R_{sub}$ and $f_{cut}$ parameter values found to be optimal in identifying hadronic $W/Z$ boson decays [52] are $R_{sub} = 0.2$ and $f_{cut} = 5\%$. Large-$R$ jets are required to be separated by $\Delta R > 1.0$ to the nearest electron candidate, as measured from the center of the jet.

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 [53]. 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 is 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 [54].

The third type of jet used in this analysis, track jets, are built with the anti-$k_T$ algorithm with $R = 0.2$ from inner-detector tracks with $p_T > 400$ MeV associated with the primary vertex 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 [55,56] 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 $R$-jets via ghost-association [48].

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 endcap calorimeters ($1.37 < |\eta| < 1.52$); to have either one or three associated tracks; and to satisfy the “medium” working point criteria [57]. 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 ($E_T^{miss}$) 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 [58]. The magnitude of the $E_T^{miss}$ is denoted by $p_T^{miss}$ for multi-jet background rejection, a similar quantity, $E_T^{miss}$, is computed using only charged-particle tracks originating from the nominal hard-scatter vertex, and its magnitude is denoted by $p_T^{miss}$.

5. Event selection

This analysis is performed for events containing zero, one, or two charged leptons (electrons or muons), targeting the $Z \rightarrow WH \rightarrow \ell \nu \ell \nu$, $W \rightarrow WH \rightarrow \ell \nu \ell \nu$ and $Z \rightarrow WH \rightarrow \ell \nu \ell \nu$ 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 $Z \rightarrow WH \rightarrow \ell \nu \ell \nu$ 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 $W \rightarrow WH \rightarrow \ell \nu \ell \nu$ 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. To be consistent with decays of highly-boosted Higgs bosons to quarks, a large-$R$ jet with significant $p_T$ is required to be present in the candidate events.

In the 0-lepton channel events are recorded using an $E_T^{miss}$ 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 $E_T^{miss}$ trigger and single-muon trigger for the muon channel, where the $E_T^{miss}$ trigger considers only the energy of objects in the calorimeter, and thus muons are seen as a source of $E_T^{miss}$. 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 $p_T^{miss}$ ($p_T^{miss} > 30$ GeV), $E_T^{miss}$ ($E_T^{miss} > 200$ GeV), the azimuthal angle between $E_T^{miss}$ and $p_T^{miss}$ ($\Delta \phi(E_T^{miss}, p_T^{miss}) < \pi/2$), and the azimuthal angle between $E_T^{miss}$ and the leading large-$R$ jet
\( (\Delta \phi (E_{\text{T}}^{\text{miss}}, \text{large}-R \text{ jet}) > 2\pi/3) \). An additional requirement is imposed on the azimuthal angle between \( E_{\text{T}}^{\text{miss}} \) and the nearest small-\( R \) jet that is not identified as a \( \tau \)-lepton \((\min(\Delta \phi (E_{\text{T}}^{\text{miss}}, \text{small}-R \text{ jet})) > \pi/9)\). 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 total expected \( W+\text{jets} \) and \( \tau t \) contribution by 18.5\% and has a negligible impact on the \( Z^* \) acceptance. Since it is not possible to fully reconstruct the invariant mass of the candidate \( ZH \rightarrow \ell \ell Vb \) system due to the neutrinos present in the final state, the transverse mass is used as the final discriminant:

\[
m_{\text{T}, VH} = \sqrt{(E_{\text{T}}^{\text{jet}} + E_{\text{T}}^{\text{miss}})^2 - (P_{\text{T}}^{\text{jet}} + P_{\text{T}}^{\text{miss}})^2},
\]

where \( P_{\text{T}}^{\text{jet}} (P_{\text{T}}^{\text{miss}}) \) is the transverse momentum (energy) of the leading large-\( R \) jet.

Events containing exactly one lepton with \( P_{\text{T}} > 25 \text{ GeV} \) (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. Additional requirements on the sums of calorimeter energy deposits and track transverse momenta in a cone with radius \( R = 0.2 \) around the lepton direction are applied such that 95\% of leptons in \( Z \rightarrow \ell \ell \) events are accepted \([45, 46]\). The event must also have significant missing transverse momentum: \( E_{\text{T}}^{\text{miss}} > 100 \text{ GeV} \). To reconstruct the invariant mass of the candidate \( WH \rightarrow \ell \ell Vb \) 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 solution with the smaller absolute value is chosen if both solutions are real.

Events containing exactly two loose leptons of the same flavour with \( P_{\text{T}} > 25 \text{ GeV} \) (and with \( |\eta| < 2.5 \) for muons) are assigned to the 2-lepton channel. Due to the potential charge ambiguity for highly boosted leptons, no opposite charge requirement is imposed. 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 \( P_{\text{T}} \). To improve the \( m_{\text{VH}} \) resolution of \( ZH \rightarrow \mu \mu Vb \) events, the four-momentum of the dimuon system is scaled by \( m_{\ell \ell}/m_{\mu \mu} \), where \( m_{\ell \ell} = 91.2 \text{ GeV} \) and \( m_{\mu \mu} \) is the invariant mass of the dimuon system.

All three channels require at least one large-\( R \) jet with \( P_{\text{T}} > 250 \text{ GeV} \) and \( |\eta| < 2.0 \). The leading large-\( R \) jet is considered to be the \( H \rightarrow bb \) 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 \([59]\). If more than two track jets are matched to the \( H \rightarrow bb \) candidate, only the two with the highest \( P_{\text{T}} \) 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 \( tt \) 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 Fig. 1. The mass of the leading large-\( R \) jet \((m_{\text{jet}})\) 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 GeV < \( m_{\text{jet}} < 145 \) GeV, is applied. This is particularly effective for discriminating the signal from \( tt \) and \( V + bb \) 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 \((1-\text{tag})\) signal region for an HVT resonance of mass of 1.5 TeV are 22\% (28\%), 16\% (25\%) and 15\% (22\%) for the \( Z^* \rightarrow ZH \rightarrow \ell \ell Vb \), \( W' \rightarrow WH \rightarrow \ell \ell Vb \) and \( Z^* \rightarrow ZH \rightarrow \ell^+\ell^- Vb \) processes, respectively. The selection efficiency of the \( W' \rightarrow WH \rightarrow \ell \ell Vb \) process in the 0-lepton channel is 2.7\% (3.5\%) in the 2-\( b \)-tag \((1-\text{tag})\) signal region. The contamination of \( Z^* \rightarrow ZH \rightarrow \ell^+\ell^- b \) in the 1-lepton channel and of \( W' \rightarrow WH \rightarrow \ell \ell Vb \) in the 2-lepton channel is found to be negligible.

**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 \( W+\text{jets} \) and \( \tau t \) production. In the 1-lepton channel the dominant backgrounds are \( W+\text{jets} \) and \( \tau t \) 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 normalisation and \( m_{\text{VH}} \) 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 \( m_{\text{jet}} < 75 \text{ GeV} \) (low-\( m_{\text{jet}} \)) or \( m_{\text{jet}} > 145 \text{ GeV} \) (high-\( m_{\text{jet}} \)) are used as control regions for the \( W/Z+\text{jets} \) 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 \( W/Z+bb \) contributions, respectively.

Control regions for the \( tt \) background prediction are also defined. For the 0- and 1-lepton channels, the \( tt \) 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 \( tt \) control regions. The \( tt \) 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 \([52]\). The uncertainty in the track-jet \( b \)-tagging efficiency arises mainly from
uncertainty in the measurement of the $b$-tagging efficiency in $tt$ events, while the mistag rate and uncertainty are determined using dijet events [55]. 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 $tt$ and single top quarks [60], 11% for dibosons [61], 10% for $W/Z+$light jets [62], 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_αMC@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 $tt$ background is derived by comparing a Powheg sample with the distribution obtained using MadGraph5_αMC@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++ 2.71 [63] and using the UEUE5 underlying-event tune. Samples of $tt$ 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 $m_{1,2,VH}$ 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 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 Fig. 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 1-lepton veto is not imposed and the search considers only the $W'\rightarrow WH$ signal, while for the $Z'$ search the 1-lepton veto is imposed and only $Z'\rightarrow ZH$ signal is considered.

The results for combined HVT production are evaluated without the 1-lepton veto imposed, including both the $W'\rightarrow WH$ and $Z'\rightarrow ZH$ signals simultaneously. The combined HVT $W'$ 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 [64], also known as $C_L$, and the profile-likelihood ratio test statistic [65] in the asymptotic approximation, using the binned $m_{VH}$ or $m_{1,2,VH}$ 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 fits. Figs. 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 sum $BR(H\rightarrow bb+c\ell)$ 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 sum $BR(H\rightarrow bb+c\ell)$ is fixed to the Standard Model prediction of 60.6% [27].

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 combined signal strength for the processes $W'\rightarrow WH$ and $Z'\rightarrow ZH$, assuming $m_{W'}=m_{Z'}$, relative to the HVT model predictions, are shown in Fig. 3(c). For Model A (Model B) with coupling constant $g_V=1$ ($g_V=3$), $m_{W'/Z'}<1730$ GeV (2310 GeV) is excluded.

The exclusion contours in the HVT parameter space $(g_{VVH}, g_{VVVV}^2/\alpha_{V})$ for resonances of mass 1.2 TeV, 2.0 TeV and 3.0 TeV are shown in Fig. 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 $\alpha_V$ is assumed to be the same for quarks and leptons, including third-generation fermions, and other parameters involving more than one heavy vector boson, $g_{VVVV}, g_{VVHH}^2$ and $g_{VWW}$, have negligible contributions to the overall cross-sections for the processes of interest.

9. Conclusion

A search for new, heavy resonances decaying to $WH/ZH$ is presented. The search is performed using $3.2\pm0.2$ 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: $t\bar{t}c\ell$, $t\bar{b}bb$, $t\bar{v}bb$. 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.

Acknowledgements

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

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPERJ, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS, CEAS-DSM/IRFU, France; GNSF, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Mo-
Fig. 3. Upper limits at the 95% CL for (a) the production cross-section of $Z'$ times its branching fraction to $ZH$ and the branching fraction sum $BR(H \rightarrow b \bar{b} + c \bar{c})$ and (b) the production cross-section of $W'$ times its branching fraction to $WH$ and the branching fraction sum $BR(H \rightarrow b \bar{b} + c \bar{c})$. 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. In all cases $H \rightarrow b \bar{b}$ and $H \rightarrow c \bar{c}$ decays are included at the branching fractions predicted in the SM.

Fig. 4. Observed 95% CL exclusion contours in the HVT parameter space $(g_{V^H}, (g_V^H/m_V)^2)$ for resonances of mass 1.2 TeV, 2.0 TeV and 3.0 TeV, corresponding to the dotted, dashed and solid contours, respectively. The parameter space outside each contour is excluded for a resonance with the corresponding mass. 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.

References


ATLAS Collaboration, Expected Performance of Boosted Higgs (\( \rightarrow b \bar{b} \)) Boson Identification with the ATLAS Detector at \( \sqrt{s} = 13 \text{ TeV} \), ATL-PHYS-PUB-2015-035, 2015, http://cds.cern.ch/record/2042155.


1 Department of Physics, University of Adelaide, Australia
2 Physics Department, SUNY Albany, Albany, NY, United States
3 Department of Physics, University of Alberta, Edmonton AB, Canada
4 (a) Department of Physics, Ankara University, Ankara; (b) Istanbul Aydin University, Istanbul; (c) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
5 LAPP- CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France
6 High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States
7 Department of Physics, University of Arizona, Tucson, AZ, United States
8 Department of Physics, The University of Texas at Arlington, Arlington, TX, United States
9 Physics Division, National and Kapodistrian University of Athens, Greece
10 Department of Physics, National Technical University of Athens, Zografou, Greece
11 Department of Physics, The University of Texas at Austin, Austin, TX, United States
12 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
13 Institut de Física d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain
14 Institute of Physics, University of Belgrade, Belgrade, Serbia
15 Department for Physics and Technology, University of Bergen, Bergen, Norway
16 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States
17 Department of Physics, Humboldt University, Berlin, Germany
18 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
19 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
20 (a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics Engineering, Gaziantep University, Gaziantep; (c) Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey; (d) Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
21 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
Also at Department of Physics, King’s College London, London, United Kingdom.

Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

Also at Novosibirsk State University, Novosibirsk, Russia.

Also at TRIUMF, Vancouver BC, Canada.

Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, United States.

Also at Physics Department, An-Najah National University, Nablus, Palestine.

Also at Department of Physics, California State University, Fresno, CA, United States.

Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.

Also at Departamento de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain.

Also at Departamento de Fisica e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal.

Also at Tomsk State University, Tomsk, Russia.

Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.

Also at Universita di Napoli Parthenope, Napoli, Italy.

Also at Institute of Particle Physics (IPP), Canada.

Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania.

Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.

Also at Department of Physics, The University of Michigan, Ann Arbor, MI, United States.

Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.

Also at Louisiana Tech University, Ruston, LA, United States.

Also at Instituto Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.

Also at Graduate School of Science, Osaka University, Osaka, Japan.

Also at Department of Physics, National Tsing Hua University, Taiwan.

Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.

Also at Department of Physics, The University of Texas at Austin, Austin, TX, United States.

Also at CERN, Geneva, Switzerland.

Also at Georgian Technical University (GTU), Tbilisi, Georgia.

Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.

Also at Manhattan College, New York, NY, United States.

Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.

Also at School of Physics, Shandong University, Shandong, China.

Also at Departamento de Fisica Teorica y del Cosmos and CAPE, Universidad de Granada, Granada, Spain.

Also at Department of Physics, California State University, Sacramento, CA, United States.

Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

Also at Departement de Physique Nucleaire et Corpusculaire, Université de Genève, Geneva, Switzerland.

Also at Eötvös Loránd University, Budapest, Hungary.

Also at Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, NY, United States.

Also at International School for Advanced Studies (SISSA), Trieste, Italy.

Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.

Also at Institut de Fisica d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain.

Also at School of Physics, Sun Yat-sen University, Guangzhou, China.

Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.

Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia.

Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.

Also at National Research Nuclear University MEPhI, Moscow, Russia.

Also at Department of Physics, Stanford University, Stanford, CA, United States.

Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.

Also at Felsberg University of Applied Sciences, Flensburg, Germany.

Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.

Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.

Also at LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.

Also at PKU-CHEP.

Deceased.