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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

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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 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 [3,4]. 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 [5–7], Little Higgs [8], or composite Higgs models [9,10].

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' ($pp \to W' \to WH$ and $pp \to Z' \to ZH$) and together as V'. The analyses described here only target leptonic decays of the vector bosons ($W \to \ell\nu$, $Z \to \ell^+\ell^-$, $Z \to \nu\bar{\nu}$; $\ell = e, \mu$) and decays of the Higgs boson to bottom-quark pairs ($H \to b\bar{b}$). This results in three search channels: $W' \to WH \to \ell\nu b\bar{b}$, $Z' \to ZH \to \ell^+\ell^-b\bar{b}$, and $Z' \to ZH \to \nu\bar{\nu}b\bar{b}$.

For the interpretation of the results in terms of a search for heavy vector bosons, a simplified benchmark model [11] is used. This simplified model incorporates a phenomenological Lagrangian describing a heavy vector triplet of fields (HVT), allowing for the interpretation of search results in a large class of models that predict heavy vector resonances. 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 derived by tuning the HVT coupling parameterization [11] are used here. In the first, referred to as *Model A* ($g_V = 1$, $c_H = -0.55$, $c_F \sim 1$), the branching fractions to fermion pairs and to the heavy SM bosons are comparable, as in some extensions of the SM gauge group [12]. For *Model B* ($g_V = 3$, $c_H \sim -1$, $c_F \sim 1$), fermionic decays are suppressed (though not necessarily vanishing) due to the increased Higgs/vector boson coupling, as for example in a composite Higgs model [13]. 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 $V' \to VH$ 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 $g_V = 1$ [14]. Searches by the CMS Collaboration for $V' \to VH$, based on HVT benchmark *Model B* with $g_V = 3$, similarly exclude heavy resonance masses up to 1.1 TeV ($Z' \to ZH$), 1.5 TeV ($W' \to WH$), yielding a combined limit of 1.7 TeV ($V' \to VH$) in the fully hadronic final state [15], and masses up to 1.5 TeV for the $W' \to WH \to \ell\nu b\bar{b}$ final state [16]. 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

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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 ($m_{\mathrm{T},VH}$) 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[1] θ 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 [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 $b\bar{b}$ and $c\bar{c}$ pairs, with relative branching fractions $\mathrm{BR}(H \to c\bar{c})/\mathrm{BR}(H \to b\bar{b}) = 0.05$ 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+jets, Z+jets) are simulated using the Sherpa 2.1.1 [28] generator. Matrix elements are calculated using the Comix [29] and OpenLoops [30] matrix element generators and merged with the Sherpa parton shower using the ME+PS@NLO prescription [31]. 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 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 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 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 $t\bar{t}$ and single top quarks in the Wt- 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 looser 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 $p_{\mathrm{T}} > 400$ MeV. If an event contains more than one

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis 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, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis.

vertex candidate, the one with the highest $\sum p_{\mathrm{T}}^2$ 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 $Z \to \ell\ell$ 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 $p_{\mathrm{T}} > 250$ 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 subjets of radius R_{sub}; the constituents of any subjet 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 $R_{\mathrm{sub}} = 0.2$ and $f_{\mathrm{cut}} = 5\%$. 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 $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.4$ or $p_{\mathrm{T}} > 30$ 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 $p_{\mathrm{T}} < 50$ 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 [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 $p_{\mathrm{T}} > 400$ MeV associated with the primary vertex and are required to have $p_{\mathrm{T}} > 10$ 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 large-R jets via ghost-association [48].

Hadronically decaying τ-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 $p_{\mathrm{T}} > 20$ 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 [57]. The leptonic decays of τ-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 ($\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$) 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 $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$ is denoted by $E_{\mathrm{T}}^{\mathrm{miss}}$. For multi-jet background rejection, a similar quantity, $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$, is computed using only charged-particle tracks originating from the nominal hard-scatter vertex, and its magnitude is denoted by $p_{\mathrm{T}}^{\mathrm{miss}}$.

5. Event selection

This analysis is performed for events containing zero, one, or two charged leptons (electrons or muons), targeting the $Z' \to ZH \to \nu\bar{\nu}b\bar{b}$, $W' \to WH \to \ell\nu b\bar{b}$ and $Z' \to ZH \to \ell^+\ell^- b\bar{b}$ 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 $Z' \to ZH \to \ell\ell b\bar{b}$ 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 $W' \to WH \to \ell\nu b\bar{b}$ signal in events in which the lepton is not detected or is a hadronically decaying τ-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 $E_{\mathrm{T}}^{\mathrm{miss}}$ 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 $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger and single-muon trigger for the muon channel, where the $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger considers only the energy of objects in the calorimeter, and thus muons are seen as a source of $E_{\mathrm{T}}^{\mathrm{miss}}$. 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 $p_{\mathrm{T}}^{\mathrm{miss}}$ ($p_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV), $E_{\mathrm{T}}^{\mathrm{miss}}$ ($E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV), the azimuthal angle between $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$ and $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ ($\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}) < \pi/2$), and the azimuthal angle between $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$ and the leading large-R jet

($\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$, large-$R$ jet$) > 2\pi/3$). An additional requirement is imposed on the azimuthal angle between $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$ and the nearest small-R jet that is not identified as a τ-lepton (min[$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$, small-$R$ jet)] $> \pi/9$). Finally, only in the search for $Z' \to ZH$, events containing one or more identified hadronically decaying τ-lepton candidates are rejected; this veto reduces the total expected W+jets and $t\bar{t}$ 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 $ZH \to \nu\nu b\bar{b}$ system due to the neutrinos present in the final state, the transverse mass is used as the final discriminant: $m_{\mathrm{T},VH} = \sqrt{(E_{\mathrm{T}}^{\mathrm{jet}} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\vec{p}_{\mathrm{T}}^{\mathrm{jet}} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}})^2}$, where $p_{\mathrm{T}}^{\mathrm{jet}}$ ($E_{\mathrm{T}}^{\mathrm{jet}}$) is the transverse momentum (energy) of the leading large-R jet.

Events containing exactly one lepton with $p_{\mathrm{T}} > 25$ 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. 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 $Z \to \ell\ell$ events are accepted [45,46]. The event must also have significant missing transverse momentum: $E_{\mathrm{T}}^{\mathrm{miss}} > 100$ GeV. To reconstruct the invariant mass of the candidate $WH \to \ell\nu b\bar{b}$ 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 solution with the smaller absolute value is chosen if both solutions are real.

Events containing exactly two loose leptons of the same flavour with $p_{\mathrm{T}} > 25$ 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_{T}. To improve the m_{VH} resolution of $ZH \to \mu\mu b\bar{b}$ 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 $p_{\mathrm{T}} > 250$ GeV and $|\eta| < 2.0$. The leading large-R jet is considered to be the $H \to b\bar{b}$ 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 [59]. If more than two track jets are matched to the $H \to b\bar{b}$ 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 ΔR to the jet axis provided it is within the jet radius. The distribution of the mass of the leading large-R jet (m_{jet}) in events passing the selection described so far is shown in Fig. 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 GeV $< m_{\mathrm{jet}} <$ 145 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 22% (28%), 16% (25%) and 15% (22%) for the $Z' \to ZH \to \nu\bar{\nu}b\bar{b}$, $W' \to WH \to \ell\nu b\bar{b}$ and $Z' \to ZH \to \ell^+\ell^- b\bar{b}$ processes, respectively. The selection efficiency of the $W' \to WH \to \ell\nu b\bar{b}$ process in the 0-lepton channel is 2.7% (3.5%) in the 2-b-tag (1-b-tag) signal region. The contamination of $Z' \to ZH \to \ell^+\ell^- b\bar{b}$ in the 1-lepton channel and of $W' \to WH \to \ell\nu b\bar{b}$ 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+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.

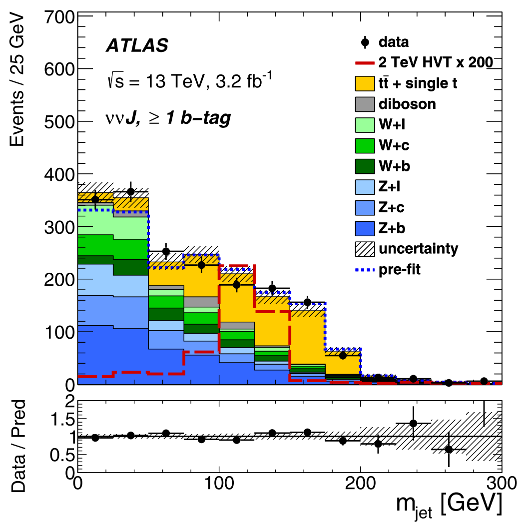
The background modelling is studied using control regions with low signal contamination, chosen to not overlap with the signal regions. These control regions are used both to evaluate the background predictions outside the signal-rich regions and to establish the normalization and m_{VH} shape of the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

Sideband regions of the m_{jet} distribution, defined as $m_{\mathrm{jet}} <$ 75 GeV (low-m_{jet}) or $m_{\mathrm{jet}} > 145$ GeV (high-m_{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_{jet} control regions mainly test the $W/Z + c$ and $W/Z + b$ contributions, respectively.

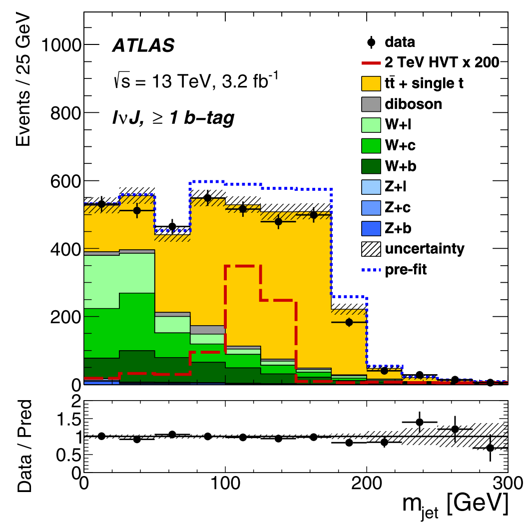
Control regions for the $t\bar{t}$ background prediction are also defined. For the 0- and 1-lepton channels, the $t\bar{t}$ control regions are defined by requiring at least one additional b-tagged track jet that is not matched to the large-R jet; no Higgs boson candidate mass window requirement is imposed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

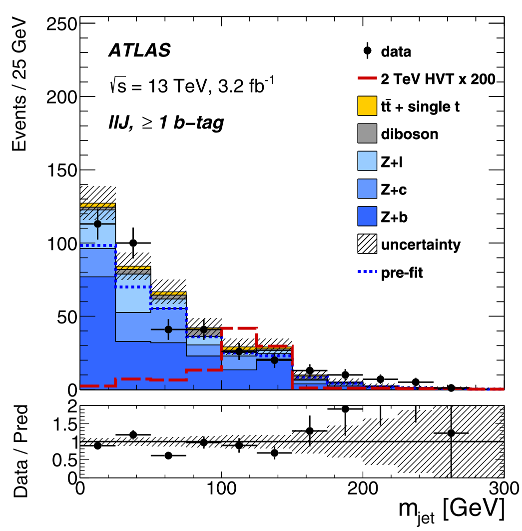
The most important experimental systematic uncertainties are associated with the measurement of the scale and resolution of the large-R jet energy and mass, as well as with the determination of the track jet b-tagging efficiency and mistag rate. The uncertainties in the scale and resolution of large-R jet energy and mass are evaluated by comparing the ratio of calorimeter-based to track-based measurements in multi-jet data and simulation [52]. The uncertainty in the track-jet b-tagging efficiency arises mainly from



(a) 0-lepton, ≥ 1 b-tag



(b) 1-lepton, ≥ 1 b-tag



(c) 2-lepton, ≥ 1 b-tag

Fig. 1. Distributions of the mass of the leading large-R jet, m_{jet}, for the (a) 0-lepton, (b) 1-lepton, and (c) 2-lepton channels. Only the $Z' \to ZH$ signal is shown for the 0-lepton channel, and no τ-lepton veto is applied. 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 SM VH prediction is summed with the diboson backgrounds, and the negligible multi-jet background is not included here. The signal for the benchmark HVT *Model A* with $m_{V'} = 2$ TeV is shown as a dotted red line and normalized to 200 times the theoretical cross-section. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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 [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 $E_{\text{T}}^{\text{miss}}$ 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 [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 $m_{\text{T},VH}$ 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 $m_{\text{T},VH}$ 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 [63] 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 $m_{\mathrm{T},VH}$ 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 scale parameters described in Section 7. High- and low-m_{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 τ-lepton veto is not imposed and the search considers only the $W' \to WH$ signal, while for the Z' search the τ veto is imposed and only $Z' \to ZH$ signal is considered.

The results for combined HVT production are evaluated without the τ veto imposed, including both the $W' \to WH$ and $Z' \to ZH$ 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 [64], also known as CL_s, and the profile-likelihood-ratio test statistic [65] in the asymptotic approximation, using the binned m_{VH} or $m_{\mathrm{T},VH}$ 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 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($H \to b\bar{b} + c\bar{c}$) 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 sum BR($H \to b\bar{b} + c\bar{c}$) is fixed to the Standard Model prediction of 60.6% [27].

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 total 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.

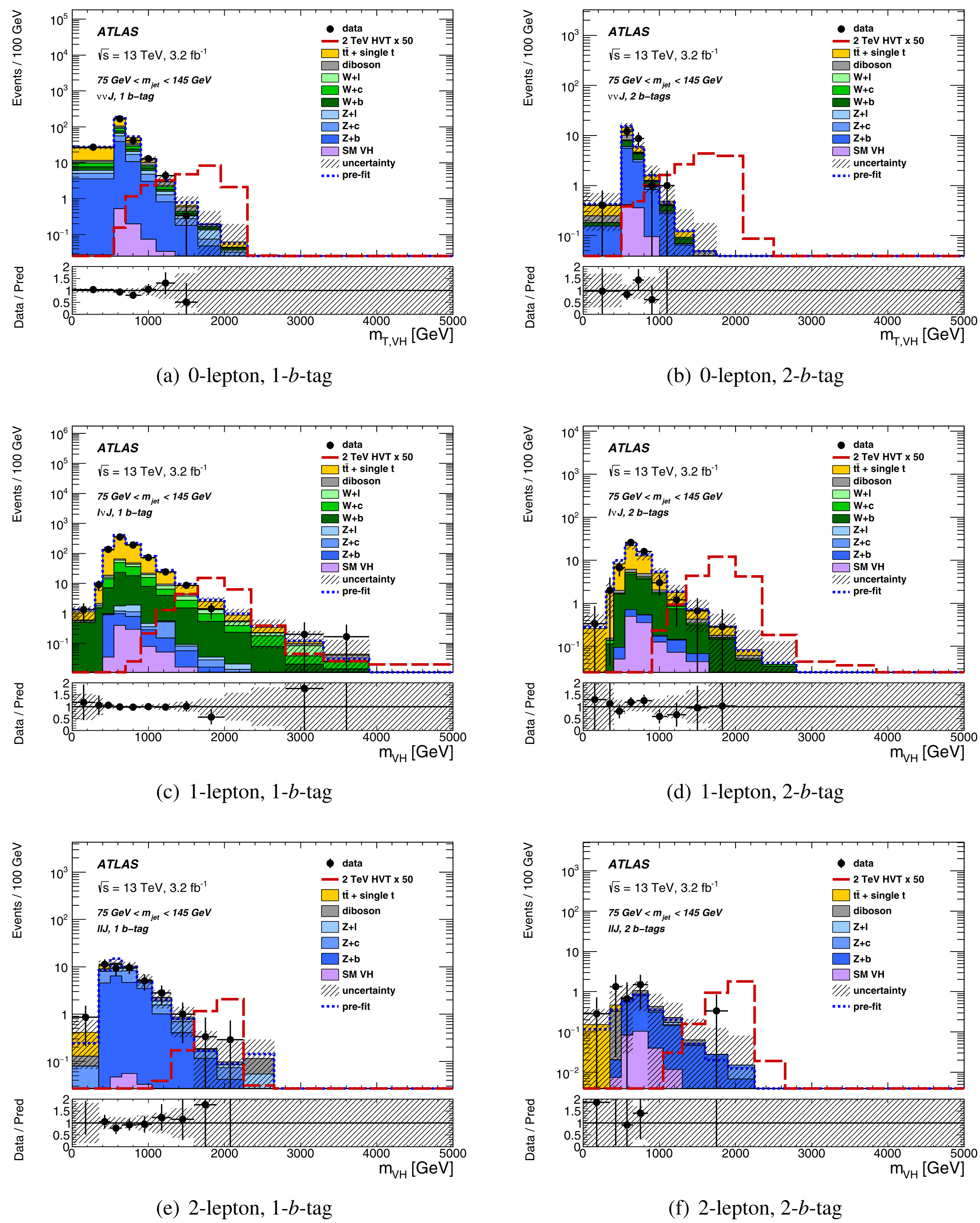
	Two b-tags		
	$\nu\nu b\bar{b}$	$\ell\nu b\bar{b}$	$\ell\ell b\bar{b}$
$t\bar{t}$	9.6 ± 1.4	50 ± 7	0.54 ± 0.36
Single top	2.0 ± 0.6	11.4 ± 3.0	0.20 ± 0.10
$W+b$	5.2 ± 1.3	18 ± 5	
$W+c$	0.64 ± 0.18	2.0 ± 0.7	
$W+q$	0.06 ± 0.03	2.0 ± 0.8	
Diboson	4.2 ± 1.8	4.6 ± 0.8	1.28 ± 0.27
SM VH	1.43 ± 0.57	0.03 ± 0.01	0.45 ± 0.19
$Z+b$	12.3 ± 2.4	1.0 ± 0.4	3.4 ± 0.8
$Z+c$	1.46 ± 0.43	0.05 ± 0.02	0.31 ± 0.10
$Z+q$	0.13 ± 0.05		0.04 ± 0.04
Backgrounds	36.9 ± 3.5	90 ± 6	6.2 ± 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 ± 17	969 ± 50	3.8 ± 0.8
Single top	26 ± 7	112 ± 30	0.58 ± 0.19
$W+b$	33 ± 8	100 ± 24	
$W+c$	41 ± 10	109 ± 31	
$W+q$	20 ± 5	53 ± 9	
Diboson	28 ± 5	32 ± 5	6.4 ± 1.0
SM VH	1.6 ± 0.6	0.04 ± 0.01	0.30 ± 0.12
$Z+b$	99 ± 17	3.8 ± 1.0	36 ± 6
$Z+c$	51 ± 13	2.7 ± 1.6	19 ± 5
$Z+q$	± 8	3.0 ± 1.0	9 ± 4
Backgrounds	548 ± 16	1385 ± 30	75 ± 7
Data	520	1364	75

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 $W' \to WH$ and $Z' \to ZH$, 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 $g_V = 1$ ($g_V = 3$), $m_{V'^{\pm}} <$ 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 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 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_{VVW}, 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 ± 0.2 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: $\ell^+\ell^- b\bar{b}$, $\ell\nu b\bar{b}$, $\nu\bar{\nu} b\bar{b}$. 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.



(a) 0-lepton, 1-*b*-tag (b) 0-lepton, 2-*b*-tag

(c) 1-lepton, 1-*b*-tag (d) 1-lepton, 2-*b*-tag

(e) 2-lepton, 1-*b*-tag (f) 2-lepton, 2-*b*-tag

Fig. 2. Distributions of reconstructed VH transverse mass, $m_{\mathrm{T},VH}$, and invariant mass, m_{VH}, for the 0-lepton (top), 1-lepton (middle), and 2-lepton (bottom) channels. Only the $Z' \to ZH$ signal is shown for the 0-lepton channel, and no τ-lepton veto is applied. 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 SM VH prediction is summed with the diboson backgrounds, and the negligible multi-jet background is not included here. 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. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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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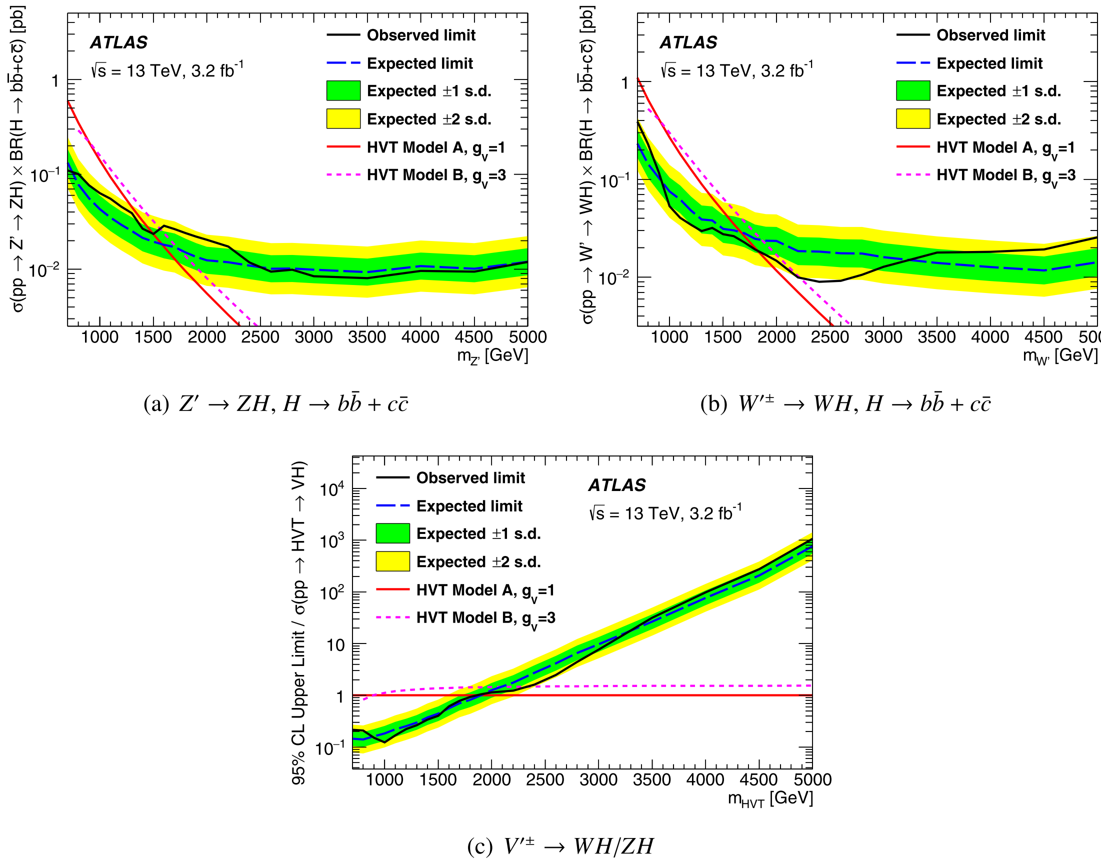

(a) $Z' \to ZH, H \to b\bar{b} + c\bar{c}$ (b) $W'^{\pm} \to WH, H \to b\bar{b} + c\bar{c}$

(c) $V'^{\pm} \to WH/ZH$

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($H \to b\bar{b} + c\bar{c}$) and (b) the production cross-section of W' times its branching fraction to WH and the branching fraction sum BR($H \to b\bar{b} + c\bar{c}$). 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 $H \to b\bar{b}$ and $H \to c\bar{c}$ decays are included at the branching fractions predicted in the SM.

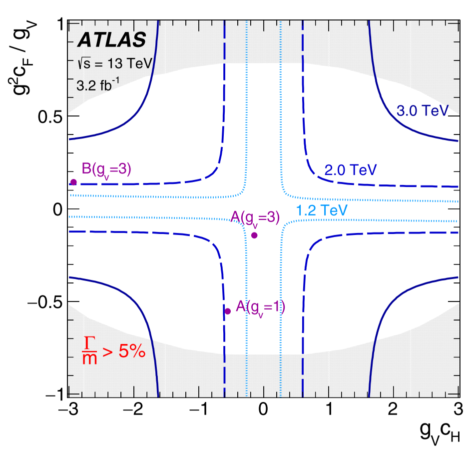

Fig. 4. Observed 95% CL exclusion contours in the HVT parameter space $\{g_V c_H, (g^2/g_V) c_F\}$ for resonances of mass 1.2 TeV, 2.0 TeV and 3.0 TeV, corresponding to the dotted, dashed and solid contours, respectively. The parameter space outside each contour is excluded for a resonance with the corresponding 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 Γ is greater than 5% of its mass, in which case it is not negligible compared to the experimental resolution.

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ATLAS Collaboration

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O.S. AbouZeid [138], N.L. Abraham [152], H. Abramowicz [156], H. Abreu [155], R. Abreu [117], Y. Abulaiti [149a,149b],
B.S. Acharya [168a,168b,a], L. Adamczyk [40a], D.L. Adams [27], J. Adelman [109], S. Adomeit [101], T. Adye [132],
A.A. Affolder [76], T. Agatonovic-Jovin [14], J. Agricola [56], J.A. Aguilar-Saavedra [127a,127f], S.P. Ahlen [24],
F. Ahmadov [67,b], G. Aielli [134a,134b], H. Akerstedt [149a,149b], T.P.A. Åkesson [83], A.V. Akimov [97],
G.L. Alberghi [22a,22b], J. Albert [173], S. Albrand [57], M.J. Alconada Verzini [73], M. Aleksa [32], I.N. Aleksandrov [67],
C. Alexa [28b], G. Alexander [156], T. Alexopoulos [10], M. Alhroob [114], B. Ali [129], M. Aliev [75a,75b], G. Alimonti [93a],
J. Alison [33], S.P. Alkire [37], B.M.M. Allbrooke [152], B.W. Allen [117], P.P. Allport [19], A. Aloisio [105a,105b],
A. Alonso [38], F. Alonso [73], C. Alpigiani [139], M. Alstaty [87], B. Alvarez Gonzalez [32], D. Álvarez Piqueras [171],
M.G. Alviggi [105a,105b], B.T. Amadio [16], K. Amako [68], Y. Amaral Coutinho [26a], C. Amelung [25], D. Amidei [91],
S.P. Amor Dos Santos [127a,127c], A. Amorim [127a,127b], S. Amoroso [32], G. Amundsen [25], C. Anastopoulos [142],
L.S. Ancu [51], N. Andari [19], T. Andeen [11], C.F. Anders [60b], G. Anders [32], J.K. Anders [76], K.J. Anderson [33],
A. Andreazza [93a,93b], V. Andrei [60a], S. Angelidakis [9], I. Angelozzi [108], P. Anger [46], A. Angerami [37],
F. Anghinolfi [32], A.V. Anisenkov [110,c], N. Anjos [13], A. Annovi [125a,125b], C. Antel [60a], M. Antonelli [49],
A. Antonov [99,*], F. Anulli [133a], M. Aoki [68], L. Aperio Bella [19], G. Arabidze [92], Y. Arai [68], J.P. Araque [127a],
A.T.H. Arce [47], F.A. Arduh [73], J-F. Arguin [96], S. Argyropoulos [65], M. Arik [20a], A.J. Armbruster [146],
L.J. Armitage [78], O. Arnaez [32], H. Arnold [50], M. Arratia [30], O. Arslan [23], A. Artamonov [98], G. Artoni [121],
S. Artz [85], S. Asai [158], N. Asbah [44], A. Ashkenazi [156], B. Åsman [149a,149b], L. Asquith [152], K. Assamagan [27],
R. Astalos [147a], M. Atkinson [170], N.B. Atlay [144], K. Augsten [129], G. Avolio [32], B. Axen [16], M.K. Ayoub [118],
G. Azuelos [96,d], M.A. Baak [32], A.E. Baas [60a], M.J. Baca [19], H. Bachacou [137], K. Bachas [75a,75b], M. Backes [151],
M. Backhaus [32], P. Bagiacchi [133a,133b], P. Bagnaia [133a,133b], Y. Bai [35a], J.T. Baines [132], O.K. Baker [180],
E.M. Baldin [110,c], P. Balek [176], T. Balestri [151], F. Balli [137], W.K. Balunas [123], E. Banas [41], Sw. Banerjee [177,e],
A.A.E. Bannoura [179], L. Barak [32], E.L. Barberio [90], D. Barberis [52a,52b], M. Barbero [87], T. Barillari [102],
M-S Barisits [32], T. Barklow [146], N. Barlow [30], S.L. Barnes [86], B.M. Barnett [132], R.M. Barnett [16],
Z. Barnovska-Blenessy [5], A. Baroncelli [135a], G. Barone [25], A.J. Barr [121], L. Barranco Navarro [171],
F. Barreiro [84], J. Barreiro Guimarães da Costa [35a], R. Bartoldus [146], A.E. Barton [74], P. Bartos [147a],
A. Basalaev [124], A. Bassalat [118,f], R.L. Bates [55], S.J. Batista [162], J.R. Batley [30], M. Battaglia [138],
M. Bauce [133a,133b], F. Bauer [137], H.S. Bawa [146,g], J.B. Beacham [112], M.D. Beattie [74], T. Beau [82],
P.H. Beauchemin [166], P. Bechtle [23], H.P. Beck [18,h], K. Becker [121], M. Becker [85], M. Beckingham [174],
C. Becot [111], A.J. Beddall [20e], A. Beddall [20b], V.A. Bednyakov [67], M. Bedognetti [108], C.P. Bee [151],
L.J. Beemster [108], T.A. Beermann [32], M. Begel [27], J.K. Behr [44], C. Belanger-Champagne [89], A.S. Bell [80],
G. Bella [156], L. Bellagamba [22a], A. Bellerive [31], M. Bellomo [88], K. Belotskiy [99], O. Beltramello [32],
N.L. Belyaev [99], O. Benary [156,*], D. Benchekroun [136a], M. Bender [101], K. Bendtz [149a,149b], N. Benekos [10],
Y. Benhammou [156], E. Benhar Noccioli [180], J. Benitez [65], D.P. Benjamin [47], J.R. Bensinger [25],
S. Bentvelsen [108], L. Beresford [121], M. Beretta [49], D. Berge [108], E. Bergeaas Kuutmann [169], N. Berger [5],
J. Beringer [16], S. Berlendis [57], N.R. Bernard [88], C. Bernius [111], F.U. Bernlochner [23], T. Berry [79], P. Berta [130],
C. Bertella [85], G. Bertoli [149a,149b], F. Bertolucci [125a,125b], I.A. Bertram [74], C. Bertsche [44], D. Bertsche [114],
G.J. Besjes [38], O. Bessidskaia Bylund [149a,149b], M. Bessner [44], N. Besson [137], C. Betancourt [50], A. Bethani [57],
S. Bethke [102], A.J. Bevan [78], R.M. Bianchi [126], L. Bianchini [25], M. Bianco [32], O. Biebel [101], D. Biedermann [17],
R. Bielski [86], N.V. Biesuz [125a,125b], M. Biglietti [135a], J. Bilbao De Mendizabal [51], T.R.V. Billoud [96],
H. Bilokon [49], M. Bindi [56], S. Binet [118], A. Bingul [20b], C. Bini [133a,133b], S. Biondi [22a,22b], T. Bisanz [56],
D.M. Bjergaard [47], C.W. Black [153], J.E. Black [146], K.M. Black [24], D. Blackburn [139], R.E. Blair [6],
J.-B. Blanchard [137], T. Blazek [147a], I. Bloch [44], C. Blocker [25], W. Blum [85,*], U. Blumenschein [56], S. Blunier [34a],
G.J. Bobbink [108], V.S. Bobrovnikov [110,c], S.S. Bocchetta [83], A. Bocci [47], C. Bock [101], M. Boehler [50],
D. Boerner [179], J.A. Bogaerts [32], D. Bogavac [14], A.G. Bogdanchikov [110], C. Bohm [149a], V. Boisvert [79],
P. Bokan [14], T. Bold [40a], A.S. Boldyrev [168a,168c], M. Bomben [82], M. Bona [78], M. Boonekamp [137],
A. Borisov [131], G. Borissov [74], J. Bortfeldt [32], D. Bortoletto [121], V. Bortolotto [62a,62b,62c], K. Bos [108],
D. Boscherini [22a], M. Bosman [13], J.D. Bossio Sola [29], J. Boudreau [126], J. Bouffard [2], E.V. Bouhova-Thacker [74],
D. Boumediene [36], C. Bourdarios [118], S.K. Boutle [55], A. Boveia [32], J. Boyd [32], I.R. Boyko [67], J. Bracinik [19],
A. Brandt [8], G. Brandt [56], O. Brandt [60a], U. Bratzler [159], B. Brau [88], J.E. Brau [117], H.M. Braun [179,*],
W.D. Breaden Madden [55], K. Brendlinger [123], A.J. Brennan [90], L. Brenner [108], R. Brenner [169], S. Bressler [176],

T.M. Bristow [48], D. Britton [55], D. Britzger [44], F.M. Brochu [30], I. Brock [23], R. Brock [92], G. Brooijmans [37], T. Brooks [79], W.K. Brooks [34b], J. Brosamer [16], E. Brost [109], J.H. Broughton [19], P.A. Bruckman de Renstrom [41], D. Bruncko [147b], R. Bruneliere [50], A. Bruni [22a], G. Bruni [22a], L.S. Bruni [108], B.H. Brunt [30], M. Bruschi [22a], N. Bruscino [23], P. Bryant [33], L. Bryngemark [83], T. Buanes [15], Q. Buat [145], P. Buchholz [144], A.G. Buckley [55], I.A. Budagov [67], F. Buehrer [50], M.K. Bugge [120], O. Bulekov [99], D. Bullock [8], H. Burckhart [32], S. Burdin [76], C.D. Burgard [50], B. Burghgrave [109], K. Burka [41], S. Burke [132], I. Burmeister [45], J.T.P. Burr [121], E. Busato [36], D. Büscher [50], V. Büscher [85], P. Bussey [55], J.M. Butler [24], C.M. Buttar [55], J.M. Butterworth [80], P. Butti [108], W. Buttinger [27], A. Buzatu [55], A.R. Buzykaev [110,c], S. Cabrera Urbán [171], D. Caforio [129], V.M. Cairo [39a,39b], O. 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Daniells [19], N.S. Dann [86], M. Danninger [172], M. Dano Hoffmann [137], V. Dao [50], G. Darbo [52a], S. Darmora [8], J. Dassoulas [3], A. Dattagupta [117], W. Davey [23], C. David [173], T. Davidek [130], M. Davies [156], P. Davison [80], E. Dawe [90], I. Dawson [142], R.K. Daya-Ishmukhametova [88], K. De [8], R. de Asmundis [105a], A. De Benedetti [114], S. De Castro [22a,22b], S. De Cecco [82], N. De Groot [107], P. de Jong [108], H. De la Torre [84], F. De Lorenzi [66], A. De Maria [56], D. De Pedis [133a], A. De Salvo [133a], U. De Sanctis [152], A. De Santo [152], J.B. De Vivie De Regie [118], W.J. Dearnaley [74], R. Debbe [27], C. Debenedetti [138], D.V. Dedovich [67], N. Dehghanian [3], I. Deigaard [108], M. Del Gaudio [39a,39b], J. Del Peso [84], T. Del Prete [125a,125b], D. Delgove [118], F. Deliot [137], C.M. Delitzsch [51], M. Deliyergiyev [77], A. Dell'Acqua [32], L. Dell'Asta [24], M. Dell'Orso [125a,125b], M. Della Pietra [105a,m], D. della Volpe [51], M. Delmastro [5], P.A. Delsart [57], D.A. DeMarco [162], S. Demers [180], M. Demichev [67], A. Demilly [82], S.P. Denisov [131],

D. Denysiuk [137], D. Derendarz [41], J.E. Derkaoui [136d], F. Derue [82], P. Dervan [76], K. Desch [23], C. Deterre [44], K. Dette [45], P.O. Deviveiros [32], A. Dewhurst [132], S. Dhaliwal [25], A. Di Ciaccio [134a,134b], L. Di Ciaccio [5], W.K. Di Clemente [123], C. Di Donato [133a,133b], A. Di Girolamo [32], B. Di Girolamo [32], B. Di Micco [135a,135b], R. Di Nardo [32], A. Di Simone [50], R. Di Sipio [162], D. Di Valentino [31], C. Diaconu [87], M. Diamond [162], F.A. Dias [48], M.A. Diaz [34a], E.B. Diehl [91], J. Dietrich [17], S. Diglio [87], A. Dimitrievska [14], J. Dingfelder [23], P. Dita [28b], S. Dita [28b], F. Dittus [32], F. Djama [87], T. Djobava [53b], J.I. Djuvsland [60a], M.A.B. do Vale [26c], D. Dobos [32], M. Dobre [28b], C. Doglioni [83], J. Dolejsi [130], Z. Dolezal [130], B.A. Dolgoshein [99,*], M. Donadelli [26d], S. Donati [125a,125b], P. Dondero [122a,122b], J. Donini [36], J. Dopke [132], A. Doria [105a], M.T. Dova [73], A.T. Doyle [55], E. Drechsler [56], M. Dris [10], Y. Du [140], J. Duarte-Campderros [156], E. Duchovni [176], G. Duckeck [101], O.A. Ducu [96,o], D. Duda [108], A. Dudarev [32], A. Chr. Dudder [85], E.M. Duffield [16], L. Duflot [118], M. Dührssen [32], M. Dumancic [176], M. Dunford [60a], H. Duran Yildiz [4a], M. Düren [54], A. Durglishvili [53b], D. Duschinger [46], B. Dutta [44], M. Dyndal [44], C. Eckardt [44], K.M. Ecker [102], R.C. Edgar [91], N.C. Edwards [48], T. Eifert [32], G. Eigen [15], K. Einsweiler [16], T. Ekelof [169], M. El Kacimi [136c], V. Ellajosyula [87], M. Ellert [169], S. Elles [5], F. Ellinghaus [179], A.A. Elliot [173], N. Ellis [32], J. Elmsheuser [27], M. Elsing [32], D. Emeliyanov [132], Y. Enari [158], O.C. Endner [85], J.S. Ennis [174], J. Erdmann [45], A. Ereditato [18], G. Ernis [179], J. Ernst [2], M. Ernst [27], S. Errede [170], E. Ertel [85], M. Escalier [118], H. Esch [45], C. Escobar [126], B. Esposito [49], A.I. Etienvre [137], E. Etzion [156], H. Evans [63], A. Ezhilov [124], F. Fabbri [22a,22b], L. Fabbri [22a,22b], G. Facini [33], R.M. Fakhrutdinov [131], S. Falciano [133a], R.J. Falla [80], J. Faltova [32], Y. Fang [35a], M. Fanti [93a,93b], A. Farbin [8], A. Farilla [135a], C. Farina [126], E.M. Farina [122a,122b], T. Farooque [13], S. Farrell [16], S.M. Farrington [174], P. Farthouat [32], F. Fassi [136e], P. Fassnacht [32], D. Fassouliotis [9], M. Faucci Giannelli [79], A. Favareto [52a,52b], W.J. Fawcett [121], L. Fayard [118], O.L. Fedin [124,p], W. Fedorko [172], S. Feigl [120], L. Feligioni [87], C. Feng [140], E.J. Feng [32], H. Feng [91], A.B. Fenyuk [131], L. Feremenga [8], P. Fernandez Martinez [171], S. Fernandez Perez [13], J. Ferrando [55], A. Ferrari [169], P. Ferrari [108], R. Ferrari [122a], D.E. Ferreira de Lima [60b], A. Ferrer [171], D. Ferrere [51], C. Ferretti [91], A. Ferretto Parodi [52a,52b], F. Fiedler [85], A. Filipčič [77], M. Filipuzzi [44], F. Filthaut [107], M. Fincke-Keeler [173], K.D. Finelli [153], M.C.N. 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R. Mashinistov [97], J. Masik [86], A.L. Maslennikov [110,c], I. Massa [22a,22b], L. Massa [22a,22b], P. Mastrandrea [5], A. Mastroberardino [39a,39b], T. Masubuchi [158], P. Mättig [179], J. Mattmann [85], J. Maurer [28b], S.J. Maxfield [76], D.A. Maximov [110,c], R. Mazini [154], S.M. Mazza [93a,93b], N.C. Mc Fadden [106], G. Mc Goldrick [162], S.P. Mc Kee [91], A. McCarn [91], R.L. McCarthy [151], T.G. McCarthy [102], L.I. McClymont [80], E.F. McDonald [90], J.A. Mcfayden [80], G. Mchedlidze [56], S.J. McMahon [132], R.A. McPherson [173,n], M. Medinnis [44], S. Meehan [139], S. Mehlhase [101], A. Mehta [76], K. Meier [60a], C. Meineck [101], B. Meirose [43], D. Melini [171,ae], B.R. Mellado Garcia [148c], M. Melo [147a], F. Meloni [18], A. Mengarelli [22a,22b], S. Menke [102], E. Meoni [166], S. Mergelmeyer [17], P. Mermod [51], L. Merola [105a,105b], C. Meroni [93a], F.S. Merritt [33], A. Messina [133a,133b], J. Metcalfe [6], A.S. Mete [167], C. Meyer [85], C. Meyer [123], J-P. 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Rossetti [149a,149b], E. Rossi [105a,105b], L.P. Rossi [52a], J.H.N. Rosten [30], R. Rosten [139], M. Rotaru [28b], I. Roth [176], J. Rothberg [139], D. Rousseau [118], C.R. Royon [137], A. Rozanov [87], Y. Rozen [155], X. Ruan [148c], F. Rubbo [146], M.S. Rudolph [162], F. Rühr [50], A. Ruiz-Martinez [31], Z. Rurikova [50], N.A. Rusakovich [67], A. Ruschke [101], H.L. Russell [139], J.P. Rutherfoord [7], N. Ruthmann [32], Y.F. Ryabov [124], M. Rybar [170], G. Rybkin [118], S. Ryu [6], A. Ryzhov [131], G.F. Rzehorz [56], A.F. Saavedra [153], G. Sabato [108], S. Sacerdoti [29], H.F-W. Sadrozinski [138], R. Sadykov [67], F. Safai Tehrani [133a], P. Saha [109], M. Sahinsoy [60a], M. Saimpert [137], T. Saito [158], H. Sakamoto [158], Y. Sakurai [175], G. Salamanna [135a,135b], A. Salamon [134a,134b], J.E. Salazar Loyola [34b], D. Salek [108], P.H. Sales De Bruin [139], D. Salihagic [102], A. Salnikov [146], J. Salt [171], D. Salvatore [39a,39b], F. Salvatore [152], A. Salvucci [62a], A. 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M. Shapiro [16], P.B. Shatalov [98], K. Shaw [168a,168b], S.M. Shaw [86], A. Shcherbakova [149a,149b], C.Y. Shehu [152], P. Sherwood [80], L. Shi [154,an], S. Shimizu [69], C.O. Shimmin [167], M. Shimojima [103], M. Shiyakova [67,ao], A. Shmeleva [97], D. Shoaleh Saadi [96], M.J. Shochet [33], S. Shojaii [93a], S. Shrestha [112], E. Shulga [99], M.A. Shupe [7], P. Sicho [128], A.M. Sickles [170], P.E. Sidebo [150], O. Sidiropoulou [178], D. Sidorov [115], A. Sidoti [22a,22b], F. Siegert [46], Dj. Sijacki [14], J. Silva [127a,127d], S.B. Silverstein [149a], V. Simak [129], Lj. Simic [14], S. Simion [118], E. Simioni [85], B. Simmons [80], D. Simon [36], M. Simon [85], P. Sinervo [162], N.B. Sinev [117], M. Sioli [22a,22b], G. Siragusa [178], S.Yu. Sivoklokov [100], J. Sjölin [149a,149b], M.B. Skinner [74], H.P. Skottowe [58], P. Skubic [114], M. Slater [19], T. Slavicek [129], M. Slawinska [108], K. Sliwa [166], R. Slovak [130], V. Smakhtin [176], B.H. Smart [5], L. Smestad [15], J. 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