Searches for heavy ZZ and ZW resonances in the $\ell\ell qq$ and $\nu\nu qq$ final states in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

This paper reports searches for heavy resonances decaying into ZZ or ZW using data from proton–proton collisions at a centre-of-mass energy of $\sqrt{s} = 13$ TeV. The data, corresponding to an integrated luminosity of 36.1 fb$^{-1}$, were recorded with the ATLAS detector in 2015 and 2016 at the Large Hadron Collider. The searches are performed in final states in which one Z boson decays into either a pair of light charged leptons (electrons and muons) or a pair of neutrinos, and the associated W boson or the other Z boson decays hadronically. No evidence of the production of heavy resonances is observed. Upper bounds on the production cross sections of heavy resonances times their decay branching ratios to ZZ or ZW are derived in the mass range 300–5000 GeV within the context of Standard Model extensions with additional Higgs bosons, a heavy vector triplet or warped extra dimensions. Production through gluon–gluon fusion, Drell–Yan or vector-boson fusion are considered, depending on the assumed model.
1 Introduction

The discovery of a Higgs boson $h$ with a mass of approximately $125$ GeV in 2012 [1, 2] represents a major milestone in the understanding of electroweak symmetry breaking. Subsequent studies [3–6] have shown that the properties of the new particle are consistent with those of the Standard Model (SM) Higgs boson. Nevertheless, the possibility that the particle is part of an extended Higgs sector or other extension of the SM cannot be ruled out. Many of these models, motivated by hierarchy and naturalness arguments [7–9], predict the existence of new heavy resonances decaying into dibosons. In models with an extended Higgs sector, such as the two-Higgs-doublet models (2HDM) [10] and the electroweak-singlet model [11], a heavy spin-0 neutral Higgs boson ($H$) can decay into a pair of $Z$ bosons. In extended gauge models [12], a heavier version of the SM $W$ boson ($W'$) is predicted to decay into $ZW$, and in models with warped extra dimensions [13, 14], spin-2 Kaluza–Klein (KK) excitations of the graviton ($G_{KK}$) are expected to decay into $ZZ$.

This paper reports searches for heavy resonances $X$ decaying into pairs of vector bosons, $ZV (V = W, Z)$. Production through gluon–gluon fusion (ggF), Drell–Yan (DY) and vector-boson fusion (VBF) processes are considered, depending on the assumed model. Representative Feynman diagrams of these processes are shown in Figure 1. Two $ZV$ decay modes are explored: one in which there is a $Z$ boson decaying into a pair of light charged leptons (electrons or muons, denoted by $\ell$), $Z \to \ell\ell$, and the other in which a $Z$ boson decays into a pair of neutrinos, $Z \to \nu\nu$. In both cases, the vector boson $V$ is required to decay into a pair of quarks, $V \to qq$, leading to $X \to ZV \to \ell\ell qq$ and $X \to ZV \to \nu\nu qq$ decay modes.

![Feynman diagrams](image)

Figure 1: Representative Feynman diagrams for the production of heavy resonances $X$ with their decays into a pair of vector bosons.

Two different reconstruction techniques for the $V \to qq$ decay are considered: resolved and merged. The resolved reconstruction attempts to identify two separate small-radius jets (small-$R$ jet, or $j$) of hadrons from the $V \to qq$ decay, while the merged reconstruction uses jet substructure techniques to identify the $V \to qq$ decay reconstructed as a large-$R$ jet. When the resonance mass is significantly higher than the

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1 To simplify the notation, antiparticles are not explicitly labelled in this paper.
$V$ boson mass, the $qq$ pair from the $V$ boson decay can be collimated. In this case, hadrons from the two quarks overlap in the detector and are more efficiently reconstructed as a single large-radius jet (large-$R$ jet, or $J$). The $X \rightarrow ZV \rightarrow \ell\ellqq$ searches utilise both reconstruction techniques for the $V \rightarrow qq$ decay, whereas the $X \rightarrow ZV \rightarrow \nu\nuqq$ search uses only the merged reconstruction.

Heavy resonances would manifest themselves as resonant structures above the SM background in the invariant-mass distributions of the $\ell\ellqq$ final state and as broad enhancements in the transverse-mass distributions of the $\nu\nuqq$ final state. Thus for the $ZV \rightarrow \ell\ellqq$ decay mode, the invariant masses of the $\ell\ell J$ system ($m_{\ell\ell J}$) from the merged reconstruction and of the $\ell\ell jj$ system ($m_{\ell\ell jj}$) from the resolved reconstruction are used as the final discriminants for signal–background separation. For the $ZV \rightarrow \nu\nuqq$ decay mode, the final discriminant used is the transverse mass ($m_T$) of the large-$R$ jet and the missing transverse momentum ($E_T^{\text{miss}}$).

Both the ATLAS and CMS collaborations have reported searches for heavy resonances in $ZV$ decays in proton-proton ($pp$) collisions at $\sqrt{s} = 8$ TeV and 13 TeV [15–19]. In addition to $\ell\ellqq$ and $\nu\nuqq$, these searches include fully hadronic ($qqqq$), semileptonic ($qq\ell\nu$), and fully leptonic ($\ell\ell\ell\ell$, $\ell\ell\ell\nu$, $\ell\ell\nu\nu$) final states. This paper extends previous ATLAS searches for $ZV$ resonances in the $\ell\ellqq$ and $\nu\nuqq$ final states at $\sqrt{s} = 13$ TeV reported in Ref. [18] and uses a dataset more than ten times larger.

2 ATLAS detector

The ATLAS detector [20] at the Large Hadron Collider (LHC) [21] covers nearly the entire solid angle\(^2\) around the collision point, and consists of an inner tracking detector surrounded by a thin superconducting solenoidal magnet producing a 2 T magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three large toroid-magnet assemblies. The inner detector (ID) consists of a high-granularity silicon pixel detector, including an insertable B-layer [22], and a silicon microstrip tracker, together providing precision tracking in the pseudorapidity range $|\eta| < 2.5$, complemented by a transition radiation tracker, providing tracking and electron identification information for $|\eta| < 2.0$. A lead/liquid-argon (LAr) electromagnetic calorimeter covers the region $|\eta| < 3.2$, and hadronic calorimetry is provided by steel/scintillator-tile calorimeters for $|\eta| < 1.7$ and by copper/LAr hadronic calorimeters for $1.7 < |\eta| < 3.2$. The forward region is covered by additional LAr calorimeters with copper and tungsten absorbers. The muon spectrometer (MS) consists of precision tracking chambers covering the region $|\eta| < 2.7$, and separate trigger chambers covering $|\eta| < 2.4$. A two-level trigger system [23] reduces the event rate to approximately 1 kHz for offline investigations.

3 Data, signal models and simulation

3.1 Data

The data used in the searches were collected with the ATLAS detector in 2015 and 2016 $pp$ collisions at a centre-of-mass energy of 13 TeV, corresponding to a total integrated luminosity of 36.1 fb\(^{-1}\).

\(^2\) ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the $z$-axis along the beam pipe. The $x$-axis points from the IP to the centre of the LHC ring, and the $y$-axis points upward. Cylindrical coordinates ($r, \phi$) are used in the transverse plane, $\phi$ being the azimuthal angle around the $z$-axis. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln\tan(\theta/2)$. 

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Events used in the $X \rightarrow ZV \rightarrow \ell\ell qq$ search were recorded with a combination of multiple single-electron or single-muon triggers with varying transverse energy $E_T$ (electron) and transverse momentum $p_T$ (muon), quality, and isolation requirements. The lowest $E_T$ or $p_T$ requirement without trigger prescaling was 26 GeV for both the electrons and muons. Events for the $X \rightarrow ZV \rightarrow \nu\nu qq$ search were recorded with an $E_T^{miss}$ trigger of varying threshold. The lowest threshold without prescaling is 100 GeV. This trigger is fully efficient for events passing the selection described below.

Events are retained for analysis if they were recorded with all detector systems operating normally and pass data-quality requirements [24]. Collision vertices are formed from tracks with $p_T > 400$ MeV. If an event contains more than one vertex candidate, the one with the highest $\sum p_T^2$ of its associated tracks is selected as the primary vertex. All events are required to contain a primary vertex with at least two associated tracks.

3.2 Signal models and simulation

Three classes of models of physics beyond the Standard Model are used as benchmarks for the interpretation of the results. Different resonances are predicted by each of these: a neutral heavy spin-0 Higgs boson $H$ using the narrow-width approximation [25], a spin-1 $W'$ boson of the heavy vector triplet (HVT) model [26, 27], and a spin-2 KK graviton $G_{KK}$ from the bulk Randall–Sundrum model [13, 28, 29]. The new HVT bosons couple to the SM Higgs boson and gauge bosons with coupling strength $c_{HgV}$ and to the SM fermions with coupling strength $(g^2/g_V)c_F$, where $g$ is the SM $SU(2)_L$ coupling constant. The parameter $g_V$ characterises the interaction strength of the new vector bosons, while the dimensionless coefficients $c_H$ and $c_F$ parameterise departures of this typical strength from interactions with the SM Higgs and gauge bosons and with fermions, respectively, and are expected to be of order unity in most models. In Model A with $g_V = 1$, the branching ratios of the new heavy vector boson to known fermions and gauge bosons are comparable, while in Model B with $g_V = 3$, fermionic couplings to the new heavy vector boson are suppressed, giving rise to larger branching ratios for decays into $ZW$ final states than in Model A. In a third model, VBF Model, the couplings to gauge bosons are similar to those in Model A, but the couplings to fermions are set to 0. In the bulk RS graviton model, the $G_{KK}$ couplings to light fermions are suppressed and decays into final states involving heavy fermions, gauge bosons or Higgs bosons are favoured. The strength of the coupling depends on $k/\sqrt{M_{Pl}}$, where $k$ corresponds to the curvature of the warped extra dimension and $M_{Pl}$ is the effective four-dimensional Planck scale $M_{Pl} = 2.4 \times 10^{18}$ GeV. The cross section and intrinsic width scale as the square of $k/\sqrt{M_{Pl}}$.

Monte Carlo (MC) samples of $H \rightarrow ZZ$ were generated by Powheg-Box v1 [30–33] with the CT10 [34] parton distribution functions (PDF) assuming a Higgs boson with width far smaller than the experimental resolution. Both the ggF and VBF production processes are considered. Benchmark samples of HVT $W' \rightarrow ZW$ and RS graviton $G_{KK} \rightarrow ZZ$ were generated with MadGraph5_aMC@NLO 2.2.2 [35], using the NNPDF23LO [36] PDF set. For the HVT model, two production modes of the charged vector triplet $W'$, DY and VBF, are considered. The $W'$ resonance from DY production of Model A has a width approximately 2.6% of its mass, while for VBF production the width is much narrower, since its couplings to fermions are set to 0 in the VBF signal. For HVT Model B, the resonance widths and experimental signatures are similar to those obtained for Model A. Thus results derived from Model A can be directly applied to benchmark Model B by rescaling the relevant branching ratios. The $G_{KK}$ has a mass-dependent width, 3.7% at 500 GeV and 6.4% at 5000 GeV relative to its mass, for $k/\sqrt{M_{Pl}} = 1$. An RS graviton with $k/\sqrt{M_{Pl}} = 0.5$ is also considered and the samples were obtained by reweighting the generated samples for $k/\sqrt{M_{Pl}} = 1$ to account for the resonance width and cross-section differences. The parton showering and
hadronisation were modelled with Pythia 8.186 [37] using the A14 set of the tuned parameters (tune) for the underlying event [38] for the W+ jets and \( G_{\text{KK}} \) samples and the AZNLO tune [39] for the \( H \) samples. Potential signal and background interference effects were ignored in the signal modelling.

MC simulated events are also used to model background processes. The main background sources are Z and W bosons produced in association with jets (Z+jets and W+jets), with significant contributions from top quark production (both \( t\bar{t} \) pair and single-top) and non-resonant vector-boson pair production (ZZ, WZ and WW). The Z+jets and W+jets events were simulated using the Sherpa 2.2.1 [40] event generator. Matrix elements were calculated for up to two partons at NLO and up to four partons at LO using the Comix [41] and OpenLoops [42] programs. Diboson processes with one of the bosons decaying hadronically and the other leptonically were simulated using Sherpa 2.1.0. They were simulated for up to one (ZZ) or zero (WZ, WW) additional partons at NLO and up to three additional partons at LO using the Comix and OpenLoops programs. For both Z+jets and diboson simulation, the matrix-element calculations were merged with the Sherpa parton shower using the ME+PS@NLO prescription [43]. The CT10 PDF set was used in conjunction with a dedicated parton shower tuning developed by the Sherpa authors. The \( Z \to \tau\tau \) and \( W \to \tau\nu \) events were included in the Z+jets and W+jets samples. For the generation of top quark pairs, the Powheg-Box v2 [44] event generator with the CT10 PDF set in the matrix element calculations was used. Electroweak \( t \) channel, \( s \) channel and \( Wt \) channel single-top quark events were generated using the Powheg-Box v1 event generator [45–47]. This event generator uses the four-flavour scheme for the NLO matrix-element calculations together with the fixed four-flavour PDF set CT10f4 [34]. For all top quark processes, top quark spin correlations were preserved (for \( t \) channel, top quarks were decayed using MadSpin). The parton shower, fragmentation, and underlying event were simulated using Pythia 6.428 [48] with the CTEQ6L1 [49] PDF set and the corresponding Perugia 2012 tune (P2012) [50]. The top quark mass was set to 172.5 GeV. The EvtGen v1.2.0 program [51] was used to decay bottom and charm hadrons for the Powheg-Box samples.

Cross sections were calculated with up to next-to-next-to-leading order (NNLO) QCD corrections for Z+jets and W+jets production [52]. Cross sections for diboson production were calculated at NLO including LO contributions with two additional partons [40, 53]. The \( t\bar{t} \) production cross section is calculated at NNLO in QCD, including resummation of next-to-next-to-leading logarithmic (NNLL) soft-gluon terms [54, 55]. The single-top production cross sections were calculated to NLO in QCD [56], including the soft-gluon resummation at NNLL [57] for the Wt process.

In the simulation of the Z+jets events for the Z\( V \to \ell\ell q q \) search, jets are labelled according to the true flavours of the hadrons with \( p_T > 5 \text{ GeV} \) found within a cone of size \( \Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.3 \) around the reconstructed jet axes. If a \( b \)-hadron is found, the jet is labelled as a \( b \)-jet; if one is not found and a charmed hadron is found, the jet is labelled as a \( c \)-jet; if neither is found, the jet is labelled as a light (i.e., \( u-, d-, \text{ or} \ s\)-quark, or gluon) jet. A simulated Z+jets event is labelled as Z+heavy-flavour if a \( b \)- or \( c \)-jet is found in the event, and otherwise as Z+light-flavour. The classification allows for flavour-dependent corrections for differences between data and MC.

MC events were processed with a detailed detector simulation [58] based on Geant4 [59]. Additional inelastic simulated \( pp \) collisions generated with Pythia 8.186 were overlaid to model both the in- and out-of-time effects from additional \( pp \) collisions in the same and neighbouring bunch crossings (pile-up). MC samples were reweighted to match the pile-up conditions in the data. All simulated events were processed using the same reconstruction algorithms as the data.
4 Event reconstruction

Electrons are identified as isolated energy clusters in the electromagnetic calorimeter matched to ID tracks, with requirements that the transverse energy $E_T > 7$ GeV and pseudorapidity $|\eta| < 2.47$. A likelihood-based requirement [60] is imposed to reduce the background from misidentified or non-prompt electrons. Electrons are classified as either ‘loose’, ‘medium’ or ‘tight’ according to the likelihood-based identification criteria described in Ref. [60].

Muons are reconstructed by a combined fit to the ID and MS tracks, and are required to have $p_T > 7$ GeV and $|\eta| < 2.5$. Muons must pass identification requirements, based on the numbers of hits in the ID and MS subsystems, and the significance of the difference $|q/p_{MS} - q/p_{ID}|$ [61], where $q$ is the charge and $p_{MS}$ ($p_{ID}$) is the moment of the muon measured in the MS (ID). Similar to electrons, muons are classified as either ‘loose’, ‘medium’ or ‘tight’, following the criteria in Ref. [61].

All electrons and muons are required to be isolated using selections on the sum of track $p_T$ (excluding the track associated with the lepton) in a $p_T$-dependent cone around their directions. The isolation selection criteria are designed to maintain a constant efficiency of 99% in the $p_T$-$\eta$ plane for the reconstructed leptons from $Z \rightarrow \ell\ell$ decays, and to minimise efficiency loss for highly boosted $Z$ bosons in the relevant kinematic range. Furthermore, leptons are required to have associated tracks satisfying $|d_0/\sigma_{d_0}| < 5$ (3) and $|z_0 \times \sin \theta| < 0.5$ mm for electrons (muons), where $d_0$ is the transverse impact parameter with respect to the beam line, $\sigma_{d_0}$ is its uncertainty, and $z_0$ is the distance between the longitudinal position of the track along the beam line at the point where $d_0$ is measured and the longitudinal position of the primary vertex.

Small-$R$ jets are reconstructed using the anti-$k_t$ algorithm [62, 63] with a radius parameter of $R = 0.4$. Energy- and $\eta$-dependent correction factors derived from MC simulations are applied to correct jets back to the particle level [64]. Jets are required to have $p_T > 20$ GeV for $|\eta| < 2.5$ and $p_T > 30$ GeV for $2.5 < |\eta| < 4.5$. Jets with $p_T > 30$ GeV and $|\eta| < 2.5$ are called ‘signal’ jets. To suppress jets from pile-up interactions, a jet vertex tagger [65] is applied to jets with $p_T < 60$ GeV and $|\eta| < 2.4$, based on information about tracks associated with the primary vertex and pile-up vertices.

The ‘signal’ jets containing $b$-hadrons are identified using a multivariate algorithm ($b$-tagging) [66] which is based on information such as track impact-parameter significances and positions of explicitly reconstructed secondary decay vertices. The chosen $b$-tagging algorithm has an efficiency of 70% for $b$-quark jets in simulated $t\bar{t}$ events, with a light-flavour jet rejection factor of about 380 and a $c$-jet rejection of about 12 [67]. Correction factors are applied to the simulated event samples to compensate for differences between data and simulation in the $b$-tagging efficiency for $b$-, $c$- and light-jets. The correction for $b$-jets is derived from $t\bar{t}$ events with final states containing two leptons, and the corrections are consistent with unity with uncertainties at the level of a few percent over most of the jet $p_T$ range.

Large-$R$ jets are reconstructed using the anti-$k_t$ algorithm, but with the radius parameter increased to $R = 1.0$. To mitigate the effects of pile-up and soft radiation, the large-$R$ jets are trimmed [68]. Trimming takes the original constituents of the jet and reclusters them using the $k_t$ algorithm [69] with a smaller radius parameter, $R_{\text{subj}}$, to produce a collection of subjets. These subjets are discarded if they carry less than a specific fraction ($f_{\text{cut}}$) of the original jet $p_T$. The trimming parameters optimised for this search are $R_{\text{subj}} = 0.2$ and $f_{\text{cut}} = 5\%$. The large-$R$ jet four-momenta are recomputed from the selected subjets, and the jet energies are calibrated to particle-level using correction factors derived from MC simulations [70]. The mass of a large-$R$ jet ($m_J$) is computed using a combination of calorimeter and tracking information [71]. The large-$R$ jets are required to have $p_T > 200$ GeV and $|\eta| < 2.0$. 


An overlap-removal procedure is applied to the selected leptons and jets to prevent double-counting. For nearby electrons and small-$R$ jets, the jet is removed if the separation between the electron and jet is within $\Delta R < 0.2$; the electron is removed if the separation is within $0.2 < \Delta R < 0.4$. For nearby muons and small-$R$ jets, the jet is removed if the separation between the muon and jet is within $\Delta R < 0.2$ and if the jet has less than three tracks or the energy and momentum differences between the muon and the jet are small; otherwise the muon is removed if the separation satisfies $\Delta R < 0.4$. To prevent double-counting of energy from an electron inside the large-$R$ jet, the large-$R$ jet is removed if the separation between the electron and the large-$R$ jet is within $\Delta R < 1.0$.

Boson tagging [72, 73] is applied to the large-$R$ jets to select those from the $V \rightarrow qq$ decays. A $p_T$-dependent requirement is applied to the jet substructure variable $D_2$, which is defined as a ratio of two- and three-point energy correlation functions [74, 75] that are based on the energies and pairwise angular distances of particles within a jet. This variable is optimised to distinguish between jets originating from a single parton and those coming from the two-body decay of a heavy particle. A detailed description of the optimisation can be found in Refs. [72, 73]. The $V$ boson jets are then selected by requiring the large-$R$ jet mass $m_J$ to be in a $p_T$-dependent window centred around the expected value of the boson mass from simulations. The boson tagging is designed to provide a constant efficiency (working point) independent of the large-$R$ jet $p_T$ for the signals studied. Two such working points, 50% efficiency and 80% efficiency, are used, with corresponding misidentification rates for jets from multijet production of $\sim 2\%$ and $\sim 10\%$, respectively.

The missing transverse momentum ($\mathbf{E}_T^{\text{miss}}$) is calculated as the negative vectorial sum of the transverse momenta of calibrated electrons, muons, and small-$R$ jets. Large-$R$ jets are not included in the $\mathbf{E}_T^{\text{miss}}$ calculation to avoid double-counting of energy between the small-$R$ jets and large-$R$ jets. Energy depositions due to the underlying event and other soft radiation are taken into account by constructing a ‘soft term’ from ID tracks associated with the primary vertex but not with any reconstructed object [76–78]. The track-based missing transverse momentum, $\mathbf{p}_T^{\text{miss}}$, is the negative vectorial sum of the transverse momenta of all good-quality inner detector tracks that are associated with the primary vertex.

5 $X \rightarrow ZV \rightarrow \ell\ell qq$ search

The $X \rightarrow ZV \rightarrow \ell\ell qq$ search explores the VBF and ggF production of a heavy Higgs boson $H$, the VBF and DY production of an HVT $W'$ boson, and the ggF production of a bulk RS graviton $G_{KK}$. It also utilises both the merged and resolved reconstruction for the $V \rightarrow qq$ decay. The search begins with the identification of the $Z \rightarrow \ell\ell$ decay, followed by classifying events into the VBF or ggF/DY categories and finally the selection of either the $ZV \rightarrow \ell\ell J$ or $ZV \rightarrow \ell\ell jj$ final states. Multiple signal regions (SRs) are defined to enhance the sensitivity of the search. Figure 2 shows a schematic view of the selection. The event selection, the expected signal performance and background estimations are described below.

5.1 Selection of $Z \rightarrow \ell\ell$

The $Z \rightarrow \ell\ell$ candidates are identified by requiring two isolated same-flavour leptons (electrons or muons) satisfying the ‘loose’ criteria. At least one of them must also satisfy the ‘medium’ criteria, and the leading electron (muon) must satisfy $E_T (p_T) > 28$ GeV. Opposite charges are required for the muon pairs but not for the electron pairs. Electrons are more susceptible to charge misidentification due to the conversions
of photons from bremsstrahlung, especially at high $E_T$. The dilepton invariant mass $m_{\ell\ell}$ is required to be consistent with the $Z$ boson mass. For electrons, a fixed $m_{\ell\ell}$ window $[83, 99]$ GeV is applied. To account for the effect of dimuon mass-resolution degradation at high transverse momentum ($p_T^{\ell\ell}$), a $p_T^{\ell\ell}$-dependent mass window $[85.6$ GeV $- 0.0117p_T^{\ell\ell}, 94.0$ GeV $+ 0.0185p_T^{\ell\ell}]$ is used for muons. For both electrons and muons, the mass windows are chosen to ensure that the $Z \rightarrow \ell\ell$ selection efficiency is approximately 95% and independent of the heavy resonance mass. Events with additional leptons passing the ‘loose’ criteria are vetoed.

### 5.2 VBF and ggF/DY categories

Signal events from VBF production possess unique kinematic signatures. In addition to the presence of a pair of vector bosons from the resonance decay, VBF events have two additional jets (referred to as tag-jets). These jets typically have a large separation in pseudorapidity and a large dijet invariant mass. They offer a powerful means for background rejection. Hence for the $H \rightarrow ZZ$ and $W' \rightarrow ZW$ searches, in which the VBF production is considered, two categories are introduced. Events are subject to the selection designed for VBF production first (VBF category), and if they fail, to the selection designed for ggF or DY production (ggF/DY category). For the $G_{KK} \rightarrow ZZ$ search, the VBF selection is bypassed as VBF production is not considered.
For the VBF category, events are required to have two tag-jets identified from the small-R jets that fail the $b$-tagging described in Section 4. The two jets must be in opposite pseudorapidity hemispheres, i.e., $\eta_1 \cdot \eta_2 < 0$, with a pseudorapidity separation $|\Delta \eta_{jj}^\text{tag}| > 4.7$, and have an invariant mass $m_{jj}^\text{tag} > 770$ GeV. Those values are chosen to optimise the search sensitivity to VBF signals for all masses considered. If there is more than one pair of jets satisfying these requirements, the one with the highest $m_{jj}^\text{tag}$ value is chosen. These jets are not considered in the $ZV \rightarrow \ell\ell qq$ selection, and large-R jets lying $\Delta R < 1.5$ of either of these two small-R jets are not considered either.

For the ggF/DY category, no tag-jets requirement is applied. Events in the VBF and ggF/DY categories are subject to an identical $ZV \rightarrow \ell\ell qq$ selection. All events not selected for the VBF category are passed to the ggF/DY selection. This includes events that contain jets satisfying the VBF requirements but which fail the $ZV \rightarrow \ell\ell qq$ selection, cf. Figure 2. In this case, jets excluded from consideration for the $ZV \rightarrow \ell\ell qq$ candidate in the VBF category are considered for the ggF/DY category.

5.3 Selection of $ZV \rightarrow \ell\ell qq$

Identification of $ZV \rightarrow \ell\ell qq$ decays proceeds by applying the merged $ZV \rightarrow \ell\ell J$ selection followed by the resolved $ZV \rightarrow \ell\ell jj$ selection. The order is motivated by a smaller background expectation in the $ZV \rightarrow \ell\ell J$ search and $ZV \rightarrow \ell\ell jj$ search, comparing data with the expected backgrounds. Next the boson tagging discussed in Section 4 is applied to select the $V \rightarrow qq$ decays. Two signal regions are defined, one for events passing the 50% working point of the boson tagging requirement and the other for events failing the 50% but passing the 80% working point requirement. The former is called the high-purity (HP) SR, and the latter the low-purity (LP) SR. Background contributions are mostly from the $Z$+jets, top quark and diboson production (Section 5.5).

5.3.1 Merged $ZV \rightarrow \ell\ell J$ selection

The $ZV \rightarrow \ell\ell J$ candidates are selected from the $Z \rightarrow \ell\ell$ events containing at least one large-R jet, among which the one with the highest $p_T$ is assumed to be from the $V \rightarrow qq$ decay. Events are further required to have $\min(p_T^{\ell\ell}, p_T^J)/m_{\ell\ell J} > 0.3$ for the $H \rightarrow ZZ$ search and $> 0.35$ for the $W' \rightarrow ZW$ and $G_{KK} \rightarrow ZZ$ searches. The criteria are optimised to reduce backgrounds while retaining high efficiencies for signals. The order is motivated by a smaller background expectation in the $ZV \rightarrow \ell\ell J$ final states. These selection criteria are summarised in Table 1 and are explained below.

5.3.2 Resolved $ZV \rightarrow \ell\ell jj$ selection

The $ZV \rightarrow \ell\ell jj$ candidates are selected from the $Z \rightarrow \ell\ell$ events that have failed the $ZV \rightarrow \ell\ell J$ selection, by requiring at least two small-R ‘signal’ jets. The leading jet $p_T$ is required to be greater than 60 GeV.

Similarly to the merged $ZV \rightarrow \ell\ell J$ selection, the kinematic quantity $\sqrt{(p_T^{\ell\ell})^2 + (p_T^J)^2} \cdot m_{\ell\ell jj}$ is required to be greater than 0.4 for $H \rightarrow ZZ$ and 0.5 for $W' \rightarrow ZW$ and $G_{KK} \rightarrow ZZ$. Here $p_T^{\ell\ell}$ is the transverse momentum of the dijet system. Signal events are expected to have a dijet invariant mass, $m_{jj}$, consistent
Figure 3: Observed and expected distributions of (a) the large-R jet mass $m_J$ of the $ZV \rightarrow \ell\ell J$ candidate and (b) the dijet mass $m_{jj}$ of the $ZV \rightarrow \ell\ell jj$ candidate. These distributions are for the $H \rightarrow ZZ$ search before the identification of the $V \rightarrow qq$ decay, combining VBF and ggF/DY categories. Background contributions are obtained from the combined likelihood fit to the data, as explained in Section 8. For illustration, expected distributions from the ggF production of a 1 TeV Higgs boson with $\sigma \times B(H \rightarrow ZZ) = 2$ pb are also shown. The middle panes show the ratios of the observed data to the background predictions. The uncertainty in the total background prediction, shown as bands, combines statistical and systematic contributions. The bottom panes are the ratios of the post-fit and pre-fit background predictions.

with a $V \rightarrow qq$ decay. Figure 3(b) shows the $m_{jj}$ distributions of the $H \rightarrow ZZ$ search. The dijet invariant mass must be in the window [70, 105] GeV for $Z \rightarrow qq$ and in the window [62, 97] GeV for $W \rightarrow qq$. The choice of asymmetric windows around $m_V$ is motivated by the asymmetry of the $m_{jj}$ distribution expected from $V \rightarrow qq$.

About 21% of the $Z \rightarrow qq$ decays have two $b$-quark jets, whereas the dominant background, $Z+\text{jets}$, has a smaller heavy-quark content. To exploit this, the $ZV \rightarrow \ell\ell jj$ candidates are divided into two signal regions: events with two $b$-tagged jets ($b$-tagged SR) and events with fewer than two $b$-tagged jets (untagged SR). Events with more than two $b$-tagged jets are rejected. No enhancement of $b$-tagged jets is expected from the $W \rightarrow qq$ decay, thus the two signal regions are combined for the $W' \rightarrow ZW$ search. Due to the small number of events, the two regions are also combined for the VBF category.

5.4 Signal regions, selection efficiencies and mass resolutions

Signal regions used in the search depend on the signal model under study. There are seven, six and four signal regions, respectively, for the searches for $H \rightarrow ZZ$, $W' \rightarrow ZW$ and $G_{KK} \rightarrow ZZ$. 
Signal selection efficiencies are dependent on the signal model, the production process and the mass of the heavy resonance. As an example, Figure 4 shows the acceptance times efficiency ($A \times \epsilon$) of the $H \rightarrow ZZ \rightarrow \ell\ell qq$ search as a function of the Higgs boson mass for both ggF and VBF production. The $ZV \rightarrow \ell\ell J$ selection is more efficient for masses over approximately 500 GeV, while the $ZV \rightarrow \ell\ell j j$ selection contributes more at lower masses. This reflects the expected large Lorentz boost of the $Z$ bosons from heavy Higgs boson decays and the higher priority given to the $ZV \rightarrow \ell\ell J$ selection. The $A \times \epsilon$ values of the $W' \rightarrow ZW$ and $G_{KK} \rightarrow ZZ$ searches are similar with the exception of noticeable decreases, by about 40% from 2 TeV to 4 TeV, due to the merging of the electrons from the $Z \rightarrow ee$ decays for resonance masses above approximately 3 TeV.

Distributions of the invariant masses $m_{\ell\ell J}$ and $m_{\ell\ell j j}$ are used to search for potential signals. To mitigate the impact of muon momentum-resolution degradation at high $p_T$, a scale factor of $m_Z/m_{\mu\mu}$ is applied to the four-momentum of the dimuon system in $Z \rightarrow \mu\mu$ events, effectively fixing its mass to $m_Z = 91.187$ GeV [79]. The scaling improves the $m_{\ell\ell J}$ resolution of the dimuon final state by approximately 13% (40%) for a heavy Higgs boson at 1 (3) TeV. For the $ZV \rightarrow \ell\ell jj$ final states, a scale factor of $m_V/m_{ij}$ is also applied to the dijet four-momentum to fix the dijet mass to $m_V = 91.187$ GeV for the $Z$ boson and $80.385$ GeV for the $W$ boson [79]. The $m_{ij}$ scaling improves the $m_{\ell\ell j j}$ resolution by approximately 14% for a 600 GeV Higgs boson. No $m_V/m_J$ scale factor is applied to the $ZV \rightarrow \ell\ell J$ final states as the expected improvement in the $m_{\ell\ell J}$ resolution is negligible.

The reconstructed $m_{\ell\ell J}$ and $m_{\ell\ell j j}$ distributions have widths of 2–3% of the resonance mass for the Higgs boson and HVT $W'$ boson of VBF production for the entire mass range studied. Given the negligible intrinsic widths of these resonances, the widths largely reflect the detector resolution. For DY-produced
Figure 4: Selection acceptance times efficiency for the $H \rightarrow ZZ \rightarrow \ell\ell qq$ events from MC simulations as a function of the Higgs boson mass for (a) ggF and (b) VBF production, combining the HP and LP signal regions of the $ZV \rightarrow ℓℓJ$ selection and the $b$-tagged and untagged regions of the $ZV \rightarrow ℓℓjj$ selection. The hatched band represents the total statistical and systematic uncertainties.

HVT $W'$ signal, the widths of the $m_{ℓJ}$ and $m_{ℓjj}$ distributions are slightly larger at 3–4% since the $W'$ boson in this production mode has an intrinsic width of approximately 2.6% of its mass. The widths of the $m_{ℓJ}$ and $m_{ℓjj}$ distributions are 4% at 500 GeV for the bulk RS graviton signal with $k/M_\text{Pl} = 1$ and rise to 8% at 5000 GeV. The increase can be attributed to the increase in the intrinsic width of the signal. For a given resonance mass, the $m_{ℓJ}$ distributions are narrower than those of $m_{ℓjj}$.

5.5 Data control regions and background estimation

The dominant backgrounds to the $X \rightarrow ZV \rightarrow ℓℓqq$ search are the $Z+$jets, top quark and diboson processes. Their contributions are estimated from a combination of MC and data-driven techniques. In all cases, the shapes of kinematic variables, including those of the final discriminants $m_{ℓJ}$ and $m_{ℓjj}$, are taken from MC simulations. The multijet background is estimated to be negligible.

The $Z+$jets events are expected to have smooth distributions of $m_J$ and $m_{jj}$, while the signal events should exhibit resonance structures at the mass of the vector-boson $V$. Thus, a $Z+$jets control region (CR) is defined for every signal region by reversing the $m_J$ or $m_{jj}$ requirement. Events in the control regions are selected in exactly the same way as those in their corresponding signal regions except for the requirement on $m_J$ or $m_{jj}$. For the $ZV \rightarrow ℓℓJ$ selection, the leading large-$R$ jet mass is required to be outside the large-$R$ jet mass window of the 80% working point of the boson tagging. For the $ZV \rightarrow ℓℓjj$ selection, a requirement of $50 < m_{jj} < 62$ GeV or $105 < m_{jj} < 150$ GeV is applied. These CRs are dominated by the $Z+$jets contribution, with a purity higher than 96% in all regions, except for the $b$-tagged CR where the top quark and $Z+$jets contributions are comparable. They are therefore used to constrain its contribution in signal regions through simultaneous fits as discussed in Section 8.

Top-quark production is a significant background source in the $b$-tagged signal region of the resolved $ZV \rightarrow ℓℓjj$ selection. Its contribution is constrained using a top-quark-enhanced control region. Events in this control region must have two different-flavour leptons, $e\mu$, with their invariant mass within [76, 106] GeV,
and two $b$-tagged jets with their invariant mass in the range [50, 150] GeV. The leading $b$-tagged jet is required to have $p_T > 60$ GeV. To emulate the selection of events in the signal regions, at least one of the leptons must satisfy the ‘medium’ criteria. This selection yields a sample of top quark events with a purity higher than 99%. This top quark control region is used to constrain top quark contributions for all signal regions.

Diboson production, mainly from the SM ZZ and ZW processes, is also a significant background source. The contribution from those processes is estimated completely from MC simulation.

As an example, Table 2 shows the numbers of events observed in the data and estimated from background processes in the seven signal regions of the $H \rightarrow ZZ \rightarrow \ell\ell qq$ search. The numbers of background events are extracted through a background-only fit of the signal and control regions discussed in Section 8.

Table 2: Numbers of events observed in the data and predicted for background processes from background-only fits to the signal and control regions (Section 8) in the seven signal regions of the $H \rightarrow ZZ \rightarrow \ell\ell qq$ search. The numbers of signal events expected from the ggF and VBF production of a heavy Higgs boson with mass of 1 TeV are also shown. The signal yields are calculated using $\sigma \times B(H \rightarrow ZZ) = 20$ fb for both processes. The uncertainties combine statistical and systematic contributions. The fit constrains the background estimate towards the observed data, which reduces the total background uncertainty by correlating those from the individual backgrounds.

| $V \rightarrow q\bar{q}$ recon. | Signal regions | $H$ (1 TeV) | Background estimates | Data |
|---|---|---|---|---|
| | ggF | VBF | Z+jets | Diboson | Top quarks | Total |
| Merged HP | 0.42 ± 0.08 | 5.1 ± 1.0 | 29.0 ± 2.6 | 3.8 ± 0.6 | 1.1 ± 0.4 | 33.9 ± 2.7 |
| Merged LP | 0.33 ± 0.08 | 3.4 ± 0.4 | 113 ± 7 | 8.4 ± 1.2 | 1.8 ± 0.6 | 123 ± 7 |
| Resolved | 0.23 ± 0.05 | 2.3 ± 0.4 | 1307 ± 34 | 60 ± 9 | 66 ± 7 | 1433 ± 34 |

| VBF category |
|---|---|---|---|---|
| 32 |
| 109 |

| ggF/DY category |
|---|---|---|---|---|
| Merged HP | 14.2 ± 1.6 | 11.0 ± 2.1 | 1728 ± 34 | 177 ± 21 |
| Merged LP | 10.0 ± 0.9 | 7.5 ± 0.8 | 6060 ± 60 | 285 ± 31 |
| Resolved $b$-tagged | 1.02 ± 0.12 | 0.62 ± 0.08 | 1740 ± 40 | 167 ± 22 |
| Untagged | 3.31 ± 0.34 | 2.5 ± 0.5 | 82200 ± 400 | 2280 ± 250 |

| Total |
|---|---|---|---|
| 1906 |
| 6375 |
| 2843 |
| 85928 |
6 $X \rightarrow ZV \rightarrow \nu\nu qq$ search

Events containing a $X \rightarrow ZV \rightarrow \nu\nu qq$ signal are characterised by a hadronically decaying $V$ boson recoiling against a large missing transverse momentum. Only the merged reconstruction of the $V \rightarrow qq$ decay is considered. The selection closely follows that of the $X \rightarrow ZV \ell\ell qq$ search as illustrated in Figure 2 with additional requirements to remove multijet backgrounds but without the resolved selection.

6.1 Selection of $ZV \rightarrow \nu\nu qq$

An initial selection is made by requiring $E_T^{\text{miss}} > 250$ GeV, and vetoing events with electrons or muons passing the ‘loose’ quality requirements. The multijet background, originating primarily from the presence of mismeasured jets, and non-collision backgrounds are suppressed by using a track-based missing transverse momentum, $\vec{p}_T^{\text{miss}}$, as defined in Section 4. The requirements are $p_T^{\text{miss}} > 50$ GeV and the azimuthal separation between $E_T^{\text{miss}}$ and $\vec{p}_T^{\text{miss}}$ directions satisfies $\Delta\phi(E_T^{\text{miss}}, \vec{p}_T^{\text{miss}}) < 1$. An additional requirement is imposed on the azimuthal separation between the directions of $E_T^{\text{miss}}$ and the nearest small-$R$ jet with $\min[\Delta\phi(E_T^{\text{miss}}, \text{small} - R \text{ jet})] > 0.4$. The multijet background is found to be negligible after these selections.

As in the $\ell\ell qq$ search, both the VBF and ggF categories are considered in the signal event selection for the $H \rightarrow ZZ$ and $W' \rightarrow ZW$ searches; the VBF selection is not motivated by the $G_{KK} \rightarrow ZZ$ search. The VBF tag-jets are selected in the same manner as in the $\ell\ell qq$ search, but they are required to satisfy $m_{\text{tag}}^{jj} > 630$ GeV and $|\Delta\eta_{\text{tag}}^{jj}| > 4.7$. Those values are chosen to optimise the search sensitivity for signals from VBF production, considering all signal masses. Events failing the VBF tag-jets selection are kept in the ggF category. For both the VBF and ggF categories, events are then subject to the selections described below.

Unlike the $\ell\ell qq$ search, this search utilises only the merged selection of the $V \rightarrow qq$ decay, i.e., considering only the $ZV \rightarrow \nu\nu J$ final state, since the resolved selection has little acceptance for the given high $E_T^{\text{miss}}$ trigger threshold. The selection of the large-$R$ jets and the boson tagging are identical to those of the $\ell\ell qq$ search and are described in Section 4. Similarly, candidate events are split into HP and LP signal regions. The $H \rightarrow ZZ$ search and the $W' \rightarrow ZW$ search use all the four signal regions, while the $G_{KK} \rightarrow ZZ$ search bypasses the VBF selection, so has only two signal regions. The distribution of the mass and $D_2$ of the leading large-$R$ jet are shown in Figure 5. There is a small overprediction of the background at high mass region, but those events are not selected in any signal regions due to the large-$R$ jet mass cut in boson tagging. The selection criteria for the $\nu\nu qq$ search are summarised in Table 3.

It is not possible to fully reconstruct the invariant mass of the $\nu\nu J$ system due to the presence of neutrinos in the final state, so the transverse mass is used as the final discriminant:

$$m_T = \sqrt{(E_{T,J} + E_T^{\text{miss}})^2 - (\vec{p}_{T,J} + \vec{E}_T^{\text{miss}})^2},$$

where $E_{T,J} = \sqrt{m_J^2 + p_{T,J}^2}$. The resolution of the transverse mass is about 10% of the signal mass and the ratio of the resolution to the signal mass has little dependence on the signal model or the resonance mass.
Figure 5: Observed and expected distributions of (a) mass of the large-R jet and (b) $D_2$ of the large-R jet in $Z \rightarrow \nu\nu$ candidates in the ggF category. All selections other than the requirements on the mass and $D_2$ are applied. Background contributions in these distributions are after applying the combined likelihood fit to the data, as explained in Section 8. For illustration, expected distributions from the ggF production of a 1.6 TeV Higgs boson with $\sigma \times B(H \rightarrow ZZ) = 60$ fb are also shown. The middle panes show the ratios of the observed data to the background predictions. The uncertainty in the total background prediction, shown as bands, combines statistical and systematic contributions. The bottom panes are the ratios of the post-fit and pre-fit background predictions.

Table 3: Summary of the $X \rightarrow ZV \rightarrow \nu\nu qq$ selection criteria.

| Category                      | Criteria                                                                 |
|-------------------------------|--------------------------------------------------------------------------|
| $Z \rightarrow \nu\nu$       | $E_{T}^{miss} > 250$ GeV                                                 |
| Multijet removal              | $p_{T}^{miss} > 50$ GeV                                                 |
|                               | $\Delta\phi(E_{T}^{miss}, P_{T}^{miss}) < 1$                            |
|                               | $\min[\Delta\phi(E_{T}^{miss}, \text{small-R jet})] > 0.4$              |
| Tag-jet selection for VBF      | Two non-$b$-tagged small-R jets with $\eta_1 \cdot \eta_2 < 0$, $|\Delta\eta_{jj}^{\text{tag}}| > 4.7$ and $m_{jj}^{\text{tag}} > 630$ GeV |
| Jet requirements              | $\geq 1$ large-R jet with $p_{T} > 200$ GeV                             |
| $V$ boson tagging             | $p_{T}$-dependent criteria on $D_2$ and $m_{J}$                          |

The signal selection efficiency strongly depends on the signal model and the mass of the resonance. As an example, Figure 6 shows the selection acceptance times efficiency as a function of $m(H)$ for $H \rightarrow ZV \rightarrow \nu\nu qq$. Similar results are obtained for the $W' \rightarrow ZW$ and $G_{KK} \rightarrow ZZ$ searches.
6.2 Background estimation

The main backgrounds for this search arise from $Z$+jets, $W$+jets and $t\bar{t}$ production. Data control regions are defined to check the modelling of each contribution. As in the $\ell\ell qq$ search, the shapes of kinematic variables, including the final discriminant $m_T$, are taken from MC simulations.

The normalisation of the $Z$+jets background is determined using the $Z$+jets control region from the $\ell\ell qq$ search (Section 5.5). Control regions specific to the $\nu\nu qq$ search are also defined to constrain the $W$+jets and top quark backgrounds. Events in these control regions are selected in the same way as those in the signal regions except that they must have exactly one muon passing the ‘tight’ quality requirement. These events are then split into the top quark and $W$+jets control regions according to the number of $b$-tagged jets that do not overlap with the large-$R$ jet. Events in the top quark control region must have at least one $b$-tagged jet and events in the $W$+jets control region must not have any $b$-tagged jets. For the $W$-jets control region, the jet mass requirement used in the signal region selection is inverted, to ensure that there is no resonant diboson signal contamination via $X \to WV \to \ell \nu qq$ decay, while for the top quark control region, the leading large-$R$ jet is required to be consistent with the mass of the $W$ boson.

For the $W$+jets and top quark CRs, the muon is treated as a missing particle to make the boson $p_T$ acceptance more similar to the signal region, and because the trigger does not include muons in the $E_T^{\text{miss}}$ calculation. Specifically, $E_{T,\text{no } \mu}^{\text{miss}} (p_{T,\text{no } \mu}^{\text{miss}})$ is computed by removing the muon $p_T$ contribution from the $E_T^{\text{miss}} (p_T^{\text{miss}})$ calculation. The requirements on $E_{T,\text{no } \mu}^{\text{miss}}$ and $p_{T,\text{no } \mu}^{\text{miss}}$ in the signal regions are used for $E_{T,\text{no } \mu}^{\text{miss}}$ and $p_{T,\text{no } \mu}^{\text{miss}}$ respectively for the control regions.

Table 4 summarises the numbers of events observed in the data and estimated from background processes in the signal regions from the background-only fit of both the signal and control regions discussed in Section 8. The expected numbers of events from both ggF and VBF production of a 1.6 TeV heavy Higgs boson, assuming $\sigma \times B(H \to ZZ) = 6$ fb, are also included for comparison.
Table 4: Numbers of events predicted from background processes and observed in the data in the signal regions of the $H \rightarrow ZZ \rightarrow \nu\nu qq$ search from the background-only fit of both the signal and control regions (Section 8). The numbers of signal events expected from a Higgs boson with mass of 1.6 TeV are also shown. The signal yields are calculated assuming $\sigma \times B(H \rightarrow ZZ) = 6$ fb for both ggF and VBF at 1.6 TeV. The uncertainties combine statistical and systematic contributions.

| Signal regions | $H$ (1.6 TeV) | Background estimates | Data |
|----------------|--------------|----------------------|------|
|                | ggF | VBF | Z+jets | W+jets | Diboson | Top quarks | Total |
| VBF category   |     |     |        |        |         |            |       |
| HP             | 0.49 ± 0.15 | 4.9 ± 1.1 | 35.0 ± 3.3 | 25 ± 4 | 6.7 ± 1.1 | 37 ± 4 | 104 ± 6 | 105 |
| LP             | 0.36 ± 0.09 | 3.2 ± 0.5 | 137 ± 10 | 94 ± 13 | 12.7 ± 2.0 | 70 ± 8 | 315 ± 13 | 335 |
| ggF category   |     |     |        |        |         |            |       |
| HP             | 15.5 ± 3.3 | 14.5 ± 3.2 | 2880 ± 80 | 1990 ± 100 | 490 ± 60 | 1500 ± 90 | 6870 ± 70 | 6888 |
| LP             | 10.6 ± 1.5 | 9.7 ± 1.4 | 11160 ± 210 | 7200 ± 300 | 830 ± 90 | 2710 ± 180 | 21910 ± 140 | 21936 |

7 Systematic uncertainties

Systematic uncertainty sources impacting the search can be divided into three categories: experimental uncertainties related to the detector or to the reconstruction algorithms, uncertainties in the estimations of background contributions, and uncertainties in modelling the signal. Unless explicitly stated, the uncertainties quoted below are the uncertainties in the quantities themselves, not the impact on the search sensitivity.

The uncertainty in the integrated luminosity of the dataset is determined to be 3.2%. It is derived, following a methodology similar to the one detailed in Ref. [80], from a preliminary calibration of the luminosity scale using a pair of $x$–$y$ beam-separation scans performed in August 2015 and May 2016. This uncertainty is applied to the normalisation of the signal and also to background contributions whose normalisations are derived from MC simulations. A variation in the pile-up reweighting of MC events is included to cover the uncertainty in the ratio of the predicted and measured inelastic cross section in Ref. [81].

The efficiencies of the lepton triggers for events with selected leptons are high, nearly 100% in the electron channel and approximately 96% in the muon channel. The corresponding uncertainties are negligible. For the selection used in the $\nu\nu qq$ search, the efficiency of the $E_T^{miss}$ trigger is also close to 100% with negligible associated uncertainty. The modelling of the electron and muon reconstruction, identification and isolation efficiencies is studied with a tag-and-probe method using $Z \rightarrow \ell\ell$ events in data and simulation at $\sqrt{s} = 13$ TeV [82, 83]. Small corrections are applied to the simulation to better model the performance seen in data. These corrections have associated uncertainties of the order of 1%. For the $\nu\nu qq$ search, the uncertainty is instead in the efficiency of the lepton veto, and is at the sub-percent level. Uncertainties in the lepton energy (or momentum) scale and resolution are also taken into account.

Uncertainties in the jet energy scale and resolution for small-radius jets are estimated using MC simulation and in situ techniques [64]. For central jets ($|\eta| < 2.0$), the total uncertainty in the jet energy scale ranges from about 6% for jets with $p_T = 25$ GeV to about 2% for $p_T = 1$ TeV. There is also an uncertainty in the jet energy resolution [84], which ranges from 10% to 20% for jets with a $p_T$ of 20 GeV to less than 5% for jets with $p_T > 200$ GeV. Uncertainties in the lepton and jet energy scales and resolutions are propagated into the uncertainty in $E_T^{miss}$. Uncertainties in the energy scale and resolution of the track
soft term are also propagated into the uncertainty in $E_{T}^{\text{miss}}$ [78], which is about 2% for the $\nu\nu qq$ search. Uncertainties in the efficiency for tagging $b$-jets and in the rejection factor for light jets are determined from $t\bar{t}$ samples [85, 86].

The uncertainties in the scale of the large-$R$ jet $p_T$, mass and $D_2$ are of the order of 2–5%. They are estimated using comparisons of data and simulation in Ref. [72]. An absolute uncertainty of 2% is assigned to the large-$R$ jet energy resolution, and relative uncertainties of 20% and 15% are assigned to the resolution of the large-$R$ jet mass and $D_2$, respectively.

For the $\ell\ell qq$ search the uncertainty in the spectrum of the final discriminant, $m_{\ell\ell J}$ or $m_{\ell\ell jj}$, for $Z$+jets, is assessed by comparing the shape difference between data and MC simulations in the control regions. For the $\nu\nu qq$ search the uncertainty in the modelling of the $m_T$ distribution for $Z$+jets and $W$+jets production is assessed by comparing the nominal SHERPA MC sample with alternative samples generated by doubling or halving the renormalisation, resummation and factorisation scales independently and varying the matrix-element matching. The approach is different from that used in the $\ell\ell qq$ search, since it is difficult to obtain a pure control region for $Z$+jets or $W$+jets in the $\nu\nu qq$ search.

An uncertainty in the shape of the $m_{\ell\ell}$ or $m_T$ distribution for the $t\bar{t}$ background is derived by comparing the Powheg-Box sample with the distribution obtained using MadGraph5_aMC@NLO 2.2.2. Additional systematic uncertainties are estimated by comparing the nominal sample showered with Pythia 6.428 using the P2012 tune to one showered with Herwig++ 2.7.1 [87] and using the UEEE5 underlying-event tune. Samples of $t\bar{t}$ events with the factorisation and renormalisation scales doubled or halved are compared to the nominal, and the differences observed are taken as an additional uncertainty.

The uncertainties in the diboson cross sections are estimated to be 10% [40, 88], and the shape uncertainty is obtained by comparing MC samples generated by SHERPA and Powheg-Box.

The signals acceptance uncertainty due to PDF uncertainties is estimated by taking the uncertainty from the PDF error sets, CT10 for the heavy Higgs boson signal and NNPDF23LO for the HVT and bulk RS signals, and adding it in quadrature to the acceptance difference obtained with the use of alternative PDF sets: MMHT2014LO [89] and NNPDF30NLO [90] for the Higgs boson, and CT10 and MMHT2014LO for the HVT and bulk RS graviton. For the HVT signal, the uncertainty ranges from 1% (2%) to 6% (12%) for the $\ell\ell qq$ ($\nu\nu qq$) search depending on the mass being tested. Similar results are obtained for the heavy Higgs boson signal, while for the bulk RS signal, the uncertainty is generally less than 1%. The signal acceptance uncertainty due to initial- and final-state radiation (ISR/FSR) is estimated by varying relevant parameters in the A14-NNPDF tune [38] for the HVT and bulk RS signals. This uncertainty ranges from less than 1% to 4% (6%) for the $\ell\ell qq$ ($\nu\nu qq$) search depending on the mass being tested. The effect of the QCD scale uncertainty on the heavy Higgs boson signal acceptance is estimated by varying the factorisation and renormalisation scales. It ranges from 1% (2%) to 4% (8%) for the $\ell\ell qq$ ($\nu\nu qq$) search depending on the mass being tested.

8 Results

8.1 Statistical and fit procedures

The statistical analysis is based on the framework described in Refs. [91–93]. A binned likelihood function $L(\mu, \theta)$ is constructed as a product of Poisson probability terms over all bins of the fit templates considered in the search. This function depends on the signal-strength parameter $\mu$, a multiplicative
factor applied to the theoretical signal production cross section, and $\theta$, a set of nuisance parameters that encode the effects of systematic uncertainties in the signal and expected backgrounds, described in Section 7. The binning is chosen based on the expected mass resolution and numbers of events. The nuisance parameters are either free to float, or constrained using Gaussian terms defined by external studies. The likelihood function for the combination of the $\ell\ell qq$ and $\nu\nu qq$ channels is the product of the Poisson likelihoods of these individual channels. However, only one constraint term per common nuisance parameter is included in the product.

For each signal process considered, a simultaneous maximum-likelihood fit is performed to the observed distributions of the final discriminants in the signal regions, $m_{\ell\ell}$ or $m_{\ell\ell jj}$ for the $X \rightarrow ZV \rightarrow \ell\ell qq$ search and $m_T$ for the $X \rightarrow ZV \rightarrow \nu\nu qq$ search, to extract the signal rate information. The shapes of the signal distributions are interpolated using the moment-morphing method [94] for intermediate mass points where simulated signal samples are not available. The product of acceptance and efficiency for each interpolated signal mass point is obtained from an interpolation with cubic splines between the simulated mass points. The $Z+$jets, $W+$jets and top quark control regions are included in the fit’s likelihood calculation with one bin per region, i.e., using only their event-count information. Background contributions, including their shapes in the signal regions, are taken from MC simulations. However, they are allowed to vary independently within their uncertainties in each bin. Moreover, normalisation scale factors (SFs) are applied to the MC estimates of the $Z+$jets, $W+$jets and top quark contributions. These scale factors are free parameters in the fit and are therefore constrained by the data in both the signal and control regions. The diboson contribution is constrained to the theoretical estimate within the corresponding uncertainties.

In general, one SF is introduced per control region for its intended background component with the following exceptions. One common $Z+$jets SF is used for HP and LP regions of the merged selection of both the $ZV \rightarrow \ell\ell qq$ and $ZV \rightarrow \nu\nu qq$ searches. However, independent SFs are used for the VBF and ggF categories. For the resolved $ZV \rightarrow \ell\ell qq$ selection, two independent $Z+$jets SFs are used for the $b$-tagged and untagged regions: one for the $Z+$heavy-flavour component and the other for the $Z+$light-jet component (Section 3). The $ZV \rightarrow \ell\ell qq$ search defines a top quark control region and consequently applies one top quark SF to all regions. The $ZV \rightarrow \nu\nu qq$ search shares the $Z+$jets control regions with $ZV \rightarrow \ell\ell qq$ and hence applies the same SFs to its $Z+$jets background contributions. The $ZV \rightarrow \nu\nu qq$ search has its own $W+$jets and top quark control regions. Similar to $Z+$jets, one common $W+$jets SF is used for HP and LP regions, but independent SFs are used for the VBF and ggF categories. All the top quark control regions in the $ZV \rightarrow \nu\nu qq$ search share one common SF and it is distinguished from the top quark SF in the $ZV \rightarrow \ell\ell qq$ search.

The test statistic $q_{\mu}$ is defined as the profile likelihood ratio [95], $q_{\mu} = -2\ln(L(\mu, \hat{\theta}_\mu)/L(\hat{\mu}, \hat{\theta}))$, where $\hat{\mu}$ and $\hat{\theta}$ are the values of the parameters that maximise the likelihood function (with the constraint $0 \leq \hat{\mu} \leq \mu$), and $\hat{\theta}_\mu$ are the values of the nuisance parameters that maximise the likelihood function for a given value of $\mu$. The test statistic $q_{\mu}$ is used to measure the compatibility of the observed data with the background-only hypothesis. In the absence of a signal, constraints on the production of a heavy resonance decaying into $ZV$ pairs are derived. The exclusion limits are calculated with a modified frequentist method [96], also known as CL$_{s}$, in the asymptotic approximation [97] for resonance masses below 2 TeV. Above 2 TeV, the small number of events makes the asymptotic approximation unreliable and the limits are calculated using pseudo-experiments. All limits are set at the 95% confidence level (CL).
8.2 Limits on the production of heavy resonances

The observed distributions of $m_{\ell\ell}$ or $m_{\ell\ell\bar{\ell}}$ from the $H \to ZZ \to \ell\ellqq$ search are compared with the background estimates in Figure 7 for the three signal regions of the VBF category and in Figure 8 for the four signal regions of the ggF category. Similarly, Figures 9 and 10 show the $m_T$ distributions from the $H \to ZZ \to \nu\nuqq$ search in the signal regions of the VBF and ggF categories, respectively. There are no events in the data beyond the ranges of the distributions shown. Background contributions shown are obtained from background-only fits described previously. The numbers of events observed and estimated in control regions are summarised in Figure 11.

The data distributions are reasonably well reproduced by the estimated background contributions in all these distributions. Similar levels of agreement are observed for the $W' \to ZW$ and $G_{KK} \to ZZ$ searches. The largest difference between the observed data and the SM background prediction is in the $H \to ZZ \to \ell\ellqq$ search, high-purity signal region, as shown in Figure 8(a). A deficit in data is seen around $m_{\ell\ell}$ of 800 GeV, with a local significance of 3.0$\sigma$, and by taking into account the look-elsewhere effect [98] in the full $m_{\ell\ell}$ spectrum, a global significance of 1.9$\sigma$. Upper limits are set on the product of the production cross section of new resonances and their decay branching ratio to $ZV$, $\sigma \times \mathcal{B}(X \to ZV)$. 


Figure 7: Comparisons of the observed data and expected background distributions of the final discriminants of the VBF category for the $H \rightarrow ZZ \rightarrow \ell\ell qq$ search: $m_{\ell\ell}$ of (a) high-purity and (b) low-purity signal regions; (c) $m_{\ell\ell jj}$ of the resolved signal region. For illustration, expected distributions from the VBF production of a 1 TeV Higgs boson with $\sigma \times B(H \rightarrow ZZ) = 20 \text{ fb}$ are also shown. The middle panes show the ratios of the observed data to the background predictions. The uncertainty in the total background prediction, shown as bands, combines statistical and systematic contributions. The blue triangles in the middle panes indicate bins where the ratio is nonzero and outside the vertical range of the plot. The bottom panes show the ratios of the post-fit and pre-fit background predictions.
Figure 8: Comparisons of the observed data and expected background distributions of the final discriminants of the ggF category for the $H \rightarrow ZZ \rightarrow ℓℓqq$ search: $m_{ℓℓJ}$ of (a) high-purity and (b) low-purity signal regions; $m_{ℓℓjj}$ of (c) $b$-tagged and (d) untagged signal regions. For illustration, expected distributions from the ggF production of a 1 TeV Higgs boson with $\sigma \times B(H \rightarrow ZZ) = 20$ fb are also shown. The middle panes show the ratios of the observed data to the background predictions. The uncertainty in the total background prediction, shown as bands, combines statistical and systematic contributions. The blue triangles in the middle panes indicate bins where the ratio is nonzero and outside the vertical range of the plot. The bottom panes show the ratios of the post-fit and pre-fit background predictions.
Figure 9: Comparisons of the observed data and expected background distributions of $m_T$ in the VBF category of the $H \rightarrow ZZ \rightarrow \nu\nu qq$ search: (a) high-purity and (b) low-purity signal regions. For illustration, expected distributions from the VBF production of a 1.6 TeV Higgs boson with $\sigma \times B(H \rightarrow ZZ) = 6$ fb are also shown. The middle panes show the ratios of the observed data to the background predictions. The uncertainty in the total background prediction, shown as bands, combines statistical and systematic contributions. The blue triangles in the middle panes indicate bins where the ratio is nonzero and outside the vertical range of the plot. The bottom panes show the ratios of the post-fit and pre-fit background predictions.
Figure 10: Comparisons of the observed data and expected background distributions of $m_T$ in the ggF category of the $H \rightarrow ZZ \rightarrow \nu\nu qq$ search: (a) high-purity and (b) low-purity signal regions. For illustration, expected distributions from the ggF production of a 1.6 TeV Higgs boson with $\sigma \times B(H \rightarrow ZZ) = 6$ fb are also shown. The middle panes show the ratios of the observed data to the background predictions. The uncertainty in the total background prediction, shown as bands, combines statistical and systematic contributions. The blue triangles in the middle panes indicate bins where the ratio is nonzero and outside the vertical range of the plot. The bottom panes show the ratios of the post-fit and pre-fit background predictions.
Figure 11: Comparisons of the observed data and expected background event yields in each control region. The middle pane shows the ratios of the observed data to the post-fit background predictions. The uncertainty in the total background prediction, shown as bands, combines statistical and systematic contributions. The bottom pane shows the ratios of the post-fit and pre-fit background predictions.
Figure 12: Observed (black solid curve) and expected (black dashed curve) 95% CL upper limits on $\sigma \times \mathcal{B}(H \rightarrow ZZ)$ at $\sqrt{s} = 13$ TeV for the (a) ggF and (b) VBF production of a heavy Higgs boson as a function of its mass, combining $\ell\ell qq$ and $\nu\nu qq$ searches. Limits expected from individual searches (dashed curves in blue and magenta) are also shown for comparison. Limits are calculated in the asymptotic approximation below 2 TeV and are obtained from pseudo-experiments above that. The green (inner) and yellow (outer) bands represent the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty in the expected limits.

Limits are presented for both the ggF and VBF productions of $H \rightarrow ZZ$ in Figure 12 in the resonance mass range between 300 GeV and 3 TeV. The observed limit on $\sigma \times \mathcal{B}(H \rightarrow ZZ)$ varies from 1.7 (0.42) pb at 300 GeV to 1.4 (1.1) fb at 3 TeV for ggF (VBF) $H \rightarrow ZZ$ production.

Figure 13: Observed (black solid curve) and expected (black dashed curve) 95% CL upper limits on $\sigma \times \mathcal{B}(W' \rightarrow ZZ)$ at $\sqrt{s} = 13$ TeV for the (a) DY and (b) VBF production of a $W'$ boson in the HVT model as a function of its mass, combining $\ell\ell qq$ and $\nu\nu qq$ searches. Limits expected from individual searches (dashed curves in blue and magenta) are also shown for comparison. Limits are calculated in the asymptotic approximation below 2 TeV and are obtained from pseudo-experiments above that. Theoretical predictions are overlaid in (a) for HVT Model A and Model B and in (b) for HVT VBF Model. The green (inner) and yellow (outer) bands represent the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty in the expected limits.
Figure 13 shows the limits on $\sigma \times B(W' \rightarrow ZW)$ for DY and VBF production of a $W'$ boson in the HVT model. The observed limit ranges from 5.7 pb at 300 GeV to 1.3 fb at 5 TeV for DY production and from 0.98 pb at 300 GeV to 2.8 fb at 4 TeV for VBF production. The theoretical predictions of the HVT Model A, Model B and VBF Model are overlaid for comparison. The observed limits exclude an HVT $W'$ boson produced in the DY process lighter than 2.9 TeV for Model A and 3.2 TeV for Model B, while none of the HVT model space can be excluded for the VBF process with the current sensitivity of the analysis.

Figure 14: Observed (black solid curve) and expected (black dashed curve) 95% CL upper limits on $\sigma \times B(G_{KK} \rightarrow ZZ)$ at $\sqrt{s} = 13$ TeV for the production of a $G_{KK}$ in the bulk RS model with couplings of (a) $k/\overline{M}_{Pl} = 1$ and (b) $k/\overline{M}_{Pl} = 0.5$ as a function of the graviton mass, combining $\ell\ell qq$ and $\nu\nu qq$ searches. Limits expected from individual searches (dashed curves in blue and magenta) are also shown for comparison. Limits are calculated in the asymptotic approximation below 2 TeV and are obtained from pseudo-experiments above that. The theoretical predictions for $\sigma \times B(G_{KK} \rightarrow ZZ)$ as a function of resonance mass for a bulk RS graviton are also shown. The green (inner) and yellow (outer) bands represent the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty in the expected limits.

For $G_{KK} \rightarrow ZZ$, limits are presented for two different couplings: $k/\overline{M}_{Pl} = 1$ and $k/\overline{M}_{Pl} = 0.5$, for masses between 300 GeV and 5 TeV, as shown in Figure 14. The observed limits on $\sigma \times B(G_{KK} \rightarrow ZZ)$ vary from 3.3 pb at 300 GeV to 0.74 fb at 5 TeV for the bulk RS model with $k/\overline{M}_{Pl} = 1$. The exclusion limit on the mass in this model is 1.3 (1.6) TeV for the observed (expected) limit. Similar results are obtained for bulk RS model with $k/\overline{M}_{Pl} = 0.5$, with a mass exclusion upper limit of 1.0 TeV for both observed and expected limits.

### 8.3 Effects of systematic uncertainties

The effects of systematic uncertainties are studied for hypothesised signals using the signal-strength parameter $\mu$. The relative uncertainties in the best-fit $\mu$ value from the leading sources of systematic uncertainty are shown in Table 5 for ggF $H \rightarrow ZZ$ production with $m(H) = 600$ GeV and 1.2 TeV. Apart from the statistical uncertainties in the data, the uncertainties with the largest impact on the sensitivity of the searches are from the size of the MC samples, measurements of small-$R$ and large-$R$ jets, $E_T^{\text{miss}}$ measurement, background modelling and luminosity. For signals with higher mass, the data statistical uncertainty becomes dominant. The effects of systematic uncertainties for the other searches are similar to those shown for the ggF $H \rightarrow ZZ$ search.
Table 5: The relative uncertainties from the leading uncertainty sources in the best-fit signal-strength parameter $\mu$ of hypothesised signal production of $ggF \rightarrow ZZ$ with $m(H) = 600$ GeV and $m(H) = 1.2$ TeV. For this study, the $H \rightarrow ZZ$ production cross section is assumed to be 95 fb at 600 GeV and 13 fb at 1.2 TeV, corresponding to approximately the expected median upper limits at these two mass values.

| Uncertainty source                | $m(H) = 600$ GeV $\Delta\mu/\mu$ [%] | Uncertainty source                | $m(H) = 1.2$ TeV $\Delta\mu/\mu$ [%] |
|----------------------------------|-------------------------------------|-----------------------------------|---------------------------------------|
| Pseudo-data statistics           | 36                                  | Pseudo-data statistics            | 41                                    |
| Total systematics                | 33                                  | Total systematics                 | 29                                    |
| MC statistics                    | 20                                  | Large-$R$ jet                     | 20                                    |
| Large-$R$ jet                    | 16                                  | Background modelling              | 13                                    |
| $E_T^{miss}$ uncertainties       | 13                                  | MC statistics                     | 13                                    |
| Small-$R$ jet                    | 11                                  | Luminosity                        | 6.5                                   |
| Background modelling             | 9.6                                 | Small-$R$ jet                     | 5.9                                   |
| Luminosity                       | 9.1                                 | Leptons                           | 3.9                                   |

9 Conclusion

Searches for heavy resonances decaying into ZZ or ZW are performed using proton–proton collision data produced at $\sqrt{s} = 13$ TeV and recorded by the ATLAS detector at the LHC in 2015 and 2016. The data correspond to a combined integrated luminosity of 36.1 fb$^{-1}$. The searches explore the final states with one Z boson decaying either into a pair of charged leptons or into a pair of neutrinos, and the other Z boson or the W boson decaying into a pair of quarks, identified either as two separate jets or as one large-radius jet. Moreover, the searches are performed in two event categories, targeting VBF and non-VBF production of the resonances.

The data are found to be consistent with the SM background predictions and no evidence of heavy resonance production is observed. Upper limits on the production cross section times branching ratio, $\sigma \times B(X \rightarrow ZV)$, as a function of the resonance mass are derived at 95% CL. In the case of a heavy Higgs boson, upper limits on $\sigma \times B(H \rightarrow ZZ)$ range from 1.7 (0.42) pb at $m(H) = 300$ GeV to 1.4 (1.1) fb at $m(H) = 3$ TeV for the ggF (VBF) production process. For the phenomenological heavy-vector-triplet benchmark Model A (Model B) with coupling constant $g_V = 1$ ($g_V = 3$), a spin-1 vector triplet produced via the Drell–Yan process is excluded for $m(W') < 2.9$ (3.2) TeV. Upper limits on $\sigma \times B(W' \rightarrow ZW)$ are also set for an HVT VBF Model with values of 0.98 pb at $m(W') = 300$ GeV and 2.8 fb at $m(W') = 4$ TeV. For the bulk Randall–Sundrum model with $k/M_{Pl} = 1$ ($k/M_{Pl} = 0.5$), a spin-2 Kaluza–Klein graviton is excluded for $m(G_{KK}) < 1.3$ (1.0) TeV.

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A. Zoccoli\textsuperscript{22a,22b}, R. Zou\textsuperscript{33}, M. zur Nedden\textsuperscript{17}, L. Zwalinski\textsuperscript{32}.

1 Department of Physics, University of Adelaide, Adelaide, Australia
2 Physics Department, SUNY Albany, Albany NY, United States of America
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 of America
7 Department of Physics, University of Arizona, Tucson AZ, United States of America
8 Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America
9 Physics Department, National and Kapodistrian University of Athens, Athens, Greece
10 Physics Department, National Technical University of Athens, Zografou, Greece
11 Department of Physics, The University of Texas at Austin, Austin TX, United States of America
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 of America
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; (d) Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
21 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
22 (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
23 Physikalisches Institut, University of Bonn, Bonn, Germany
24 Department of Physics, Boston University, Boston MA, United States of America
25 Department of Physics, Brandeis University, Waltham MA, United States of America
26 (a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFJJ), Sao Joao del Rei; (d) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
27 Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
28 (a) Transilvania University of Brasov, Brasov; (b) Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; (c) Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi; (d) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (e) University Politehnica Bucharest, Bucharest; (f) West University in Timisoara, Timisoara, Romania
29 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
30 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
31 Department of Physics, Carleton University, Ottawa ON, Canada
32 CERN, Geneva, Switzerland
33 Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
34 (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
35 (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Physics, Nanjing University, Jiangsu; (c) Physics Department, Tsinghua University, Beijing 100084, China
36 (a) Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Anhui; (b) School of Physics, Shandong University, Shandong; (c) Department of Physics and Astronomy, Key Laboratory for Particle Physics, Astrophysics and Cosmology, Ministry of Education; Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai(also at PKU-CHEP), China
37 Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France
38 Nevis Laboratory, Columbia University, Irvington NY, United States of America
39 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
40 (a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
41 (a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
42 Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
43 Physics Department, Southern Methodist University, Dallas TX, United States of America
44 Physics Department, University of Texas at Dallas, Richardson TX, United States of America
45 DESY, Hamburg and Zeuthen, Germany
46 Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
47 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
48 Department of Physics, Duke University, Durham NC, United States of America
49 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
50 INFN e Laboratori Nazionali di Frascati, Frascati, Italy
51 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
52 Département de Physique Nucléaire et Corpusculaire, Université de Genève, Geneva, Switzerland
53 (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
54 (a) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
55 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
56 SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
57 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
58 Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
59 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
60 (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
61 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
62 (a) Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; (b) Department of Physics, The University of Hong Kong, Hong Kong; (c) Department of Physics and Institute for Advanced Study, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
Department of Physics, National Tsing Hua University, Taiwan, Taiwan
Department of Physics, Indiana University, Bloomington IN, United States of America
Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
University of Iowa, Iowa City IA, United States of America
Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
Graduate School of Science, Kobe University, Kobe, Japan
Faculty of Science, Kyoto University, Kyoto, Japan
Kyoto University of Education, Kyoto, Japan
Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan
INFN Sezione di Lecce; Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia
School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
Department of Physics and Astronomy, University College London, London, United Kingdom
Louisiana Tech University, Ruston LA, United States of America
Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
Fysiska institutionen, Lunds universitet, Lund, Sweden
Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
Institut für Physik, Universität Mainz, Mainz, Germany
School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
CPPM, Aix-Marseille Université et CNRS/IN2P3, Marseille, France
Department of Physics, University of Massachusetts, Amherst MA, United States of America
Department of Physics, McGill University, Montreal QC, Canada
School of Physics, University of Melbourne, Victoria, Australia
Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
INFN Sezione di Milano; Dipartimento di Fisica, Università di Milano, Milano, Italy
B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Republic of Belarus
Group of Particle Physics, University of Montreal, Montreal QC, Canada
P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
National Research Nuclear University MEPhI, Moscow, Russia
D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
Nagasaki Institute of Applied Science, Nagasaki, Japan
Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
(a) INFN Sezione di Napoli; (b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
(a) INFN Sezione di Napoli; (b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
Department of Physics, Northern Illinois University, DeKalb IL, United States of America
Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
Department of Physics, New York University, New York NY, United States of America
Ohio State University, Columbus OH, United States of America
Faculty of Science, Okayama University, Okayama, Japan
Department of Physics, Oklahoma State University, Stillwater OK, United States of America
Palacký University, Olomouc, Czech Republic
Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
Graduate School of Science, Osaka University, Osaka, Japan
Department of Physics, University of Oslo, Oslo, Norway
Department of Physics, Oxford University, Oxford, United Kingdom
(a) INFN Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
National Research Centre "Kurchatov Institute" B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
(a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
(a) Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa; (b) Faculdade de Ciências, Universidade de Lisboa, Lisboa; (c) Department of Physics, University of Coimbra, Coimbra; (d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; (e) Departamento de Física, Universidade do Minho, Braga; (f) Departamento de Física Teorica y del Cosmos, Universidad de Granada, Granada; (g) Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
Czech Technical University in Prague, Praha, Czech Republic
Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia
Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
(a) INFN Sezione di Roma; (b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
(a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
(a) INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
137 (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; (b) Centre National de l’Energie des Sciences Techniques Nucléaires, Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) Faculté des sciences, Université Mohammed V, Rabat, Morocco
138 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
139 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
140 Department of Physics, University of Washington, Seattle WA, United States of America
141 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
142 Department of Physics, Shinshu University, Nagano, Japan
143 Department Physik, Universität Siegen, Siegen, Germany
144 Department of Physics, Simon Fraser University, Burnaby BC, Canada
145 SLAC National Accelerator Laboratory, Stanford CA, United States of America
146 (a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
147 (a) Department of Physics, University of Cape Town, Cape Town; (b) Department of Physics, University of Johannesburg, Johannesburg; (c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
148 (a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden
149 Physics Department, Royal Institute of Technology, Stockholm, Sweden
150 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
151 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
152 School of Physics, University of Sydney, Sydney, Australia
153 Institute of Physics, Academia Sinica, Taipei, Taiwan
154 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
155 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
156 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
157 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
158 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
159 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
160 Tomsk State University, Tomsk, Russia
161 Department of Physics, University of Toronto, Toronto ON, Canada
162 (a) INFN-TIFPA; (b) University of Trento, Trento, Italy
163 (a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON, Canada
164 Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan
165 Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
166 Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
167 (a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; (b) ICTP, Trieste; (c) Dipartimento di
Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
168 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
169 Department of Physics, University of Illinois, Urbana IL, United States of America
170 Instituto de Fisica Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Spain
171 Department of Physics, University of British Columbia, Vancouver BC, Canada
172 Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
173 Department of Physics, University of Warwick, Coventry, United Kingdom
174 Waseda University, Tokyo, Japan
175 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
176 Department of Physics, University of Wisconsin, Madison WI, United States of America
177 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
178 Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
179 Department of Physics, Yale University, New Haven CT, United States of America
180 Yerevan Physics Institute, Yerevan, Armenia
181 Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
182 Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
1a Also at Department of Physics, King’s College London, London, United Kingdom
1b Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
1c Also at Novosibirsk State University, Novosibirsk, Russia
1d Also at TRIUMF, Vancouver BC, Canada
1e Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, United States of America
1f Also at Physics Department, An-Najah National University, Nablus, Palestine
1g Also at Department of Physics, California State University, Fresno CA, United States of America
1h Also at Department of Physics, University of Fribourg, Fribourg, Switzerland
1i Also at II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
1j Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain
1k Also at Departamento de Fisica e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal
1l Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
1m Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China
1n Also at Universita di Napoli Parthenope, Napoli, Italy
1o Also at Institute of Particle Physics (IPP), Canada
1p Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
1q Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia
1r Also at Borough of Manhattan Community College, City University of New York, New York City, United States of America
1s Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece
1t Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa
1u Also at Louisiana Tech University, Ruston LA, United States of America
1v Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
1w Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
1x Also at Graduate School of Science, Osaka University, Osaka, Japan
1y Also at Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany

51
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 of America

Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia

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 of America

Also at The City College of New York, New York NY, United States of America

Also at Departamento de Fisica Teorica y del Cosmos, Universidad de Granada, Granada, Portugal

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

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 Institut de Física 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 National Research Nuclear University MEPhI, Moscow, Russia

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

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

Also at Giresun University, Faculty of Engineering, Turkey

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

Also at Department of Physics, Nanjing University, Jiangsu, China

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

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

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

* Deceased