Search for a right-handed gauge boson decaying into a high-momentum heavy neutrino and a charged lepton in pp collisions with the ATLAS detector at \(13\) TeV


Published in:
Physics Letters B

DOI:
10.1016/j.physletb.2019.134942

Link to publication

License
CC BY

Citation for published version (APA):
https://doi.org/10.1016/j.physletb.2019.134942

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: https://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

UvA-DARE is a service provided by the library of the University of Amsterdam (http://dare.uva.nl)
Search for a right-handed gauge boson decaying into a high-momentum heavy neutrino and a charged lepton in $pp$ collisions with the ATLAS detector at $\sqrt{s} = 13$ TeV

The ATLAS Collaboration *

**A B S T R A C T**

A search for a right-handed gauge boson $W_R$, decaying into a boosted right-handed heavy neutrino $N_R$ in the framework of Left-Right Symmetric Models is presented. It is based on data from proton–proton collisions with a centre-of-mass energy of 13 TeV collected by the ATLAS detector at the Large Hadron Collider during the years 2015, 2016 and 2017, corresponding to an integrated luminosity of 80 fb$^{-1}$. The search is performed separately for electrons and muons in the final state. A distinguishing feature of the search is the use of large-radius jets containing electrons. Selections based on the signal topology result in smaller background compared to the expected signal. No significant deviation from the Standard Model prediction is observed and lower limits are set in the $W_R$ and $N_R$ mass plane. Mass values of the $W_R$ smaller than 3.8–5 TeV are excluded for $N_R$ in the mass range 0.1–1.8 TeV.

1. Introduction

Over the past decades, there have been several important developments at the theoretical and experimental frontiers to address the question of neutrino mass generation, which is not explained in the Standard Model (SM) of particle interactions. A widely adopted approach to explain small neutrino masses is the so-called seesaw mechanism [1], where the light neutrinos acquire their Majorana masses from dimension-5 operators through electroweak symmetry breaking. The simplest seesaw mechanism can be categorised into a few different classes, such as the Type-I [2–4], Type-II [5–7] and Type-III [5,8] seesaw scenarios. Type-I and Type-II models can further be embedded into a Left-Right Symmetric Model (LRSM) [9–11]. The LRSM contains SM-singlet heavy neutrinos $N_R$, which are introduced as the parity gauge partners of the corresponding left-handed neutrino fields, and a right-handed gauge boson $W_R$.

The LRSM framework provides a natural set-up for the seesaw mechanism and offers several features including parity symmetry at high energy, mass generation of the light and heavy neutrinos, explanation of parity violation in the SM and existence of the right-handed charged current. This model can naturally explain the small neutrino masses through the Type-I seesaw via the right-handed neutrinos, and the Type-II seesaw via SU(2)-triplet scalars. Both the Type-I and Type-II contributions can coexist. In the LRSM, left-handed neutrinos (SM neutrinos) as well as the right-handed neutrinos are considered to be Majorana particles (i.e. to be their own antiparticles). The LRSM thus features violation of the global lepton number symmetry of the SM. Hence, the model can be tested by observing lepton-number-violating processes, such as the Keung–Senjanović process [12], shown in Fig. 1.

Searches by the ATLAS [13,14] and CMS [15–19] collaborations for signatures of LRSMs have considered the final state containing two charged leptons and two jets and have excluded regions of the $(m_{W_R}, m_{N_R})$ parameter space for $m_{W_R}$ and $m_{N_R}$ up to several TeV, where $m_{N_R}$ and $m_{W_R}$ denote the masses of $N_R$ and $W_R$, respectively.

This search is focused on the regime where the $W_R$ is very heavy compared with the $N_R$ ($m_{N_R}/m_{W_R} \lesssim 0.1$), and investigates an alternative signature for $W_R \rightarrow N_R \ell$ decays, following Ref. [20]. The probed mass regime enables exploration of a parameter space complementary to the one used in previous searches that reconstruct the $N_R$ decay into a charged lepton and two jets, later referred to as the “resolved topology”. In the probed mass regime, the heavy neutrinos are produced with large transverse momentum (i.e. are highly boosted) and their decay products are very collimated. Therefore a large-radius jet (large-$R$ jet) can be used to reconstruct all or part of the $N_R$. Since jet construction in ATLAS includes the energy deposition of electrons in the calorimeters but no muons, the analysis strategy is different for the two cases. In the electron channel, the electron energy deposit is included in the constructed large-$R$ jet originating from the decay of the $N_R$, and the large-$R$ jet can be considered as a proxy for the $N_R$. In
the muon channel, the four-momentum of the muon is added to the large-R jet to obtain the $N_\text{R}$ four-momentum. The search is restricted to the scenarios where both leptons have the same flavour. No constraint on their charge is enforced, because of the higher probability of charge misidentification for high-$p_T$ electrons.

The results obtained in this search are also applicable to other variations of the LRSM that contain a right-handed gauge boson and neutral leptons, such as inverse seesaw models [21]. Additionally, this search is also applicable to R-parity-violating supersymmetry [22,23], where a selectron is resonantly produced and subsequently decays into an electron and a neutralino, and the latter decays to a lepton and quarks through a non-zero $\lambda'$ coupling. When the neutralino is boosted, its decay products can be reconstructed as a single large-R jet [24], analogous to the final state probed in this analysis.

2. ATLAS detector

The ATLAS detector [25] at the Large Hadron Collider (LHC) is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near 4$\pi$ coverage in solid angle.\footnote{ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the $z$-axis along the beam pipe. The $x$-axis points from the IP to the centre of the LHC ring, and the $y$-axis points upwards. 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 $\eta = -\ln \tan(\theta/2)$. The angular separation between two objects is defined as $\Delta \eta = \sqrt{\Delta y^2 + \Delta \phi^2}$, where $\Delta y$ and $\Delta \phi$ are the separations in $\eta$ and $\phi$. The rapidity is defined as $y = \frac{1}{2} \ln \frac{E + p_T}{E - p_T}$, where $E$ is the energy and $p_T$ is the longitudinal component of the momentum along the beam pipe. The angular separation between two objects in terms of rapidity is defined as $\Delta \eta = \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$, where $\Delta y$ and $\Delta \phi$ are the separations in $y$ and $\phi$. Momentum in the transverse plane is denoted by $p_T$.}

For $|\eta| < 2.5$, the LAr calorimeters are divided into three layers in depth. Hadronic calorimetry is provided by a steel/scintillator-tile calorimeter, segmented into three barrel structures within $|\eta| < 1.7$, and two copper/LAr hadronic endcap calorimeters, which cover the region $1.5 < |\eta| < 3.2$. The forward solid angle up to $|\eta| = 4.9$ is covered by copper/LAr and tungsten/LAr calorimeter modules, which are optimised for energy measurements of electrons/photons and hadrons, respectively. The muon spectrometer is the outermost layer of the detector, and is designed to measure muons up to $|\eta|$ of 2.7. It comprises separate trigger and high-precision tracking chambers that measure the deflection of muons in a magnetic field generated by superconducting air-core toroids. The muon trigger chambers cover up to $|\eta|$ of 2.4.

The ATLAS detector selects events using a tiered trigger system [26]. The first level is implemented in custom electronics and reduces the event rate from the bunch-crossing frequency of 40 MHz to a design value of 100 kHz. The second level is implemented in software, running on a general-purpose processor farm which processes the events and reduces the rate of recorded events to about 1 kHz.

3. Data and simulation samples

This analysis uses proton–proton ($pp$) collision data at a centre-of-mass energy $\sqrt{s} = 13$ TeV collected in 2015, 2016 and 2017 that satisfy a number of data-quality criteria. The amount of data used in this analysis corresponds to an integrated luminosity of 80 fb$^{-1}$.

Simulated signal and background events are used to optimise the event selection, to validate the performance of large-R jets containing an electron, evaluate the $Z$+jets background contribution, and calculate signal yields and their systematic uncertainties. Signal events were simulated at leading order (LO) in QCD using MG5_aMC@NLO 2.2.2 [27], with Pythia 8.186 [28] using the NNPDF23LO [29] parton distribution function [PDF] set and the A14 set of tuned parameters (tune) [30] for parton showering and hadronisation. A version of a LRSM model produced with FeynRules [31] was implemented [32] in MG5_aMC@NLO and further modified by the authors of Refs. [33,34]. This model assumes the equivalence of left and right-handed weak gauge couplings, universality of all the right-handed quarks and right-handed leptons, and the same masses for all three flavours of heavy right-handed neutrinos. Events were generated without constraints on the charge of leptons, in line with the production of Majorana neutrinos. Signal samples were generated for different $m_{W_3}$ and $m_{N_3}$ hypotheses, covering the range of 3–6 TeV for $m_{W_3}$ and 150–600 GeV for $m_{N_3}$. The production cross-sections are scaled to next-to-leading order (NLO) in QCD following Ref. [35].

The background processes considered are top-quark pairs ($t\bar{t}$), $Z$/W+jets, single top-quark, diboson and multijet production. Table 1 summarises the generator configurations used to produce the samples. The $t\bar{t}$ sample cross-sections are scaled to next-to-next-to-leading order (NNLO) in perturbative QCD, including soft-gluon resummation to next-to-next-to-leading-log (NLLN) accuracy [36], assuming a top-quark mass $m_t = 172.5$ GeV [37]. The resummation damping parameter, $h_{\text{damp}}$ in the POWHEG model, which controls the matching of matrix elements to parton showers and regulates the high-$p_T$ radiation, was set to 1.5$m_t$. The single-top-quark and $W$/Z+jets samples are scaled to the NNLO theoretical cross-sections [38–41].

The MC samples were processed through the full ATLAS detector simulation [50] based on GEANT4 [51], or a faster simulation [52] based on a parameterisation of the calorimeter response and GEANT4 for the other detector systems, and reconstructed and analysed using the same procedure and software as used for the data. The signal modelling is found to be consistent between the
full and the fast simulation, after application of dedicated calibration procedures. To simulate the effects of additional collisions in the same and neighbouring bunch crossings (pile-up), additional minimum-bias events generated using PyTHIA with the A3 tune [53] and MSTW2008 [54] PDF set were overlaid onto the signal and background simulated events, with a distribution of the number of collisions matching that of the data. To account for the differences in particle reconstruction, trigger, identification and isolation efficiencies between simulation and data, correction factors are derived in dedicated measurements and applied to the simulated events.

4. Event selection and characterisation

The event selection is designed to select signal events, while rejecting background events, based on the signal topology. The events are selected if they contain exactly two same-flavour leptons (with no charge requirement) and at least one tight large-R jet [55] with large transverse momentum $p_T > 200$ GeV. The highest-$p_T$ (leading) lepton should be back-to-back in azimuth with the large-R jet, while other (subleading) lepton should be contained in the large-R jet. In Fig. 2, the reconstructed $p_T$ distributions of the leading and subleading lepton, as well as of the selected large-R jet, and the candidate $N_R$ are shown for four representative signal samples. The leading electron and the large-R jet are balanced in $p_T$, with the maxima at roughly half of the corresponding $m_{WW}$ values. The leading muon $p_T$ shows the same characteristic, but the $p_T$ of the large-R jet is lower and has a broader distribution, as it does not contain the energy from the subleading muon, and the muon $p_T$ resolution for high-$p_T$ muons is worse. The reconstructed mass of the $N_R$ in each event is consistent with the expected value. The natural width of the resonance varies with the mass and is 100 GeV for $m_{WW} = 3$ TeV. At this mass the width of the reconstructed mass peak is about 150 GeV in the electron channel, and about 350 GeV in the muon channel.

The detailed selection criteria are listed in Table 2 and further discussed below. Events with electrons and muons are analysed separately. The leading lepton is required to pass a single-lepton trigger. For data collected in 2015, the lowest $p_T$ trigger threshold is 24 GeV and 20 GeV for single-electron and single-muon triggers, respectively. For 2016 and 2017 data, the threshold is 26 GeV for both.

Electron candidates are reconstructed from an isolated energy deposit in the electromagnetic calorimeter matched to an ID track, within the fiducial region of transverse energy $p_T > 26$ GeV and $|\eta| < 2.47$. Candidates within the transition region between the barrel and endcap electromagnetic calorimeters, $1.37 < |\eta| < 1.52$, are excluded. Muon candidates are reconstructed by combining tracks found in the ID with tracks found in the muon spectrometer and are required to satisfy $p_T > 28$ GeV and $|\eta| < 2.5$. Electrons and muons are required to be isolated using criteria based on tracks and calorimeter energy deposits. For track-based isolation, the discriminating variable is the scalar sum of the $p_T$ of tracks coming from the primary vertex in a variable-size cone around the lepton direction (excluding the track identified as the lepton), with the cone size given by the maximum of $\Delta R = 10$ GeV/$p_T^2$ and $R_0$, where $p_T^2$ is the $p_T$ of the lepton, and $R_0$ is a constant, set to 0.2 for electrons, and 0.3 for muons. For calorimeter-based isolation, the discriminating variable is the sum of the transverse energies of topological clusters [56] around the lepton in a cone of size $\Delta R = 0.2$.

The inputs to the jet construction are noise-suppressed three-dimensional topological clusters of energy deposits in the calorimeters, built from calorimeter cells [56]. They are classified as either electromagnetic or hadronic, based on their shape, depth and energy density. The energy clusters are calibrated to the hadronic scale. The momenta of the jets are corrected for energy losses in passive material and for the non-compensating response of the calorimeter [57]. The large-R jets are constructed with the anti-$k_t$ algorithm [58] with a radius parameter of $R = 1.0$, through its implementation in Fastjet [59]. They are further trimmed [55] to reduce the contamination from soft uncorrelated radiation. In this method, the original constituents of the jets are reclustered using the $k_t$ algorithm [60] with a radius parameter $R_{sub} = 0.2$ in order to produce a collection of subjets. These subjets are discarded if they carry less than a specific fraction ($f_{cut} = 5\%$) of the $p_T$ of the original jet. The remaining constituents are summed to form the four-momentum of the final jet.

In the electron channel, the large-R jets are required to have a mass of at least 50 GeV, while no such requirement is applied in the muon channel. This is because in the former case, the large-R jet includes the electron, while in the muon channel, the muon is not included in the large-R jet.

Small-radius jets constructed with the anti-$k_t$ algorithm using energy clusters calibrated to the electromagnetic scale with a radius parameter of $R = 0.4$ are used to check for possible overlap between objects, and to perform $b$-tagging (described in Section 5). In the muon channel, the event is discarded if either muon satisfies $\Delta R_{\ell,\mu,\text{jet}} < \min(0.4, 0.04 + 10 \text{ GeV}/p_T^2)$, in order to avoid jets formed from energy deposits associated to high energy muons. In the electron channel, for the leading electron, first all small-radius jets within $\Delta R_{\ell} = 0.2$ of a selected electron are removed. Then the event is discarded if the leading electron is within $\Delta R_{\ell} = 0.4$ of a remaining small-radius jet. This is referred to as the nominal overlap removal procedure for electrons. A modified procedure, described in Section 5, is applied for the subleading electron as, unlike muons, electron clusters can overlap with a jet and the signal efficiency drops off if the standard overlap removal approach is followed.

Further requirements based on the characteristics of the signal are applied:

\[^2\text{Collision vertices are formed from tracks with } p_T > 400 \text{ MeV. If an event contains more than one vertex candidate, the one with the highest } \sum p_T^2 \text{ of its associated tracks is selected as the primary vertex.}\]

<table>
<thead>
<tr>
<th>Process</th>
<th>Top quark</th>
<th>W + jets</th>
<th>Z + jets</th>
<th>Diboson</th>
<th>Multijet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator</td>
<td>Powheg [42–45] + PyTHIA8</td>
<td>Powheg + PyTHIA8</td>
<td>Sherpa [46]</td>
<td>PyTHIA8</td>
<td></td>
</tr>
<tr>
<td>ME order in pQCD</td>
<td>NLO</td>
<td>NLO</td>
<td>LO</td>
<td>LO</td>
<td></td>
</tr>
<tr>
<td>Version</td>
<td>v2, 8.186</td>
<td>v2, 8.186</td>
<td>v2, 8.186</td>
<td>v2, 8.186</td>
<td></td>
</tr>
<tr>
<td>PDF (ME, PS)</td>
<td>NNPDF30NLO [47], NNPDF30LO</td>
<td>CTEQ6L1 [48], CT10 [49]</td>
<td>NNPDF30NLO, NNPDF30LO</td>
<td>NNPDF30NLO, NNPDF30LO</td>
<td></td>
</tr>
<tr>
<td>PS tune</td>
<td>A14</td>
<td>Default</td>
<td>A14</td>
<td>A14</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 2. Reconstructed distributions of the transverse momentum of the leading lepton, subleading lepton, the selected large-\( R \) jet, and the \( N_k \) candidate mass in electron (left column) and muon (right column) channels for four representative signal samples in the signal region. The indices 1 and 2 indicate leading and subleading lepton, respectively.
Table 2

Object selection criteria. The significance of the transverse impact parameter is defined as the transverse impact parameter divided by its uncertainty, \( \sigma_R \), of tracks relative to the primary vertex with the highest sum of track \( p_T \). The longitudinal impact parameter \( z_R \) is multiplied by \( \sin \theta \), where \( \theta \) is the polar angle of the track.

<table>
<thead>
<tr>
<th>Lepton:</th>
<th>Electron channel</th>
<th>Muon channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_T )</td>
<td>&gt;35 GeV</td>
<td>&gt;28 GeV</td>
</tr>
<tr>
<td>(</td>
<td>\eta</td>
<td>)</td>
</tr>
<tr>
<td>Leading lepton quality</td>
<td>Medium [61], isolated [61]</td>
<td>Medium [62], isolated [62]</td>
</tr>
<tr>
<td>Subleading lepton quality</td>
<td>Medium, no isolation</td>
<td>Medium, no isolation</td>
</tr>
<tr>
<td>Transverse impact parameter significance</td>
<td>(</td>
<td>d_0</td>
</tr>
<tr>
<td>Longitudinal impact parameter</td>
<td>(</td>
<td>z_0</td>
</tr>
</tbody>
</table>

| Trimmed large-\( R \) jet: | |
| \( p_T \) | >300 GeV |
| \( |\eta| \) | <2.0 |
| Mass | >50 GeV | None |

- \( \Delta R \) between the subleading lepton and the large-\( R \) jet is required to be less than 1, in order for the lepton to be inside the jet.
- \( \Delta \phi \) between the leading lepton and the large-\( R \) jet is required to be greater than 2, in order to have a balanced topology between the \( N_R \) and the lepton from the \( W_R \) decay.
- In order to reduce the \( Z+\)jets background, events with a dilepton invariant mass of less than 200 GeV are vetoed, and the \( \Delta \phi \) between the leading and subleading leptons is required to be greater than 1.5.

After applying these requirements, simulation studies show that the background consists mainly of \( t\bar{t} \) and \( Z+\)jets processes (including off-shell \( Z/\gamma^* \) production), while contributions from \( W+\)jets, single-tag-quark and multijet processes are negligible. Requirements on \( b \)-tagged jets are applied, as the \( W_R \) in the signal can decay to a top and bottom quark pair.

The final discriminating observable used in the analysis is the reconstructed mass of the \( W_R \) candidate, \( m_{\text{rec}W_R} \). In the electron channel, the selected large-\( R \) jet corresponds to the \( N_R \) candidate, and therefore the \( W_R \) candidate four-momentum is obtained by adding the large-\( R \) jet and the leading electron four-momenta. In the muon channel, the \( N_R \) candidate four-momentum is obtained by adding the four-momentum of the selected large-\( R \) jet to that of the muon contained in the jet. The \( W_R \) four-momentum is obtained by adding the \( N_R \) candidate four-momentum to that of the leading muon. In both cases, if there is more than one large-\( R \) jet in the event, the large-\( R \) jet with the largest mass is used.

Based on the range of \( m_{\text{rec}W_R} \), control and signal regions (CR, SR) are defined as specified in Table 3. The CR is defined in a region of low reconstructed \( m_{\text{rec}W_R} \) corresponding to a parameter space excluded by previous searches [14]. The background in the SR is evaluated from a combined fit of MC and data events in the CR (described in Section 6). To test the performance of large-\( R \) jets containing electrons, a validation region (VR) is defined with a selection orthogonal to the CR and the SR. This requires a muon balanced in \( p_T \) by a large-\( R \) jet with an electron inside. By construction, the VR is dominated by \( t\bar{t} \) events decaying dileptonically to \( e\mu \) final states.

In Fig. 3, good agreement is observed between data and simulation in the \( m_{\text{rec}W_R} \) distributions in the control regions of the electron and muon channels, as well as in the validation region. In the bottom-right plot, the selection efficiency times acceptance is shown for different signal samples. The efficiency decreases for lower \( m_{\text{rec}W_R} \) and higher \( m_{\text{rec}W_R} \) values. The largest inefficiency arises from the difficulty of electron reconstruction close to hadronic activity, which is discussed in the next section. The probability of producing an off-shell \( W_R \) increases with the mass. This can result in a less boosted \( N_R \), explaining the drop in signal efficiency for higher \( m_{\text{rec}W_R} \) values.

5. Performance of large-\( R \) jets containing electrons

A distinguishing feature of this search is the use of large-\( R \) jets containing electrons as a proxy for \( N_R \) in the electron channel. Since the large-\( R \) jet construction procedure is based on energy clusters calibrated at the hadronic scale, the effect of a non-negligible fraction of EM clusters in the large-\( R \) jet needs to be investigated. The analysis does not use the kinematic properties of the identified electron inside the large-\( R \) jets to reconstruct the \( N_R \) or \( W_R \) invariant masses, but uses the mass of the large-\( R \) jet, which includes the associated electron clusters. The presence of real hadronic activity close to an electron may affect the reconstruction of the electron.

The jet mass and energy scales, JMS and JES, defined as the average of the ratio of the mass or energy of the reconstructed and corresponding generator-level large-\( R \) jets, are used to study the effect of including the large EM-cluster of the electron in the jet reconstruction. The matching between detector-level and generator-level large-\( R \) jets is performed with \( \Delta R < 0.75 \). The generator-level jet is obtained by clustering stable final-state particles (with lifetime greater than 30 ps) except muons and neutrinos using the same jet algorithm, radius parameter and trimming used at the detector-level. The JMS and JES of the selected large-\( R \) jets for a few representative signal samples are shown in Fig. 4 as a function of the ratio of the energy of the electron to the energy of the large-\( R \) jet. This ratio can be considered a proxy for the electromagnetic energy fraction in the large-\( R \) jet. Constant values of JES and JMS within a few percent of unity indicate that the large-\( R \) jet has only a weak dependence on the fraction of electromagnetic energy inside the jet, and thus no particular additional corrections are required for the signal large-\( R \) jets. Typical numbers for the large-\( R \) jet mass resolution (JMR) in signal events are about 4-6% in the electron channel and about 7-14% in the muon channel, while the large-\( R \) jet energy resolution (JER) is about 3-5% GeV in both channels. As opposed to the muon channel, in the electron channel the large-\( R \) jet does contain the electron as a compact and high energy deposit. This implies a more precise angular distribu-
tion of the energies in the jet and thus a better JMR in the electron channel.

In signal events, as almost all selected large-R jets contain activity from both the \(W_R\) hadronic decay and the nearby electron, application of the nominal overlap removal procedure, as described in Section 4, for the subleading electron results in a large loss of signal efficiency. However, it is observed that removing events where the electron and the nearest jet are within \(\Delta R < 0.04\) retains a sizeable fraction of the signal events and rejects a large fraction of the background events. The discarded events are dominated by the case where isolated electrons are reconstructed as jets.

A study is performed to check the validity of the electron efficiency correction factors, which account for potential differences in electron reconstruction, identification and isolation efficiency between data and simulation and are derived using well-isolated electrons [61]. A sample of \(t\bar{t}\) events decaying into a mixed-flavour dileptonic final state is chosen. The leading lepton is chosen to be a muon with nominal isolation requirements, and the subleading lepton is chosen to be an electron with no isolation requirements. The rest of the selection is the same as the signal selection, except that the events are selected with at least one \(b\)-tagged small-radius jet. The \(b\)-tagging is based on a multivariate algorithm [63]. Several observables based on the long lifetime of \(b\)-hadrons and the
b- to c-hadron decay topology, are used as algorithm input to discriminate between b-jets, c-jets and other jets. The b-tagging requirement corresponds to the 70% efficient working point for b-jets, as determined in simulated tt events, while the rejection rates of τ-jets, c-jets and light-flavour jets are 55, 12 and 381, respectively [64,65].

The large-R jet requirements are the same as in the nominal selection. Only the events in which the electrons and the nearest small-radius jet are within 0.04 < ΔR< 0.4 are studied. The distributions of electron pT and ΔRy between the electron and the small-radius jet show satisfactory agreement between data and simulation, as shown in Fig. 5. An additional uncertainty of 30% on the electron efficiency for electrons within 0.04 < ΔR< 0.4 is derived from the difference in yields between data and the simulation, statistical uncertainties as well as the theoretical and b-tagging uncertainties on the simulation.

6. Background estimation and systematic uncertainty

While the CR is dominated by tt events, the fraction of Z+jets events becomes larger at higher masses as they have a less steeply falling mass distribution than tt events, as shown in Fig. 3. In order to take this into account in evaluating the background in the SR, which is located at higher masses, a data-driven approach is used to evaluate the tt contribution in conjunction with a fitted MC prediction of the Z+jets background. The fit to the data in the CR is extrapolated to the SR.

Different steeply falling functions are tested, motivated by Refs. [66,67], where they are found to fit steeply falling distributions like the scalar sum of jet transverse momenta in multijet events or the diejet mass. It is observed that the functional form $A \exp(-Bu)/u^c$ describes the data distribution in the CR the best, while the functional form $A'(1−u)^B(1+u)^c/u^c$ best describes the Z+jets MC distribution. In both cases, $u = m_{W_R}^{\text{reco}}/\sqrt{s}$ and the choice of fit function is determined by the goodness of fit (based on the $\chi^2$ per degree of freedom) as well as by the best agreement with the yields from the MC background estimate in the CR. First, the fit parameters $A$, $B$, and $C$ are determined from Z+jets MC using a reconstructed $m_{W_R}^{\text{reco}}$ range of 400–4000 GeV, then the fit to data is performed using the function $A \exp(-Bu)/u^c + A'(1−u)^B(1+u)^c/u^c$, to determine the values of the parameters $A$, $B$ and $C$. This functional form is fitted in the CR range of 600–1800 GeV, where the range is chosen depending on the goodness of the fits. The slope of the background fit is steeper in the muon channel compared to the electron channel.

In the VR the fit performed for reconstructed W_R candidate masses 600–1800 GeV is extrapolated to the region > 2 TeV and the fit prediction is compared to the data yield finding consistency. In order to assess the systematic uncertainty related to the tt data-driven fit, variations of the data fit range are made, and the largest change in the SR yield obtained from these variations is taken as the uncertainty. The same is done for the Z+jets MC fit, and the uncertainty is added in quadrature to the uncertainty derived from fitting alternative Z+jets MC samples obtained after varying the scale (by factors of two and one half) and using alternative PDF sets [14]. This uncertainty is larger than the difference yield obtained using POWHEG + PYTHIA8. The relative uncertainty of the background yield in the SR is about 25% for both channels. Statistical uncertainties on the fits are estimated using pseudo-experiments built by varying the input data points within their statistical uncertainties. The resultant background fit, along with the estimated uncertainty is shown in Fig. 6.

7. Systematic uncertainties of the signal yield

Systematic uncertainties affect the shape and normalisation of the $m_{W_R}^{\text{reco}}$ distributions, thereby changing the signal yield. The dominant uncertainties in the SR are shown in Table 4. They can be classified as originating from experimental or theoretical sources.

The yields from simulated samples are affected by uncertainties related to the description of the detector response. The dominant uncertainty is related to the electron and muon identification, which is (4–20)% in the electron channel (including the additional 30% uncertainty for electrons reconstructed nearby a small-radius jet) and (4–8)% in the muon channel, depending on the values of $m_{W_R}$ and $m_{t_R}$. The uncertainties related to the electron trigger, reconstruction, and isolation are (4–5)%. The uncertainties related to the muon trigger and isolation are about 1%. These uncertainties are assessed by comparing data and simulation samples of $Z \to \ell^+\ell^−$ decays [62,61]. The simulation is used to extrapolate to lepton $p_T$ beyond a few hundred GeV. The other uncertainties such as those related to JES and JMS of the large-R jets are evaluated by comparing the ratio of calorimeter-based to track-based measurements in multijet events in data and simulation [68,69,57]. The uncertainties related to JMR and JER modelling are evaluated by increasing the nominal resolution by 20% [70] and 2% respectively. These uncertainties are at sub-percent level. The average number of interactions per bunch crossing is rescaled to improve the agreement of simulation with data, and the corresponding uncertainty, as large as the correction, has an effect of 0.5% in the
electron channel, and up to 3% in the muon channel, caused by the lack of a large-R jet mass threshold in the latter case. The uncertainty in the 2015, 2016 and 2017 integrated luminosity is 2%. It is derived from the calibration of the luminosity scale using ×-y beam-separation scans, following a methodology similar to that detailed in Ref. [71], and using the LUCID-2 detector for the baseline luminosity measurements [72].

The theory uncertainty of the signal yield is evaluated by varying the renormalisation and factorisation scales by factors of 2 and 0.5, and using alternative PDF sets, CTEQ6L1 [73] and MSTW2008LO [54] via SysCalc [74]. The dominant effect on the yield comes from the scale variation. The total effect on the signal yield is at most 10%. The uncertainties on the background yield are described in Section 6.

8. Results

Fig. 6 shows the  in the electron and muon channels. In order to search for the presence of a massive resonance, yields from simulated signal samples and the data-driven background estimate (corresponding to  in 2 TeV) are fit to the data, separately in the electron and muon channels, using a single bin covering the entire SR. The integral of the background functional shape in the SR is used to evaluate the expected background, as shown in Table 5. The statistical analysis is based on a likelihood fit to data. The likelihood is constructed using a single-bin Poissonian counting-experiment approach based on the RootStats framework [75,76]. The uncertainties of the background yield are incorporated as Gaussian constraints in the likelihood itself in terms of a set of nuisance parameters.

The compatibility of the observed data with the background-only hypothesis is tested by fitting the data with the background model to obtain the p-value. The significance of an excess can be quantified by the probability (p-value) that a background-only experiment is more signal-like than observed. The p-values are given in Table 5. In the electron channel, 8 events are observed, while the expected background is 2.8 and 2.5 events in the muon channel.

Table 4

<table>
<thead>
<tr>
<th>Component</th>
<th>Electron channel (%)</th>
<th>Muon channel (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton identification</td>
<td>4–20</td>
<td>4–8</td>
</tr>
<tr>
<td>Lepton isolation</td>
<td>4–5</td>
<td>1.0–1.5</td>
</tr>
<tr>
<td>Lepton reconstruction</td>
<td>4–5</td>
<td>1–4</td>
</tr>
<tr>
<td>Lepton trigger</td>
<td>4–5</td>
<td>0.3</td>
</tr>
<tr>
<td>Pile-up</td>
<td>&lt;0.5</td>
<td>2–3</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Theory</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 5

<table>
<thead>
<tr>
<th>Component</th>
<th>Electron channel</th>
<th>Muon channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal (mWt = 3 TeV, mNh = 150 GeV)</td>
<td>346±48</td>
<td>411±36</td>
</tr>
<tr>
<td>Signal (mWt = 3 TeV, mNh = 300 GeV)</td>
<td>471±42</td>
<td>429±26</td>
</tr>
<tr>
<td>Signal (mWt = 4 TeV, mNh = 400 GeV)</td>
<td>66±6</td>
<td>57±4</td>
</tr>
<tr>
<td>Expected background</td>
<td>2.8±0.5</td>
<td>1.9±0.5</td>
</tr>
<tr>
<td>Observed events</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Significance</td>
<td>2.4σ</td>
<td>1.2σ</td>
</tr>
<tr>
<td>p-value</td>
<td>0.0082</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Lower limits on the masses of N0 and Wt for each of the considered signal scenarios are determined by using the profile likelihood test statistic [77] with the CLs method [78,79]. The inputs to the limit calculations are the signal cross-sections and the signal efficiencies in the mWt−mNh grid. A linear interpolation between several benchmark samples in the mWt range 3–6 TeV and in the mNh range 0.1–1.8 TeV is performed. The results are shown in Fig. 7, separately for electron and muon channels. The CLs is computed using pseudo-experiments. The data statistical uncertainty has a significantly larger impact on the limits than the systematic uncertainties. The leading systematic uncertainty is the background modelling uncertainty and, in the case of the Wt and N0 mass limits, the signal theory uncertainties or the electron identification uncertainty, depending on the signal mass values.

The excluded region extends to mWt of 4.8 TeV in the electron channel and to 5 TeV in the muon channel, for mNh of 0.4–0.5 TeV where the search is most sensitive. For mNh of 1.8 TeV the excluded mWt is 4 TeV in both channels. The limits in the electron channel are weaker compared to those in the muon channel for low mNh values, as the electron reconstruction and identification efficiency is lower for these Wt, N0 mass configurations. For higher mNh values, the worsening muon resolution and reconstruction efficiency result in weaker limits in the muon channel.
tour for the resolved topology [14] is overlaid for both channels in Fig. 7, to indicate the complementarity of the present analysis, as lower values of $m_{N_R}$ are excluded.

As the analysis is a single-bin Poissonian counting experiment, the limits on the cross-section are only sensitive to the efficiencies of each signal, and do not depend significantly on $m_{W_R}$ and $m_{N_R}$. The observed limits on the number of selected signal events are 13.3 events for the electron channel and 8.1 for the muon channel. The corresponding expected limits are 5.4 events for the electron channel and 4.9 for the muon channel.

9. Summary

A search for a heavy right-handed $W_R$ boson decaying into a boosted right-handed neutrino $N_R$ is presented using 80 fb$^{-1}$ of $\sqrt{s} = 13$ TeV proton–proton collision data recorded by the ATLAS detector at the LHC. Both electron and muon final states are analysed for the decay into two same-flavour leptons, $W_R \to N_R\ell$, $N_R \to \ell'\text{jets}$. In the electron final state, the analysis makes use of a large-$R$ jet containing an electron as a proxy for $N_R$, while in the muon channel, the muon four-momentum is added to the large-$R$ jet four-momentum. The observed $m_{W_R}$ spectrum is consistent with the background prediction and exclusion limits at 95% confidence level are set on the $N_R$ masses as a function of the $W_R$ masses. The excluded region extends to $m_{W_R}$ of 4.8 TeV in the electron channel and to 5 TeV in the muon channel, for $m_{N_R}$ of 0.4–0.5 TeV. The use of large-$R$ jets results in a significant reduction of the background contribution. Due to the signal topology, and a higher integrated luminosity this result represents an increase of the exclusion limits in a complementary parameter space compared with previous results that reconstruct the $W_R$ as two resolved jets.

Acknowledgements

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

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MESMT CR, MPO CR and VSC CR, Czech Republic; DURAS and DNSR, Denmark; IN2P3-CNRS, CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT, JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCUK, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IIFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America; in addition, individual groups and members have received support from BKDFK, Canarie, CRC and Compute Canada, Canada; COST, ERC, ERDF, Horizon 2020, and Marie Sklodowska-Curie Actions, European Union; Investissements d’ Avenir Labex and Idex, ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSF, Greece; BSF-NSF and GIF, Israel; CERCA Programme Generalitat de Catalunya, Spain; The Royal Society and Leverhulme Trust, United Kingdom.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [80].

References

The ATLAS Collaboration


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 (i) Department of Physics, Ankara University, Ankara; (ii) Istanbul Aydin University, Istanbul; (iii) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
5 LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, 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, 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, University of Texas at Austin, Austin, TX, United States of America
12 (a) Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul; (b) Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul; (c) Department of Physics, Bogazici University, Istanbul; (d) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
13 Institut für Physik, Azerbaijan Academy of Sciences, Baku, Azerbaijan
14 Institut de Fisica d’Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain
15 (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Physics Department, Tsinghua University, Beijing; (c) Department of Physics, Nanjing University, Nanjing;
16 (a) University of Chinese Academy of Science (UCAS), Beijing, China
17 Institute of Physics, University of Belgrade, Belgrade, Serbia
18 Department for Physics and Technology, University of Bergen, Bergen, Norway
19 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States of America
20 Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany
21 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
22 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
23 Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogota, Colombia
24 (a) INFN Bologna and Università di Bologna, Dipartimento di Fisica; (b) INFN Sezione di Bologna, Italy
25 Physikalisches Institut, Universität Bonn, Bonn, Germany
26 Department of Physics, Boston University, Boston, MA, United States of America
27 Department of Physics, Brandeis University, Waltham, MA, United States of America
28 (a) Transilvania University of Brașov, Brașov; (b) Iohia 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;
29 (a) West University in Timisoara, Timisoara, Romania
30 (a) Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
31 Physics Department, Brookhaven National Laboratory, Upton, NY, United States of America
32 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
33 California State University, CA, United States of America
34 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
35 (a) Department of Physics, University of Cape Town, Cape Town; (b) Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg; (c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
36 Department of Physics, Carleton University, Ottawa, ON, Canada
37 (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Énergies – Université Hassan II, Casablanca; (b) Faculté des Sciences, Université Ibn-Tofail, Kénitra; (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
38 CERN, Geneva, Switzerland
39 Enrico Fermi Institute, University of Chicago, Chicago, IL, United States of America
40 LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France
41 Nevis Laboratory, Columbia University, Irvington, NY, United States of America
42 Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
43 (a) Dipartimento di Fisica, Università della Calabria, Rende; (b) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
44 Physics Department, Southern Methodist University, Dallas, TX, United States of America
45 Physics Department, University of Texas at Dallas, Richardson, TX, United States of America
46 National Centre for Scientific Research “Demokritos”, Agia Paraskevi, Greece
47 (a) Department of Physics, Stockholm University; (b) Oskar Klein Centre, Stockholm, Sweden
48 Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany
49 Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
50 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
51 Department of Physics, Duke University, Durham, NC, United States of America
52 SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
53 INFN e Laboratori Nazionali di Frascati, Frascati, Italy
54 Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
55 II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
56 Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland
57 (a) Dipartimento di Fisica, Università di Genova, Genova; (b) INFN Sezione di Genova, Italy
58 II. Physikalisches Institut, Justus-Liebig-Universität Gießen, Gießen, Germany
59 SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom

132 LAI, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
133 Graduate School of Science, Osaka University, Osaka, Japan
134 Department of Physics, University of Oslo, Oslo, Norway
135 Department of Physics, Oxford University, Oxford, United Kingdom
136 LPHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France
137 Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
138 Konstantinov Nuclear Physics Institute of National Research Centre “Kurchatov Institute”; PNI, St. Petersburg, Russia
139 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States of America
140 (a) Laboratório de Instrumentação e Física Experimental de Partículas – LIP; (b) Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa; (c) Departamento de Física, Universidade de Coimbra, Coimbra; (d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; (e) Departamento de Física, Universidade do Minho, Braga; (f) Universidad de Granada, Granada (Spain); (g) Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
141 Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
142 Czech Technical University in Prague, Prague, Czech Republic
143 Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
144 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
145 RFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
146 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States of America
147 (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
148 Department of Physics, University of Washington, Seattle, WA, United States of America
149 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
150 Department of Physics, Shinshu University, Nagano, Japan
151 Department Physik, Universität Siegen, Siegen, Germany
152 Department of Physics, Simon Fraser University, Burnaby, BC, Canada
153 SLAC National Accelerator Laboratory, Stanford, CA, United States of America
154 Physics Department, Royal Institute of Technology, Stockholm, Sweden
155 Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY, United States of America
156 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
157 School of Physics, University of Sydney, Sydney, Australia
158 Institute of Physics, Academia Sinica, Taipei, Taiwan
159 (a) E. Andronikashvili Institute of Physics, Tbilisi, Georgia; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
160 Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel
161 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
162 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
163 International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan
164 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
165 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
166 Tomsk State University, Tomsk, Russia
167 Department of Physics, University of Toronto, Toronto, ON, Canada
168 (a) TRIUMF, Vancouver, BC; (b) Department of Physics and Astronomy, York University, Toronto, ON, Canada
169 Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
170 Department of Physics and Astronomy, Tufts University, Medford, MA, United States of America
171 Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States of America
172 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
173 Department of Physics, University of Illinois, Urbana, IL, United States of America
174 Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia – CSIC, Valencia, Spain
175 Department of Physics, University of British Columbia, Vancouver, BC, Canada
176 Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
177 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany
178 Department of Physics, University of Warwick, Coventry, United Kingdom
179 Waseda University, Tokyo, Japan
180 Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel
181 Department of Physics, University of Wisconsin, Madison, WI, United States of America
182 Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
183 Department of Physics, Yale University, New Haven, CT, United States of America
184 Yerevan Physics Institute, Yerevan, Armenia

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

Also at CERN, Geneva, Switzerland.

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

d Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.

Also at Departamento de Física de la Universidad Autonoma de Barcelona, Barcelona, Spain.

Also at Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal.

Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah, United Arab Emirates.

Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.

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

Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.

Also at Department of Physics, California State University, East Bay, United States of America.

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

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

Also at Department of Physics, King’s College London, London, United Kingdom.

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

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

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

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

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

Also at Giresun University, Faculty of Engineering, Giresun, Turkey.

Also at Graduate School of Science, Osaka University, Osaka, Japan.
Also at Hellenic Open University, Patras, Greece.

Also at Institut Catalana de Recerca i Estudis Avançats, ICREA, Barcelona, Spain.

Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

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

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

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

Also at Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China.

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

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

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

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

Also at Instituto de Física Teorica, IFT-UAM/CSIC, Madrid, Spain.

Also at Istanbul University, Dept. of Physics, Istanbul, Turkey.

Also at Joint Institute for Nuclear Research, Dubna, Russia.

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

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

Also at LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France.

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

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

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

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

Also at Physics Dept, University of South Africa, Pretoria, South Africa.

Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany.

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

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

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

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

Also at TRIUMF, Vancouver BC, Canada.

Also at Universita di Napoli Parthenope, Napoli, Italy.

Deceased.