Search for production of WW/WZ resonances decaying to a lepton, neutrino and jets in pp collisions at √s = 8 TeV with the ATLAS detector


DOI 10.1140/epjc/s10052-015-3425-6

Publication date 2015

Document Version Final published version

Published in European Physical Journal C

License CC BY


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).

UvA-DARE is a service provided by the library of the University of Amsterdam (https://dare.uva.nl)
Search for production of $WW/ZZ$ resonances decaying to a lepton, neutrino and jets in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

ATLAS Collaboration

CERN, 1211 Geneva 23, Switzerland

Received: 17 March 2015 / Accepted: 22 April 2015 / Published online: 12 May 2015
© CERN for the benefit of the ATLAS collaboration 2015. This article is published with open access at Springerlink.com

Abstract A search is presented for narrow diboson resonances decaying to $WW$ or $ZZ$ in the final state where one $W$ boson decays leptonically (to an electron or a muon plus a neutrino) and the other $W/Z$ boson decays hadronically. The analysis is performed using an integrated luminosity of 20.3 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 8$ TeV collected by the ATLAS detector at the large hadron collider. No evidence for resonant diboson production is observed, and resonance masses below 700 and 1490 GeV are excluded at 95 % confidence level for the spin-2 Randall–Sundrum bulk graviton $G^*$ with coupling constant of 1.0 and the extended gauge model $W'$ boson respectively.

1 Introduction

Several new physics scenarios beyond the standard model (SM), such as technicolour [1–3], warped extra dimensions [4–6], and grand unified theories [7], predict new particles that predominantly decay to a pair of on-shell gauge bosons. In this paper, a search for such particles in the form of $WW/ZZ$ resonances where one $W$ boson decays leptonically ($W \rightarrow \ell \nu$ with $\ell = e, \mu$) and the other $W/Z$ boson decays hadronically ($W/Z \rightarrow q\bar{q}/q\bar{q}$, with $q, q' = u, c, d, s$ or $b$) is presented. This search makes use of jet-substructure techniques for highly boosted $W/Z$ bosons decaying hadronically and is optimized to significantly improve the sensitivity to high mass resonances compared to previous searches.

Two benchmark signal models are used to optimize the analysis strategy and interpret the search results. A spin-2 Kaluza–Klein (KK) graviton ($G^*$) is used to model a narrow resonance decaying to a $WW$ final state. The KK graviton interpretation is based on an extended Randall–Sundrum model of a warped extra dimension (RS1) [8] where the SM fields can propagate into the bulk of the extra dimension. This extended “bulk” RS model, referred to as bulk RS hereafter, avoids constraints on the original RS1 model from limits on flavour-changing neutral currents and electroweak precision tests, and has a dimensionless coupling constant $k/M_{Pl} \sim 1$, where $k$ is the curvature of the warped extra dimension and $M_{Pl} = M_{Pl}/\sqrt{8\pi}$ is the reduced Planck mass. A spin-1 gauge boson ($W'$) of the sequential standard model with modified coupling to $WZ$, also referred to as the extended gauge model (EGM) [7], is used to model a narrow resonance that decays to a $WZ$ final state. The EGM introduces $W'$ and $Z'$ bosons with SM couplings to fermions and with the coupling strength of the heavy $W'$ to $WZ$ modified by a mixing factor $\xi = c \times (m_W/m_{W'})^2$ relative to the SM couplings, where $m_W$ and $m_{W'}$ are the pole masses of the $W$ and $W'$ bosons respectively, and $c$ is a coupling scaling factor. In this scenario the partial width of the $W'$ boson scales linearly with $m_{W'}$, leading to a narrow resonance over the accessible mass range. The width of the $W'$ resonance at 1 TeV is approximately 35 GeV.

Searches for these particles in several decay channels have been performed at the Tevatron and the large hadron collider (LHC) and are reported elsewhere [9–13]. Previous results from the ATLAS experiment in the $\ell\ell q\bar{q}$ channel excluded EGM $W'$ bosons with masses up to 1.59 TeV for $WZ$ final states and RS1 gravitons with $k/M_{Pl} = 1$ and masses up to 740 GeV for $ZZ$ final states [13]. The CMS experiment set limits on the production cross sections of bulk RS gravitons as well as excluded RS1 gravitons with $k/M_{Pl} = 0.1$ for masses up to 1.2 TeV and $W'$ bosons for masses up to 1.7 TeV [9].

This analysis is based on $pp$ collision data at a centre-of-mass energy $\sqrt{s} = 8$ TeV corresponding to an integrated luminosity of 20.3 fb$^{-1}$ collected by the ATLAS experiment at the LHC.

2 The ATLAS detector

The ATLAS detector [14] is a general-purpose particle detector used to investigate a broad range of physics processes. It
includes inner tracking devices surrounded by a superconducting solenoid, electromagnetic and hadronic calorimeters and a muon spectrometer with a toroidal magnetic field. The inner detector (ID) provides precision tracking of charged particles with pseudorapidity $|\eta| < 2.5$. The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. It is composed of sampling calorimeters with either liquid argon (LAr) or scintillator tiles as the active media. The muon spectrometer (MS) provides muon identification and measurement for $|\eta| < 2.7$. The ATLAS detector has a three-level trigger system to select events for offline analysis.

3 Monte Carlo samples

Simulated event samples are used to define the event selection and optimize the analysis. Benchmark signal samples are generated for a range of resonance masses from 300 to 2500 GeV in steps of 100 GeV. The bulk RS $G^*$ signal events are generated with CalcHEP [15], using $k/\sqrt{\tmathcal{M}_t} = 1.0$, interfaced to PYTHIA8 [16] to model fragmentation and hadronization, and the EGM $W'$ signal is generated using PYTHIA8 with $c = 1$. The factorization and renormalization scales are set to the generated resonance mass. The CTEQ6L1 [17] and MSTW2008LO [18] parton distribution functions (PDFs) are used for the $G^*$ and $W'$ signal samples respectively. The $W'$ cross section is normalized to a next-to-next-to-leading-order (NNLO) calculation in $a_t$ from ZWPR [19].

Simulated event samples are used to model the shape and normalization of most SM background processes. The main background sources in the analysis arise from $W$ bosons produced in association with jets ($W + \text{jets}$), followed by top-quark and multijet production, with smaller contributions from dibosons and $Z + \text{jets}$. Production of $W$ and $Z$ bosons in association with up to five jets is simulated using SHERPA 1.4.1 [20] with the CT10 PDFs [21], where $b$- and $c$-quarks are treated as massive particles. Samples generated with MC@NLO [22] and interfaced to HERWIG [23] for hadronization and to JIMMY [24] for the underlying event are used for $t\bar{t}$ production as well as for single top-quark production in the $s$-channel and the $Wt$ process. The $t\bar{t}$ cross section is normalized to the calculation at NNLO in QCD including resummation of next-to-next-to-leading logarithmic soft gluon terms with Top+±2.0 [25–31]. Single top-quark production in the $t$-channel is simulated with ACERMC [32].

1 ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the $z$-axis along the beam 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 beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$.

4 Event selection

Events are required to have a vertex with at least three associated tracks, each with transverse momentum $p_T > 400$ MeV. The primary vertex is chosen to be the reconstructed vertex with the largest track $\sum p_T^2$.

The main physics objects used in this analysis are electrons, muons, jets and missing transverse momentum. Electrons are selected from clusters of energy depositions in the calorimeter that match a track reconstructed in the ID and satisfy “tight” identification criteria defined in Ref. [37]. The electrons are required to have transverse momentum $p_T > 25$ GeV and $|\eta| < 2.47$, excluding the transition region between the barrel and endcaps in the LAr calorimeter (1.37 < $|\eta| < 1.52$). Muons are reconstructed by combining ID and MS tracks that have consistent trajectories and curvatures [38]. The muon tracks are required to have $p_T > 25$ GeV and $|\eta| < 2.5$. In addition, leptons are required to be isolated from other tracks and calorimetric activity. The scalar sum of transverse momenta of tracks with $p_T > 1$ GeV within $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.2$ around the lepton track is required to be $< 15$% of the lepton $p_T$. Similarly, the sum of transverse energy deposits in the calorimeter within a cone of $\Delta R = 0.2$, excluding the transverse energy from the lepton and corrected for the expected pile-up contribution, is required to be $< 14$% of the lepton $p_T$. In order to ensure that leptons originate from the interaction point, a requirement of $|d_0|/\sigma_{d_0} < 6$ (3.5) and $|z_0| < 0.5$ mm is imposed on the electrons (muons), where $d_0$ ($z_0$) is the transverse (longitudinal) impact parameter of the lepton with respect to the reconstructed primary vertex and $\sigma_{d_0}$ is the uncertainty on the measured $d_0$.

In this analysis, jets are reconstructed from three-dimensional clusters of energy depositions in the calorimeter using two different algorithms. The jet constituents are considered massless. The low-$p_T$ hadronically decaying $W/Z$
candidates are selected by combining the two highest-$p_T$ jets which are constructed by the anti-$k_t$ algorithm [39] with a distance parameter of $R = 0.4$. These jets are referred to as small-$R$ jets and denoted by “$J$” hereafter. The energy of small-$R$ jets is corrected for losses in passive material, the non-compensating response of the calorimeter, and extra energy due to multiple $pp$ interactions [40]. The small-$R$ jets are required to have $p_T > 30$ GeV and $|\eta| < 2.8$. For jets with $p_T < 50$ GeV, the summed scalar $p_T$ of associated tracks from the reconstructed primary vertex is required to be at least 50 % of the summed scalar $p_T$ of all associated tracks. In the pseudorapidity range $|\eta| < 2.5$, jets containing hadrons from $b$-quarks are identified using the MV1 $b$-tagging algorithm [41] with an efficiency of 70 %, determined from $t\bar{t}$ simulated events, and with a misidentification rate for selecting light-quark or gluon jets of < 1 %.

For high-$p_T$ $W/Z$ bosons, such as the ones from a resonance with mass above 1 TeV, the hadronically decaying $W/Z$ candidates are identified using a single large-$R$ jet, referred to as “$J$” hereafter. The Cambridge–Aachen jet clustering algorithm [42] with a distance parameter of $R = 1.2$ is used. This jet algorithm offers the advantage of allowing the usage of a splitting and filtering algorithm similar to that described in Ref. [43] but optimized for the identification of highly boosted boson decays. To exploit the characteristics of the decay of massive bosons into a light-quark pair, the splitting and filtering algorithm used here does not impose a mass relation between the large-$R$ jet and its subjets [44]. The momentum balance is defined as $\sqrt{\Delta y} = \min(p_{T1}^j, p_{T2}^j)\Delta R_{12}/m_{12}$, where $p_{T1}^j$ and $p_{T2}^j$ are the transverse momenta of the two leading subjets, $\Delta R_{12}$ is their separation and $m_{12}$ is their invariant mass. To suppress jets from gluon radiation and splitting, $\sqrt{\Delta y}$ is required to be $>0.45$. Furthermore, the large-$R$ jets are required to have $p_T > 400$ GeV and $|\eta| < 2.0$.

The missing transverse momentum (with magnitude $E_T^{\text{miss}}$) is calculated as the negative of the vectorial sum of the transverse momenta of all electrons, muons, and jets, as well as calibrated calorimeter energy clusters within $|\eta| < 4.9$ that are not associated with any other objects [45].

The data used were recorded by single-electron and single-muon triggers, which are fully efficient for leptons with $p_T > 25$ GeV. The analysis selects events that contain exactly one reconstructed electron or muon matching a lepton trigger candidate, $E_T^{\text{miss}} \geq 30$ GeV and no $b$-tagged small-$R$ jets. The transverse momentum of the neutrino from the leptonically decaying $W$ boson is assumed to be equal to the missing transverse momentum. The momentum of the neutrino in the $z$-direction, $p_z$, is obtained by imposing the $W$ boson mass constraint on the lepton and neutrino system, which leads to a quadratic equation. The $p_z$ is defined as either the real component of the complex solution or the smaller in absolute value of the two real solutions.

In order to maximize the sensitivity to resonances with different masses, three different optimized sets of selection criteria are used to classify the events according to the $p_T$ of the leptonically decaying $W$ candidate ($p_T^l$) and hadronically decaying $W/Z$ candidate ($p_T^j$ or $p_T^\ell$), namely the “low-$p_T$ resolved region” (LRR), “high-$p_T$ resolved region” (HRR) and “merged region” (MR), where the highly boosted $W/Z$ decay products are observed as a single merged jet in the final state. To ensure the orthogonality of the signal regions, events are assigned exclusively to the first region for which the criteria are fulfilled, applying sequentially the MR, HRR, and LRR event selection. The hadronically decaying $W/Z$ candidate is formed by combining the two small-$R$ jets with highest $p_T$ in the resolved regions and its invariant mass $m_{jj}$ is required to be between 65 and 105 GeV. In the LRR (HRR), the event is required to have $p_T^{|\ell|} > 100$ (300) GeV and $\Delta\phi(J, E_T^{\text{miss}}) > 1$, where $\Delta\phi(J, E_T^{\text{miss}})$ is the azimuthal angle between the leading jet and the missing transverse momentum. The HRR additionally requires the two leading jets to have $p_T > 80$ GeV. In the MR, the large-$R$ jet with the highest $p_T$ is selected as the hadronically decaying $W/Z$ candidate and $p_T^{|\ell|} > 400$ GeV is also imposed. The jet mass of the selected large-$R$ jet ($m_J$) is required to be consistent with a $W/Z$ boson mass ($65 < m_J < 105$ GeV) and the azimuthal angle between the jet and the missing transverse momentum, $\Delta\phi(J, E_T^{\text{miss}})$, is required to satisfy $\Delta\phi(J, E_T^{\text{miss}}) > 1$. The signal acceptance efficiency after all selection requirements increases from about 5 % at $m_{W'} = 300$ GeV to a plateau of around 25 % for $m_{W'} > 500$ GeV for $W' \to WZ \to \ell\nu q\bar{q}$ with $\ell = e, \mu, \tau$.

5 Background estimation

The reconstructed $WW/WZ$ mass, $m_{\ell\nu j\ell}$ ($m_{\ell\nu j}$), defined as the invariant mass of the $\ell\nu j\ell$ ($\ell\nu j$) system, is used to distinguish the signal from the background. The background distributions from $W/Z + \text{jets}$ where $W$ ($Z$) decays leptonically to $\ell\nu$ ($\ell\ell$) considering the three lepton flavors, $t\bar{t}$, single top-quark and diboson processes are modelled using simulated events. The background shape from multijet production is obtained from an independent data sample that satisfies the signal selection criteria except for the lepton requirement: the electrons are required to satisfy a loose identification criterion (“medium” in Ref. [37]) but not meet the “tight” selection criteria; the selected muons are required to satisfy all the selection criteria after inverting the transverse impact parameter significance cut. The contribution from other processes is subtracted from data in the extraction of the multijet background shape.

The background contributions from $t\bar{t}$, single top-quark and diboson production are normalized to the number of
background events predicted by simulation. The \( p_T(W) \) distribution in the \( W + \) jets simulated sample is corrected by comparing it to data in the LRR sidebands defined as \( 40 < m_{jj} < 65 \) or \( 105 < m_{jj} < 200 \) GeV. The normalizations of the \( W/Z + \) jets and multijet background contributions are derived in a control data sample which is obtained by requiring the mass of the hadronic \( W/Z \) candidate to be within the \( m_{jj} \) sidebands. They are determined from binned minimum \( \chi^2 \) fits to the \( E_T^{\text{miss}} \) distributions in the control data samples corresponding to each signal region and channel separately. The fitted parameters are the normalizations of these two processes. The difference of the \( W/Z + \) jets normalization from the expected background from simulation ranges between 1 and 18 %.

The multijet background templates were validated in the electron channel using samples enriched in multijet events, obtained by inverting the \( E_T^{\text{miss}} \) requirement. The description of the \( t\bar{t} \) background in simulation was validated in a sample dominated by top-pair events by requiring at least one \( b \)-tagged small-\( R \) jet. Good agreement within uncertainties is observed between data and expectation in these validation regions.

6 Systematic uncertainties

The main systematic uncertainty on the background estimation is the uncertainty on the normalization of \( W/Z + \) jets background obtained from the fit described above. This uncertainty is 3–4 % in the LRR and HRR, and 13–19 % in the MR. An uncertainty on the shape of the \( W/Z + \) jets background is obtained in the LRR by comparing data and simulation in the \( m_{jj} \) sidebands, leading to an approximately 5 % uncertainty for \( m_{\ell\nu} \) \(<\) 600 GeV. Due to the low numbers of data events in the sidebands for the HRR and MR, the \( W + \) jets shape uncertainty in these regions is evaluated by comparing a sample of simulated events from SHERPA with a sample of simulated events from ALPGEN [46] interfaced to PYTHIA6. The uncertainty in the shape of the \( t\bar{t} \) mass distribution is estimated by comparing a sample from MC@NLO interfaced to HERWIG with a sample from POWHEG [47–49] interfaced to PYTHIA6. The uncertainty on the shape of the multijet background is evaluated by using alternative templates obtained by removing the calorimeter-based lepton isolation cuts. For the remaining background processes, detector-related uncertainties from the small-\( R \) jet energy scale and resolution, large-\( R \) jet energy and mass scale, lepton reconstruction and identification efficiencies, lepton momentum scales and resolutions, and missing transverse momentum were considered when evaluating possible systematic effects on the shape or normalization of the background estimation and are found to have a minor impact. The large-\( R \) jet energy and mass scale uncertainties are evaluated by comparing the ratio of calorimeter-based to track-based measurements in dijet data and simulation, and are validated by in-situ data of high-\( p_T \) \( W \) production in association with jets.

The dominant uncertainty on the signal arises from initial- and final-state radiation modelling in PYTHIA and is <12 % (6 %) for \( G^* (W') \) channels. Uncertainties due to the choice of PDFs are below 1 %.

The uncertainty on the integrated luminosity is ±2.8 %. It is determined, following the same methodology as that detailed in Ref. [50], from a calibration of the luminosity scale derived from beam-separation scans performed in November 2012.

7 Results and interpretation

Table 1 shows the number of events predicted and observed in each signal region. The reconstructed \( m_{\ell\nu j} (m_{\ell\nu j}) \) distributions for data and predicted background events as well as selected benchmark signal models in the three signal regions are shown in Fig. 1 for the combined electron and muon channels. Good agreement is observed between the data and the background prediction. In the absence of a significant excess, the result is interpreted as 95 % confidence level (CL) upper limits on the production cross section times branching ratio for the \( G^* \) and \( W' \) models. These upper limits are determined with the CLs modified frequentist formalism [51] with a profile-likelihood test statistic [52]. The test statistic is evaluated with a maximum-likelihood fit of signal models and background predictions to the reconstructed \( m_{\ell\nu j} (m_{\ell\nu j}) \) spectra. Systematic uncertainties are taken into account as nuisance parameters with Gaussian sampling distributions. For each source of systematic uncertainty, the

<table>
<thead>
<tr>
<th>Sample</th>
<th>LRR</th>
<th>HRR</th>
<th>MR</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W/Z + ) jets</td>
<td>104800</td>
<td>415</td>
<td>180</td>
</tr>
<tr>
<td>( t\bar{t} + ) single top</td>
<td>37700</td>
<td>271</td>
<td>42</td>
</tr>
<tr>
<td>Multijet</td>
<td>13500</td>
<td>84</td>
<td>29.3</td>
</tr>
<tr>
<td>Diboson</td>
<td>5500</td>
<td>96</td>
<td>43</td>
</tr>
<tr>
<td>Total</td>
<td>161500</td>
<td>870</td>
<td>295</td>
</tr>
<tr>
<td>Data</td>
<td>157837</td>
<td>801</td>
<td>323</td>
</tr>
<tr>
<td>( G^* ) signal</td>
<td>7000</td>
<td>36</td>
<td>5.5</td>
</tr>
<tr>
<td>( W' ) signal</td>
<td>6800</td>
<td>318</td>
<td>70</td>
</tr>
</tbody>
</table>
Fig. 1 Reconstructed mass distributions in data and the predicted backgrounds in the three kinematic regions referred to in the text as the low-\(p_T\) resolved region (top left), high-\(p_T\) resolved region (top right) and merged region (bottom). \(G^*\) and \(W'\) signal hypotheses of masses 400, 800 and 1200 GeV are also shown. The band denotes the statistical and systematic uncertainty on the background before the fit to the data. The lower panels show the ratio of data to the SM background estimate.

8 Summary

A search for \(WW\) and \(WZ\) resonances decaying to a lepton, neutrino and jets is presented in this paper. The search is performed using an integrated luminosity of 20.3 fb\(^{-1}\) of \(pp\) collisions at \(\sqrt{s} = 8\) TeV collected by the ATLAS detector at the LHC. A set of event selections for bulk RS \(G^*\) and EGM \(W'\) boson signal is derived using simulated events and applied to the data. No evidence for resonant diboson production is observed and 95 % CL upper limits on the production cross section times branching fraction of \(G^*\) and \(W'\) are determined. Resonance masses below 700 GeV are excluded for the spin-2 RS graviton \(G^*\) and masses below 1490 GeV are excluded for the spin-1 EGM \(W'\) boson at
The analysis also sets the most stringent limits to date on the production cross section for $W'$-like resonances decaying to $WZ$ with masses around 2 TeV, where $\sigma(pp \to W') \times BR(W' \to WZ)$ values of 9.6 fb are excluded. The results represent a significant improvement over previously reported limits [11] in the same final state due to an increased data set size and the development of new techniques to analyse highly boosted bosons that decay hadronically.

Acknowledgments 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; BMWF 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; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; EPLANET, ERC and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT and NSRF, Greece; RGC, Hong Kong SAR, China; ISF, MZM, GIF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, The Netherlands; BRF and RCN, Norway; MNiSW and NCN, Poland; GRICES and FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (The Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. Funded by SCOAP3.

References


Kyoto University of Education, Kyoto, Japan
Department of Physics, Kyushu University, Fukuoka, Japan
Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
Physics Department, Lancaster University, Lancaster, UK
(a) INFN Sezione di Lecce, Lecce, Italy; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
Olivey Laboratory, University of Liverpool, Liverpool, UK
Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
School of Physics and Astronomy, Queen Mary University of London, London, UK
Department of Physics, Royal Holloway University of London, Surrey, UK
Department of Physics and Astronomy, University College London, London, UK
Louisiana Tech University, Ruston, LA, USA
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 Física 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, UK
CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
Department of Physics, University of Massachusetts, Amherst, MA, USA
Department of Physics, McGill University, Montreal, QC, Canada
School of Physics, University of Melbourne, Melbourne, VIC, Australia
Department of Physics, The University of Michigan, Ann Arbor, MI, USA
Department of Physics and Astronomy, Michigan State University, East Lansing, MI, USA
(a) INFN Sezione di Milano, Milan, Italy; (b) Dipartimento di Fisica, Università di Milano, Milan, Italy
B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, USA
Group of Particle Physics, University of Montreal, Montreal, QC, Canada
P.N. Lebedev Institute of Physics, 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, Munich, Germany
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Munich, 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, Naples, Italy; (b) Dipartimento di Fisica, Università di Napoli, Naples, Italy
Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, USA
Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, The Netherlands
Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, The Netherlands
Department of Physics, Northern Illinois University, De Kalb, IL, USA
Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
Department of Physics, New York University, New York, NY, USA
Ohio State University, Columbus, OH, USA
Faculty of Science, Okayama University, Okayama, Japan
Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, USA
Department of Physics, Oklahoma State University, Stillwater, OK, USA
Palacký University, RCPTM, Olomouc, Czech Republic
Center for High Energy Physics, University of Oregon, Eugene, OR, USA
LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
Graduate School of Science, Osaka University, Osaka, Japan
Department of Physics, University of Oslo, Oslo, Norway
Department of Physics, University of Toronto, Toronto, ON, Canada

(a) TRIUMF, Vancouver, BC, Canada; (b) Department of Physics and Astronomy, York University, Toronto, ON, Canada

Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan

Department of Physics and Astronomy, Tufts University, Medford, MA, USA

Centro de Investigaciones, Universidad Antonio Narino, Bogotá, Colombia

Department of Physics and Astronomy, University of California Irvine, Irvine, CA, USA

(a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy; (b) ICTP, Trieste, Italy; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy

Department of Physics, University of Illinois, Urbana, IL, USA

Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain

Department of Physics, University of British Columbia, Vancouver, BC, Canada

Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada

Department of Physics, University of Warwick, Coventry, UK

Waseda University, Tokyo, Japan

Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel

Department of Physics, University of Wisconsin, Madison, WI, USA

Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany

Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany

Department of Physics, Yale University, New Haven, CT, USA

Yerevan Physics Institute, Yerevan, Armenia

Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

a Also at Department of Physics, King’s College London, London, UK
b Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
c Also at Novosibirsk State University, Novosibirsk, Russia
d Also at TRIUMF, Vancouver, BC, Canada
e Also at Department of Physics, California State University, Fresno, CA, USA
f Also at Department of Physics, University of Fribourg, Fribourg, Switzerland
g Also at Departamento de Física e Astronomía, Facultade de Ciencias, Universidade do Porto, Porto, Portugal
h Also at Tomsk State University, Tomsk, Russia
i Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
j Also at Università di Napoli Parthenope, Naples, Italy
k Also at Institute of Particle Physics (IPP), Victoria, Canada
l Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, UK
m Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia
n Also at Louisiana Tech University, Ruston, LA, USA
o Also at Institut Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
p Also at Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
q Also at Department of Physics, The University of Texas at Austin, Austin, TX, USA
r Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia
s Also at CERN, Geneva, Switzerland
f Also at Georgian Technical University (GTU), Tbilisi, Georgia
u Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan
v Also at Manhattan College, New York, NY, USA
w Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
x Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
y Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
z Also at Dipartimento di Fisica, Sapienza Università di Roma, Rome, Italy
aa Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
ab Also at Section de Physique, Université de Genève, Geneva, Switzerland
ac Also at International School for Advanced Studies (SISSA), Trieste, Italy
ad Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA
ae Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China
af Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
ag Also at National Research Nuclear University MEPhI, Moscow, Russia
ah Also at Department of Physics, Stanford University, Stanford, CA, USA
ai Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
aj Also at Department of Physics, Oxford University, Oxford, UK
ak Also at Department of Physics, The University of Michigan, Ann Arbor, MI, USA
al Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa
am Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia

* Deceased