Search for High-Mass Resonances Decaying to tau nu in pp Collisions at root s=13 TeV with the ATLAS Detector

Aaboud, M.; Aad, G.; Abbott, B.; Abdinov, O.; Abeloos, B.; Abidi, S.H.; Abouzeid, Ossama Sherif Alexander; Abraham, NL; Abramowicz, H.; Abreu, H.; Abulaiti, Y.; Abreu, H.; Abulaiti, Y.; Acharya, B.S.; Adachi, Sosuke; Adamczyk, L.; Adelman, J P; Adersberger, M.; Adye, T.; Affolder, A. A.; Afik, Y.; Agheorghiesei, C.; Aguilar-Saavedra, J. A.; Ahlen, S. P.; Dam, Mogens; Hansen, Jørn Dines; Hansen, Jørgen Beck; Hansen, Peter Henrik; Petersen, Troels Christian; Xella, Stefania; Alonso Diaz, Alejandro; Wiglesworth, Graig; Monk, James William; hqz214, hqz214; Stark, Simon Holm; Bajic, Milena; de Almeida Dias, Flavia; Besjes, Geert-Jan

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Search for High-Mass Resonances Decaying to $\tau\nu$ in $pp$ Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector

M. Aaboud et al.*
(ATLAS Collaboration)

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A search for high-mass resonances decaying to $\tau\nu$ using proton-proton collisions at $\sqrt{s} = 13$ TeV produced by the Large Hadron Collider is presented. Only $\tau$-lepton decays with hadrons in the final state are considered. The data were recorded with the ATLAS detector and correspond to an integrated luminosity of 36.1 fb$^{-1}$. No statistically significant excess above the standard model expectation is observed; model-independent upper limits are set on the visible $\tau\nu$ production cross section. Heavy $W'$ bosons with masses less than 3.7 TeV in the sequential standard model and masses less than 2.2–3.8 TeV depending on the coupling in the nonuniversal $G(221)$ model are excluded at the 95% credibility level.

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Heavy charged gauge bosons ($W'$) appear frequently in theories of physics beyond the standard model (SM). They are often assumed to obey lepton universality, such as in the sequential standard model (SSM) [1], which predicts a $W'_{SSM}$ boson with couplings identical to those of the SM $W$ boson. However, this assumption is not required. In particular, models in which the $W'$ boson couples preferentially to third-generation fermions may be linked to the high mass of the top quark [2–5] or to recent indications of lepton flavor universality violation in $B$ meson decays [6, 7]. An example is the nonuniversal $G(221)$ model (NU) [4, 5], which exhibits a $SU(2)_L \times SU(2)_R \times U(1)$ gauge symmetry, where $SU(2)_L$ couples to heavy fermions (third generation), and $SU(2)_R$ couples to light fermions (first two generations), and $\phi_{NU}$ is the mixing angle between them. The model predicts $W_{NU}'$ and $Z_{NU}'$ bosons which are approximately degenerate in mass and couple only to left-handed fermions. At leading order and neglecting sign, the $W_{NU}'$ couplings to heavy (light) fermions are scaled by $\cot \phi_{NU} \tan \phi_{NU}$ relative to those of $W_{SSM}'$. Thus $\cot \phi_{NU} > 1$ corresponds to enhanced couplings to tau leptons while $\cot \phi_{NU} = 1$ yields $W_{NU}'$ couplings identical to those of $W_{SSM}'$. For $Z_{NU}'$, the coupling to heavy (light) fermions is given by $g \cot \phi_{NU} \tan \phi_{NU}$, where $g$ is the SM weak coupling constant. At high values of $\cot \phi_{NU}$, the branching fraction of $W_{NU}'$ to a tau lepton ($\tau$) and a neutrino ($\nu$) approaches 26%.

In this Letter, a search for high-mass resonances (0.5–5 TeV) decaying to $\tau\nu$ using proton-proton ($pp$) collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV produced by the Large Hadron Collider (LHC) is presented. The data were recorded with the ATLAS detector and correspond to an integrated luminosity of 36.1 fb$^{-1}$. Only $\tau$ decays with hadrons in the final state are considered; these account for 65% of the total $\tau$ branching fraction. A counting experiment is performed from events that pass a high transverse-mass threshold, optimized separately for each of the signal mass hypotheses.

A direct search for high-mass resonances decaying to $\tau\nu$ has been performed by the CMS Collaboration using 19.7 fb$^{-1}$ of integrated luminosity at $\sqrt{s} = 8$ TeV [8]. The search excludes $W'_{SSM}$ with a mass below 2.7 TeV at the 95% credibility level and $W'_{NU}$ with a mass below 2.7–2.0 TeV for $\cot \phi_{NU}$ in the range 1.0–5.5. The most stringent limit on $W'_{SSM}$ from searches in the $e\nu$ and $\mu\nu$ final states is 5.1 TeV from ATLAS [9] using 36.1 fb$^{-1}$ of integrated luminosity at $\sqrt{s} = 13$ TeV.

The ATLAS experiment is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry [10, 11]. It consists of an inner detector for charged-particle tracking in the pseudorapidity region $|\eta| < 2.5$, electromagnetic and hadronic calorimeters that provide energy measurements up to $|\eta| = 4.9$, and a muon spectrometer that covers $|\eta| < 2.7$. A two-level trigger system is used to select events [12].

Hadrronic $\tau$ decays are composed of a neutrino and a set of visible decay products ($\tau_{\text{had-vis}}$), typically one or three charged pions and up to two neutral pions. The reconstruction of the visible decay products [13] is seeded by jets reconstructed from topological clusters of energy depositions [14] in the calorimeter. The $\tau_{\text{had-vis}}$ candidates must have a transverse momentum $p_T > 50$ GeV, $|\eta| < 2.4$...
suppressing background from additional contributions from additional jet (jet background) and those where it does not (nonjet background). The jet background originates primarily from W/Z + jets and multijet production and is estimated using a data-driven technique. The nonjet background is estimated using simulation and originates primarily from W/Z + jets with additional minor contributions from W/Z/γ*, ττ, single top-quark, and diboson (WW, WZ, and ZZ) production (collectively called others).

The event generators and other software packages used to produce the simulated samples are summarized in Table I. The W/Z/γ* sample is artificially enriched in high-mass events to improve statistical coverage in the scanned mass range. Particle interactions with the ATLAS detector are simulated with GEANT 4 [25,26] and contributions from additional pp interactions (pileup) are simulated using PYTHIA 8.186 and the MSTW2008LO parton distribution function (PDF) set [27]. Finally, the simulated events are processed through the same reconstruction software as the data. Corrections are applied to account for mismodeling of the momentum scales and resolutions of reconstructed objects, the τ_had-vis reconstruction and identification efficiency, the electron to τ_had-vis misidentification rate, and the E_T miss trigger efficiency.

The simulated samples are normalized using the integrated luminosity of the collected data set and their theoretical cross sections. The W/Z/γ* cross sections are calculated as a function of the boson mass at next-to-next-to-leading order (NNLO) [49] using the CT14NNLO PDF set, including electroweak corrections at next-to-leading order (NLO) [50] using the MRST2004QED PDF set [51]. Uncertainties are taken from Ref. [52] and include variations of the PDF sets, scale, α_s, beam energy, and electroweak corrections. The variations amount to a ~5% total uncertainty in the W/Z/γ* cross section at low mass, increasing to 34% at 2 TeV. The ττ and single top-quark production cross sections are

### Table I. The event generators and other software packages used to generate the matrix-element process and model nonperturbative effects in the simulated event samples. The top-quark mass is set to 172.5 GeV.

<table>
<thead>
<tr>
<th>Process</th>
<th>Matrix element</th>
<th>Nonperturbative</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/Z/γ*</td>
<td>POWHEG-Box 2, CT10, PHOTOS++ 3.52</td>
<td>PYTHIA 8.186, AZNLO, CTEQ6L1, EVTGEN 1.2.0</td>
<td>[28–36]</td>
</tr>
<tr>
<td>ττ</td>
<td>POWHEG-Box 2, CT10</td>
<td>PYTHIA 6.428, P2012, CTEQ6L1, EVTGEN 1.2.0</td>
<td>[37–39]</td>
</tr>
<tr>
<td>Single top</td>
<td>POWHEG-Box 1, CT10F4, MadSpin</td>
<td>PYTHIA 6.428, P2012, CTEQ6L1, EVTGEN 1.2.0</td>
<td>[40–43]</td>
</tr>
<tr>
<td>Diboson</td>
<td>SHERPA 2.1.1, CT10</td>
<td>SHERPA 2.1.1</td>
<td>[44–48]</td>
</tr>
</tbody>
</table>
calculated to at least NLO with an uncertainty of 3\%–6\% [53–56]. The diboson cross sections are calculated to NLO with an uncertainty of 10\% [44,57].

The simulated samples are affected by uncertainties associated with the generation of the events, the detector simulation, and the determination of the integrated luminosity. Uncertainties related to the modeling of the hard scatter, radiation, and fragmentation are at most 2\% of the total background estimate. Uncertainties in the detector scatter, radiation, and fragmentation are at most 2\% of the simulation, and the determination of the integrated luminosity is 2\%, derived following a methodology similar to that used in Ref. [59], and has a minor impact. The uncertainty related to the simulation of pileup is \sim 1\%.

The \(W'\) signal events are modeled by reweighting the \(W\) sample using a leading-order matrix-element calculation. Electroweak corrections for the \(W\) cross section and interference between \(W\) and \(W'\) are not included as they are model dependent. Uncertainties in the \(W'\) cross section are estimated in the same way as for \(W\) bosons. They are not included in the fitting procedure used to extract experimental cross-section limits, but are instead included when overalying predicted model cross sections. Uncertainties in the \(W'\) acceptance due to PDF, scale, and \(\alpha_S\) variations are negligible. In the NU model, the total decay width increases to 35\% of the pole mass for large values of \(\cot \phi_{\text{NNU}}\), which decreases the signal acceptance as more events are produced at low mass. Decays to \(WZ\) and \(W\ell\) are not considered in the calculation of the total \(W'_{\text{NU}}\) decay width as their impact is small (< 7\%) and model dependent. Values of \(\cot \phi_{\text{NNU}} > 5.5\) are not considered as the model is nonperturbative in this range.

The jet background contribution is estimated using events in three control regions (CR1, CR2, and CR3). The events must pass the selection for the signal region, except in CR1 and CR3 they must fail loose but pass very loose \(\tau\) identification and in CR2 and CR3 they must have \(E_T^{\text{miss}} < 100\) GeV and the requirement on \(p_T / E_T^{\text{miss}}\) is removed. The low-\(E_T^{\text{miss}}\) requirement yields high multijet purity in CR2 and CR3, while the very loose identification preferentially rejects gluon-initiated jets over quark-initiated jets. This produces a similar fraction of quark-initiated jets in all control regions, which ensures minimal correlation between the identification and \(E_T^{\text{miss}}\). The estimated jet contribution is defined as \(N_{\text{jet}} = N_{\text{CR1}} / N_{\text{CR2}} / N_{\text{CR3}}\). The nonjet contamination in CR1 (10\%), CR2 (3.7\%), and CR3 (0.5\%) is subtracted using simulation. The transfer factor, \(N_{\text{CR2}} / N_{\text{CR3}}\), is parametrized in \(E_{\text{had-vis}}\) and \(p_T\) and track multiplicity and is in the range 0.4–0.7 (0.15–0.3) for 1-track (3-track) \(\tau\) candidates. Systematic uncertainties are assigned to account for any residual correlation between the transfer factor and the \(E_T^{\text{miss}}\) and \(p_T / E_T^{\text{miss}}\) selection criteria, which would arise if the jet composition was different in CR1 and CR3.

They are evaluated by repeating the jet estimate with the following modified control region definitions: (a) altered very loose \(\tau\) identification criteria, (b) modified \(E_T^{\text{miss}}\) selection, and (c) CR2 and CR3 replaced by alternative control regions rich in \(W(\tau)\) + jets events. The corresponding variations define the dominant uncertainty in the jet background contribution, which ranges from 20\% at \(m_T = 0.2\) TeV to \(\sim 50\%\) at \(m_T = 2\) TeV, where the jet background is subdominant. The uncertainty due to the subtraction of nonjet contamination in the control regions is negligible.

To reduce the impact of statistical fluctuations in the jet background estimate, a function \(f(m_T) = m_T^a + b \log m_T\), where \(a\) and \(b\) are free parameters, is fitted to the estimate in the range \(400 < m_T < 800\) GeV and is used to evaluate the jet background in the range \(m_T > 500\) GeV. The impact of altering the fit range leads to an uncertainty that increases with \(m_T\), reaching 50\% at \(m_T = 2\) TeV. The statistical uncertainty from the control regions is propagated using pseudoexperiments and also reaches 50\% at \(m_T = 2\) TeV.

Figure 1 shows the observed \(m_T\) distribution of the data after event selection, including the estimated SM background contributions and predictions for \(W'_{\text{SSM}}\) and \(W'_{\text{NU}}\) (\(\cot \phi_{\text{NNU}} = 5.5\)) bosons with masses of 3 TeV. The number of observed events is consistent with the expected SM background. Therefore, upper limits are set on the production of a high-mass resonance decaying to \(\tau\nu\). The statistical analysis uses a likelihood function constructed as the Poisson probability describing the total number of observed events given the signal-plus-background expectation. Systematic uncertainties in the expected number of events are incorporated into the likelihood via nuisance parameters constrained by Gaussian prior probability density distributions. Correlations between signal and background are taken into account. A signal-strength parameter, with a uniform prior probability density distribution, multiplies the expected signal. The dominant relative uncertainties in the expected signal and background contributions are shown in Fig. 2 as a function of the \(m_T\) threshold.

Limits are set at the 95\% credibility level (C.L.) using the Bayesian Analysis Toolkit [60]. Figure 3 shows the
model-independent upper limits on the visible $\tau\tau$ production cross section, $\sigma(pp \rightarrow \tau\tau + X)\mathcal{A}$, as a function of the $m_T$ threshold, where $\mathcal{A}$ is the fiducial acceptance (including the $m_T$ threshold) and $\epsilon$ is the reconstruction efficiency. Model-specific limits can be derived by evaluating $\sigma$, $\mathcal{A}$, and $\epsilon$ for the model in question and checking if the corresponding visible cross section is excluded at any $m_T$ threshold. This allows the results to be reinterpreted for a broad range of models, regardless of their $m_T$ distribution. Good agreement between the generated and reconstructed $m_T$ distributions is found, indicating that a reliable calculation of the $m_T$ threshold acceptance can be made at generator level. The reconstruction efficiency depends on $m_T$, $\epsilon(m_T[\text{TeV}]) = 0.633 - 0.313m_T + 0.0688m_T^2 - 0.00575m_T^3$, ranging from 60% at 0.2 TeV to 7% at 5 TeV, and must be appropriately integrated out given the $m_T$ distribution of the model. The relative uncertainty in the parametrized efficiency due to the choice of signal model is $\sim 10\%$. With these inputs the visible cross sections for $W'_{\text{SSM}}$ and $W'_{\text{NU}}$ bosons could be reproduced within 10% using only generator-level information. Data and details to facilitate reinterpretations can be found at Ref. [61].

Limits are also set on benchmark models by selecting the most sensitive $m_T$ threshold for each $W'$ mass hypothesis ($\sim 0.6m_{W'}$ up to a maximum of 1.45 TeV). The chosen threshold is found to have little dependence on the $W'$ width. Figure 4(a) shows the 95% C.L. upper limit on the cross section times branching fraction as a function of $m_{W'}$ in the SSM. Heavy $W'_{\text{SSM}}$ bosons with a mass lower than 3.7 TeV are excluded, with an expected exclusion limit of 3.8 TeV. Figure 4(b) shows the excluded region in the parameter space of the nonuniversal $G(221)$ model. Heavy $W'_{\text{SSM}}$ bosons with a mass lower than 2.2–3.8 TeV are excluded depending on $\cot\phi_{\text{NU}}$, thereby probing a significantly larger region of parameter space than previous searches [8]. The $W'_{\text{NU}}$ limits are typically weaker than the $W'_{\text{SSM}}$ limits as the increased $W'$ width yields lower acceptances, while the enhancement in the decay rate cancels with the suppression in the production via first- and second-generation quarks. Limits from the ATLAS $ee$, $\mu\mu$, and $\tau\tau$ searches [58,62] are

FIG. 1. Transverse mass distribution after the event selection. The total impact of the statistical and systematic uncertainties on the SM background is depicted by the hatched area. The ratio of the data to the estimated SM background is shown in the lower panel. The prediction for $W'_{\text{SSM}}$ and $W'_{\text{NU}}$ (cot$\phi_{\text{NU}} = 5.5$) bosons with masses of 3 TeV are superimposed.

FIG. 2. Dominant relative uncertainties in the expected signal and background contributions as a function of the $m_T$ threshold. For each threshold a $W'_{\text{SSM}}$ boson with a mass of approximately 1.7 times the threshold is chosen. Theory includes uncertainties in the cross sections used to normalize the simulated samples and uncertainties associated with the modeling provided by the event generators. Other is the impact of all other uncertainties added in quadrature.

FIG. 3. The 95% C.L. upper limit on the visible $\tau\tau$ production cross section as a function of the $m_T$ threshold.
also overlaid, showing that the $\tau\nu$ search is complementary and extends the sensitivity over a large fraction of the parameter space. These results suggest that the $\tau\nu$ searches should be considered when placing limits on nonuniversal extended gauge groups, such as those seeking to explain lepton flavor violation (LFV) [64], CKM unitarity [65], and the original Z-pole data [2] are overlaid.

In summary, a search for $W' \rightarrow \tau\nu$ in 36.1 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 13$ TeV recorded by the ATLAS detector at the LHC is presented. The channel where the $\tau$ decays hadronically is analyzed and no significant excess over the SM expectation is found. Upper limits are set on the visible cross section for $\tau\nu$ production, allowing interpretation in a broad range of models. Sequential standard model $W'_{\text{SM}}$ bosons with masses less than 3.7 TeV are excluded at 95% C.L., while nonuniversal $G(221)$ $W'_{\text{NU}}$ bosons with masses less than 2.2–3.8 TeV are excluded depending on the model parameters.

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


[61] ATLAS Collaboration, HepData entry for this article, https://www.hepdata.net/record/80812.


[63] Q.-H. Cao, Z. Li, J.-H. Yu, and C.-P. Yuan, Discovery and Identification of $W'$ and $Z'$ in $SU(2)_{1} \otimes SU(2)_{2} \otimes U(1)_{X}$ models at the LHC, Phys. Rev. D 86, 095010 (2012).


LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France
High Energy Physics Division, Argonne National Laboratory, Argonne Illinois, USA
Department of Physics, University of Arizona, Tucson Arizona, USA
Physics Department, The University of Texas at Arlington, Arlington Texas, USA
Physics Department, National and Kapodistrian University of Athens, Athens, Greece
Department of Physics, The University of Texas at Austin, Austin Texas, USA
Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
Institut de Física d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain
Institute of Physics, University of Belgrade, Belgrade, Serbia
Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley California, USA
Department of Physics, Humboldt University, Berlin, Germany
Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
Department of Physics, Bogazici University, Istanbul, Turkey
Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
INFN Sezione di Bologna, Bologna, Italy
Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
Physikalisches Institut, University of Bonn, Bonn, Germany
Department of Physics, Boston University, Boston Massachusetts, USA
Department of Physics, Brandeis University, Waltham Massachusetts, USA
Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
Physics Department, Brookhaven National Laboratory, Upton New York, USA
Transilvania University of Brasov, Brasov, Romania
Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania
National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania
University Politehnica Bucharest, Bucharest, Romania
West University in Timisoara, Timisoara, Romania
Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
Department of Physics, Carleton University, Ottawa Ontario, Canada
CERN, Geneva, Switzerland
Enrico Fermi Institute, University of Chicago, Chicago Illinois, USA
Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
Department of Physics, Nanjing University, Jiangsu, China
Physics Department, Tsinghua University, Beijing, China
University of Chinese Academy of Science (UCAS), Beijing, China
Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Anhui, China
School of Physics, Shandong University, Shandong, China
School of Physics and Astronomy, Key Laboratory for Particle Physics, Astrophysics and Cosmology, Ministry of Education; Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, China
Tsung-Dao Lee Institute, Shanghai, China
Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France
Nevis Laboratory, Columbia University, Irvington New York, USA
Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
Dipartimento di Fisica, Università della Calabria, Rende, Italy
AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
Department of Physics and Astronomy, Michigan State University, East Lansing Michigan, USA

INFN Sezione di Milano, Milano, Italy

B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus

Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Republic of Belarus

Group of Particle Physics, University of Montreal, Montreal Québec, Canada

P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia

Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia

National Research Nuclear University MEPhI, Moscow, Russia

D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia

Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany

Nagasaki Institute of Applied Science, Nagasaki, Japan

Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan

INFN Sezione di Napoli, Napoli, Italy

Dipartimento di Fisica, Università di Napoli, Napoli, Italy

Department of Physics and Astronomy, University of New Mexico, Albuquerque New Mexico, USA

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

Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands

Department of Physics, Northern Illinois University, DeKalb Illinois, USA

Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia

Department of Physics, New York University, New York New York, USA

Ohio State University, Columbus Ohio, USA

Faculty of Science, Okayama University, Okayama, Japan

Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman Oklahoma, USA

Department of Physics, Oklahoma State University, Stillwater Oklahoma, USA

Palacký University, RCPTM, Olomouc, Czech Republic

Center for High Energy Physics, University of Oregon, Eugene Oregon, USA

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

Graduate School of Science, Osaka University, Osaka, Japan

Department of Physics, University of Oslo, Oslo, Norway

Department of Physics, Oxford University, Oxford, United Kingdom

INFN Sezione di Favia, Italy

Dipartimento di Fisica, Università di Pavia, Pavia, Italy

Department of Physics, University of Pennsylvania, Philadelphia Pennsylvania, USA

National Research Centre “Kurchatov Institute” B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia

INFN Sezione di Pisa, Pisa, Italy

Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy

Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh Pennsylvania, USA

Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal

Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal

Department of Physics, University of Coimbra, Coimbra, Portugal

Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal

Departamento de Física, Universidade do Minho, Braga, Portugal

Departamento de Física Teorica y del Cosmos, Universidad de Granada, Granada, Spain

Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal

Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic

Czech Technical University in Prague, Praha, Czech Republic

Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic

State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia

Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom

INFN Sezione di Roma, Roma, Italy

INFN Sezione di Roma Tor Vergata, Roma, Italy

INFN Sezione di Roma Tre, Roma, Italy

INFN Sezione di Roma Tor Vergata, Roma, Italy

Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy

Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca, Morocco

Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat, Morocco
Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco
Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco
Faculté des sciences, Université Mohammed V, Rabat, Morocco
DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz California, USA
Department of Physics, University of Washington, Seattle Washington, USA
Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
Department of Physics, Shinshu University, Nagano, Japan
Department Physik, Universität Siegen, Siegen, Germany
Department of Physics, Simon Fraser University, Burnaby British Columbia, Canada
SLAC National Accelerator Laboratory, Stanford California, USA
Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic
Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
Department of Physics, University of Cape Town, Cape Town, South Africa
Department of Physics, University of Johannesburg, Johannesburg, South Africa
School of Physics, University of the Witwatersrand, Johannesburg, South Africa
Department of Physics, Stockholm University, Sweden
The Oskar Klein Centre, Stockholm, Sweden
Physics Department, Royal Institute of Technology, Stockholm, Sweden
Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook New York, USA
Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
School of Physics, University of Sydney, Sydney, Australia
Institute of Physics, Academia Sinica, Taipei, Taiwan
Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
Tomsk State University, Tomsk, Russia
Department of Physics, University of Toronto, Toronto Ontario, Canada
INFN-TIFPA, Trento, Italy
University of Trento, Trento, Italy
TRIUMF, Vancouver British Columbia, Canada
Department of Physics and Astronomy, York University, Toronto Ontario, Canada
Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan
Department of Physics and Astronomy, Tufts University, Medford Massachusetts, USA
Department of Physics and Astronomy, University of California Irvine, Irvine California, USA
INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
ICTP, Trieste, Italy
Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
Department of Physics, University of Illinois, Urbana Illinois, USA
Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Spain
Department of Physics, University of British Columbia, Vancouver British Columbia, Canada
Department of Physics and Astronomy, University of Victoria, Victoria British Columbia, Canada
Department of Physics, University of Warwick, Coventry, United Kingdom
Waseda University, Tokyo, Japan
Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
Department of Physics, University of Wisconsin, Madison Wisconsin, USA
Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
Department of Physics, Yale University, New Haven Connecticut, USA
Yerevan Physics Institute, Yerevan, Armenia
Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
a) Deceased.
b) Also at Department of Physics, King’s College London, London, United Kingdom.
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 & Astronomy, University of Louisville, Louisville, KY, USA.
f) Also at Physics Department, An-Najah National University, Nablus, Palestine.
g) Also at Department of Physics, California State University, Fresno CA, USA.
h) Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
i) Also at II Physikalisches Institut, Georg-August-Universit"at, Göttingen, Germany.
j) Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain.
k) Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
l) Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.
m) Also at Universita di Napoli Parthenope, Napoli, Italy.
n) Also at Institute of Particle Physics (IPP), Canada.
o) Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania.
p) Also at CPPM, Aix-Marseille Universit"e and CNRS/IN2P3, Marseille, France.
q) Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
r) Also at Borough of Manhattan Community College, City University of New York, New York City, USA.
s) Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
t) Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.
u) Also at Louisiana Tech University, Ruston LA, USA.
v) Also at Instituto Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
w) Also at Department of Physics, The University of Michigan, Ann Arbor MI, USA.
x) Also at LAL, Univ. Paris-Sud, CNRS/IN2P3, Universit"e Paris-Saclay, Orsay, France.
y) Also at Graduate School of Science, Osaka University, Osaka, Japan.
z) Also at Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany.
Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.
Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
Also at CERN, Geneva, Switzerland.
Also at Georgian Technical University (GTU),Tbilisi, Georgia.
Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.
Also at Manhattan College, New York NY, USA.
Also at Hellenic Open University, Patras, Greece.
Also at The City College of New York, New York NY, USA.
Also at Departamento de Fisica Teorica y del Cosmos, Universidad de Granada, Granada, Spain.
Also at Department of Physics, California State University, Sacramento CA, USA.
Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
Also at Departement de Physique Nucleaire et Corpusculaire, Universit"e de Genève, Geneva, Switzerland.
Also at Department of Physics, The University of Texas at Austin, Austin TX, USA.
Also at Institut de Física d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain.
Also at School of Physics, Sun Yat-sen University, Guangzhou, China.
Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.
Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia.
Also at National Research Nuclear University MEPhI, Moscow, Russia.
Also at Department of Physics, Stanford University, Stanford CA, USA.
Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
Also at Giresun University, Faculty of Engineering, Turkey.
Also at Department of Physics, Nanjing University, Jiangsu, China.
Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.
Also at Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia.