Search for a Heavy Neutral Particle Decaying to $e\mu$, $e\tau$, or $\mu\tau$ in $pp$ Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector

The ATLAS Collaboration

Abstract

This Letter presents a search for a heavy neutral particle decaying into an opposite-sign different-flavor dilepton pair, $e^+\mu^-$, $e^+\tau^-$, or $\mu^+\tau^-$ using 20.3 fb$^{-1}$ of $pp$ collision data at $\sqrt{s} = 8$ TeV collected by the ATLAS detector at the LHC. The numbers of observed candidate events are compatible with the Standard Model expectations. Limits are set on the cross section of new phenomena in two scenarios: the production of $\tilde{\nu}_\tau$ in $R$-parity-violating supersymmetric models and the production of a lepton-flavor-violating $Z'$ vector boson.
Lepton-flavor-violation (LFV) in the charged sector, if observed at present sensitivities, would be a clear signature of new physics. Such signatures occur in several new physics scenarios, including R-parity-violating (RPV) [1] supersymmetry (SUSY) [2–10] and models with an additional heavy neutral gauge boson $Z'$ [11] allowing for LFV couplings.

In RPV SUSY, the lagrangian terms allowing LFV can be expressed as $\frac{1}{2} \lambda_{jk} L_i L_k + \lambda'_{jk} L_i Q_j d_k$ [1], where $L$ and $Q$ are the $SU(2)$ doublet superfields of leptons and quarks; $e$ and $d$ are the $SU(2)$ singlet superfields of leptons and down-like quarks; $\lambda$ and $\lambda'$ are Yukawa couplings; and the indices $i$, $j$ and $k$ denote fermion generations. A $\tau$ sneutrino ($\tilde{\nu}_\tau$) may be produced in $pp$ collisions by $d\bar{d}$ annihilation and subsequently decay to $e\mu$, $e\tau$, or $\mu\tau$. Although only $\tilde{\nu}_\tau$ is considered here in order to compare with previous searches performed at the Tevatron, the results of our analysis apply to any sneutrino flavor.

The Sequential Standard Model (SSM), where the $Z'$ boson is often assumed to have the same quark and lepton couplings as the Standard Model (SM) $Z$ boson, can be extended to include LFV couplings for the $Z'$. The $Z' \rightarrow e\mu$, $e\tau$, or $\mu\tau$ couplings ($Q_{12}$, $Q_{13}$, or $Q_{23}$) [12] are typically expressed as fractions of the SSM $Z' \rightarrow e^+e^-$ ($e$, $\mu$, $\tau$) coupling.

The CDF [13], D0 [14], and ATLAS [15] collaborations have searched for a $\tilde{\nu}_\tau$ in LFV final states and placed limits for various $\tilde{\nu}_\tau$ mass hypotheses. Both the CDF [16] and ATLAS [17] collaborations have placed limits on $Q_{12}$ as a function of the $Z'$ mass.

This Letter describes a search for a neutral heavy particle ($\tilde{\nu}_\tau$ or $Z'$) decaying into $e^+\mu^-$ ($e\mu$), $e^+\tau^+_{\text{had}}$ ($e\tau$), or $\mu^+\tau^-_{\text{had}}$ ($\mu\tau$) using $pp$ collision data collected at $\sqrt{s} = 8$ TeV, where $\tau_{\text{had}}$ is a $\tau$ lepton that decays into hadrons. The ATLAS detector is described in detail elsewhere [18]. Events are selected with a three-level trigger system that requires one or two leptons ($e$ or $\mu$) with high transverse momentum ($p_T$). The dataset has a total integrated luminosity of $20.3 \pm 0.6$ fb$^{-1}$, where the uncertainty is derived following the same methodology as that detailed in Ref. [19].

Electrons are required to have $p_T > 25$ GeV, $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$ [20], and satisfy the “tight” selection in Ref. [21], which was modified in 2012 to reduce the impact of additional inelastic $pp$ interactions, termed pileup. Muon candidates must have $p_T > 25$ GeV, $|\eta| < 2.4$ and be reconstructed in both the inner tracker detector and the muon spectrometer. The muon momenta measured by the inner detector and muon spectrometer must match within five standard deviations of their combined uncertainty. Good quality reconstruction and $p_T$ resolution at high momentum are ensured by requiring a minimum number of associated hits on the inner detector track [22] and in each of the three muon spectrometer stations.

Candidate events must contain at least one primary interaction vertex reconstructed with more than three associated tracks with $p_T > 400$ MeV. If there is more than one such vertex, the one with the highest sum of $p_T^2$ of associated tracks is chosen. The longitudinal impact parameter is required to be smaller than 2 mm for candidate electrons and smaller than 1 mm for candidate muons. It is further required that the transverse impact parameter is less than six times its resolution for candidate electrons, and that the transverse impact parameter is smaller than 0.2 mm for candidate muons. A calorimeter isolation criterion $E_T^{\Delta R<0.2}/E_T < 0.06$ and a tracker isolation criterion $p_T^{\Delta R<0.4}/p_T < 0.06$ are applied for both the electrons and muons, where $E_T^{\Delta R<0.2}$ is the transverse energy deposited in the calorimeter within a cone of size $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.2$ around the lepton, and $p_{T}^{\Delta \theta<0.4}$ is the sum of the $p_T$ of tracks with $p_T > 1$ GeV within a cone size of 0.4 around the lepton. $E_T$ and $p_T$ are the lepton transverse energy and momentum, respectively.
Hadronic decays of \( \tau \) leptons are characterized by one or three charged tracks associated to a narrow energy cluster in the calorimeters [23]. This search uses \( \tau_{\text{had}} \) candidates with only one charged track due to reduced identification and reconstruction efficiency for high-\( p_T \) \( \tau \) decays with three charged tracks. Boosted-decision-tree multivariate discriminators, based on tracking and calorimeter information, are used to reject jets and electrons misidentified as \( \tau_{\text{had}} \). The \( \tau_{\text{had}} \) candidates must have \( |\eta| < 2.47 \) and \( E_T > 25 \text{GeV} \). Candidates with \( |\eta| < 0.03 \) are removed to exclude a region with increased misidentification of electrons due to reduced coverage by the inner detector and calorimeters.

Jets are reconstructed from clusters of energy in the calorimeter using the anti-\( k_T \) algorithm [24] with radius parameter \( R = 0.4 \). Jet energies are calibrated using Monte Carlo (MC) simulation and a combination of several in situ calibrations [25]. The calculation of the missing transverse momentum vector \( \vec{p}_T^{\text{miss}} \) (with magnitude \( E_T^{\text{miss}} \)) is based on the vector sum of the calibrated \( p_T \) of reconstructed jets, electrons, and muons, as well as calorimeter energy clusters not associated with reconstructed objects [26].

Candidate signal events are required to have exactly two leptons, of opposite charge and of different flavor, satisfying the above lepton selection criteria. The two leptons are required to be back-to-back in the azimuthal plane with \( |\Delta \phi_{\ell\ell}| > 2.7 \), where \( \Delta \phi_{\ell\ell} \) is the \( \phi \) difference between the two leptons. Due to the presence of the undetected neutrino in the \( \tau \) decay, the \( E_T \) of the \( \tau_{\text{had}} \) candidate is required to be less than the \( E_T \) (\( p_T \)) of the electron (muon) for the \( e\tau_{\text{had}} (\mu\tau_{\text{had}}) \) channel.

A collinear neutrino approximation is used to reconstruct the dilepton invariant mass \( (m_{\ell\ell}) \) in the \( e\tau_{\text{had}} \) and \( \mu\tau_{\text{had}} \) channels. In the hadronic decay of a \( \tau \) lepton from a heavy resonance, the neutrino and the resultant jet are nearly collinear. The four-vector of the neutrino is reconstructed from the \( \vec{p}_T^{\text{miss}} \) and \( \eta \) of the \( \tau_{\text{had}} \) jet. Four-vectors of the electron or muon, \( \tau_{\text{had}} \) candidate and neutrino are then used to calculate \( m_{\ell\ell} \). For \( e\tau_{\text{had}} \) and \( \mu\tau_{\text{had}} \) signal events, the above technique significantly improves the mass resolution and search sensitivity.

Events with \( m_{\ell\ell} < 200 \text{GeV} \) form a validation region to verify the background modeling, and events with \( m_{\ell\ell} > 200 \text{GeV} \) are used as the search region.

The SM processes that produce \( \ell^+\ell^- \) final states can be divided into two categories: processes that produce two prompt leptons such as \( Z/\gamma^* \rightarrow \tau\tau, t\bar{t}, \) single-top \( Wt \) channel, diboson production, and processes where one or more photons or jets are misidentified as leptons, predominantly \( W/Z + \gamma, W/Z+\text{jets} \), and multijet events. The decay of a \( \tau \) to an electron or a muon is considered as prompt production. For the \( e\tau_{\text{had}} (\mu\tau_{\text{had}}) \) channel, additional background can originate from the \( Z/\gamma^* \rightarrow e\mu \) process if one lepton is misidentified as a \( \tau_{\text{had}} \) candidate. The contributions of these processes are even larger with respect to the \( Z/\gamma^* \rightarrow \tau\tau \) background, since the final states \( e \) or \( \mu \) are usually harder than those from leptonic \( \tau \) decay.

Contributions from processes in the prompt two-lepton category, as well as photon-related and \( Z/\gamma^* \rightarrow e\mu \) backgrounds, are estimated using MC simulation [27]. The detector response model is based on the \textsc{geant4} program [28]. Lepton reconstruction and identification efficiencies, energy scales, and resolutions in the MC simulation are corrected to the corresponding values measured in the data. Pileup is included to match distributions observed in the data. Top quark production is generated with \textsc{mc@nlo} v4.06 [29] for \( t\bar{t} \) and single-top, the Drell–Yan process \((Z/\gamma^* \rightarrow \ell\ell)\) is generated with \textsc{alpgen} v2.14 [30], and diboson processes are generated with \textsc{herwig} v6.520.2 [31]. Samples of \( W\gamma \) and \( Z\gamma \) events are generated with \textsc{sherpa} v1.04 [32]. These generated samples are normalized to the most accurate available cross-section calculations. For the dominant backgrounds, the Drell–Yan processes are corrected to next-to-next-to-leading order (NNLO) [33], and \( t\bar{t} \) is corrected to NNLO, including soft-gluon resummation to next-to-next-to-leading-logarithm order [34].
Since it is difficult to model misidentification of jets as leptons, particularly at high $p_T$, the $W$+jets and multijet backgrounds are determined from control regions in the data. The $W$+jets background is determined in a control region selected with the same criteria as used for the signal selection except requiring $E_T^{\text{miss}} > 30$ GeV (to enhance the $W$ contribution) and requiring that the electron or muon $p_T$ be less than 150 GeV (to eliminate potential signal). Simulation studies indicate that there is negligible multijet background in this control region. For the $e\tau$ and $\mu\tau$ channels, the number of events in the control region is corrected for the other SM background sources using MC samples. For the $e\mu$ channel, the number of $W$+jets events in the control region is too small to yield a statistically meaningful measurement. Instead, the control region is enlarged by removing the isolation criterion on one lepton, and the $W$+jets contribution is estimated using the lepton $E_T^{\Delta R<0.2}/E_T$ distribution to fit the data with the MC predictions for other SM processes (dominant at low values of the isolation variable) and $W$+jets (dominant at large values). For the $W$+jets background in all three channels, the extrapolation factor from the control region to the signal region and the shape of the $m_{\ell\ell}$ distribution are taken from the $W$+jets MC sample.

The contribution from multijet production is estimated from a control region with the same selection as the signal region except that the leptons are required to have the same electric charge, under the assumption that the probability of misidentifying a jet as a lepton is independent of the charge. The number of events in this same-sign control region is corrected for contributions from backgrounds with prompt leptons and from $W$+jets backgrounds using the procedure described above. The assumption of charge independence of the jet misidentification rates is tested in a multijet-enriched region with two nonisolated leptons. After subtraction of other SM backgrounds, the ratio of opposite-sign to same-sign events is found to be $1.07 \pm 0.06$ (stat.) $\pm 0.02$ (syst.).

The background estimates are verified in validation regions defined with the same selection criteria as for the signal regions but with $1.0 < |\Delta \phi_{\ell\ell}| < 2.7$. In these validation regions, simulation studies show the backgrounds have compositions similar to the signal regions, and the predictions agree with the data within 20% over the entire $m_{\ell\ell}$ range. An uncertainty of 20% is hence placed on the total background estimate that is used in the final results.

MC signal events are generated with HERWIG v6.520.2 for $\tilde{\nu}_\tau$ and PYTHIA v8.165 [35] for $Z^\prime$. Samples are produced with $\tilde{\nu}_\tau$ and $Z^\prime$ masses ranging from 0.5 to 3 TeV. Signal cross sections are calculated to next-to-leading order for $\tilde{\nu}_\tau$, and NNLO for $Z^\prime$. The theoretical uncertainties are taken from an envelope of cross-section predictions using different parton distribution function (PDF) sets and factorization and renormalization scales [36, 37].

The selection efficiency, including $\tau$ decay branching ratio if $\tau$ is involved, for $m_{\tilde{\nu}_\tau} = 2$ TeV are 42%, 14%, and 10% in the $e\mu$, $e\tau$, and $\mu\tau$ channels, respectively. The corresponding numbers for a $Z^\prime$ boson with $m_{Z^\prime} = 2$ TeV are 37%, 11%, and 9%. The systematic uncertainties on the signal efficiency vary from 3% to 6% depending on the resonance mass and decay mode. The primary contributions are due to the number of MC events, and the uncertainties related to the muon and $\tau$ $p_T$ scales.

The observed and expected event yields in both the validation and search $m_{\ell\ell}$ regions for all three final states are in good agreement, as summarized in Table 1. The $m_{\ell\ell}$ distributions (Fig. 1) show no significant excess above the SM expectation in any of the three modes. The dominant contributions to the uncertainty bands in Fig. 1 are due to the number of MC events, the MC cross-section uncertainties, the $E_T^{\text{miss}}$ scale and resolution, and the uncertainty in the shape of the $m_{\ell\ell}$ distribution for $W$+jets.

Upper limits are placed on the production cross section times branching ratio $[\sigma(pp \to \tilde{\nu}_\tau/Z^\prime) \times \text{BR}(\tilde{\nu}_\tau/Z^\prime \to \ell\ell')]$. For each $\tilde{\nu}_\tau$ or $Z^\prime$ mass, $m$, the search region is defined to be $m \pm 3\sigma_{\ell\ell}'$, where $\sigma_{\ell\ell}'$ is the standard deviation of the simulated signal $m_{\ell\ell}$ distribution. The relative width of the signal $m_{\ell\ell}$ distribution ranges
from 3% to 17% for different mass points, channels and models. To reduce the statistical error, if the upper side of the search region is greater than 1 TeV, all events above 1 TeV are used. To further reduce the effect of fluctuations in the high-mass region due to low MC event counts, the number of background events in each mass window is estimated using a double exponential fit to the total background.

Table 1: Estimated SM backgrounds and observed event yields for the validation ($m_{Z'} < 200$ GeV) and search ($m_{Z'} > 200$ GeV) regions. Both the statistical and systematic uncertainties are included. Due to correlations, the total uncertainties are not exactly the sum in quadrature of the components.

<table>
<thead>
<tr>
<th>Process</th>
<th>$m_{Z'} &lt; 200$ GeV</th>
<th>$m_{Z'} &gt; 200$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$N_{\text{exp}}$</td>
<td>$N_{\text{exp}}$</td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow \tau\tau$</td>
<td>6000±400</td>
<td>11000±900</td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow ee$</td>
<td>—</td>
<td>6100±1100</td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow \mu\mu$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>4220±290</td>
<td>690±60</td>
</tr>
<tr>
<td>Diboson</td>
<td>1440±80</td>
<td>321±29</td>
</tr>
<tr>
<td>Single top quark</td>
<td>470±40</td>
<td>87±11</td>
</tr>
<tr>
<td>W+jets</td>
<td>54±18</td>
<td>17000±4000</td>
</tr>
<tr>
<td>Multijet</td>
<td>227±32</td>
<td>4800±1000</td>
</tr>
<tr>
<td>Total</td>
<td>12400±600</td>
<td>40400±2900</td>
</tr>
<tr>
<td>Data</td>
<td>12954</td>
<td>41304</td>
</tr>
</tbody>
</table>

Figure 1: Observed and predicted $e\mu, \mu_{\text{had}}, \mu_{\text{THad}}$ invariant mass distributions. The contributions of the different processes are also shown: “Others” includes diboson and single-top while “Jet fake” refers to $W$+jets and multijet. All overflows are included in the rightmost bin. Signal simulations are shown for $m_t = 1$ TeV and $m_{Z'} = 0.75$ TeV. The couplings $\lambda_{311} = 0.11$ and $\lambda_{333} = 0.07$ ($Q_{Z'} = 1$) are used for the RPV ($Z'$) model. The uncertainty bands include both the statistical and systematic uncertainties.

A frequentist technique [38] is used to set the expected and observed upper limits as a function of $m_{\ell\ell}$ and $m_{Z'}$. The likelihood of observing the number of events in data as a function of the expected number of signal and background events is constructed from a Poisson distribution for each $m_{\ell\ell}$ bin. Systematic uncertainties are taken into account with Gaussian-distributed nuisance parameters. A 95% confidence level (CL) limit is then determined. The expected exclusion limits are determined, using simulated pseudoex-
experiments containing only background processes, as the median of the 95% CL limit distributions for each set of pseudoexperiments at each value of $m_{\tilde{\nu}}$, or $m_{Z'}$, including systematic uncertainties. The ensemble of limits is also used to assess the 1σ and 2σ uncertainty envelopes of the expected limits.

Figure 2 shows the observed and expected cross section times branching ratio limits as a function of $m_{\tilde{\nu}}$, together with the ±1σ and ±2σ uncertainty bands. For a $\tilde{\nu}$, mass of 1 TeV, the observed limits on the production cross section times branching ratio are 0.5 fb, 2.7 fb, and 9.1 fb for the $e\mu$, $e\tau$ and $\mu\tau$ channels, respectively. The corresponding limits for a $Z'$ boson mass of 1 TeV are 1.0 fb, 4.0 fb and 9.9 fb for the $e\mu$, $e\tau$ and $\mu\tau$ channels, respectively.

Theoretical predictions of cross section times branching ratio [33, 39] are also shown, assuming $\lambda'_{311} = 0.11$ and $\lambda'_{33k} = 0.07$ for the $\tilde{\nu}$, and $Q_{ij} = 1$ for the $Z'$, consistent with benchmark couplings used in previous searches. For these benchmark couplings, the lower limits on the $\tilde{\nu}$, mass are 2.0 TeV, 1.7 TeV, and 1.7 TeV for the $e\mu$, $e\tau$ and $\mu\tau$ channels, respectively. The corresponding lower limits on the $Z'$ mass are 2.5 TeV, 2.2 TeV and 2.2 TeV for the $e\mu$, $e\tau$ and $\mu\tau$ channels, respectively. The observed lower mass limits are a factor of three to four higher than the best limits from the Tevatron [13, 14] and also more stringent than the previous limits from ATLAS [15] for the same couplings.

In summary, a search has been performed for a heavy particle decaying to $e\mu$, $e\tau$, or $\mu\tau$ final states using 20.3 fb$^{-1}$ of $pp$ collision data at $\sqrt{s} = 8$ TeV recorded by the ATLAS detector at the LHC. The data are found to be consistent with SM predictions. Limits are placed on the cross section times branching ratio for an RPV SUSY $\tilde{\nu}$, and a LFV $Z'$ boson. These results considerably extend previous constraints from the Tevatron and LHC experiments.

![Figure 2: The 95% CL limits on cross section times branching ratio as a function of $\tilde{\nu}$ mass (top plots) and $Z'$ mass (bottom plots) for $e\mu$ (left), $e\tau$ (middle), and $\mu\tau$ (right). Theory curves are for the arbitrary choice of couplings $\lambda'_{311} = 0.11$ and $\lambda'_{33k} = 0.07$ for $\tilde{\nu}$, and $Q_{ij} = 1$ for $Z'$. The gray band around the theory curve represents the theoretical uncertainty from the PDFs and factorization and renormalization scales.](image-url)
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References


ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the center of the detector and the $z$-axis along the beam direction. The $x$-axis points toward 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 beam direction. Pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$. Transverse projections are defined relative to the beam axis.


12 Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
13 Institute of Physics, University of Belgrade, Belgrade, Serbia
14 Department for Physics and Technology, University of Bergen, Bergen, Norway
15 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
16 Department of Physics, Humboldt University, Berlin, Germany
17 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
18 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19 (a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics, Dogus University, Istanbul; (c) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
20 (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
21 Physikalisches Institut, University of Bonn, Bonn, Germany
22 Department of Physics, Boston University, Boston MA, United States of America
23 Department of Physics, Brandeis University, Waltham MA, United States of America
24 (a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
25 Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
26 (a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (c) University Politehnica Bucharest, Bucharest; (d) West University in Timisoara, Timisoara, Romania
27 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
28 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
29 Department of Physics, Carleton University, Ottawa ON, Canada
30 CERN, Geneva, Switzerland
31 Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
32 (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
33 (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) School of Physics, Shandong University, Shandong; (e) Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai; (f) Physics Department, Tsinghua University, Beijing 100084, China
34 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
35 Nevis Laboratory, Columbia University, Irvington NY, United States of America
36 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
37 (a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
38 (a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
39 Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
40 Physics Department, Southern Methodist University, Dallas TX, United States of America
41 Physics Department, University of Texas at Dallas, Richardson TX, United States of America

20
42 DESY, Hamburg and Zeuthen, Germany
43 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
44 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
45 Department of Physics, Duke University, Durham NC, United States of America
46 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
49 Section de Physique, Université de Genève, Geneva, Switzerland
50 (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
51 (a) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi, Georgia
52 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
53 SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
54 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
55 Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
56 Department of Physics, Hampton University, Hampton VA, United States of America
57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
58 (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
59 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
60 (a) Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; (b) Department of Physics, The University of Hong Kong, Hong Kong; (c) Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
61 Department of Physics, Indiana University, Bloomington IN, United States of America
62 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
63 University of Iowa, Iowa City IA, United States of America
64 Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
65 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
66 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
67 Graduate School of Science, Kobe University, Kobe, Japan
68 Faculty of Science, Kyoto University, Kyoto, Japan
69 Kyoto University of Education, Kyoto, Japan
70 Department of Physics, Kyushu University, Fukuoka, Japan
71 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
72 Physics Department, Lancaster University, Lancaster, United Kingdom
73 (a) INFN Sezione di Lecce; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
74 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
75 Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
76 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
77 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
78 Department of Physics and Astronomy, University College London, London, United Kingdom
79 Louisiana Tech University, Ruston LA, United States of America
80 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and
CNRS/IN2P3, Paris, France
81 Fysiska institutionen, Lunds universitet, Lund, Sweden
82 Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
83 Institut für Physik, Universität Mainz, Mainz, Germany
84 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
85 CPPM, Aix-Marseille Université et CNRS/IN2P3, Marseille, France
86 Department of Physics, University of Massachusetts, Amherst MA, United States of America
87 Department of Physics, McGill University, Montreal QC, Canada
88 School of Physics, University of Melbourne, Victoria, Australia
89 Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
90 Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
91 (a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano, Italy
92 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
93 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
94 Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
95 Group of Particle Physics, University of Montreal, Montreal QC, Canada
96 P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
97 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
98 National Research Nuclear University MEPhI, Moscow, Russia
99 D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
100 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
101 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
102 Nagasaki Institute of Applied Science, Nagasaki, Japan
103 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
104 (a) INFN Sezione di Napoli; (b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
105 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
106 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
107 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
108 Department of Physics, Northern Illinois University, DeKalb IL, United States of America
109 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
110 Department of Physics, New York University, New York NY, United States of America
111 Ohio State University, Columbus OH, United States of America
112 Faculty of Science, Okayama University, Okayama, Japan
113 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
114 Department of Physics, Oklahoma State University, Stillwater OK, United States of America
115 Palacký University, RCPTM, Olomouc, Czech Republic
116 Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
117 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, Oxford University, Oxford, United Kingdom
(a) INFN Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
Petersburg Nuclear Physics Institute, Gatchina, Russia
(a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
(a) INFN Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
Petersburg Nuclear Physics Institute, Gatchina, Russia
(a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
(a) INFN Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
(a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
(a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
(a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
(a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
(a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
(a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
(a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
(a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
(a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
(a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
(a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
(a) INFN Sezione di Roma; (b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
(a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
(a) INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
(a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; (b) Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; (d) Faculté des Sciences, Université Mohammed Premier and LPTPM, Oujda; (e) Faculté des sciences, Université Mohammed V-Agdal, 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 CA, United States of America
Department of Physics, University of Washington, Seattle WA, United States of America
Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
Department of Physics, Shinshu University, Nagano, Japan
Fachbereich Physik, Universität Siegen, Siegen, Germany
Department of Physics, Simon Fraser University, Burnaby BC, Canada
SLAC National Accelerator Laboratory, Stanford CA, United States of America
(a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
(a) Department of Physics, University of Cape Town, Cape Town; (b) Department of Physics, University of Johannesburg, Johannesburg; (c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
(a) Department of Physics, Stockholm University; (b) 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 NY, United States of America
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
Department of Physics and Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
Department of Physics, University of Toronto, Toronto ON, Canada
(a) TRIUMF, Vancouver BC; (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, United States of America
Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
(a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; (b) ICTP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
Department of Physics, University of Illinois, Urbana IL, United States of America
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-CNMM), 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, United Kingdom
Waseda University, Tokyo, Japan
Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
Department of Physics, University of Wisconsin, Madison WI, United States of America
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, United States of America
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, United Kingdom
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, United States of America
f Also at Department of Physics, University of Fribourg, Fribourg, Switzerland

Also at Departamento de Fisica e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal

Also at Tomsk State University, Tomsk, Russia

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

Also at Universitá di Napoli Parthenope, Napoli, Italy

Also at Institute of Particle Physics (IPP), Canada

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

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

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

Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain

Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America

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

Also at CERN, Geneva, Switzerland

Also at Georgian Technical University (GTU), Tbilisi, Georgia

Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan

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

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

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

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

Also at School of Physics, Shandong University, Shandong, China

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

Also at Section de Physique, Université de Genève, Geneva, Switzerland

Also at International School for Advanced Studies (SISSA), Trieste, Italy

Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America

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

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

Also at National Research Nuclear University MEPhI, Moscow, Russia

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

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

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

Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa

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

* Deceased