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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 $\frac{1}{2} \lambda_{ijk} L_i L_j \tilde{e}_k + \lambda'_{ijk} L_i Q_j \tilde{d}_k$ [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 $Z' \rightarrow \ell^+\ell^-$ ($\ell = e, \mu, \tau$) 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 $p_T^{\Delta R=0.4}$ 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 τ leptons are characterized by one or three charged tracks associated to a narrow energy cluster in the calorimeters [23]. This search uses τ_{had} candidates with only one charged track due to reduced identification and reconstruction efficiency for high-\(p_T\) τ 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 τ_{had}. The τ_{had} candidates must have |\(\eta| < 2.47\) and \(E_T > 25\) 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-\(kT\) 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 \(\vec{p}^\text{miss}_T\) (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 τ decay, the \(E_T\) of the τ_{had} candidate is required to be less than the \(E_T\) (\(p_T\)) of the electron (muon) for the \(e\tau\) (\(\mu\tau\)) channel.

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

Events with \(m_{\ell\ell} < 200\) GeV form a validation region to verify the background modeling, and events with \(m_{\ell\ell} > 200\) 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 τ to an electron or a muon is considered as prompt production. For the \(e\tau\) (\(\mu\tau\)) channel, additional background can originate from the \(Z/\gamma^* \rightarrow ee (\mu\mu)\) process if one lepton is misidentified as a τ_{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 μ are usually harder than those from leptonic τ decay.

Contributions from processes in the prompt two-lepton category, as well as photon-related and \(Z/\gamma^* \rightarrow ee (\mu\mu)\) 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 $E_T^{\text{miss}} > 30 \text{ GeV}$ (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 and the shape of the $m_{\ell\ell'}$ distribution. The selection efficiency, including $\tau$ decay branching ratio if $\tau$ is involved, for $m_{\nu\tau} = 2$ TeV are 42%, 14%, and 10% in the $e\mu$, $e\tau$ and $\mu\tau$ channels, respectively. The corresponding numbers for a $Z'$ boson with $m_{Z'} = 2$ 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, and 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 $[\sigma(pp \to \tilde{\nu}_\tau/Z'\to \ell\ell')\times BR(\tilde{\nu}_\tau/Z' \to \ell\ell')]$. For each $\tilde{\nu}_\tau$ or $Z'$ 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
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>$N_{\text{ee}}$</td>
<td>$N_{\text{e\tau had}}$</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 SM</td>
<td>12400±600</td>
<td>40400±2900</td>
</tr>
<tr>
<td>Data</td>
<td>12954</td>
<td>41304</td>
</tr>
</tbody>
</table>

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 distribution. The fit uncertainty is taken into account in the limit-setting procedure, including a contribution from varying the fit function range.

Figure 1: Observed and predicted $\mu\tau$, $e\tau$ had, $\mu$ had 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 $m_{\nu}=1$ TeV and $m_{Z'}=0.75$ TeV. The couplings $\lambda_{311}=0.11$ and $\lambda_{333}=0.07$ ($Q_{\ell\ell}=1$) 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 $m_{\nu}$ 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-
periments containing only background processes, as the median of the 95% CL limit distributions for each set of pseudoexperiments at each value of $m_{\nu_t}$ or $m_{Z'}$, including systematic uncertainties. The ensemble of limits is also used to assess the $1\sigma$ and $2\sigma$ uncertainty envelopes of the expected limits.

Figure 2 shows the observed and expected cross section times branching ratio limits as a function of $m_{\nu_t}(m_{Z'})$, together with the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty bands. For a $\tilde{\nu}_t$ 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 $e\mu$, $\mu\tau$ and $\nu\tau$ 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 $e\mu$, $\mu\tau$ and $\nu\tau$ channels, respectively.

Theoretical predictions of cross section times branching ratio [33, 39] are also shown, assuming $\lambda'_{311} = 0.11$ and $\lambda'_{3k} = 0.07$ for the $\tilde{\nu}_t$ and $Q_{ij} = 1$ for the $Z'$, consistent with benchmark couplings used in previous searches.

For these benchmark couplings, the lower limits on the $\tilde{\nu}_t$ mass are 2.0 TeV, 1.7 TeV, and 1.7 TeV for the $e\mu$, $\mu\tau$ and $\nu\tau$ channels, respectively. The corresponding lower limits on the $Z'$ mass are 2.5 TeV, 2.2 TeV and 2.2 TeV for the $e\mu$, $\mu\tau$ and $\nu\tau$ 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 $e\mu$, $e\tau_{had}$, or $\mu\tau_{had}$ 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 $\tilde{\nu}_t$ and a LFV $Z'$ boson. These results considerably extend previous constraints from the Tevatron and LHC experiments.

![Figure 2](image-url)  
**Figure 2:** The 95% CL limits on cross section times branching ratio as a function of $\tilde{\nu}_t$ mass (top plots) and $Z'$ mass (bottom plots) for $e\mu$ (left), $\mu\tau$ (middle), and $\nu\tau$ (right). Theory curves are for the arbitrary choice of couplings $\lambda'_{311} = 0.11$ and $\lambda'_{3k} = 0.07$ for $\tilde{\nu}_t$ 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.
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References


[20] 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, φ) are used in the transverse plane, φ being the azimuthal angle around the beam direction. Pseudorapidity is defined in terms of the polar angle θ as η = −ln tan(θ/2). Transverse projections are defined relative to the beam axis.


The ATLAS Collaboration

DESY, Hamburg and Zeuthen, Germany
Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
Department of Physics, Duke University, Durham NC, United States of America
SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
INFN Laboratori Nazionali di Frascati, Frascati, Italy
Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
Section de Physique, Université de Genève, Geneve, Switzerland
(a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi, Georgia
II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
Department of Physics, Hampton University, Hampton VA, United States of America
Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
(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
Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
(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
Department of Physics, Indiana University, Bloomington IN, United States of America
Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
University of Iowa, Iowa City IA, United States of America
Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
Graduate School of Science, Kobe University, Kobe, Japan
Faculty of Science, Kyoto University, Kyoto, Japan
Kyoto University of Education, Kyoto, Japan
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, United Kingdom
(a) INFN Sezione di Lecce; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
Department of Physics and Astronomy, University College London, London, United Kingdom
Louisiana Tech University, Ruston LA, United States of America
Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and
CNRS/IN2P3, Paris, France
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 and 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
- INFN Sezione di Pavia;
- 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
- INFN Sezione di Pisa;
- Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
- Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa;
- Faculdade de Ciências, Universidade de Lisboa, Lisboa;
- Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- INFN Sezione di Roma Tor Vergata;
- Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- INFN Sezione di Roma Tre;
- 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;
- Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat;
- Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech;
- Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda;
- 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
- Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava;
- 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;
- Department of Physics, University of Johannesburg, Johannesburg;
- School of Physics, University of the Witwatersrand, Johannesburg, South Africa