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Published in:
Physical Review Letters

DOI:
10.1103/PhysRevLett.106.251801

Citation for published version (APA):
Aad, G., et al., U., Bentvelsen, S., Colijn, A. P., de Jong, P., de Nooij, L., ... Vreeswijk, M. (2011). Search for a heavy particle decaying into an electron and a muon with the ATLAS detector in \( s = 7 \text{ TeV} \) pp collisions at the LHC. Physical Review Letters, 106(25), [251801]. https://doi.org/10.1103/PhysRevLett.106.251801

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Download date: 25 Sep 2020
Search for a Heavy Particle Decaying into an Electron and a Muon with the ATLAS Detector in $\sqrt{s} = 7$ TeV $pp$ collisions at the LHC

G. Aad et al.*

(ATLAS Collaboration)

(Received 29 March 2011; published 22 June 2011)

This Letter presents the first search for a heavy particle decaying into an $e^\pm \mu^\mp$ final state in $\sqrt{s} = 7$ TeV $pp$ collisions at the LHC. The data were recorded by the ATLAS detector during 2010 and correspond to a total integrated luminosity of 35 pb$^{-1}$. No excess above the standard model background expectation is observed. Exclusions at 95% confidence level are placed on two representative models. In an $R$-parity violating supersymmetric model, tau sneutrinos with a mass below 0.75 TeV are excluded, assuming all $R$-parity violating couplings are zero except $A_{311} = 0.11$ and $\lambda_{312} = 0.07$. In a lepton flavor violating model, a $Z'$-like vector boson with masses of 0.70–1.00 TeV and corresponding cross sections times branching ratios of 0.175–0.183 pb is excluded. These results extend to higher mass $R$-parity violating sneutrinos and lepton flavor violating $Z'$s than previous constraints from the Tevatron.

DOI: 10.1103/PhysRevLett.106.251801

PACS numbers: 12.60.Jv, 12.60.Cn, 13.85.Rm, 14.80.Ly

Events with $e^\pm \mu^\mp$ ($e\mu$) in the final state, which played an important role in the discoveries of the tau lepton and the top quark, have a clean experimental signature and low background. Many new physics models allow an $e\mu$ signature. For example, in $R$-parity violating (RPV) supersymmetric models [1] a sneutrino can decay to $e\mu$. Models with additional gauge symmetry can accommodate an $e\mu$ signature through lepton flavor violating (LFV) decays of an extra gauge boson $Z'$ [2]. Standard model (SM) processes that can produce an $e\mu$ signature typically have small cross sections, and the $e\mu$ invariant mass ($m_{e\mu}$) lies below the range favored for new physics signals. This Letter reports a search for a heavy particle decaying into the $e\mu$ final state using data taken with the ATLAS detector. The results are interpreted in terms of the production and decay of a tau sneutrino $\tilde{\nu}_\tau$ and a $Z'$. Both the CDF and D0 Collaborations at the Tevatron collider have reported searches for the RPV production and decay of the $\tilde{\nu}_\tau$ [3–7]. The CDF Collaboration has also set limits on the LFV couplings as a function of the $Z'$ mass [4].

The ATLAS detector [8] is a multipurpose particle physics apparatus with a forward-backward symmetric cylindrical geometry and near 4π coverage in solid angle [9]. The inner tracking detector (ID) consists of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker. The ID is surrounded by a thin superconducting solenoid providing a 2 T magnetic field and by a finely segmented, hermetic calorimeter. The latter covers $|\eta| < 4.9$ and provides three-dimensional reconstruction of particle showers using lead-liquid argon sampling for the electromagnetic compartment followed by a hadronic compartment which is based on iron-scintillating tiles sampling in the central region and on liquid argon sampling with copper or tungsten absorbers for $|\eta| > 1.7$. The muon spectrometer surrounds the calorimeters and consists of three large superconducting toroids, a system of precision tracking chambers, and detectors for triggering.

The data used in this analysis were recorded in 2010 at a center-of-mass energy $\sqrt{s} = 7$ TeV. Application of data-quality requirements results in a total integrated luminosity of 35 pb$^{-1}$ with an estimated uncertainty of 11% [10]. Events are required to satisfy one of the single lepton ($e$ or $\mu$) triggers, which have nominal transverse momentum $p_T$ thresholds up to 15 GeV for $e$ and 13 GeV for $\mu$. The trigger efficiency is measured to be 100%, with a precision of 1%, for $e\mu$ candidates containing two leptons with transverse momentum $p_T > 20$ GeV.

To select $e\mu$ events, the electron candidate is required to have $p_T > 20$ GeV and to lie inside the pseudorapidity regions $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$. The event is rejected if the candidate cluster is located in a problematic region of the electromagnetic calorimeter. Electron identification and isolation requirements provide rejection against hadrons. A set of electron identification criteria based on the calorimeter shower shape, track quality, and track matching with the calorimeter cluster, referred to as “medium” in Ref. [11], is applied. In addition, a calorimeter isolation criterion $E_{T}^{Calorimeter} < 0.2 < E_{T}$ is applied, where $E_{T}^{Calorimeter}$ is defined as the transverse energy deposited in the calorimeter within a cone of radius $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.2$ around the electron cluster, excluding the core energy deposited by the electron, and $E_{T}$ is the transverse energy of the electron.

The muon candidate must be reconstructed in both the ID and the muon spectrometer. A good match of the
parameters of the ID and muon spectrometer tracks is required, and the $p_T$ values measured by these two systems must be compatible. Furthermore, the muon candidate must have $p_T > 20$ GeV, $|\eta| < 2.4$, and be isolated in the ID with $p_T^{2\text{nd}}/p_T < 0.1$, where $p_T^{2\text{nd}}$ is defined as the sum of the $p_T$ of tracks with $p_T > 1$ GeV within a cone of radius $\Delta R < 0.2$ around the muon track, excluding the muon track.

Jets are reconstructed by using the anti-$k_T$ jet clustering algorithm [12] with a radius parameter of 0.4. Only jets with $p_T > 20$ GeV and $|\eta| < 2.5$ are considered. If such a jet and an electron lie within $\Delta R = 0.2$ of each other, the jet is discarded. Leptons are considered only if they are separated from all of the remaining jets by $\Delta R > 0.4$. Electrons and muons are also required to be separated from each other by $\Delta R > 0.2$.

The $e\mu$ candidate events are required to have exactly one electron and one muon with opposite charge satisfying the above selection criteria. Furthermore, events have to contain at least one primary vertex reconstructed with more than four associated tracks with $p_T > 150$ MeV.

The SM processes that can produce an $e\mu$ signature are predominantly $t\bar{t}$, $Z/\gamma^* \rightarrow \tau\tau$, $W/Z + \text{jets}$, diboson, single top, and QCD multijet events. Among the processes listed above, $t\bar{t}$, $Z/\gamma^* \rightarrow \tau\tau$, single top, $WW$, $WZ$, and $ZZ$ produce electrons and muons in the final state and amount to $\sim 80\%$ of the expected $e\mu$ data yield. The contributions from these processes are estimated by using Monte Carlo (MC) samples generated at $\sqrt{s} = 7$ TeV and processed with the standard chain of the ATLAS GEANT4 [13] simulation and reconstruction [14] using the ATLAS MC09 parameter tune [15]. The event generators used are PYTHIA 6.421 [16] ($W$ and $Z/\gamma^*$), POWHEG 1.0 [17] ($t\bar{t}$), MADGRAPH 4 [18] ($W/Z + \gamma$), MC@NLO 3.4 [19] (single top), and HERWIG 6.510 [20] ($WW$, $WZ$, and $ZZ$). The MC samples are normalized to cross sections with higher order corrections applied, as follows. The cross section is calculated to next-to-next-to-leading-order accuracy for $W$ and $Z/\gamma^*$ [21], next-to-leading-order plus next-to-next-to-leading-log for $t\bar{t}$ [22], and next-to-leading-order for $WW$, $WZ$, and $ZZ$ [23]. Single top and $W/Z + \gamma$ cross sections come from MC@NLO and MADGRAPH, respectively. Studies of $Z/\gamma^* \rightarrow \ell\ell$ ($\ell = e, \mu$) events have shown that the lepton reconstruction and identification efficiencies, energy scale, and resolution need to be adjusted in the MC calculations to properly describe the data. The appropriate corrections are applied to the MC calculations in order to improve the modeling of the backgrounds.

The processes $W/Z + \gamma$, $W/Z + \text{jets}$, and pure QCD jet production give rise to background in addition to prompt leptons, which come from $W$ and $Z$ decay. Jets misidentified as leptons, electrons from photon conversions, and leptons from hadron decays (including $b$- and $c$-hadron decays) are classified as instrumental background. The instrumental background accounts for $\sim 20\%$ of the expected $e\mu$ data yield. The dominant component of the instrumental background comes from events with one prompt lepton and one jet identified as a lepton, with an additional contribution from events with two misidentified jets. These sources are referred to as jet instrumental background and are estimated by using data. The background component initiated by prompt photons, referred to as the photon instrumental background, is estimated from MC calculations.

The jet instrumental background is estimated by using data in the following way. Two selections are defined, both requiring at least one lepton satisfying all lepton criteria. The selections are defined by the second lepton candidate: The “tight” selection requires the second candidate to pass all lepton criteria, while the “loose” selection does not enforce the lepton isolation requirement. The probability for a lepton to satisfy the lepton isolation requirement is estimated by applying the loose and tight selections on $Z/\gamma^* \rightarrow \ell\ell$ events. The probability for a jet to satisfy the lepton isolation requirement is estimated by applying the loose and tight selections on a sample of QCD dijet events to which a cut on the missing transverse energy $E_T^{\text{miss}} < 15$ GeV is applied to remove $W + \text{jets}$ events. These two probabilities, along with numbers of events selected in the loose and tight samples, are used to estimate the background in the final selected sample. The background is estimated to be $12^{+10}_{-5}$ events for candidates with one electron and one jet satisfying the muon selection criteria and $19^{+28}_{-7}$ events for candidates with one muon and one jet satisfying the electron selection criteria. The dominant uncertainty on the jet instrumental background estimation comes from the $p_T$ dependence of the probability for a jet to pass the lepton isolation criterion. The background due to two jets satisfying the lepton requirements is estimated to be $1.3^{+5}_{-1.5}$ events from same-sign dilepton events in the data with the subtraction of contributions estimated from MC calculations for all physics processes except the QCD multijet. The overall jet instrumental background is found to be $29^{+30}_{-10}$ events. This background level has been checked in simulated samples, which agree with the data-driven estimates.

The dominant photon instrumental background comes from the $W(\rightarrow \mu\nu)\gamma$ and $Z(\rightarrow \mu\mu)\gamma$ processes where the photon is reconstructed as an electron. A photon can be reconstructed as an electron if it lies close to a charged particle track or the photon converts to $e^+e^-$ after interacting with the material in front of the calorimeter. The photon instrumental background is found to be $4.0 \pm 0.7$ events.

Table I shows the number of events selected in the data and the estimated background contributions with their uncertainties. A total of 160 $e\mu$ candidates are observed in the data, while the expectation from SM processes is $163^{+34}_{-18}$ events. The dominant sources of systematic uncertainty for the SM prediction arise from the uncertainty on...
the probability for a jet to satisfy the lepton isolation requirement (70% for an electron and 30% for a muon), theoretical cross sections on the physics background processes (5%-15%), and the integrated luminosity (11%). Other systematic uncertainties from the lepton trigger, reconstruction and identification efficiencies, energy or momentum scale, and resolution have been included and are small.

Since no excess is observed in the data, limits are set for the production of $\tilde{\nu}_e$ in RPV supersymmetric models and an LFV $Z'$-like vector boson.

The RPV production of $\tilde{\nu}_e$ by $d\bar{d}$ annihilation decaying into $e\mu$ is considered. By fixing all RPV couplings but $\lambda'_{311}$ and $\lambda_{312}$ to zero, the contributions to the $e\mu$ final state originate from the $\tilde{\nu}_e$ only. With these couplings, along with the assumption that $\tilde{\nu}_e$ is the lightest supersymmetric particle, the $\tilde{\nu}_e$ can decay only to $d\bar{d}$ or $e\mu$. The signal cross section depends on the $\tilde{\nu}_e$ mass ($m_{\tilde{\nu}_e}$), $\lambda'_{311}$, and $\lambda_{312}$. The third-generation $\tilde{\nu}_e$ is considered since stringent limits exist on the electron sneutrino and muon sneutrino [1]. The couplings $\lambda'_{311} = 0.11$ and $\lambda_{312} = 0.07$, compatible with the current indirect limits [1], are chosen as a benchmark point.

An $e\mu$ resonance can be generated in models containing a heavy neutral gauge boson with nondiagonal lepton flavor couplings $Z'$ [24]. Very stringent limits on the combination of the mass and the coupling to $ee$ and $e\mu$ of such models have been inferred from searches for rare muon decay [2]. By using the data presented in this Letter, a limit on the production cross section times branching ratio to $e\mu$ can be placed on a $Z'$-like vector boson. To calculate the acceptance and efficiency, the $Z'$ is assumed to have the same quark and lepton couplings as the SM $Z$.

MC events with $\tilde{\nu}_e$ or $Z'$ decaying into $e\mu$ are generated with HERWIG [20,25] or PYTHIA, respectively. Samples are produced with sneutrino masses ranging from 0.1 to 1 TeV and $Z'$ masses from 0.7 to 1 TeV.

The $e\mu$ invariant mass distribution is presented in Fig. 1 for data, background contributions, and two possible new physics signals: a $\tilde{\nu}_e$ with $m_{\tilde{\nu}_e} = 650$ GeV and a $Z'$ with $m_{Z'} = 700$ GeV. The cross section is 0.31 pb for $m_{\tilde{\nu}_e} = 650$ GeV [26] and 0.61 pb for $m_{Z'} = 700$ GeV [27]. The corresponding overall acceptance times efficiency is 55% for $\tilde{\nu}_e$ and 50% for $Z'$.

The $m_{e\mu}$ spectrum is examined for the presence of a new heavy particle. For $m_{\tilde{\nu}_e} < 500$ GeV, the search region for specific $m_{\tilde{\nu}_e}$ is defined to be $(m_{\tilde{\nu}_e} - 3\sigma, m_{\tilde{\nu}_e} + 3\sigma)$, where $\sigma$ is the expected $m_{e\mu}$ resolution (e.g., $\sigma \approx 15$ GeV for $m_{\tilde{\nu}_e} = 400$ GeV). For higher $m_{\tilde{\nu}_e}$, the region $m_{e\mu} > 400$ GeV is used. The expected and observed 95% C.L. upper limits on $\sigma(pp \rightarrow \tilde{\nu}_e) \times \text{BR}(\tilde{\nu}_e \rightarrow e\mu)$ are calculated by using a Bayesian method [28] with a flat prior for the signal cross section as a function of $m_{\tilde{\nu}_e}$. Figure 2(a) shows the expected and observed limits, as a function of $m_{\tilde{\nu}_e}$, together with the $\pm 1$ and $\pm 2$ standard deviation uncertainty bands. The expected exclusion limits are determined by using simulated pseudoexperiments containing only SM processes by evaluating the 95% C.L. upper limits for each pseudoexperiment at each value of $m_{\tilde{\nu}_e}$. The median of the distribution of limits is shown as the expected limit. The ensemble of limits is also used to find the 1σ and 2σ envelope of the expected limits as a function of $m_{\tilde{\nu}_e}$. For a sneutrino with a mass of 100 GeV (1 TeV), the limit on the cross section times branching ratio is 0.951 (0.154) pb. The theoretical cross sections for $\lambda'_{311} = 0.11$, $\lambda_{312} = 0.07$ and $\lambda'_{311} = 0.10$, $\lambda_{312} = 0.05$ are also shown. Sneutrinos with masses below 0.75 (0.65) TeV are excluded by using $\lambda'_{311} = 0.11$ and $\lambda_{312} = 0.07$ ($\lambda'_{311} = 0.10$ and $\lambda_{312} = 0.05$). The results improve on the previous CDF 95% C.L. limit of 0.56 TeV assuming $\lambda'_{311} = 0.10$ and $\lambda_{312} = 0.05$. The 95% C.L. observed upper limits on $\lambda'_{311}$ as a function of $m_{\tilde{\nu}_e}$ are shown in Fig. 2(b) for three values of $\lambda_{312}$, together with the exclusion region obtained from the D0 experiment [7]. The limits derived here are extended to a higher mass region than was available at D0.
also zero. For a because the median background event count expectation is 0; therefore, the C.L. upper limits on the : 0.11 and : 0.07. Higher values of the RPV coupling are also excluded as a function of for three values of :. Regions above the three curves represent ranges of values that are excluded. These results are compared to the exclusion region obtained from the D0 experiment.

even though the limits are worse than those obtained by the D0 Collaboration in the low mass region due to limited statistics.

A similar method is used to set limits on the LFV Z0-like vector boson, by using only events with m_ee > 400 GeV. After finding no events in the data, the 95% C.L. upper limits on \( \sigma(pp \rightarrow Z') \times BR(Z' \rightarrow e\mu) \) are set, as shown in Fig. 3. The expected limit is the same as the observed limit because the median background event count expectation is also zero. For a Z0 with a mass of 700 GeV (1 TeV), the limit on the cross section times branching ratio is 0.175 (0.183) pb. This result improves upon previous CDF limits by probing a higher mass range of Z0-like vector particles.

In conclusion, a search has been performed for a heavy particle decaying into the final state by using pp collision data at \( \sqrt{s} = 7 \) TeV recorded by the ATLAS detector. The data are found to be consistent with the SM prediction. Exclusions are placed on two representative models at 95% C.L. In an RPV supersymmetric model, tau sneutrinos with a mass below 0.75 TeV are excluded, assuming single coupling dominance and coupling values : = 0.11 and : = 0.07. Higher values of the RPV coupling are also excluded as a function of m_ee. In an LFV model, extra Z0-like gauge bosons are excluded with a cross section times branching ratio above 0.183 pb, assuming m_Z0 = 1 TeV. These results extend to higher mass RPV sneutrinos and LFV Z0s than previous constraints from the Tevatron.

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC, and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST, and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR, and VSC CR, Czech Republic; DNRF, DNSRC, and Lundbeck Foundation, Denmark; ARTEMIS, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNAS, Georgia; BMBF, DFG, HGF, MPG, and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP, and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, The Netherlands; RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERSYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; AARS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF, and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme.
Trust, United Kingdom; DOE and NSF, United States of America. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular, from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (The Netherlands), PIC (Spain), ASGC (Taiwan), RAL (United Kingdom), and BNL (USA) and in the Tier-2 facilities worldwide.

[9] 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 pipe. The x axis points from the interaction point to 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 pipe. The pseudorapidity is defined in terms of the polar angle θ as η = − ln tan(θ/2).


1 University at Albany, Albany, New York, USA
2 Department of Physics, University of Alberta, Edmonton Alberta, Canada
3a Department of Physics, Ankara University, Ankara, Turkey
3b Department of Physics, Dumlupinar University, Kutahya, Turkey
3c Department of Physics, Gazi University, Ankara, Turkey
3d Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
3e Turkish Atomic Energy Authority, Ankara, Turkey
4 LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
5 High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA
6 Department of Physics, University of Arizona, Tucson, Arizona, USA
7 Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA
8 Physics Department, Athens, Greece
9 Physics Department, National Technical University of Athens, Zografou, Greece
10 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
11 Institut de Física d’Altes Energies and Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain
12a Institute of Physics, University of Belgrade, Belgrade, Serbia
12b Vinca Institute of Nuclear Sciences, Belgrade, Serbia
13 Department for Physics and Technology, University of Bergen, Bergen, Norway
14 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA
15 Department of Physics, Humboldt University, Berlin, Germany
16 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
17 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
18a Department of Physics, Bogazici University, Istanbul, Turkey
18b Division of Physics, Dogus University, Istanbul, Turkey
18c Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
18d Department of Physics, Istanbul Technical University, Istanbul, Turkey
19a INFN Sezione di Bologna, Italy
19b Dipartimento di Fisica, Università di Bologna, Bologna, Italy
20 Physikalisches Institut, University of Bonn, Bonn, Germany
21 Department of Physics, Boston University, Boston, Massachusetts, USA
22 Department of Physics, Brandeis University, Waltham, Massachusetts, USA
23a Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
23b Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
24 Physics Department, Brookhaven National Laboratory, Upton, New York, USA
25a National Institute of Physics and Nuclear Engineering, Bucharest, Romania
25b University Politehnica Bucharest, Bucharest, Romania
25c West University in Timisoara, Timisoara, Romania
26 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
27 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
28 Department of Physics, Carleton University, Ottawa Ontario, Canada
29 CERN, Geneva, Switzerland
30 Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
31a Departamento de Física, Pontificia Universidade Católica de Chile, Santiago, Chile
31b Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
32a Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
32b Department of Modern Physics, University of Science and Technology of China, Anhui, China
32c Department of Physics, Nanjing University, Jiangsu, China
32d High Energy Physics Group, Shandong University, Shandong, China
33 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France
INFN Sezione di Milano, Italy
B. I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
Group of Particle Physics, University of Montreal, Montreal Quebec, Canada
P. N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
Skobeltsyn Institute of Nuclear Physics, 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, Nagoya University, Nagoya, Japan
INFN Sezione di Napoli, Italy
Dipartimento di Scienze Fisiche, 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, The Netherlands
Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, The Netherlands
Department of Physics, Northern Illinois University, DeKalb, Illinois, USA
Budker Institute of Nuclear Physics (BINP), 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
Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Pavia, Italy
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
Petersburg Nuclear Physics Institute, Gatchina, Russia
INFN Sezione di Pavia, Italy
Department of Physics, 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 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, Italy
Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, USA
Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
Laboratorio de Instrumentació e Física Experimental de Partículas - LIP, Lisboa, Portugal
Departamento de Física Teórica y del Cosmos y CAPE, Universidad de Granada, Granada, Portugal
Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
Czech Technical University in Prague, Praha, Czech Republic
State Research Center Institute for High Energy Physics, Protvino, Russia
Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
Physics Department, University of Regina, Regina Saskatchewan, Canada
Ritsumeikan University, Kusatsu, Shiga, Japan
INFN Sezione di Roma I, Italy
Dipartimento di Fisica, Università La Sapienza, Roma, Italy
INFN Sezione di Roma Tor Vergata, Italy
Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
INFN Sezione di Roma Tre, Italy
Dipartimento di 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
Université Cadi Ayyad, Faculté des sciences Semlalia Département de Physique, B.P. 2390 Marrakech 40000, Morocco
Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco
Faculté des Sciences, Université Mohammed V, Rabat, Morocco
Also at Università di Napoli Parthenope, Napoli, Italy.
Also at Institute of Particle Physics (IPP), Canada.
Also at Louisiana Tech University, Ruston, LA, USA.
Also at Group of Particle Physics, University of Montreal, Montreal QC, Canada.
Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
Also at Manhattan College, New York, NY, USA.
Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.
Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
Also at High Energy Physics Group, Shandong University, Shandong, China.
Also at California Institute of Technology, Pasadena, CA, USA.
Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
Also at Section de Physique, Université de Genève, Geneva, Switzerland.
Also at Departamento de Física, Universidade de Minho, Braga, Portugal.
Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA.
Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.
Also at Institute of Physics, Jagiellonian University, Krakow, Poland.
Also at Department of Physics, Oxford University, Oxford, United Kingdom.
Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France.
Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.
Also at Department of Physics, Nanjing University, Jiangsu, China.