Search for the lepton flavor violating decay $Z \rightarrow e\mu$ in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector


DOI
10.1103/PhysRevD.90.072010

Publication date
2014

Document Version
Final published version

Published in
Physical Review D. Particles, Fields, Gravitation, and Cosmology

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).
I. INTRODUCTION

Lepton flavor conservation in the charged lepton sector is a fundamental assumption of the Standard Model (SM) but there is no associated symmetry. Thus, searches for lepton flavor violation (LFV) processes are good candidates for probing new physics. The observation of neutrino oscillations is a clear indication of LFV in the neutral lepton sector; however, such an oscillation mechanism cannot induce observable LFV in the charged lepton sector. All searches in the charged lepton sector have produced null results so far [1]. Lepton flavor violation in the charged lepton sector may have a different origin than LFV induced by neutrino oscillations and the search for this effect provides constraints on theories beyond the SM (see for example Refs. [2–4]).

In this paper, a search for the lepton flavor violating decay \( Z \to e\mu \) is presented. There are stringent experimental limits on other charged lepton flavor violating processes, which can be used to derive an upper limit on the branching fraction for \( Z \to e\mu \) with some theoretical assumptions. For example, the upper limit on \( \mu \to 3e \) yields \( \mathcal{B}(Z \to e\mu) < 10^{-12} \) [5] and on \( \mu \to e\gamma \) yields \( \mathcal{B}(Z \to e\mu) < 10^{-10} \) [6]. The experiments at the Large Electron-Positron Collider (LEP) searched directly for the decay \( Z \to e\mu \) [7–10]. The most stringent upper limit is \( \mathcal{B}(Z \to e\mu) < 1.7 \times 10^{-6} \) at the 95% confidence level (C.L.) using a data sample of \( 5.0 \times 10^6 \) Z bosons produced in \( e^+e^- \) collisions at \( \sqrt{s} = 88-94 \) GeV [7]. The Large Hadron Collider (LHC) has already produced many more Z bosons in \( pp \) collisions, but with substantially more background. In this paper, the 20.3 ± 0.6 fb\(^{-1} \) [11] of data collected at \( \sqrt{s} = 8 \) TeV by the ATLAS experiment corresponds to \( 7.8 \times 10^8 \) Z bosons produced. Despite the larger background at the LHC, a more restrictive direct limit on the \( Z \to e\mu \) decay is reported in this paper.

II. ATLAS DETECTOR

The ATLAS detector [12] consists of an inner detector (ID) surrounded by a solenoid that produces a 2 T magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer (MS) immersed in a magnetic field produced by a system of toroids. The ID measures the trajectories of charged particles over the full azimuthal angle and in a pseudorapidity [13] range of \( |\eta| < 2.5 \) using silicon pixel, silicon microstrip, and straw-tube transition-radiation tracker (TRT) detectors. Liquid-argon (LAr) electromagnetic (EM) sampling calorimeters cover the range \( |\eta| < 3.2 \) and a scintillator-tile calorimeter provides hadronic calorimetry for \( |\eta| < 1.7 \). In the end caps (\( |\eta| > 1.5 \)), LAr is also used for the hadronic calorimeters, matching the outer \( |\eta| \) limit of end-cap electromagnetic calorimeters. The LAr forward calorimeters extend the coverage to \( |\eta| < 4.9 \) and provide both the electromagnetic and hadronic energy measurements. The MS measures the deflection of muons within \( |\eta| < 2.7 \) using three stations of precision drift tubes (with cathode strip chambers in the innermost station for \( |\eta| > 2.0 \)) and provides separate trigger measurements from dedicated chambers in the region \( |\eta| < 2.4 \).

A three-level trigger system is used to select interesting events to be recorded for subsequent offline analysis [14]. For this analysis, the candidate events of interest are required to satisfy either a single electron or a single muon trigger that have transverse momentum (\( p_T \)) thresholds of 24 GeV.

III. ANALYSIS STRATEGY

The event selection requires two high-\( p_T \) isolated, oppositely charged leptons of different flavor: \( e^{\pm}\mu^{\mp} \). Events are required to contain little jet energy (i.e. small

* Full author list given at the end of the article.

Published by the American Physical Society under the terms of the Creative Commons Attribution 3.0 License. Further distribution of this work must maintain attribution to the author(s) and the published articles title, journal citation, and DOI.
\[ \mathcal{E}_{\text{T}}^\text{miss}, \text{the maximum transverse momentum of any jet in an event} \] and small missing transverse momentum (with magnitude \( E_{\text{T}}^\text{miss} \)). The former eliminates background processes such as \( \bar{t}t \rightarrow e\mu b\bar{b} \) while the latter rejects \( WW \rightarrow e\mu \nu \bar{\nu} \). These \( p_{\text{T}}^\text{jet} \) and \( E_{\text{T}}^\text{miss} \) requirements are chosen to maximize the Monte Carlo (MC) simulated signal efficiency divided by the square root of the number of candidate background events in the data. Further details of this procedure are given in Sec. VI. After all selection criteria are applied, the dominant background process is \( Z \rightarrow \tau \tau \rightarrow e\mu \nu \bar{\nu} \), which has an \( e\mu \) invariant mass \( (m_{e\mu}) \) spectrum extending into the \( Z \) signal region.

An excess of events above the background expectation is searched for in the \( m_{e\mu} \) spectrum at the \( Z \)-boson mass. The number of \( Z \rightarrow e\mu \) candidates is estimated by fitting the \( m_{e\mu} \) spectrum. The expected signal shape is obtained from MC simulation, while the background is parametrized using a Chebychev polynomial. The branching fraction is obtained from the ratio of the number of observed \( Z \rightarrow e\mu \) candidates to the number of observed \( Z \rightarrow \ell\ell \) events in the data in the mass range \( 70 < m_{\ell\ell} < 110 \text{ GeV} \), where \( \ell = e, \mu \). These \( Z \rightarrow ee \) and \( \mu\mu \) samples are selected with the same selection criteria, resulting in the cancellation of the majority of systematic uncertainties due to electron, muon, and jet reconstruction and modeling. The simulated events are used to cross-check the background level in data and to calculate the selection efficiency for \( Z \rightarrow e\mu/ee/\mu\mu \). All selection requirements were fixed before analyzing the data in the \( Z \) signal region from 85 to 95 GeV.

**V. OBJECT SELECTION**

Candidate electrons must have \( p_{T}^e > 25 \text{ GeV} \) and, to ensure the shower is well contained in the high-granularity region of the EM calorimeter, \( |\eta^e| < 2.47 \) \[28\]. The candidate must not be in the transition region between the barrel and end-cap calorimeters, \( 1.37 < |\eta| < 1.52 \). The impact parameters of the candidate must also be consistent with originating from the primary vertex, defined as the reconstructed vertex with the largest sum of track \( p_{T}^\text{hot} \), constructed from at least three tracks each with \( p_T > 400 \text{ MeV} \). The longitudinal impact parameter, \( z_0 \), measured with respect to the primary vertex, of the candidate must satisfy \( |z_0 \sin \theta| < 0.5 \text{ mm} \) and the transverse impact parameter, \( d_0 \), must satisfy \(|d_0| < 6\sigma_{d_0} \), where \( \sigma_{d_0} \) is the uncertainty of the impact parameter. The electron candidate must be isolated from other event activity by requiring the sum of the transverse momentum of tracks with \( p_{T} > 1 \text{ GeV} \) in a cone of size \( \Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.2 \) around the candidate to satisfy \( \sum p_{T}(\Delta R < 0.2)/p_{T}^e < 0.13 \). In the calorimeter, the sum of the transverse energy deposits in the calorimeter clusters in a cone of size \( \Delta R = 0.2 \) around the candidate must satisfy \( \sum E_T(\Delta R < 0.2)/p_{T}^e < 0.14 \). Candidates must also satisfy the “tight” identification requirements of Ref. \[28\], which are based on calorimeter shower shape, ID track quality, and the spatial match between the shower and the track.

Muon candidates must have \( p_{T}^\mu > 25 \text{ GeV} \) and \( |\eta^\mu| < 2.5 \) to ensure coverage by the ID. Muons are required to have a high-quality TRT track segment if they are within the detector acceptance of the TRT. To ensure the muon originated from the primary vertex, the distances of closest approach to the primary vertex in both \( z \) and the transverse plane must satisfy \(|z_0 \sin \theta| < 0.5 \text{ mm} \) and \(|d_0| < 3\sigma_{d_0} \), respectively. To reject secondary muons from hadronic jets, the ID track used in the muon reconstruction must be isolated by requiring the sum of the \( p_T \) of the tracks around the muon candidate to satisfy \( \sum p_T(\Delta R < 0.2)/p_{T}^\mu < 0.15 \). In the calorimeter, there should be little activity around the muon candidate by requiring the sum of the \( E_T \) around the muon candidate to satisfy \( \sum E_T(\Delta R < 0.2)/p_{T}^\mu < 0.3 \). Candidates must also satisfy the “tight” identification requirements of Ref. \[29\] and have their MS track matched to the ID track \[30\].

Hadronic jets \[31\] are reconstructed using the anti-\( k_T \) algorithm with distance parameter \( R = 0.4 \) \[32\]. The scalar sum of \( p_T \) of tracks associated with the jet which come
from the primary vertex, divided by the scalar sum of $p_T$ of all tracks associated with the jet, must be greater than 50% for jets with $|\eta| < 2.4$ and $p_T < 50$ GeV to remove jets originating from pileup in the central region. The rapidity $|\eta|$ of jets must satisfy $|\eta| < 4.4$. Finally, only jets with $p_T > 20$ GeV are considered in the event selection.

The $E_T^{\text{miss}}$ is defined as the $p_T$ imbalance in the detector. It is formed from the vector sum of the $p_T$ of reconstructed high-$p_T$ objects—electrons, photons, jets, $\tau$ leptons, and muons—as well as energy deposits not associated with any reconstructed objects [34].

VI. EVENT SELECTION

A $Z$ candidate is constructed from two opposite-sign, different-flavor leptons ($e$ or $\mu$). Electron candidates are vetoed if they are within $\Delta R = 0.1$ of a candidate muon. Jets are removed if they are within $\Delta R = 0.3$ of a candidate lepton. Events with more than two candidate leptons are vetoed, as are events with an additional electron or muon that passed the lepton requirements but is not isolated.

As stated above, the selection criteria for $E_T^{\text{miss}}$ and $p_T^{\text{jet max}}$ are chosen to maximize the reconstruction efficiency divided by the square root of the estimated number of background events. The efficiency for selecting $e\mu$ candidates is calculated using MC signal events in the $Z$ signal region, $85 < m_{e\mu} < 95$ GeV. The background is determined by fitting the $m_{e\mu}$ spectrum in data in the mass range $70 < m_{e\mu} < 110$ GeV, excluding the $Z$ signal region, and then interpolating the fitted curve into the $Z$ signal region to estimate the number of background events. The fitting range is chosen so that the $m_{e\mu}$ spectrum can be parametrized with a polynomial. In particular, the lower $m_{e\mu}$ limit is chosen to be above the peak in the $Z \rightarrow \tau\tau \rightarrow e\mu$ mass distribution. The optimum selection criteria are found to be $E_T^{\text{miss}} < 17$ GeV and $p_T^{\text{jet max}} < 30$ GeV.

Several background functions with a small number of free parameters in the fit were investigated before analyzing (“unblinding”) the events in the $Z$ mass region. This includes Chebychev polynomials of second to fourth orders, a Landau function, and an exponential function plus a linear term. The second-order polynomial has an unacceptable $\chi^2$ per degree of freedom, $\chi^2$/d.o.f. = 3.3. All other functions have $\chi^2$/d.o.f. $\sim$ 1. The third-order polynomial is chosen as the default background function for simplicity. The systematic error due to the choice of fitting functions is discussed below.

The $E_T^{\text{miss}}$ and $p_T^{\text{jet max}}$ distributions in the data are compared with the expectation for a MC simulation of the background and signal in Fig. 1. Each plot has all kinematic cuts applied with the exception of the cut on the kinematic variable being shown—as indicated by the vertical lines and arrows. The signal MC is scaled to the 95% C.L. upper limit presented in Sec. VII. The multijet background in these distributions refers to events where at least two jets are misidentified as leptons. The shape and normalization of this background can be estimated from like-sign $e\mu$ candidates in the data. The contributions to the same-sign distribution from top-quark and $W/Z$ events are estimated using simulation (Sec. IV) and subtracted from the same-sign data.

The $E_T^{\text{miss}}$ distribution of $e\mu$ candidate events is shown in Fig. 1(a). The $E_T^{\text{miss}}$ requirement removes most of the
diboson background while retaining the majority of the simulated signal events. The distribution of the \( p_{T}^{\text{max}} \) of the candidate events is shown in Fig. 1(b). The entries in the first bin correspond to events that have no jets passing the jet-selection requirements described in Sec. V. The jet veto eliminates most of the \( t\bar{t} \) background while maintaining a high reconstruction efficiency for \( Z \to e\mu \). The remaining major backgrounds in the \( Z \) signal region are diboson, multijet, \( Z \to \tau\tau \), and \( Z \to \mu\mu \). For the \( Z \to \mu\mu \) background, one of the muons can interact with the detector material leading to the muon being misidentified as an electron due to its overlap with a bremsstrahlung photon. The \( E_{T}^{\text{miss}} \) and the \( p_{T}^{\text{jet}} \) distributions of the background are well reproduced by the MC simulation. However, in extracting the upper limit on the branching fraction for \( Z \to e\mu \), the background is estimated from the data instead of using MC simulation.

VII. RESULT

The \( m_{e\mu} \) distribution with the background expectations superimposed is shown in Fig. 2. The mass spectrum is consistent with the MC background expectation with no evidence of an enhancement at the \( Z \) mass. The mass spectrum is fit as a sum of signal and background contributions as shown in Fig. 3. The signal shape is a binned histogram obtained from the signal MC sample and the absolute normalization is a free parameter in the fit. The background is a third-order Chebychev polynomial function. The fit yields a signal of \( 4 \pm 35 \) events.

![FIG. 2 (color online). The \( e\mu \) invariant mass distribution in data with the background expectations from various processes after all cuts are applied. The hatched bands show the total statistical uncertainty of backgrounds. The expected distribution of \( Z \to e\mu \) signal events, normalized to 13 times the upper limit on the branching fraction \( [13 \times B(Z \to e\mu) = 1.0 \times 10^{-3}] \), is indicated by a black line.](image1)

![FIG. 3 (color online). The \( e\mu \) invariant mass distribution fitted with a signal shape obtained from MC simulation and a third-order Chebychev polynomial to describe the background (solid). The observed 95% C.L. upper limit (dashed) is indicated \( B(Z \to e\mu) = 7.5 \times 10^{-7} \). The lower plot shows the data with the background component of the fit subtracted.](image2)

The upper limit on \( B(Z \to e\mu) \) is given by

\[
B(Z \to e\mu) < \frac{N_{95\%}}{\epsilon_{e\mu} N_{Z}},
\]

where \( N_{95\%} \) is the upper limit on the number of \( Z \to e\mu \) candidate events at 95% C.L., \( \epsilon_{e\mu} \) is the reconstruction efficiency for a \( Z \to e\mu \) event, and \( N_{Z} \) is an estimate of the total number of \( Z \) bosons produced in the data sample. This estimate is obtained from the weighted average of two measurements. One is the number of \( Z \) bosons produced as calculated from the number of \( Z \to ee \) events detected in the data, after correcting for the reconstruction efficiency and branching fraction [35]. The other is calculated with the same procedure using the \( Z \to \mu\mu \) channel. The numbers of \( ee \) and \( \mu\mu \) events are estimated by counting the candidates with dilepton invariant mass in the region \( 70 < m_{ee} < 110 \text{ GeV} \). The reconstruction efficiencies are estimated using MC simulation, calibrated with \( Z \) candidates using the tag-and-probe method [28,30]. The result is summarized in Table I. The weight of each measurement is given by the total uncertainty, which is the quadratic sum of the statistical and systematic uncertainties. The systematic uncertainties include the uncertainties in the electron and muon reconstruction and trigger efficiencies and the absolute scale and resolution of the electron energy and muon \( p_{T} \) [30,36]. These systematic uncertainties are uncorrelated between \( ee \) and \( \mu\mu \) events. Other systematic uncertainties such as those due to imperfect simulation of the \( E_{T}^{\text{miss}} \) and \( p_{T}^{\text{jet}} \) distributions are correlated for the \( e\mu \),
**VIII. Conclusions**

A search for the lepton flavor violating process $Z \rightarrow e\mu$ in $pp$ collisions was performed with the ATLAS detector at the LHC. There is no evidence of an enhancement at the $Z$-boson mass in the $m_{e\mu}$ spectrum for the data set with an integrated luminosity of 20.3 fb$^{-1}$ at $\sqrt{s} = 8$ TeV. Using the $CL_s$ method with a one-sided profile likelihood as a test statistic, an upper limit of 83 signal events at 95% C.L. was found. This leads to an upper limit on the branching fraction of $B(Z \rightarrow e\mu) < 7.5 \times 10^{-7}$ at 95% C.L., significantly more restrictive than that from the LEP experiments.

**Acknowledgments**

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICyT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; EPLANET, ERC and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT and NSRF, Greece; ISF, MINERVA, GIF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW and NCN, Poland; GRICES and FCT, Portugal; MNE/IFA, Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, USA. 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 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

**Table I.** The reconstruction efficiencies for $Z \rightarrow ee, e\mu, \mu\mu$ events are shown. Also shown are the number of $Z$ bosons produced, $N_Z$, as estimated from the number of $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ events, after correcting for the corresponding reconstruction efficiencies and branching fractions, as well as the weighted average. The total uncertainties are given.

<table>
<thead>
<tr>
<th>$Z$ decay</th>
<th>Efficiency (%)</th>
<th>$N_Z$ (10$^6$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ee$</td>
<td>10.8 ± 0.3</td>
<td>7.85 ± 0.24</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>17.8 ± 0.4</td>
<td>7.79 ± 0.17</td>
</tr>
<tr>
<td>$\langle ee, \mu\mu \rangle$</td>
<td>14.2 ± 0.4</td>
<td>7.80 ± 0.15</td>
</tr>
</tbody>
</table>

$ee$, and $\mu\mu$ channels and cancel in the ratio [Eq. (1)], although they are major contributors to the systematic uncertainties shown in Table I before the cancellation. With the cancellation, the systematic uncertainty on $B(Z \rightarrow e\mu)$ is 1.2%, which is small compared to the overall fitting systematic uncertainty, and is neglected in the final result.

A one-sided profile likelihood [37] is used as a test statistic to calculate an upper limit on the number of signal events using the $CL_s$ procedure [38]. The procedure yields an observed 95% C.L. upper limit of 72 events. This is consistent with the expected upper limit of 69 events obtained by generating pseudoexperiments from the observed background spectrum. For the pseudoexperiments, the observed data distribution in the sideband is fitted with a third-order Chebychev polynomial and the fitted function is then interpolated into the signal region to predict the central value for the number of background events in each bin. The central value of the background events in the background region or interpolated data for the signal region is then fluctuated.

There is a systematic uncertainty due to the choice of fitting function used to estimate the background and the associated fitting region (Sec. VI). The upper and lower limits of the fit region are varied in the ranges 100–120 GeV and 70–80 GeV in 5 GeV increments. The background parametrization that yields the largest upper limit on the number of signal events (83 events) is used to set an upper limit on the branching fraction at the 95% confidence level,

$$B(Z \rightarrow e\mu) < 7.5 \times 10^{-7}. \tag{2}$$

---


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


SEARCH FOR THE LEPTON FLAVOR VIOLATING DECAY ...

(AGL Collaboration)

1Department of Physics, University of Adelaide, Adelaide, Australia
2Physics Department, SUNY Albany, Albany, New York, USA
3Department of Physics, University of Alberta, Edmonton AB, Canada
4Department of Physics, Ankara University, Ankara, Turkey
5Department of Physics, Gazi University, Ankara, Turkey
6Istanbul Aydin University, Istanbul, Turkey
7Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
8LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
9High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA
10Department of Physics, University of Arizona, Tucson, Arizona, USA
11Physics Department, The University of Texas at Arlington, Arlington, Texas, USA
12Physics Department, University of Athens, Athens, Greece
13Institute of Physics, University of Belgrade, Belgrade, Serbia
14Institute of Physics, University of Belgrade, Belgrade, Serbia
15Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA
16Department of Physics, Humboldt University, Berlin, Germany

072010-14
Il 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, Virginia, USA
Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
Department of Physics, Shatin, N.T., Hong Kong, China
Department of Physics, Hong Kong, China
Department of Physics, Clear Water Bay, Kowloon, Hong Kong, China
Department of Physics, Indiana University, Bloomington, Indiana, USA
Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
University of Iowa, Iowa City, Iowa, USA
Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA
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
INFN Sezione di Lecce, Italy
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, Louisiana, USA
Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
Fysiska institutionen, Lunds universitet, Lund, Sweden
Departamento de Física Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
Institut für Physik, Universität Mainz, Mainz, Germany
School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA
Department of Physics, McGill University, Montreal QC, Canada
School of Physics, University of Melbourne, Victoria, Australia
Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
INFN Sezione di Milano, Italy
Dipartimento di Fisica, Università di Milano, 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 QC, Canada
P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
Nagasaki Institute of Applied Science, Nagasaki, Japan
Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
INFN Sezione di Napoli, Italy
SEARCH FOR THE LEPTON FLAVOR VIOLATING DECAY ... PHYSICAL REVIEW D 90, 072010 (2014)

104b Dipartimento di Fisica, Università di Napoli, Napoli, Italy
105 Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA
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, Illinois, USA
109 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
10a Department of Physics, New York University, New York, New York, USA
11 Ohio State University, Columbus, Ohio, USA
112 Faculty of Science, Okayama University, Okayama, Japan
113 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
114 Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
115 Palacký University, RCPTM, Olomouc, Czech Republic
116 Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA
117 LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
118 Graduate School of Science, Osaka University, Osaka, Japan
119 Department of Physics, University of Oslo, Oslo, Norway
120 Department of Physics, Oxford University, Oxford, United Kingdom
121 INFN Sezione di Pavia, Italy
122 Dipartimento di Fisica, Università di Pavia, Pavia, Italy
123 Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
124 INFN Sezione di Pisa, Italy
125 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
126 Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal
126a Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
126b Department of Physics, University of Coimbra, Coimbra, Portugal
126c Centro de Física Nuclear da Universidade de Lisboa, Lisbon, Portugal
126d Departamento de Fisica, Universidade do Minho, Braga, Portugal
126e Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
126f Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
127 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
128 Czech Technical University in Prague, Praha, Czech Republic
129 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
130 State Research Center Institute for High Energy Physics, Protvino, Russia
131 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
132 Physics Department, University of Regina, Regina SK, Canada
133 Ritsumeikan University, Kusatsu, Shiga, Japan
134 INFN Sezione di Roma, Italy
135 INFN Sezione di Roma Tor Vergata, Italy
136 INFN Sezione di Roma Tre, Italy
137 Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca, Morocco
137b Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat, Morocco
137c Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco
137d Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco
137e Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
138 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
139 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA
140 Department of Physics, University of Washington, Seattle, Washington, USA
141 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom

072010-17