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

G. Aad et al.*
(ATLAS Collaboration)

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The ATLAS detector at the Large Hadron Collider is used to search for the lepton flavor violating process $Z \rightarrow e\mu$ in $pp$ collisions using 20.3 fb$^{-1}$ of data collected at $\sqrt{s} = 8$ TeV. An enhancement in the $e\mu$ invariant mass spectrum is searched for at the $Z$-boson mass. The number of $Z$ bosons produced in the data sample is estimated using events of similar topology, $Z \rightarrow ee$ and $\mu\mu$, significantly reducing the systematic uncertainty in the measurement. There is no evidence of an enhancement at the $Z$-boson mass, resulting in an upper limit on the branching fraction, $B(Z \rightarrow e\mu) < 7.5 \times 10^{-7}$ at the 95% confidence level.

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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 $Z \rightarrow e\mu$ 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 $Z \rightarrow e\mu$ with some theoretical assumptions. For example, the upper limit on $\mu \rightarrow 3e$ yields $B(Z \rightarrow e\mu) < 10^{-12}$ [5] and on $\mu \rightarrow e\gamma$ yields $B(Z \rightarrow e\mu) < 10^{-10}$ [6]. The experiments at the Large Electron-Positron Collider (LEP) searched directly for the decay $Z \rightarrow e\mu$ [7–10]. The most stringent upper limit on $B(Z \rightarrow e\mu) < 1.7 \times 10^{-6}$ 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 $20.3 \pm 0.6$ 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 $Z \rightarrow e\mu$ 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

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\( p_{T,\text{max}} \), 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 \( \tilde{t} \tilde{t} \rightarrow e\mu b\bar{b} \) while the latter rejects \( WW \rightarrow e\mu \nu \nu \). These \( p_{T,\text{max}} \) 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 \( Z \rightarrow e\mu \nu \nu \), 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 \( 70 < m_{\ell\ell} < 110 \) 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.

IV. MONTE CARLO SAMPLES

Monte Carlo simulated samples normalized to the data integrated luminosity are used to determine the major backgrounds pertinent to this analysis as well as to determine the optimal \( E_{\text{T}}^{\text{miss}} \) and \( p_{T,\text{max}} \) requirements. All MC samples are produced using the ATLAS detector simulation [15] based on GEANT4 [16]. Signal \( Z \rightarrow e\mu \) MC events are produced with POWHEG-BOX r1556 [17] using the CT10 parton distribution function (PDF) [18] and the AU2 set of tunable parameters (tune) [19] along with PYTHIA 8.175 [20] for parton showering, hadronization and underlying event simulation. To ensure proper normalization of the upper limit to the number of \( Z \rightarrow ee \) and \( Z \rightarrow \mu\mu \) events, these events are simulated using the same generator as for the signal simulation. In practice, the \( Z \rightarrow e\mu \) sample is created from a \( Z \rightarrow ee \) sample by replacing one of the electrons by a muon at the generator level. The \( Z \rightarrow \tau\tau \) and \( W/W \) samples are simulated with ALPGEN 2.13 [21] interfaced to HERWIG 6.520.2 and PYTHIA 6.426 [22], respectively, using the CTEQ6L1 PDF [23] with the AUET2 tune [24]. The three diboson backgrounds, \( gg \rightarrow WW, gg \rightarrow WW, \) and \( WZ \), are simulated with the CT10 PDF with MC@NLO 4.0 [25] with the AUET2 tune, \( ggWW \) [26] with the AUET2 tune, and POWHEG-BOX interfaced to PYTHIA 8.165 with the AU2 tune, respectively. The top-quark backgrounds, \( \tilde{t} \) and single top-quark production, are simulated with MC@NLO 4.0 and AcerMC 3.8 [27] interfaced to HERWIG 6.520.2 and PYTHIA 6.426, respectively, for parton showering and fragmentation. An average of 20 additional \( pp \) collisions per event in the same bunch crossing, known as pileup, are included in each event to match the data.

V. OBJECT SELECTION

Candidate electrons must have \( p_{T}^{e} > 25 \) 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, \( 1.37 < |\eta^{e}| < 1.52 \). 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 \( p_{T} \), constructed from at least three tracks each with \( p_{T} > 400 \) MeV. The longitudinal impact parameter, \( z_{0} \), measured with respect to the primary vertex, of the candidate must satisfy \( |z_{0} \sin \theta| < 0.5 \) mm and the transverse impact parameter, \( d_{0} \), must satisfy \( |d_{0}| < 3\sigma_{d_{0}} \), 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 \( p_{T} > 1 \) GeV in a cone of size \( \Delta R = \sqrt{(\Delta \phi)^{2} + (\Delta \eta)^{2}} = 0.2 \) around the candidate to satisfy \( \Sigma p_{T}(\Delta R < 0.2)/p_{T}^{e} < 0.13 \). 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 \( \Sigma E_{T}(\Delta R < 0.2)/p_{T}^{e} < 0.14 \). 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 \( p_{T}^{\mu} > 25 \) 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 \( |z_{0} \sin \theta| < 0.5 \) 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 \( \Sigma p_{T}(\Delta R < 0.2)/p_{T}^{\mu} < 0.15 \). 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 \( \Sigma E_{T}(\Delta R < 0.2)/p_{T}^{\mu} < 0.3 \). 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
The systematic error due to the choice of fitting polynomial is chosen as the default background function for events 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.

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. ~ 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 $p_{T}^{\text{jet max}}$ 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 $\bar{t}t$ background while maintaining a high reconstruction efficiency for $Z \rightarrow e\mu$. The remaining major backgrounds in the $Z$ signal region are diboson, multijet, $Z \rightarrow \tau\tau$, and $Z \rightarrow \mu\mu$. For the $Z \rightarrow \mu\mu$ 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 $Z \rightarrow e\mu$, the background is estimated from the data instead of using MC simulation.

VII. RESULT

The $m_{\mu\mu}$ 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 $Z \rightarrow e\mu$ signal events, normalized to 13 times the upper limit on the branching fraction $[13 \times B(Z \rightarrow e\mu) = 1.0 \times 10^{-5}]$, 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 $[B(Z \rightarrow e\mu) = 7.5 \times 10^{-7}]$. The lower plot shows the data with the background component of the fit subtracted.](image2)
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>$N_Z (10^b)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ee$</td>
<td>$10.8 \pm 0.3$</td>
<td>$7.85 \pm 0.24$</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>$17.8 \pm 0.4$</td>
<td>$7.79 \pm 0.17$</td>
</tr>
<tr>
<td>$\langle ee, \mu\mu \rangle$</td>
<td>$7.80 \pm 0.15$</td>
<td></td>
</tr>
<tr>
<td>$e\mu$</td>
<td>$14.2 \pm 0.4$</td>
<td></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 $B(Z \to e\mu)$ 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,

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

**VIII. CONCLUSIONS**

A search for the lepton flavor violating process $Z \to e\mu$ 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 $m_{ee}$ 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 $B(Z \to e\mu) < 7.5 \times 10^{-7}$ at 95% C.L., significantly more restrictive than that from the LEP experiments.

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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, 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

\[ \eta = -\ln(\tan(\theta/2)). \]

Transverse momentum and energy are defined relative to the beamline as

\[ p_T = p \sin \theta \]

and

\[ E_T = E \sin \theta. \]


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[33] The rapidity is defined in terms of the energy, E, and the z component of the momentum along the beam axis, p_z, as

\[ y = \frac{1}{2}\ln\frac{E + p_z}{E - p_z}. \]


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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 Department of Physics, Bogazici University, Istanbul, Turkey
20 Department of Physics, Dogus University, Istanbul, Turkey
21 Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
22 INFN Sezione di Bologna, Italy
23 Physikalisches Institut, University of Bonn, Bonn, Germany
24 Department of Physics, Boston University, Boston, Massachusetts, USA
25 Department of Physics, Brandeis University, Waltham, Massachusetts, USA
26 Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
27 Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
28 Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
29 Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
30 Physics Department, Brookhaven National Laboratory, Upton, New York, USA
31 National Institute of Physics and Nuclear Engineering, Bucharest, Romania
32 National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania
33 West University in Timisoara, Timisoara, Romania
34 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
35 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
36 Department of Physics, Carleton University, Ottawa ON, Canada
37 CERN, Geneva, Switzerland
38 Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
39 Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
40 Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
41 Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
42 Department of Modern Physics, University of Science and Technology of China, Anhui, China
43 School of Physics, Nanjing University, Jiangsu, China
44 School of Physics, Shandong University, Shandong, China
45 Physics Department, Shanghai Jiao Tong University, Shanghai, China
46 Physics Department, Tsinghua University, Beijing 100084, China
47 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
48 Nevis Laboratory, Columbia University, Irvington, New York, USA
49 Niels Bohr Institute, University of Copenhagen, København, Denmark
50 INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
51 Dipartimento di Fisica, Università della Calabria, Rende, Italy
52 AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
53 Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
54 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
55 Physics Department, Southern Methodist University, Dallas, Texas, USA
56 Physics Department, University of Texas at Dallas, Richardson, Texas, USA
57 DESY, Hamburg and Zeuthen, Germany
58 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
59 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
60 Department of Physics, Duke University, Durham, North Carolina, USA
61 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
62 INFN Laboratori Nazionali di Frascati, Frascati, Italy
63 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
64 Section de Physique, Université de Genève, Geneva, Switzerland
65 INFN Sezione di Genova, Italy
66 Dipartimento di Fisica, Università di Genova, Genova, Italy
67 E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
68 High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
69 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
70 SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom

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Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic
Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
Department of Physics, University of Cape Town, Cape Town, South Africa
School of Physics, University of the Witwatersrand, Johannesburg, South Africa
Department of Physics, Stockholm University, Sweden
The Oskar Klein Centre, Stockholm, Sweden
Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, New York, USA
Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
School of Physics, University of Sydney, Sydney, Australia
Institute of Physics, Academia Sinica, Taipei, Taiwan
Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
Department of Physics, University of Toronto, Toronto ON, Canada
TRIUMF, Vancouver BC, Canada
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, Massachusetts, USA
Centro de Investigaciones, Universidad Antonio Nariño, Bogota, Colombia
Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
ICTP, Trieste, Italy
Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
Department of Physics, University of Illinois, Urbana, Illinois, USA
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-CNMT), 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, Wisconsin, USA
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, Connecticut, USA
Yerevan Physics Institute, Yerevan, Armenia
Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

\*Deceased.
\textsuperscript{1}Also at Department of Physics, King’s College London, London, United Kingdom.
\textsuperscript{2}Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
\textsuperscript{3}Also at Novosibirsk State University, Novosibirsk, Russia.
\textsuperscript{4}Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
\textsuperscript{5}Also at TRIUMF, Vancouver BC, Canada.
\textsuperscript{6}Also at Department of Physics, California State University, Fresno CA, USA.