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

G. Aad *et al.*[*]

(ATLAS Collaboration)

The ATLAS detector at the Large Hadron Collider is used to search for the lepton flavor violating process $Z \to e\mu$ 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, $Z \to ee$ 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, $\mathcal{B}(Z \to e\mu) < 7.5 \times 10^{-7}$ at the 95% confidence level.

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 5.0×10^6 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 7.8×10^8 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

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

$p_{\mathrm{Tmax}}^{\mathrm{jet}}$, the maximum transverse momentum of any jet in an event) and small missing transverse momentum (with magnitude $E_{\mathrm{T}}^{\mathrm{miss}}$). The former eliminates background processes such as $t\bar{t} \to e\mu\nu\bar{\nu}b\bar{b}$ while the latter rejects $WW \to e\mu\nu\bar{\nu}$. These $p_{\mathrm{Tmax}}^{\mathrm{jet}}$ and $E_{\mathrm{T}}^{\mathrm{miss}}$ 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 $Z \to \tau\tau \to e\mu\nu\bar{\nu}\nu\bar{\nu}$, 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 $Z \to e\mu$ 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 $Z \to e\mu$ candidates to the number of observed $Z \to \ell\ell$ events in the data in the mass range $70 < m_{\ell\ell} < 110$ GeV, where $\ell = e, \mu$. These $Z \to ee$ 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 $Z \to e\mu/ee/\mu\mu$. 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 $E_{\mathrm{T}}^{\mathrm{miss}}$ and $p_{\mathrm{Tmax}}^{\mathrm{jet}}$ requirements. All MC samples are produced using the ATLAS detector simulation [15] based on GEANT4 [16]. Signal $Z \to e\mu$ 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 $Z \to ee$ and $Z \to \mu\mu$ events, these events are simulated using the same generator as for the signal simulation. In practice, the $Z \to e\mu$ sample is created from a $Z \to ee$ sample by replacing one of the electrons by a muon at the generator level. The $Z \to \tau\tau$ and 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, $q\bar{q} \to WW$, $gg \to WW$, and WZ, are simulated with the CT10 PDF using MC@NLO 4.0 [25] with the AUET2 tune, GG2WW [26] with the AUET2 tune, and POWHEG-BOX interfaced to PYTHIA 8.165 with the AU2

tune, respectively. The top-quark backgrounds, $t\bar{t}$ 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 $p_{\mathrm{T}}^{e} > 25$ 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}^{2}, constructed from at least three tracks each with $p_{\mathrm{T}} > 400$ 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 $|d_0| < 6\sigma_{d_0}$, where σ_{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 $p_{\mathrm{T}} > 1$ GeV in a cone of size $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.2$ around the candidate to satisfy $\Sigma p_{\mathrm{T}}(\Delta R < 0.2)/p_{\mathrm{T}}^{e} < 0.13$. 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 $\Sigma E_{\mathrm{T}}(\Delta R < 0.2)/p_{\mathrm{T}}^{e} < 0.14$. 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 $p_{\mathrm{T}}^{\mu} > 25$ 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 $\Sigma p_{\mathrm{T}}(\Delta R < 0.2)/p_{\mathrm{T}}^{\mu} < 0.15$. 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 $\Sigma E_{\mathrm{T}}(\Delta R < 0.2)/p_{\mathrm{T}}^{\mu} < 0.3$. 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 [33] of jets must satisfy $|y| < 4.4$. Finally, only jets with $p_T > 20$ GeV are considered in the event selection.

The E_T^{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, τ 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 μ). 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^{miss} and p_{Tmax}^{jet} 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 $Z \to \tau\tau \to e\mu$ mass distribution. The optimum selection criteria are found to be $E_T^{miss} < 17$ GeV and $p_{Tmax}^{jet} < 30$ 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 χ^2 per degree of freedom, $\chi^2/\text{d.o.f.} = 3.3$. All other functions have $\chi^2/\text{d.o.f.} \sim 1$. 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^{miss} and p_{Tmax}^{jet} 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
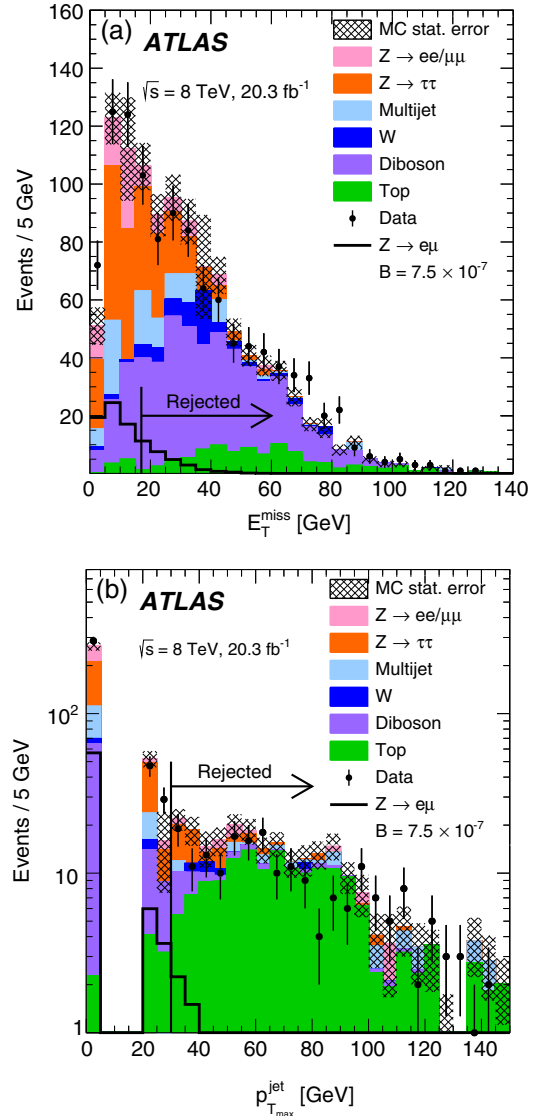

FIG. 1 (color online). Distributions of (a) E_T^{miss} and (b) p_{Tmax}^{jet} for $Z \to e\mu$ candidate events with $85 < m_{e\mu} < 95$ GeV. The expectations for backgrounds from various sources are shown as stacked histograms. Each plot has all cuts applied except for the kinematic variable being shown. The vertical lines and arrows indicate the E_T^{miss} and p_{Tmax}^{jet} requirements. The hatched bands show the total statistical uncertainty of the backgrounds. The expected distribution of $Z \to e\mu$ signal events, normalized to the upper limit on the branching fraction $[\mathcal{B}(Z \to e\mu) = 7.5 \times 10^{-7}]$, is indicated by a black line. The entries at zero in the p_{Tmax}^{jet} distribution correspond to events with no jets that satisfy the jet selection.

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^{miss} distribution of $e\mu$ candidate events is shown in Fig. 1(a). The E_T^{miss} requirement removes most of the

diboson background while retaining the majority of the simulated signal events. The distribution of the $p_{\mathrm{Tmax}}^{\mathrm{jet}}$ 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 $E_{\mathrm{T}}^{\mathrm{miss}}$ and the $p_{\mathrm{Tmax}}^{\mathrm{jet}}$ 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 ± 35 events.
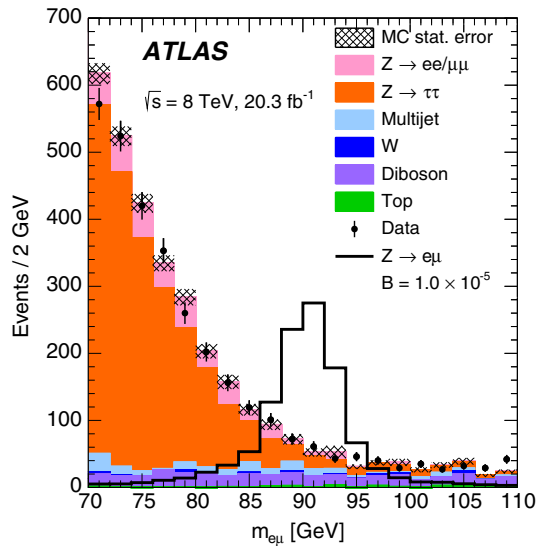
FIG. 2 (color online).   The $e\mu$ invariant mass distribution in data with the background expectations from various processes after all cuts are applied. The hatched bands show the total statistical uncertainty of backgrounds. The expected distribution of $Z \to e\mu$ signal events, normalized to 13 times the upper limit on the branching fraction [$13 \times \mathcal{B}(Z \to e\mu) = 1.0 \times 10^{-5}$], is indicated by a black line.
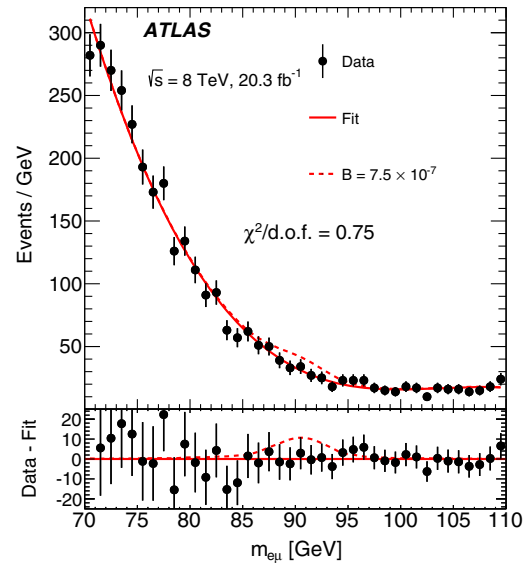
FIG. 3 (color online).   The $e\mu$ invariant mass distribution fitted with a signal shape obtained from MC simulation and a third-order Chebychev polynomial to describe the background (solid). The observed 95% C.L. upper limit (dashed) is indicated [$\mathcal{B}(Z \to e\mu) = 7.5 \times 10^{-7}$]. The lower plot shows the data with the background component of the fit subtracted.

The upper limit on $\mathcal{B}(Z \to e\mu)$ is given by

$$\mathcal{B}(Z \to e\mu) < \frac{N_{95\%}}{\epsilon_{e\mu} N_Z}, \tag{1}$$

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 $70 < m_{\ell\ell} < 110$ 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 $E_{\mathrm{T}}^{\mathrm{miss}}$ and $p_{\mathrm{Tmax}}^{\mathrm{jet}}$ distributions are correlated for the $e\mu$,

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

Z decay	Efficiency (%)	N_Z (10^8)
ee	10.8 ± 0.3	7.85 ± 0.24
$\mu\mu$	17.8 ± 0.4	7.79 ± 0.17
$\langle ee, \mu\mu \rangle$		7.80 ± 0.15
$e\mu$	14.2 ± 0.4	

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 $\mathcal{B}(Z \to e\mu)$ 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,

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

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 $m_{e\mu}$ 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 $\mathcal{B}(Z \to e\mu) < 7.5 \times 10^{-7}$ at 95% C.L., significantly more restrictive than that from the LEP experiments.

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Turk Cakir,[4c] R. Turra,[91a,91b] A. J. Turvey,[40] P. M. Tuts,[35] A. Tykhonov,[49] M. Tylmad,[148a,148b] M. Tyndel,[131] K. Uchida,[21] I. Ueda,[157] R. Ueno,[29] M. Ughetto,[85] M. Ugland,[14] M. Uhlenbrock,[21] F. Ukegawa,[162] G. Unal,[30] A. Undrus,[25] G. Unel,[165] F. C. Ungaro,[48] Y. Unno,[66] C. Unverdorben,[100] D. Urbaniec,[35] P. Urquijo,[88] G. Usai,[8] A. Usanova,[62] L. Vacavant,[85] V. Vacek,[128] B. Vachon,[87] N. Valencic,[107] S. Valentinetti,[20a,20b] A. Valero,[169] L. Valery,[34] S. Valkar,[129] E. Valladolid Gallego,[169] S. Vallecorsa,[49] J. A. Valls Ferrer,[169] W. Van Den Wollenberg,[107] P. C. Van Der Deijl,[107] R. van der Geer,[107] H. van der Graaf,[107] R. Van Der Leeuw,[107] D. van der Ster,[30] N. van Eldik,[30] P. van Gemmeren,[6] J. Van Nieuwkoop,[144] I. van Vulpen,[107] M. C. van Woerden,[30] M. Vanadia,[134a,134b] W. Vandelli,[30] R. Vanguri,[122] A. Vaniachine,[6] P. Vankov,[42] F. Vannucci,[80] G. Vardanyan,[179] R. Vari,[134a] E. W. Varnes,[7] T. Varol,[86] D. Varouchas,[80] A. Vartapetian,[8] K. E. Varvell,[152] F. Vazeille,[34] T. Vazquez Schroeder,[54] J. Veatch,[7] F. Veloso,[126a,126c] S. Veneziano,[134a] A. Ventura,[73a,73b] D. Ventura,[86] M. Venturi,[171] N. Venturi,[160] A. Venturini,[23] V. Vercesi,[121a] M. Verducci,[134a,134b] W. Verkerke,[107] J. C. Vermeulen,[107] A. Vest,[44] M. C. Vetterli,[144,f] O. Viazlo,[81] I. Vichou,[167] T. Vickey,[147c,ii] O. E. Vickey Boeriu,[147c] G. H. A. Viehhauser,[120] S. Viel,[170] R. Vigne,[30] M. Villa,[20a,20b] M. Villaplana Perez,[91a,91b] E. Vilucchi,[47] M. G. Vincter,[29] V. B. Vinogradov,[65] J. Virzi,[15] I. Vivarelli,[151] F. Vives Vaque,[3]

S. Vlachos,[10] D. Vladoiu,[100] M. Vlasak,[128] A. Vogel,[21] M. Vogel,[32a] P. Vokac,[128] G. Volpi,[124a,124b] M. Volpi,[88] H. von der Schmitt,[101] H. von Radziewski,[48] E. von Toerne,[21] V. Vorobel,[129] K. Vorobev,[98] M. Vos,[169] R. Voss,[30] J. H. Vossebeld,[74] N. Vranjes,[138] M. Vranjes Milosavljevic,[13a] V. Vrba,[127] M. Vreeswijk,[107] T. Vu Anh,[48] R. Vuillermet,[30] I. Vukotic,[31] Z. Vykydal,[128] P. Wagner,[21] W. Wagner,[177] H. Wahlberg,[71] S. Wahrmund,[44] J. Wakabayashi,[103] J. Walder,[72] R. Walker,[100] W. Walkowiak,[143] R. Wall,[178] P. Waller,[74] B. Walsh,[178] C. Wang,[153,jj] C. Wang,[45] F. Wang,[175] H. Wang,[15] H. Wang,[40] J. Wang,[42] J. Wang,[33a] K. Wang,[87] R. Wang,[105] S. M. Wang,[153] T. Wang,[21] X. Wang,[178] C. Wanotayaroj,[116] A. Warburton,[87] C. P. Ward,[28] D. R. Wardrope,[78] M. Warsinsky,[48] A. Washbrook,[46] C. Wasicki,[42] P. M. Watkins,[18] A. T. Watson,[18] I. J. Watson,[152] M. F. Watson,[18] G. Watts,[140] S. Watts,[84] B. M. Waugh,[78] S. Webb,[84] M. S. Weber,[17] S. W. Weber,[176] J. S. Webster,[31] A. R. Weidberg,[120] P. Weigell,[101] B. Weinert,[61] J. Weingarten,[54] C. Weiser,[48] H. Weits,[107] P. S. Wells,[30] T. Wenaus,[25] D. Wendland,[16] Z. Weng,[153,ee] T. Wengler,[30] S. Wenig,[30] N. Wermes,[21] M. Werner,[48] P. Werner,[30] M. Wessels,[58a] J. Wetter,[163] K. Whalen,[29] A. White,[8] M. J. White,[1] R. White,[32b] S. White,[124a,124b] D. Whiteson,[165] D. Wicke,[177] F. J. Wickens,[131] W. Wiedenmann,[175] M. Wielers,[131] P. Wienemann,[21] C. Wiglesworth,[36] L. A. M. Wiik-Fuchs,[21] P. A. Wijeratne,[78] A. Wildauer,[101] M. A. Wildt,[42,kk] H. G. Wilkens,[30] J. Z. Will,[100] H. H. Williams,[122] S. Williams,[28] C. Willis,[90] S. Willocq,[86] A. Wilson,[89] J. A. Wilson,[18] I. Wingerter-Seez,[5] F. Winklmeier,[116] B. T. Winter,[21] M. Wittgen,[145] T. Wittig,[43] J. Wittkowski,[100] S. J. Wollstadt,[83] M. W. Wolter,[39] H. Wolters,[126a,126c] B. K. Wosiek,[39] J. Wotschack,[30] M. J. Woudstra,[84] K. W. Wozniak,[39] M. Wright,[53] M. Wu,[55] S. L. Wu,[175] X. Wu,[49] Y. Wu,[89] E. Wulf,[35] T. R. Wyatt,[84] B. M. Wynne,[46] S. Xella,[36] M. Xiao,[138] D. Xu,[33a] L. Xu,[33b,ll] B. Yabsley,[152] S. Yacoob,[147b,mm] R. Yakabe,[67] M. Yamada,[66] H. Yamaguchi,[157] Y. Yamaguchi,[118] A. Yamamoto,[66] K. Yamamoto,[64] S. Yamamoto,[157] T. Yamamura,[157] T. Yamanaka,[157] K. Yamauchi,[103] Y. Yamazaki,[67] Z. Yan,[22] H. Yang,[33e] H. Yang,[175] U. K. Yang,[84] Y. Yang,[111] S. Yanush,[93] L. Yao,[33a] W-M. Yao,[15] Y. Yasu,[66] E. Yatsenko,[42] K. H. Yau Wong,[21] J. Ye,[40] S. Ye,[25] I. Yeletskikh,[65] A. L. Yen,[57] E. Yildirim,[42] M. Yilmaz,[4b] R. Yoosoofmiya,[125] K. Yorita,[173] R. Yoshida,[6] K. Yoshihara,[157] C. Young,[145] C. J. S. Young,[30] S. Youssef,[22] D. R. Yu,[15] J. Yu,[8] J. M. Yu,[89] J. Yu,[114] L. Yuan,[67] A. Yurkewicz,[108] I. Yusuff,[28,nn] B. Zabinski,[39] R. Zaidan,[63] A. M. Zaitsev,[130,aa] A. Zaman,[150] S. Zambito,[23] L. Zanello,[134a,134b] D. Zanzi,[88] C. Zeitnitz,[177] M. Zeman,[128] A. Zemla,[38a] K. Zengel,[23] O. Zenin,[130] T. Ženiš,[146a] D. Zerwas,[117] G. Zevi della Porta,[57] D. Zhang,[89] F. Zhang,[175] H. Zhang,[90] J. Zhang,[6] L. Zhang,[153] X. Zhang,[33d] Z. Zhang,[117] Z. Zhao,[33b] A. Zhemchugov,[65] J. Zhong,[120] B. Zhou,[89] L. Zhou,[35] N. Zhou,[165] C. G. Zhu,[33d] H. Zhu,[33a] J. Zhu,[89] Y. Zhu,[33b] X. Zhuang,[33a] K. Zhukov,[96] A. Zibell,[176] D. Zieminska,[61] N. I. Zimine,[65] C. Zimmermann,[83] R. Zimmermann,[21] S. Zimmermann,[21] S. Zimmermann,[48] Z. Zinonos,[54] M. Ziolkowski,[143] G. Zobernig,[175] A. Zoccoli,[20a,20b] M. zur Nedden,[16] G. Zurzolo,[104a,104b] V. Zutshi[108] and L. Zwalinski[30]

(ATLAS Collaboration)

[1]*Department of Physics, University of Adelaide, Adelaide, Australia*
[2]*Physics Department, SUNY Albany, Albany, New York, USA*
[3]*Department of Physics, University of Alberta, Edmonton AB, Canada*
[4a]*Department of Physics, Ankara University, Ankara, Turkey*
[4b]*Department of Physics, Gazi University, Ankara, Turkey*
[4c]*Istanbul Aydin University, Istanbul, Turkey*
[4d]*Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey*
[5]*LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France*
[6]*High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA*
[7]*Department of Physics, University of Arizona, Tucson, Arizona, USA*
[8]*Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA*
[9]*Physics Department, University of Athens, Athens, Greece*
[10]*Physics Department, National Technical University of Athens, Zografou, Greece*
[11]*Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*
[12]*Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain*
[13a]*Institute of Physics, University of Belgrade, Belgrade, Serbia*
[13b]*Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia*
[14]*Department for Physics and Technology, University of Bergen, Bergen, Norway*
[15]*Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA*
[16]*Department of Physics, Humboldt University, Berlin, Germany*

[17]*Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*
[18]*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
[19a]*Department of Physics, Bogazici University, Istanbul, Turkey*
[19b]*Department of Physics, Dogus University, Istanbul, Turkey*
[19c]*Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey*
[20a]*INFN Sezione di Bologna, Italy*
[20b]*Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy*
[21]*Physikalisches Institut, University of Bonn, Bonn, Germany*
[22]*Department of Physics, Boston University, Boston, Massachusetts, USA*
[23]*Department of Physics, Brandeis University, Waltham, Massachusetts, USA*
[24a]*Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil*
[24b]*Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil*
[24c]*Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil*
[24d]*Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil*
[25]*Physics Department, Brookhaven National Laboratory, Upton, New York, USA*
[26a]*National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
[26b]*National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania*
[26c]*University Politehnica Bucharest, Bucharest, Romania*
[26d]*West University in Timisoara, Timisoara, Romania*
[27]*Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina*
[28]*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
[29]*Department of Physics, Carleton University, Ottawa ON, Canada*
[30]*CERN, Geneva, Switzerland*
[31]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA*
[32a]*Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile*
[32b]*Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile*
[33a]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China*
[33b]*Department of Modern Physics, University of Science and Technology of China, Anhui, China*
[33c]*Department of Physics, Nanjing University, Jiangsu, China*
[33d]*School of Physics, Shandong University, Shandong, China*
[33e]*Physics Department, Shanghai Jiao Tong University, Shanghai, China*
[33f]*Physics Department, Tsinghua University, Beijing 100084, China*
[34]*Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France*
[35]*Nevis Laboratory, Columbia University, Irvington, New York, USA*
[36]*Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark*
[37a]*INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy*
[37b]*Dipartimento di Fisica, Università della Calabria, Rende, Italy*
[38a]*AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland*
[38b]*Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland*
[39]*The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland*
[40]*Physics Department, Southern Methodist University, Dallas, Texas, USA*
[41]*Physics Department, University of Texas at Dallas, Richardson, Texas, USA*
[42]*DESY, Hamburg and Zeuthen, Germany*
[43]*Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany*
[44]*Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany*
[45]*Department of Physics, Duke University, Durham, North Carolina, USA*
[46]*SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
[47]*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
[48]*Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany*
[49]*Section de Physique, Université de Genève, Geneva, Switzerland*
[50a]*INFN Sezione di Genova, Italy*
[50b]*Dipartimento di Fisica, Università di Genova, Genova, Italy*
[51a]*E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia*
[51b]*High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia*
[52]*II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany*
[53]*SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*

[54]II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany

[55]Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France

[56]Department of Physics, Hampton University, Hampton, Virginia, USA

[57]Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA

[58a]Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

[58b]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

[58c]ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany

[59]Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan

[60a]Department of Physics, Shatin, N.T., Hong Kong, China

[60b]Department of Physics, Hong Kong, China

[60c]Department of Physics, Clear Water Bay, Kowloon, Hong Kong, China

[61]Department of Physics, Indiana University, Bloomington, Indiana, USA

[62]Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria

[63]University of Iowa, Iowa City, Iowa, USA

[64]Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA

[65]Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia

[66]KEK, High Energy Accelerator Research Organization, Tsukuba, Japan

[67]Graduate School of Science, Kobe University, Kobe, Japan

[68]Faculty of Science, Kyoto University, Kyoto, Japan

[69]Kyoto University of Education, Kyoto, Japan

[70]Department of Physics, Kyushu University, Fukuoka, Japan

[71]Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina

[72]Physics Department, Lancaster University, Lancaster, United Kingdom

[73a]INFN Sezione di Lecce, Italy

[73b]Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy

[74]Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom

[75]Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia

[76]School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom

[77]Department of Physics, Royal Holloway University of London, Surrey, United Kingdom

[78]Department of Physics and Astronomy, University College London, London, United Kingdom

[79]Louisiana Tech University, Ruston, Louisiana, USA

[80]Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France

[81]Fysiska institutionen, Lunds universitet, Lund, Sweden

[82]Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain

[83]Institut für Physik, Universität Mainz, Mainz, Germany

[84]School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom

[85]CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France

[86]Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA

[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, Michigan, USA

[90]Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA

[91a]INFN Sezione di Milano, Italy

[91b]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, Massachusetts, USA

[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]Moscow Engineering and Physics Institute (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

[104a]INFN Sezione di Napoli, Italy

[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

[110]Department of Physics, New York University, New York, New York, USA

[111]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

[121a]INFN Sezione di Pavia, Italy

[121b]Dipartimento di Fisica, Università di Pavia, Pavia, Italy

[122]Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA

[123]Petersburg Nuclear Physics Institute, Gatchina, Russia

[124a]INFN Sezione di Pisa, Italy

[124b]Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy

[125]Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA

[126a]Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal

[126b]Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal

[126c]Department of Physics, University of Coimbra, Coimbra, Portugal

[126d]Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal

[126e]Departamento de Fisica, Universidade do Minho, Braga, Portugal

[126f]Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain

[126g]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

[134a]INFN Sezione di Roma, Italy

[134b]Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy

[135a]INFN Sezione di Roma Tor Vergata, Italy

[135b]Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy

[136a]INFN Sezione di Roma Tre, Italy

[136b]Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy

[137a]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

[142]Department of Physics, Shinshu University, Nagano, Japan

[143]Fachbereich Physik, Universität Siegen, Siegen, Germany

[144]Department of Physics, Simon Fraser University, Burnaby BC, Canada

[145]SLAC National Accelerator Laboratory, Stanford, California, USA

[146a]Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic

[146b]Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic

[147a]Department of Physics, University of Cape Town, Cape Town, South Africa

[147b]Department of Physics, University of Johannesburg, Johannesburg, South Africa

[147c]School of Physics, University of the Witwatersrand, Johannesburg, South Africa

[148a]Department of Physics, Stockholm University, Sweden

[148b]The Oskar Klein Centre, Stockholm, Sweden

[149]Physics Department, Royal Institute of Technology, Stockholm, Sweden

[150]Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, New York, USA

[151]Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom

[152]School of Physics, University of Sydney, Sydney, Australia

[153]Institute of Physics, Academia Sinica, Taipei, Taiwan

[154]Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel

[155]Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel

[156]Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece

[157]International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan

[158]Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan

[159]Department of Physics, Tokyo Institute of Technology, Tokyo, Japan

[160]Department of Physics, University of Toronto, Toronto ON, Canada

[161a]TRIUMF, Vancouver BC, Canada

[161b]Department of Physics and Astronomy, York University, Toronto ON, Canada

[162]Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan

[163]Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA

[164]Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

[165]Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA

[166a]INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy

[166b]ICTP, Trieste, Italy

[166c]Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy

[167]Department of Physics, University of Illinois, Urbana, Illinois, USA

[168]Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

[169]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-CNM), University of Valencia and CSIC, Valencia, Spain

[170]Department of Physics, University of British Columbia, Vancouver BC, Canada

[171]Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada

[172]Department of Physics, University of Warwick, Coventry, United Kingdom

[173]Waseda University, Tokyo, Japan

[174]Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel

[175]Department of Physics, University of Wisconsin, Madison, Wisconsin, USA

[176]Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany

[177]Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany

[178]Department of Physics, Yale University, New Haven, Connecticut, USA

[179]Yerevan Physics Institute, Yerevan, Armenia

[180]Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

[a]Deceased.

[b]Also at Department of Physics, King's College London, London, United Kingdom.

[c]Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

[d]Also at Novosibirsk State University, Novosibirsk, Russia.

[e]Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.

[f]Also at TRIUMF, Vancouver BC, Canada.

[g]Also at Department of Physics, California State University, Fresno CA, USA.

[h]Also at Tomsk State University, Tomsk, Russia.

[i]Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.

[j]Also at Università di Napoli Parthenope, Napoli, Italy.

[k]Also at Institute of Particle Physics (IPP), Canada.

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

[m]Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.

[n]Also at Louisiana Tech University, Ruston LA, USA.

[o]Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.

[p]Also at Department of Physics, The University of Texas at Austin, Austin TX, USA.

[q]Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.

[r]Also at CERN, Geneva, Switzerland.

[s]Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.

[t]Also at Manhattan College, New York NY, USA.

[u]Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.

[v]Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.

[w]Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.

[x]Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.

[y]Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India.

[z]Also at Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy.

[aa]Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

[bb]Also at Section de Physique, Université de Genève, Geneva, Switzerland.

[cc]Also at International School for Advanced Studies (SISSA), Trieste, Italy.

[dd]Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, USA.

[ee]Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.

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

[gg]Also at Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia.

[hh]Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.

[ii]Also at Department of Physics, Oxford University, Oxford, United Kingdom.

[jj]Also at Department of Physics, Nanjing University, Jiangsu, China.

[kk]Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

[ll]Also at Department of Physics, The University of Michigan, Ann Arbor MI, USA.

[mm]Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.

[nn]Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.