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

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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.

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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 $Z \to e\mu$ 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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$p_{\mathrm{T}\max}^{\mathrm{jet}}$, 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 $p_{\mathrm{T}\max}^{\mathrm{jet}}$ 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 $p_{\mathrm{T}\max}^{\mathrm{jet}}$ 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 $p_{T\max}^{jet}$ 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 $p_{T\max}^{jet} < 30$ 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 $p_{T\max}^{jet}$ 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 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.

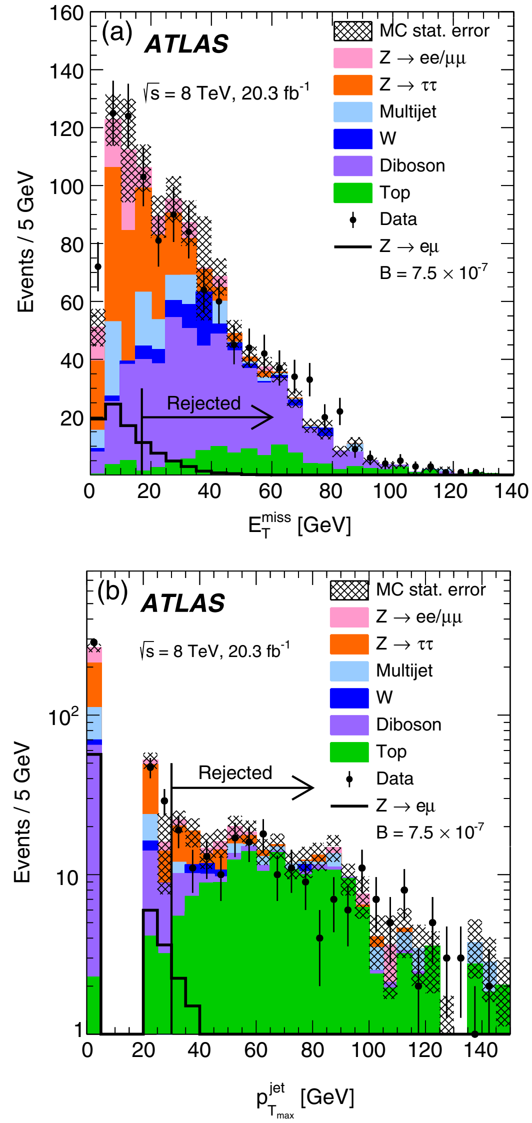

FIG. 1 (color online). Distributions of (a) E_T^{miss} and (b) $p_{T\max}^{jet}$ for $Z \to e\mu$ candidate events with $85 < m_{e\mu} < 95$ GeV. The expectations for backgrounds from various sources are shown as stacked histograms. Each plot has all cuts applied except for the kinematic variable being shown. The vertical lines and arrows indicate the E_T^{miss} and $p_{T\max}^{jet}$ 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 $p_{T\max}^{jet}$ distribution correspond to events with no jets that satisfy the jet selection.

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.

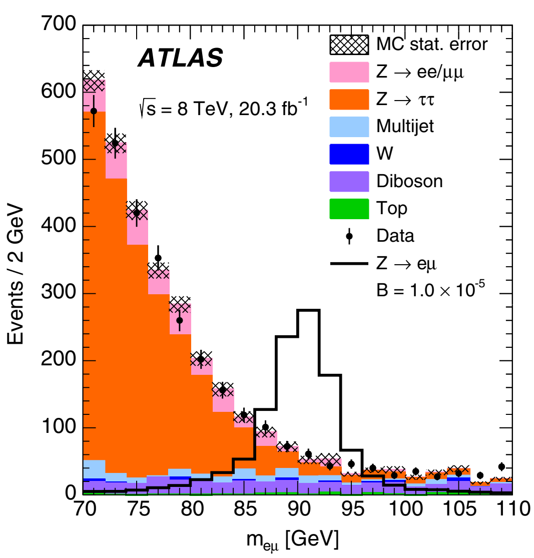

FIG. 2 (color online). The $e\mu$ invariant mass distribution in data with the background expectations from various processes after all cuts are applied. The hatched bands show the total statistical uncertainty of backgrounds. The expected distribution of $Z \to e\mu$ signal events, normalized to 13 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.

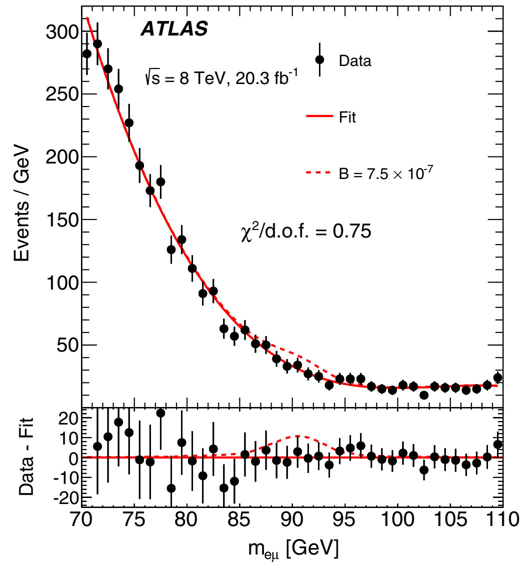

FIG. 3 (color online). The $e\mu$ invariant mass distribution fitted with a signal shape obtained from MC simulation and a third-order Chebychev polynomial to describe the background (solid). The observed 95% C.L. upper limit (dashed) is indicated [$\mathcal{B}(Z \to e\mu) = 7.5 \times 10^{-7}$]. The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

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

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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