MU to E Gamma

The decay $\mu^- \rightarrow e^- + \gamma$

has never been observed.

The current upper bound on the decay branching ratio is

$$\Gamma/\Gamma_{total} < 5.7 \times 10^{-13}$$

(MEG collaboration)

The decay $\mu^- \rightarrow e^- + \gamma$ would violate the conservation of Lepton Flavor Number.

Neutrino oscillations do violate conservation of Lepton Flavor Number.

So Lepton Flavor Number conservation is not an absolute symmetry of nature.

Because $\nu_e \rightarrow \nu_\mu$ occurs in neutrino oscillations , the decay $\mu^- \rightarrow e^- + \gamma$ must occur.

But the decay rate in the Standard Model is very *VERY* small.

From author Petcov, 1977

С.Т.Петков

ПРОЦЕССЫ $\mu \to e + \gamma$, $\mu \to e + e + \bar{e}$, $\nu' \to \nu + \gamma$
В МОДЕЛИ ВАЙНБЕРГА-САЛАМА
СО СМЕШИВАНИЕМ НЕЙТРИНО

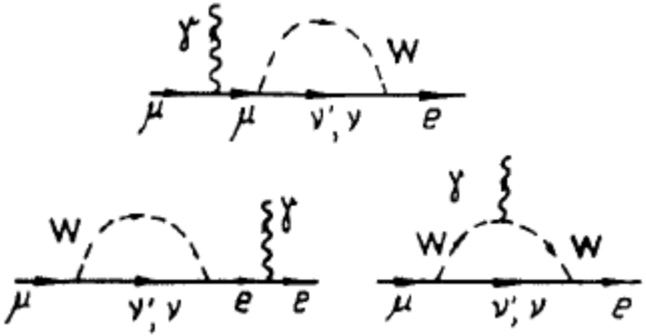
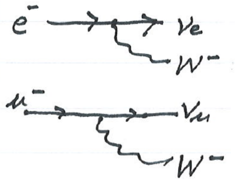


Рис. 1. Диаграммы третьего порядка для распада $\mu \to e + \gamma$.

Neutrino interactions

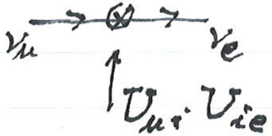


$$J_\alpha = \bar{\nu}_{eL} \gamma_\alpha e_L + \bar{\nu}_{\mu L} \gamma_\alpha \mu_L$$

$$\mathcal{L}_{int} = g J_\alpha W^\alpha$$

Neutrino mass mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



Flavor Conversion:
How do neutrinos propagate
in spacetime?

$$M_1 = ie \frac{G_F}{8\pi^2\sqrt{2}} (m'^2 - m^2) \sin\theta \cos\theta \times \bar{u}(p') \frac{1}{6}(1-\gamma_5) \frac{\sigma_{\rho\alpha} q_\alpha}{m_\mu + m_e} u(p) \varepsilon_\rho(q), \qquad /7/$$

$$\Gamma(\mu \to e + \gamma) = \frac{G_F^2 (m'^2 - m^2)^2}{192\pi^3} \frac{2\alpha}{3\pi} \left(\frac{\sin\theta \cos\theta}{4}\right)^2 m_\mu, \qquad /8/$$

Also 1977 ...

LEPTON MIXING, $\mu \to e + \gamma$ DECAY AND NEUTRINO OSCILLATIONS

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Joint Institute for Nuclear Research, Laboratory of Theoretical Physics, Dubna, USSR

Received 22 February 1977

1. Neutrinos only. It is well known that the charged lepton current in the standard theory of weak interaction has the form:

$$j_\alpha = \bar{\nu}_{eL}\gamma_\alpha e_L + \bar{\nu}_{\mu L}\gamma_\alpha \mu_L , \tag{1}$$

where ν_e and ν_μ are the operators of the electron and muon neutrino fields $e_L = \{(1+\gamma_5)/2\}\, e$ etc. In such a theory, the decay $\mu \to e + \gamma$ obviously is strictly forbidden.

In refs. [1,2] the assumption was made that ν_e and ν_μ in the expression of the current are orthogonal combinations of the fields of two neutrinos ν_1, ν_2 with finite masses m_1, m_2

$$\nu_e = \nu_1 \cos\theta + \nu_2 \sin\theta$$

$$\nu_\mu = -\nu_1 \sin\theta + \nu_2 \cos\theta , \tag{2}$$

where θ is a mixing angle.

In such a theory new phenomena arise as neutrino oscillations [2] and the processes $\mu \to e\gamma$, $\mu \to 3e$ etc, due to neutral asymmetrical lepton currents induced by a high order perturbation theory.

$$R_\mu = \frac{\Gamma(\mu^+ \to e^+ \gamma)}{\Gamma(\mu^+ \to e^+ \nu_e \bar{\nu}_\mu)} = \frac{3}{32}\frac{\alpha}{\pi}\left(\frac{m_1^2 - m_2^2}{M_W^2}\right)^2 \sin^2\theta \cos^2\theta , \tag{3}$$

where M_W is the mass of the intermediate W boson ($M_W \geqslant 37$ GeV).

$$R_\mu = \frac{\Gamma(\mu^+ \to e^+ \gamma)}{\Gamma(\mu^+ \to e^+ \nu_e \bar{\nu}_\mu)} = \frac{3}{32}\frac{\alpha}{\pi}\left(\frac{m_1^2 - m_2^2}{M_W^2}\right)^2 \sin^2\theta \cos^2\theta, \quad (3)$$

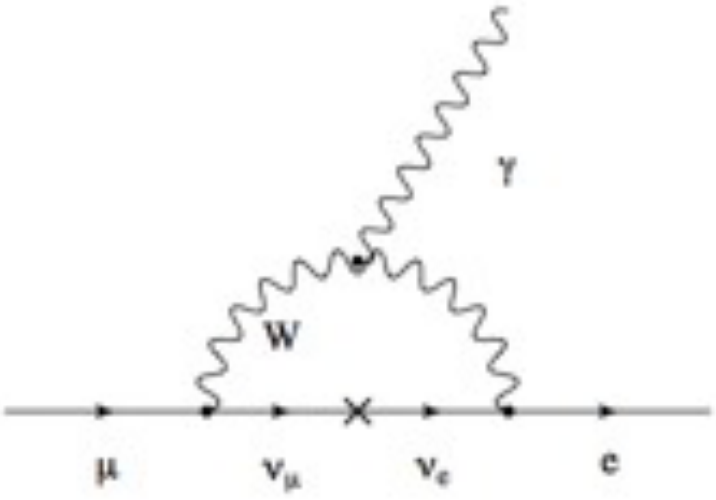
where M_W is the mass of the intermediate W boson ($M_W \geqslant 37$ GeV).

< ~ 0.1 * (1/137) / Pi * $(0.01\ eV^2)^2$ / $(80\ GeV)^4$

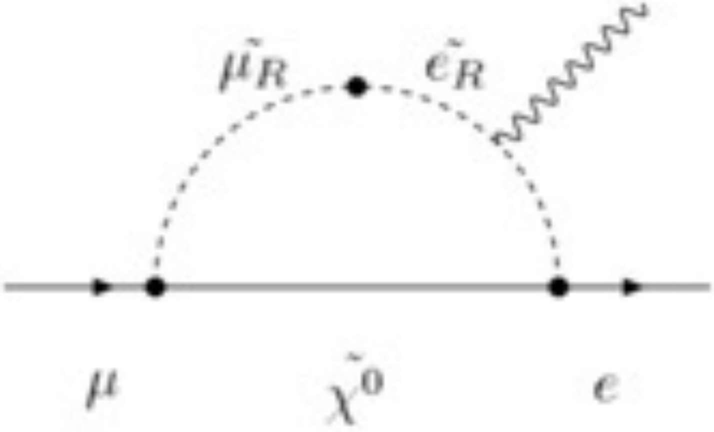
= 6 * 10^{-56}

truly unobservable

Standard model process



A SUSY process



Marciano and Sanda

EXOTIC DECAYS OF THE MUON AND HEAVY LEPTONS IN GAUGE THEORIES*

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Department of Physics, The Rockefeller University, New York, NY 10021, USA

Received 25 January 1977

We have studied the decay $\ell_1 \to \ell_2 + \gamma$ for arbitrary like charged spin $\frac{1}{2}$ leptons in a manner which is applicable to a large class of models. Our computations assume that this process is induced by one loop diagrams. When the leading effect is cancelled by a leptonic G.I.M. mechanism, we find an extremely large enhancement of $O(M_W^4/M_L^4)$ in $\Gamma(\mu^- \to e^- + e^+ + e^-)/\Gamma(\mu^- \to e^- + \gamma)$ if the intermediate lepton is charged.

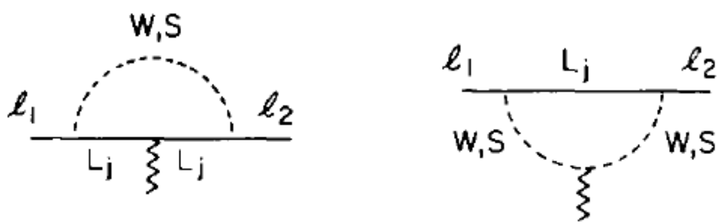
The starting point for our work is the assumption that the decay in (1) is induced in gauge theories through the one loop diagrams of fig. 1 because of lepton flavor changing terms in the interaction Lagrangian of the form [‡1]

$$\mathcal{L}_I = -g \sum_{ij} W^\mu \bar{\ell}_i \gamma_\mu (a_{ij}\gamma_- + b_{ij}\gamma_+) L_j - \left(\frac{g}{M_W}\right) \sum_{ij} S \bar{\ell}_i [m_{\ell_i}(a_{ij}\gamma_- + b_{ij}\gamma_+) - m_{L_j}(a_{ij}\gamma_+ + b_{ij}\gamma_-)] L_j + \text{h.c.}\,,$$

$$\gamma_\pm \equiv (1 \pm \gamma_5)/2\,, \qquad (4)$$

where the leptons ℓ_i, L_j and the intermediate vector boson carry electric charges Qe, $Q'e$ and $(Q - Q')e$ respectively, the couplings of the unphysical Higgs boson S have been added to insure gauge invariance [5] and g is the usual usual weak coupling. The real constants [‡2] a_{ij} and b_{ij} are arbitrary; however they would be fixed by the choice of

Marciano and Sanda



(a) (b)

Because of gauge invariance, the non-vanishing invariant amplitude for the decay process $\ell_1 \to \ell_2 + \gamma$ must be of the general form

$$\mathcal{M} = \epsilon^\mu q^\nu \bar{\ell}_2(p_2)\,\sigma_{\mu\nu}(A + B\gamma_5)\ell_1(p_1), \qquad q = p_1 - p_2, \qquad \sigma_{\mu\nu} = \mathrm{i}\,[\gamma_\mu, \gamma_\nu]/2\,, \tag{5}$$

which leads to the decay rate

$$\Gamma(\ell_1 \to \ell_2 + \gamma) = \frac{1}{8\pi}\left(\frac{m_{\ell_1}^2 - m_{\ell_2}^2}{m_{\ell_1}}\right)^3 (|A|^2 + |B|^2)\,. \tag{6}$$

Using the couplings in (4), we computed the graphs in fig. 1 and found to leading order in $1/M_W^2$

$$\begin{pmatrix} A \\ B \end{pmatrix} = \frac{eG_F}{4\sqrt{2}\pi^2}\sum_j \left(\frac{9Q' - 5Q}{12}(a_{2j}a_{1j} \pm b_{2j}b_{1j})(m_{\ell_1} \pm m_{\ell_2}) + (Q - 2Q')(a_{2j}b_{1j} \pm b_{2j}a_{1j})m_{L_j}\right), \tag{7}$$

where $G_F \equiv g^2/2\sqrt{2}M_W^2$ is the Fermi constant [‡3]. Specializing to the case $\ell_1 = \mu$, $\ell_2 = e$ and remembering

$$\Gamma(\mu \to e\nu\nu) \simeq \frac{G_F^2 m_\mu^5}{192\pi^3}, \tag{8}$$

MEG Collaboration

PRL **110,** 201801 (2013) PHYSICAL REVIEW LETTERS week ending 17 MAY 2013

New Constraint on the Existence of the $\mu^+ \rightarrow e^+\gamma$ Decay

J. Adam,[1,2] X. Bai,[3] A. M. Baldini,[4a] E. Baracchini,[3,5,6] C. Bemporad,[4a,4b] G. Boca,[7a,7b] P. W. Cattaneo,[7a] G. Cavoto,[8a] F. Cei,[4a,4b] C. Cerri,[4a] A. de Bari,[7a,7b] M. De Gerone,[9a,9b] T. Doke,[10] S. Dussoni,[4a] J. Egger,[1] Y. Fujii,[3] L. Galli,[1,4a] F. Gatti,[9a,9b] B. Golden,[6] M. Grassi,[4a] A. Graziosi,[8a] D. N. Grigoriev,[11,12] T. Haruyama,[5] M. Hildebrandt,[1] Y. Hisamatsu,[3] F. Ignatov,[11] T. Iwamoto,[3] D. Kaneko,[3] P.-R. Kettle,[1] B. I. Khazin,[11] N. Khomotov,[11] O. Kiselev,[1] A. Korenchenko,[13] N. Kravchuk,[13] G. Lim,[6] A. Maki,[5] S. Mihara,[5] W. Molzon,[6] T. Mori,[3] D. Mzavia,[13] R. Nardò,[7a] H. Natori,[5,3,1] D. Nicolò,[4a,4b] H. Nishiguchi,[5] Y. Nishimura,[3] W. Ootani,[3] M. Panareo,[14a,14b] A. Papa,[1] G. Piredda,[8a] A. Popov,[11] F. Renga,[8a,1] E. Ripiccini,[8a,8b] S. Ritt,[1] M. Rossella,[7a] R. Sawada,[3] F. Sergiampietri,[4a] G. Signorelli,[4a] S. Suzuki,[10] F. Tenchini,[4a,4b] C. Topchyan,[6] Y. Uchiyama,[3,1] C. Voena,[8a] F. Xiao,[6] S. Yamada,[5] A. Yamamoto,[5] S. Yamashita,[3] Z. You,[6] Yu. V. Yudin,[11] and D. Zanello[8a]

(MEG Collaboration)

The analysis of a combined data set, totaling 3.6×10^{14} stopped muons on target, in the search for the lepton flavor violating decay $\mu^+ \rightarrow e^+\gamma$ is presented. The data collected by the MEG experiment at the Paul Scherrer Institut show no excess of events compared to background expectations and yield a new upper limit on the branching ratio of this decay of 5.7×10^{-13} (90% confidence level). This represents a four times more stringent limit than the previous world best limit set by MEG.

DOI: 10.1103/PhysRevLett.110.201801 PACS numbers: 13.35.Bv, 11.30.Hv, 11.30.Pb, 12.10.Dm

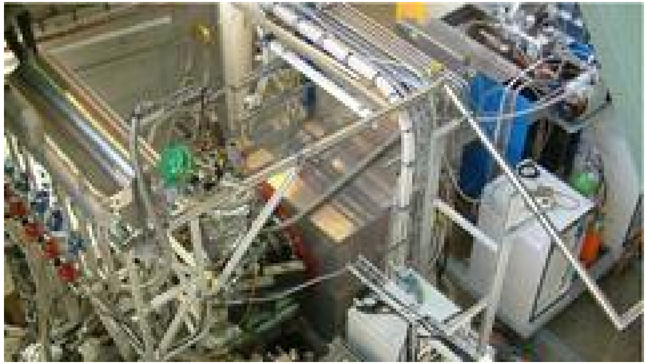
MEG Collaboration

The Paul Scherrer Institute

Zurich, Switzerland

590 MeV proton accelerator

The Swiss Muon Source



Swiss Muon Source (SμS)

Low Energy Muon Beamline of the Swiss Muon Source (SμS)
The Swiss muon source – powered by the PSI 590 MeV cyclotron with a proton current of 2200 mA – is the world's most intense continuous beam muon source. The proton beam hits two graphite targets. Attached to those are seven beamlines for muon (or pion) extraction, two of them are equipped with superconducting decay channels. The available muon energies range from 0.5 kV to 60 MeV.

MEG Collaboration

The observed profile likelihood ratios as a function of the branching ratio are shown in Fig. 3. The best $\mathcal{B}$ estimates, upper limits at 90% C.L. ($\mathcal{B}_{90}$) and $\mathcal{S}_{90}$ for the combined 2009–2010 data set, the 2011 data alone and the total 2009–2011 data set are listed in Table I. The $\mathcal{B}_{90}$ for the latter is 5.7×10^{-13}. As a quality check the maximum likelihood fit is repeated for the 2009–2011 data set omitting the constraint on the number of background events. We obtain $N_{\mathrm{RMD}} = 163 \pm 32$ and $N_{\mathrm{ACC}} = 2411 \pm 57$, in good agreement with the expectations estimated

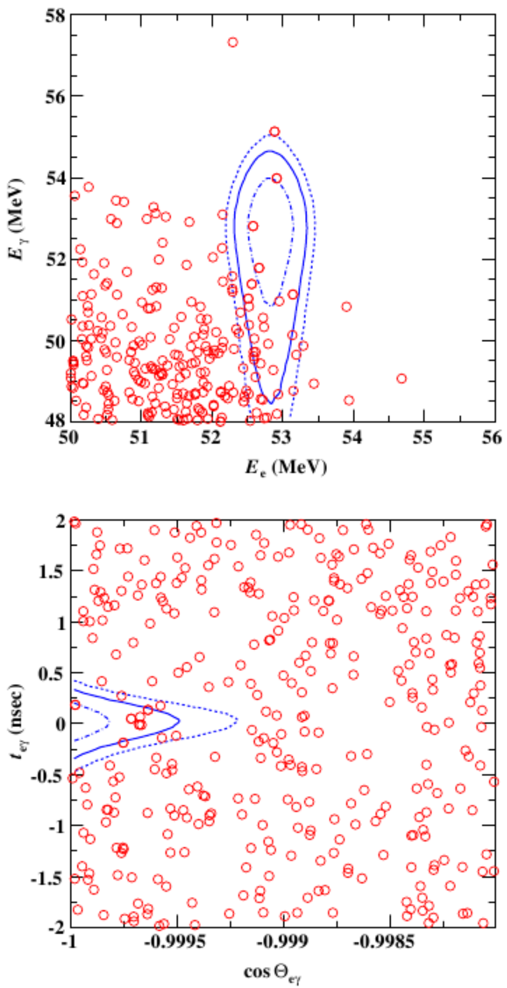


FIG. 2 (color online). Event distributions for the combined 2009–2011 data set in the (E_e, E_γ) and $(\cos\Theta_{e\gamma}, t_{e\gamma})$ planes. In the top (bottom) panel, a selection of $|t_{e\gamma}| < 0.244$ ns and $\cos\Theta_{e\gamma} < -0.9996$ with 90% efficiency for each variable ($52.4 < E_e < 55$ MeV and $51 < E_\gamma < 55.5$ MeV with 90% and 74% efficiencies for E_e and E_γ, respectively) is applied. The signal PDF contours (1, 1.64 and 2 σ) are also shown.

TABLE I. Best fit values ($\mathcal{B}_{\mathrm{fit}}$'s), branching ratios ($\mathcal{B}_{90}$) and sensitivities ($\mathcal{S}_{90}$).

Data set	$\mathcal{B}_{\mathrm{fit}} \times 10^{12}$	$\mathcal{B}_{90} \times 10^{12}$	$\mathcal{S}_{90} \times 10^{12}$
2009–2010	0.09	1.3	1.3
2011	−0.35	0.67	1.1
2009–2011	−0.06	0.57	0.77

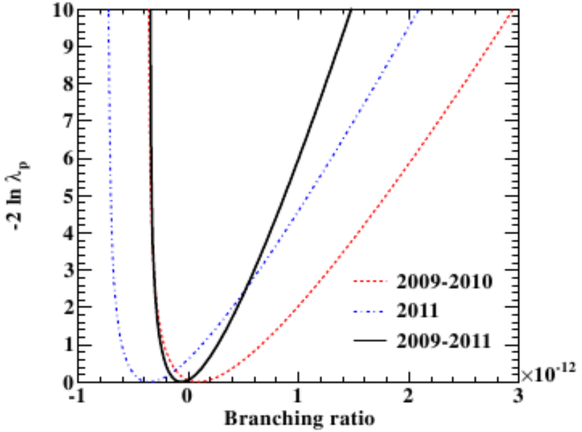
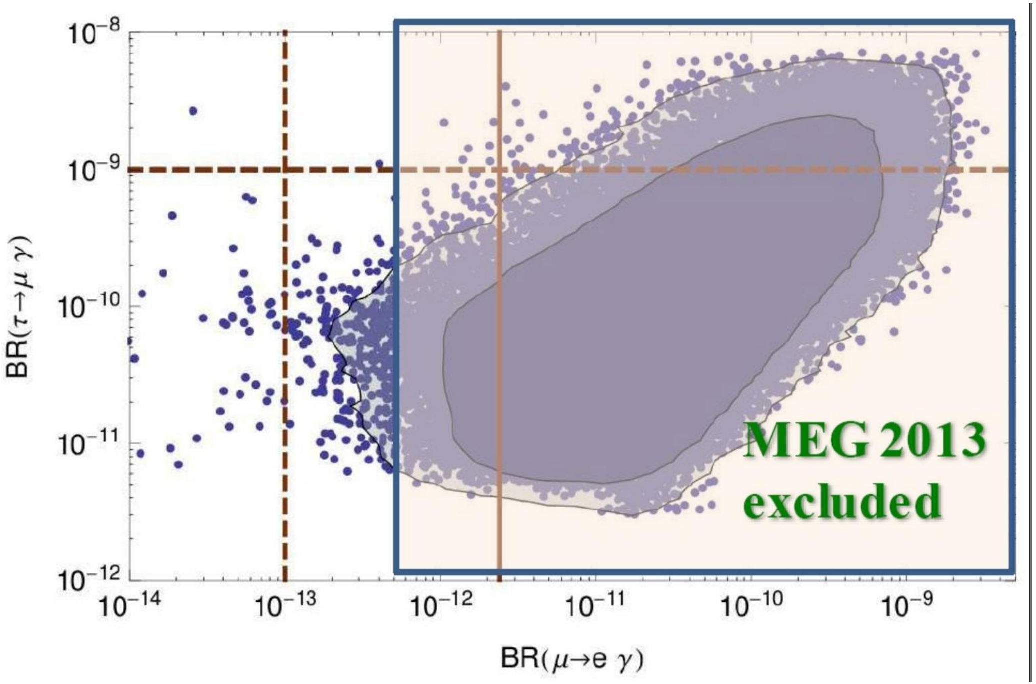


FIG. 3 (color online). Observed profile likelihood ratios (λ_p) as a function of the branching ratio for the 2009–2010 combined data, the 2011 data alone, and the combined 2009–2011 data sample.

In conclusion the MEG experiment has established the most stringent upper limit to date on the branching ratio of the $\mu^+ \to e^+\gamma$ decay, $\mathcal{B} < 5.7 \times 10^{-13}$ at 90% C.L. using data collected between 2009 and 2011, which improves the previous best upper limit by a factor of 4. Further data have also been acquired in 2012 with an additional three-month run scheduled for 2013; the final number of stopped muons is expected to be almost twice that of the sample analyzed so far. Currently an upgrade program is underway aiming at a sensitivity improvement of a further order of magnitude [21].

MEG Collaboration - public website



It is getting close to the wire for the alternative theories: the blue dots represent the cloud of predictions for the probabilities of the rare decays – based on varying the model parameters that might describe the theories beyond the Standard Model. Through the PSI-researchers' new measurements, the brighter area on the right has now been ruled out. (Blankenburg et al. Eur. Phys. J. C 72, 2126 (2012) und Daten aus J. Adam et al. Phys. Rev. Lett. 110, 201801 (2013))

ATLAS (LHC)

PHYSICAL REVIEW D **90,** 072010 (2014)

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)
(Received 26 August 2014; published 23 October 2014)

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.

DOI: 10.1103/PhysRevD.90.072010 PACS numbers: 12.60.-i

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.

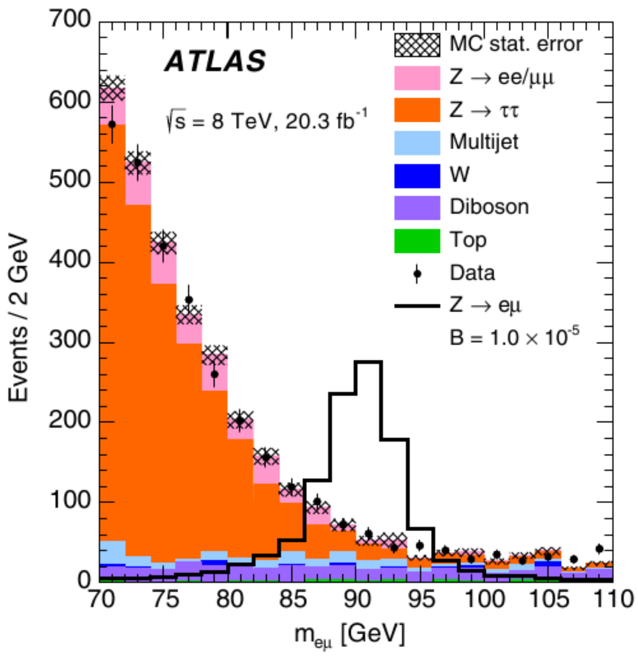


FIG. 2 (color online). The $e\mu$ invariant mass distribution in data with the background expectations from various processes after all cuts are applied. The hatched bands show the total statistical uncertainty of backgrounds. The expected distribution of $Z \to e\mu$ signal events, normalized to 13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

ATLAS (LHC)

PHYSICAL REVIEW D **90**, 072010 (2014)

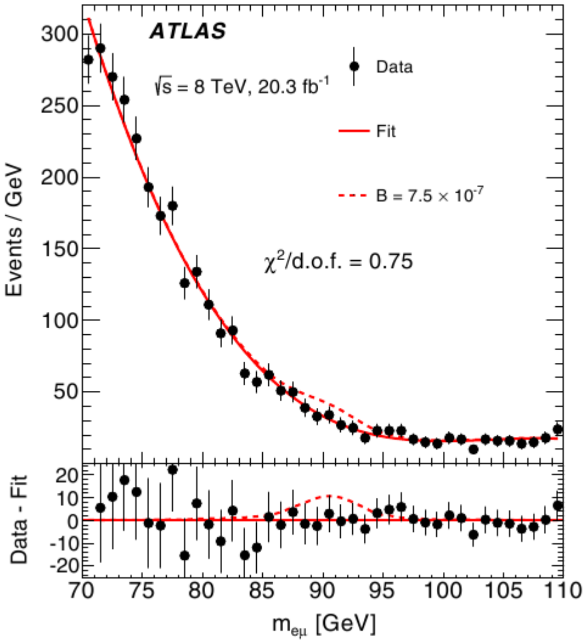


FIG. 3 (color online). The $e\mu$ invariant mass distribution fitted with a signal shape obtained from MC simulation and a third-order Chebychev polynomial to describe the background (solid). The observed 95% C.L. upper limit (dashed) is indicated [$\mathcal{B}(Z \to e\mu) = 7.5 \times 10^{-7}$]. The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

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.