Status and future prospects for CLFV searches at BESIII

Minggang Zhao (For the BESIII Collaboration)
School of Physics, Nankai University,
Tianjin, 300071, China

Here we present the latest results of the charged Lepton Flavor Violation process searches at the BESIII experiment in the decay of $J/\psi \rightarrow e\mu$, using $(225.3 \pm 2.8) \times 10^6 J/\psi$ events collected with the BESIII detector at the BEPCII collider. An upper limit on the branching fraction of $B(J/\psi \rightarrow e\mu) < 1.6 \times 10^{-7}$ (90% C.L.) is obtained. The prospects and challenges with the future data are also discussed based on MC simulation.

1 Introduction

As is well known, the Lepton Flavor Violation (LFV) is highly suppressed in the prediction of Standard Model (SM) by the finite but tiny neutrino masses. Its branching fraction is calculated to be at a negligible level and so far none has been found in all the historical experiments. However, there are various theoretical models which can enhance the LFV effect large enough to be detected by the present experiments. Such as the SUSY grand unified theory, SUSY with a right-handed neutrino, gauge-mediated SUSY breaking, SUSY with vector-like leptons, SUSY with R-parity violation, models with $Z'$, or models with Lorentz non-invariance.

Therefore, detection of such LFV decays could be taken as distinct evidence for new physics. Experimentally, the search for LFV effect has been carried out in many ways, including lepton ($\mu, \tau$) decays, pseudoscalar meson ($K, \pi$) decays, vector meson ($\phi, J/\psi, \Upsilon$) decays, etc. For example, a recent measurement based on $\mu^+ \rightarrow \gamma e^+$ performed by the MEG Collaboration yields an upper limit of $B(\mu^+ \rightarrow \gamma e^+) < 2.4 \times 10^{-12}$, and a similar searching in $\tau$ decay by the BABAR Collaboration reports $B(\tau^+ \rightarrow \gamma e^+) < 3.3 \times 10^{-8}$. Moreover, for neutral kaon and pion decays, the current results are $B(K^0_L \rightarrow \mu^+ e^-) < 4.7 \times 10^{-12}$ produced by the E871 Collaboration and $B(\pi^0 \rightarrow \mu^+ e^-) < 3.8 \times 10^{-10}$ by the E865 Collaboration. For LFV decays of vector mesons, despite having just collected relatively small data samples, evidences with better signal-significance have been observed, thanks to the simple background components. The best measurement in $\phi$ decay, based on the data sample of 8.5 pb$^{-1}$ at the $e^+e^-$ annihilated energy region $\sqrt{s} = 984 - 1060$ MeV, is obtained by the SND Collaboration in 2010 setting upper limit of $B(\phi \rightarrow \mu^+ e^-) < 2.0 \times 10^{-6}$. In bottomonium systems, based on about 20.8 million $\Upsilon(1S)$ events, 9.3 million $\Upsilon(2S)$ events, and 5.9 million $\Upsilon(3S)$ events accumulated with the CLEO-III detector, the CLEOIII Collaboration presented the most stringent LFV upper limit of $B(\Upsilon(1S, 2S, 3S) \rightarrow \mu \tau) \sim 10^{-6}$. In charmonium systems, the BESII Collaboration obtained $B(J/\psi \rightarrow \mu e) < 1.1 \times 10^{-6}$, $B(J/\psi \rightarrow e\tau) < 8.3 \times 10^{-6}$ and $B(J/\psi \rightarrow \mu\tau) < 2.0 \times 10^{-6}$ by analysing a data sample of 58 million $J/\psi$ events collected with the BESII detector, which are the best current upper limits on LFV effect in charmonium meson decays. In this talk, we introduce the latest result from the BESIII Collaboration of searching for charged Lepton Flavor Violation decays based on about 225 million $J/\psi$ events collected at the BESIII detector.
2 The Detector and Simulation

The BESIII experiment is composed of the LINAC, the BEPCII collider, and the BESIII detector, which is a large solid-angle magnetic spectrometer with a geometrical acceptance of 93% of $4\pi$. It has four main components: (1) A small-cell, helium-based (40% He, 60% C$_3$H$_8$) main drift chamber (MDC) with 43 layers providing an average single-hit resolution of 135 $\mu$m, charged-particle momentum resolution in a 1.0 T magnetic field of 0.5% at 1.0 GeV, and a ionization energy loss information ($dE/dx$) resolution better than 6%. (2) A time-of-flight (TOF) system constructed of 5 cm thick plastic scintillators, with 176 detectors of 2.4 m length in two layers in the barrel and 96 fan-shaped detectors in the end-caps. The barrel (end-cap) time resolution of 80 ps (110 ps) provides a $2\sigma K/\pi$ separation for momenta up to $\sim 1.0$ GeV. (3) An electromagnetic calorimeter (EMC) consisting of 6240 CsI(Tl) crystals in a cylindrical structure (barrel) and two end-caps. The energy resolution at 1.0 GeV is 2.5% (5%) and the position resolution is 6 mm (9 mm) in the barrel (end-caps). (4) The muon system (MUC) consists of 1000 m$^2$ of Resistive Plate Chambers (RPCs) in nine barrel and eight end-cap layers and provides 2 cm position resolution.

The event selection and the estimation of backgrounds are optimized through Monte Carlo (MC) simulation. The GEANT4-based simulation software BOOST includes the geometric description and material composition of the BESIII detector and the detector response and digitization models, as well as the tracking of the detector running conditions and performance. The generic simulated events are generated by $e^+e^-$ annihilation into a $J/\psi$ meson using the generator KKMC at energies around the center-of-mass energy $\sqrt{s} = 3.097$ GeV. The beam energy and its energy spread are set according to the measurement of the BEPCII, and the initial state radiation (ISR) is implemented in the $J/\psi$ generation. The decays of the $J/\psi$ resonance are generated by EVTGEN for the known modes with branching fractions according to the world’s average values, and by LUNDCHARM for the remaining unknown decays.

3 Result of $J/\psi \to e\mu$

At the BESIII experiment, the signal events are produced as $e^+e^- \to J/\psi$ at $\sqrt{s} = 3.097$ GeV, and then $J/\psi \to e\mu$, where the signal tracks are back-to-back opposite charged tracks with no extra EMC showers. The details of the event selection can be found in Ref. ref::bes3-emu. Based on a full simulation to the physics around the $J/\psi$ resonance, we found most of the backgrounds are from $J/\psi \to e^+e^-$, $J/\psi \to \mu^+\mu^-$, $J/\psi \to \pi^+\pi^-$, $J/\psi \to K^+K^-$, $e^+e^- \to (\gamma)e^+e^-$ and $e^+e^- \to (\gamma)\mu^+\mu^-$, in which one or more tracks are misidentified as muon or electron. To suppress these contamination events, several powerful criteria are employed.

For $e^+/e^-$ identification, there must be no associated hit in the MUC and the value of $E/p$ is required to be greater than 0.95 and less than 1.5, where $E$ is the energy deposited in the EMC and $p$ is the momentum measured by the MDC. The absolute value of $\lambda dE/dx$ from the $dE/dx$ measurement with electron hypothesis should be less than 1.8. Electron, muon, pion and kaon samples are simulated with MC method to investigate the above cut values, which are shown.
in figure 2, where the $E/p$ and $|\chi_{dE/dx}|$ distributions of electron can be well discriminated from other particles.

For $\mu^+ / \mu^-$ identification, the charged tracks in the active area of the barrel MUC ($|\cos \theta| < 0.75$) are required to have a $E/p$ value less than 0.5, and the deposited energy in the EMC between 0.1 GeV and 0.3 GeV. In order to remove those tracks which are poorly reconstructed in the MUC, we require the penetration depth in the MUC larger than 40 cm and $\chi^2$ of track fitting in the MUC should be less than 100 if the track penetrates more than 3 detecting layers in the MUC. Furthermore, the $\chi_{dE/dx}$ value from the $dE/dx$ measurement with electron hypothesis must be less than -1.8. With the above simulated samples, distributions of the deposited energy in the EMC and the penetration depth in the MUC are shown in figure 3, we can suppress the misidentification from pion and kaon with this two information.

After the above analysis, surviving events of $J/\psi \rightarrow e^+ \mu^-$ are examined with two variables, $|\Sigma \vec{p}|/\sqrt{s}$ and $E_{vis}/\sqrt{s}$, where $|\Sigma \vec{p}|$ is the vector sum of the total momentum in one event, $E_{vis}$ is the total reconstructed energy, and $\sqrt{s}$ is the center-of-mass (c.m.) energy. A candidate event should be located in the signal box defined by $0.93 \leq E_{vis}/\sqrt{s} \leq 1.10$ and $|\Sigma \vec{p}|/\sqrt{s} \leq 0.10$, which corresponds to about 2 standard deviations of the variables determined by MC simulation.

Finally, 4 candidate events in the signal region are obtained from 225 million $J/\psi$ meson decays, which are shown in figure 4. The detection efficiency for signal is determined to be $(18.99 \pm 0.12)\%$. Based on a full simulated $J/\psi$ MC sample whose size is 4 times of our experimental data, we find nineteen background events surviving in the signal region. This yields a predicted
Figure 4 – The scatter plot of $E_{vis}/\sqrt{s}$ versus $|\Sigma\bar{p}|/\sqrt{s}$ for $J/\psi$ data. The signal region, defined by $0.93 \leq E_{vis}/\sqrt{s} \leq 1.10$ and $|\Sigma\bar{p}|/\sqrt{s} \leq 0.1$, is shown as a box.

The background of $N_{exp} = (4.75 \pm 1.09)$. Considering the fact that only four events survived in signal region which is consistent with the number of potential backgrounds, the pure signal events should be quite poor. Therefore, we set the upper limit on the branching fraction of $J/\psi \rightarrow e\mu$ based on the Feldman-Cousins method in which systematic uncertainties have been incorporated. The upper limit on the number of observed signal events at 90% C.L. is obtained to be 6.15 by the POLE program inputing the number of expected background events, the number of observed events and the systematic uncertainty (5.84%). The upper limit on the branching fraction is determined to be $B(J/\psi \rightarrow e\mu) < 1.6 \times 10^{-7}$.

4 Prospects

Here we make a full simulation to estimate the prospects of searching for cLFV signals in $J/\psi \rightarrow e\tau$ and $J/\psi \rightarrow \mu\tau$ based on the 1300 million $J/\psi$ sample. The tracks in the final states of $J/\psi \rightarrow e\tau$ and $J/\psi \rightarrow \mu\tau$ are the same despite the momentum distribution, both have two opposite charge tracks and two missing tracks, so the analysis procedure of the two decays are similar. By analyzing the generic MC sample of $J/\psi$ decay, we can found most of the backgrounds for the two decay modes are from $J/\psi \rightarrow \pi^+K_LK^-$, $J/\psi \rightarrow K_LK_L$, and $J/\psi \rightarrow K^{*0}K^0$. After background suppression, the detection efficiency is estimated to be 14% and 19% for $J/\psi \rightarrow e\tau$ and $J/\psi \rightarrow \mu\tau$, respectively. The sensitivities of the branching fraction are obtained to be $B_{sensitivity}^{J/\psi \rightarrow e\tau} < 6.3 \times 10^{-8}$ and $B_{sensitivity}^{J/\psi \rightarrow \mu\tau} < 7.3 \times 10^{-8}$ at 90% C.L. with similar calculation method used in $J/\psi \rightarrow e\mu$.

5 Summary

In summary, by analyzing 255 million $J/\psi$ data collected at the BESIII detector at the BEPCII collider, the charged Lepton Flavor Violation process is searched. Four signal events are observed which are consistent with the background estimation. As a result, we got the best upper limit in the world on the $J/\psi \rightarrow e\mu$ branching fraction at a 90% CL. To get the prospects based on 1300 million $J/\psi$ data which has been accumulated by the BESIII experiment, we make a full
MC simulation. The sensitivities on searching for cLFV signals in the $J/\psi \rightarrow e\tau$ and $J/\psi \rightarrow \mu\tau$ decays are estimated to be $6.3 \times 10^{-8}$ and $7.3 \times 10^{-8}$ at 90% C.L., respectively, which will be the world best constraints.

Acknowledgments

I would like to thank the committee of NuFact 2016 for the invitation and their excellent organizing. This work is supported by the National Natural Science Foundation of China (NSFC) under Contracts No. 11475090 and No. 11005061.

References

1. S. Dimopoulos and H. Georgi, NPB 193, 150 (1981); N. Sakai, ZPC 11, 153 (1981)
2. F. Borzumati and A. Masiero, PRL 57, 961 (1986)
3. M. Dine, Y. Nir and Y. Shirman, PRD 55, 1501 (1997); S. L. Dubovsky and D. S. Gorbonov, PLB 419, 223 (1998)
4. R. Kitano and K. Yamamoto, PRD 62, 073007 (2000)
5. J. E. Kim and D. G. Lee, PRD 56, 100 (1997); K. Huitu et al, PLB 430, 355 (1998); A. Faessler et al, NPB 587, 25 (2000); M. Chaichian and K. Huitu, PLB 384, 157 (1996)
6. J. Bernabeu, E. Nardi and D. Tommasini, NPB 409, 69 (1993)
7. S. Coleman and S. L. Glashow, PRD 59, 116008 (1999)
8. J. Adam et al, PRL 107, 171801 (2011)
9. B. Aubert et al, PRL 104, 021802 (2010)
10. D. Ambrose et al, PRL 81, 5734 (1998)
11. R. Appel et al, PRL 85, 2450 (2000)
12. M. N. Achasov et al, PRD 81, 057102 (2010)
13. W. Love et al, PRL 101, 201601 (2008)
14. J. Z. Bai et al, PLB 561, 49 (2003)
15. M. Ablikim et al, PLB 598, 172 (2004)
16. M. Ablikim et al, CPC 36, 915 (2012)
17. M. Ablikim et al, Nucl. Instrum. Methods Phys. Res., Sect. A 614, 345 (2010)
18. Z. Y. Deng et al, HEP&NP 30, 371 (2006)
19. S. Jadach, B. Ward and Z. Was, Comp. Phys. Commu 130, 260 (2000); S. Jadach, B. Ward and Z. Was, PRD 63, 113009 (2001)
20. D. J. Lange, NIMA 462, 152 (2001)
21. K. Nakamura et al, JPG 37, 075021 (2010)
22. R. G. Ping et al, CPC 32, 599 (2008)
23. M. Ablikim et al, Phys. Rev. D 87, 112007 (2013)