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Status and future prospects for charged lepton flavor violation searches at BESIII

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Based on $(225.3 \pm 2.8) \times 10^6$ J/ψ events collected with the BESIII detector at the BEPCII collider in Beijing in 2009, the charged Lepton Flavor Violation (cLFV) process $J/\psi \to e\mu$ is studied. The upper limit of the branching fraction is measured to be $\mathscr{B}(J/\psi \to e\mu) < 1.6 \times 10^7$ at 90% confidence level (C.L.). Compared with BESII result, the precision is improved. The sensitivity of branching fraction based on MC simulation is provided.

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1. Introduction

In the standard model (SM), lepton-flavor-violating (LFV) decays are highly suppressed if the theory is to be renormalizable. But the LFV couplings may be introduced if the theory is valid only to a finite mass scale. The branching fraction of LFV process is calculated to be at rare level with standard model. However, there are some theoretical models which may enhance LFV effects up to a detectable level. These models include the supersymmetry (SUSY) grand unified theory [1], SUSY with a right-handed neutrino [2], gauge-mediated SUSY breaking [3], SUSY with vector-like leptons [4], SUSY with R-parity violation [5], models with Z′[6], or models with Lorentz non-invariance [7]. The charged lepton flavor violation (cLFV) is a clear signal of new physics, it directly addresses the physics of flavor and of generations [8]. And the detection of a LFV decay above SM predictions would be distinctive the evidence for new physics.

The search for cLFV has continued from the early 1940s, when the muon was identified as a separate particle, until today[8]. The experimental search for cLFV effect has been carried out mainly in following ways, the lepton (μ,τ) decays, the pseudoscalar meson (K,π) decays and the vector meson (ϕ,J/ψ,Υ) decays, etc. For the lepton decays, the upper limit of $\mathscr{B}(\mu^+ \to \gamma e^+)$ is measured to be less than 2.4×10^{-12} by MEG Collaboration [11]. The BABAR Collaboration reports the upper limit of $\mathscr{B}(\tau^+ \to \gamma e^+) < 3.3\times10^{-8}$ [12]. For the pseudoscalar meson decays, the current results are $\mathscr{B}(K_L^0 \to \mu^+e^-) < 4.7\times10^{-12}$ [13] measured by the E871 Collaboration and $\mathscr{B}(\pi^0 \to \mu^+e^-) < 3.8\times10^{-10}$ [14] by the E865 Collaboration. For vector mesons decays, despite having just collected relatively small data samples, evidences with better signal-significance have been observed, thanks to the simple background components. Based on the 8.5 pb^{-1} data sample at the e^+e^- annihilated with energy $\sqrt{s}$ between $984-1060$ MeV, which is obtained by the SND Collaboration in 2010, the upper limit of $\mathscr{B}(\phi \to \mu^+e^-) < 2.0\times10^{-6}$ is provided[15]. In bottonium 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 $\mathscr{B}(\Upsilon(1S,2S,3S) \to \mu\tau) <\sim 10^{-6}$ [16].

The results of search for cLFV with charmonium meson decays mainly provided by BESII and BESIII Collaborations. The Beijing Spectrometer II (BESII) is a large general purpose solenoidal detector at the Beijing Electron Positron Collider (BEPC). The beam energy of BEPC ranges from 1.0 to 2.5 GeV, and the peak luminosity at the J/ψ is around $5\times10^{30}cm^{-2}s^{-1}$ [9, 10]. Based on a data sample of 58 million J/ψ events collected with the BESII detector, the upper limits on cLFV effect in charmonium meson decays are measured to be $\mathscr{B}(J/\psi \to \mu e) < 1.1\times10^{-6}$ [17], $\mathscr{B}(J/\psi \to e\tau) < 8.3\times10^{-6}$ and $\mathscr{B}(J/\psi \to \mu\tau) < 2.0\times10^{-6}$ [18]. In this talk, we introduce the latest result from the BESIII Collaboration of searching for cLFV decays based on $(225.3\pm2.8)\times 10^6$ J/ψ events collected with the BESIII detector at the BEPCII collider in Beijing in 2009 [19]. And this is the best current upper limit on cLFV effect in charmonium meson decay.

2. The Detector and Simulation

The BESIII experiment is composed of the LINAC, the BEPCII collider, and the BESIII detector [20] (Fig. 1), which is a large solid-angle magnetic spectrometer with a geometrical acceptance of 93% of 4π. It has four main components: (1) A small-cell, helium-based (40% He, 60% C_3H_8)

main drift chamber (MDC) with 43 layers providing an average single-hit resolution of 135 μm, 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 2σ K/π separation for momenta up to ~ 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.

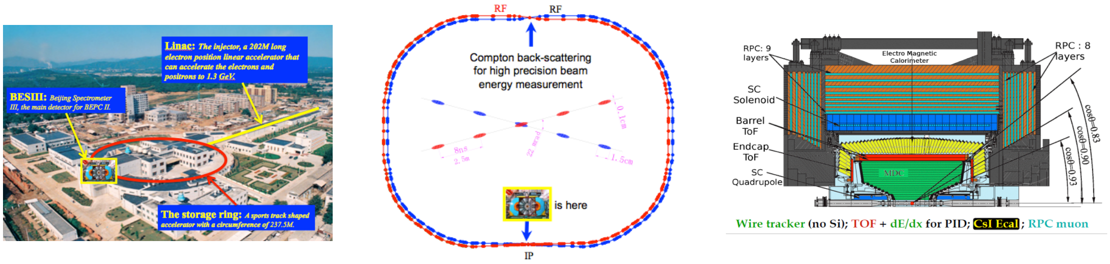

Figure 1: Illustration for the birdview of the experiment(left), the storage ring (center) and the detector (right)

The event selection and the estimation of backgrounds are optimized through Monte Carlo (MC) simulation. The GEANT4-based simulation software BOOST [21] 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/ψ meson using the generator KKMC [22] 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/ψ generation. The decays of the J/ψ resonance are generated by EVTGEN [23] for the known modes with branching fractions according to the world's average values [24], and by LUNDCHARM [25] for the remaining unknown decays.

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

The BESIII Collaboration provide the search for events in which J/ψ decays into an electron and a muon directly, $J/\psi \to e\mu$, 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. [26]. Possible backgrounds are studied with a MC sample containing 225×10^6 inclusive J/ψ decays. Most of the remaining events originate from the background processes $J/\psi \to e^+e^-$, $J/\psi \to \mu^+\mu^-$, $J/\psi \to \pi^+\pi^-$, $J/\psi \to K^+K^-$, $e^+e^- \to (\gamma)e^+e^-$ 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.

Electron identification requires no associated hits in the MUC and $0.95 < E/p < 1.50$, where E is the energy deposited in the EMC and p is the momentum measured by the MDC. The absolute

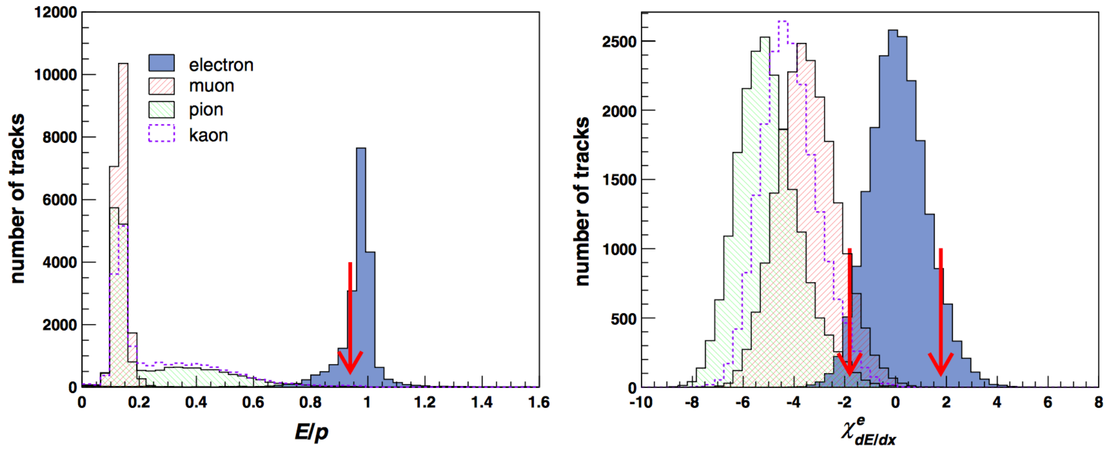

Figure 2: The distributions of E/p (left) and $\chi^e_{dE/dx}$ (right) for the simulated electron, muon, pion and kaon samples.

value of $\chi_{dE/dx}$ should be less than 1.8. Fig. 2 shows the E/p and $\chi_{dE/dx}$ distributions for electrons, which are well separated from other particles.

Muon identification uses the barrel MUC system which covers $|\cos\theta| < 0.75$. Charged tracks are required to have $E/p < 0.5$ and a deposited energy in the $0.1 < E < 0.3$ GeV. We require the penetration depth in the MUC to be larger than 40 cm. To remove those poorly reconstructed tracks in the MUC, the χ^2/ndf of the trajectory fit in the MUC is required to be less than 100 if the tracks penetrate more than three detecting layers in the MUC. Finally, the $\chi^e_{dE/dx}$ value of muon from the dE=dx measurement calculated with the electron hypothesis must be less than -1.8. The simulated distributions of the deposited energy in the EMC and the penetration depth in the MUC are shown in Fig. 3.

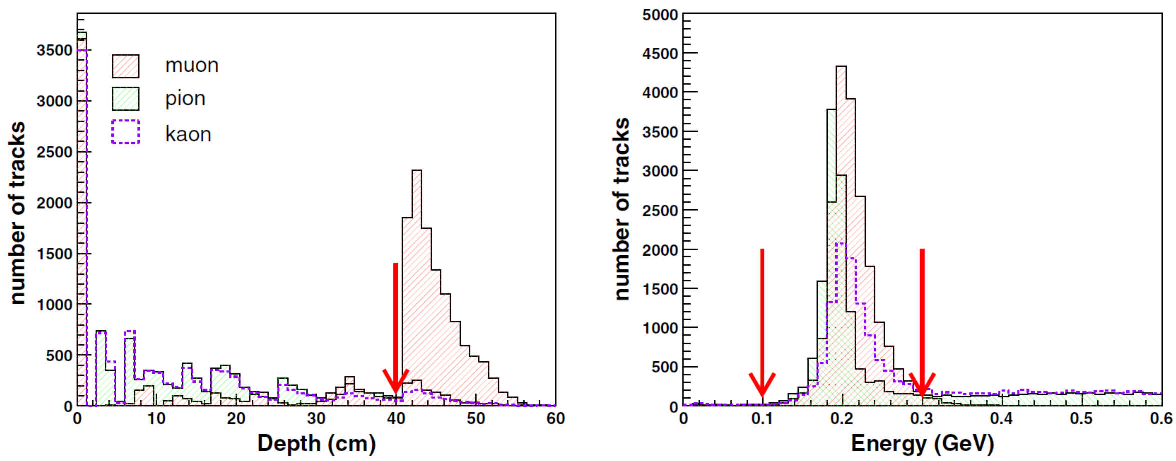

Figure 3: The distributions of the penetration depth in the MUC (left) and the deposited energy in the EMC (right) for the simulated muon, pion and kaon samples.

After the above analysis, the surviving events of $J/\psi \to e^+\mu^-$ are performed with two variables, $|\Sigma\overrightarrow{p}|/\sqrt{s}$ and $E_{vis}/\sqrt{s}$, where $|\Sigma\overrightarrow{p}|$ is the vector sum of the total momentum in event, E_{vis} is the total reconstructed energy, and $\sqrt{s}$ is the center-of-mass (c.m.) energy. The indicated signal region is defined as $0.93 \leq E_{vis}/\sqrt{s} \leq 1.10$ and $|\Sigma\overrightarrow{p}|/\sqrt{s} \leq 0.10$.

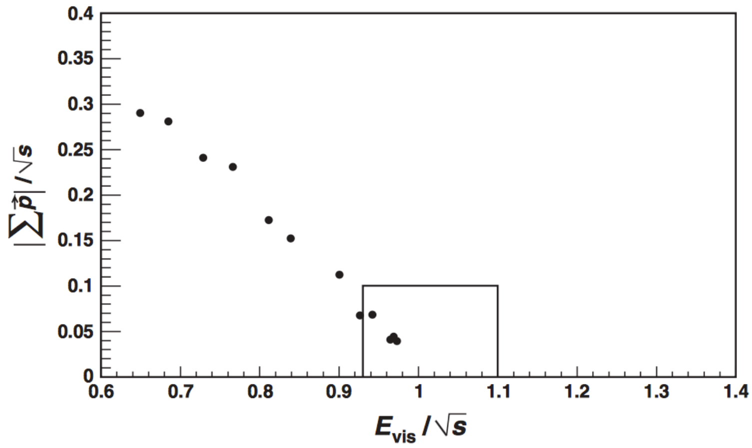

Figure 4: The scatter plot of $E_{vis}/\sqrt{s}$ versus $|\Sigma\vec{p}|/\sqrt{s}$ for J/ψ data.

After applying the optimized selections criteria, four candidate events remain in our signal region, see Fig. 4. The detection efficiency for the signal is determined to be (18.99 ± 0.12)%. Using an inclusive sample of simulated J/ψ decays with four times the size of BESIII data sample, 19 background events are found surviving in the signal region. This yields a predicted background of $N^{exp} = (4.75 \pm 1.09)$. The upper limit on the number of observed signal events at 90 % C.L. is 6.15 which is obtained by the POLE program [27]. The upper limit on the branching fraction of $J/\psi \to e\mu$ is calculated based on the Feldman-Cousins method in which systematic uncertainties have been incorporated. And the upper limit on the branching fraction is determined to be $\mathscr{B}(J/\psi \to e\mu) < 1.6 \times 10^{-7}$.

4. Prospects

A full simulation is made to estimate the prospects of searching for cLFV signals in $J/\psi \to e\tau$ and $J/\psi \to \mu\tau$ based on the 1.3×10^9 inclusive J/ψ sample. For both of the $J/\psi \to e\tau$ and $J/\psi \to \mu\tau$ processes, two opposite charged tracks and two missing momentums are required in the final states. By analyzing the MC sample of J/ψ decay, it is found that the backgrounds for the two decay modes are from $J/\psi \to \pi^+ K_L K^-$, $J/\psi \to K_S K_L$, and $J/\psi \to K^{\star 0} K^0$. The detection efficiency is estimated to be 14% and 19% for $J/\psi \to e\tau$ and $J/\psi \to \mu\tau$, respectively, after background supression. With similar calculation method used in $J/\psi \to e\mu$, the sensitivities of the branching fraction are calculated to be $\mathscr{B}^{sensitivity}_{J/\psi \to e\tau} < 6.3 \times 10^{-8}$ and $\mathscr{B}^{sensitivity}_{J/\psi \to \mu\tau} < 7.3 \times 10^{-8}$ at 90% C.L.

5. Summary

In summary, the BES and BESIII Collaborations play the key roles in the search of cLFV in charmonium meson decays. The results obtained are shown in Fig. 5. Recently, the cLFV

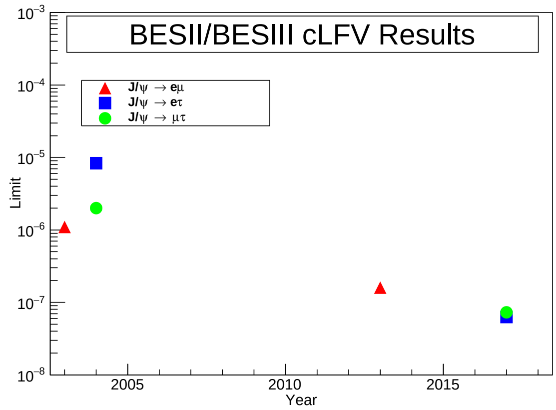

Figure 5: The cLFV results obtained by the BESII and BESIII Collaborations with charmonium meson decays. The results obtained before 2008 are the results of BESII, and the results obtained after 2008 are the results of BESIII, the two results obtained in 2017 are the sensitivities of branching fraction.

process is searched with $(225.3 \pm 2.8) \times 10^6$ J/ψ events collected at the BESIII detector at the BEPCII collider in 2009. The upper limit of branching fraction for $J/\psi \to e\mu$ is measured to be $\mathscr{B}(J/\psi \to e\mu) < 1.6 \times 10^{-7}$ at 90% C. L.. This is the most stringent limit obtained for a cLFV effect in the heavy quarkonium system. To get the prospects based on 1.3×10^9 J/ψ event which has been accumulated by the BESIII experiment, a full MC simulation is made. The sensitivities on searching for cLFV signals in the $J/\psi \to e\tau$ and $J/\psi \to \mu\tau$ decays are estimated to be 6.3×10^{-8} and 7.3×10^{-8} at 90% C.L., respectively.

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