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## Abstract

We search for the lepton-flavor-violating decay of the $J/\psi$ into an electron and a muon using $(225.3 \pm 2.8) \times 10^6$ $J/\psi$ events collected with the BESIII detector at the BEPCII collider. Four candidate events are found in the signal region, consistent with background expectations. An upper limit on the branching fraction of $\mathcal{B}(J/\psi \to e\mu) < 1.6 \times 10^{-7}$ (90% C.L.) is obtained.



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## I. INTRODUCTION

With finite neutrino masses included, the Standard Model allows for Lepton Flavor Violation (LFV). Yet the smallness of these masses leads to a very large suppression, with predicted branching fractions well beyond current experimental sensitivity. However, there are various theoretical models which may enhance LFV effects up to a detectable level. Examples of such model predictions, which often involve super-symmetry (SUSY), include SUSY-based grand unified theories [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 a Z′ [6], and models violating Lorentz invariance [7]. The detection of a LFV decay well above Standard Model expectations would be distinctive evidence for new physics.

Experimentally, the search for LFV effects has been carried out using lepton ($\mu$,$\tau$) decays, pseudoscalar meson (K,$\pi$) decays, and vector meson ($\phi$,$J/\psi$,$\Upsilon$) decays, etc. For example, a recent search for the decay of $\mu^+ \to \gamma e^+$ from the MEG Collaboration yields an upper limit of $\mathcal{B}(\mu^+ \to \gamma e^+) < 5.7 \times 10^{-13}$ [8], and in a similar search with $\tau$ decays the BaBar Collaboration reports $\mathcal{B}(\tau^+ \to \gamma e^+) < 3.3 \times 10^{-8}$ [9]. The latest results for neutral kaon and pion decays from the E871 Collaboration and the E865 Collaboration, respectively, are $\mathcal{B}(K^0_L \to \mu^+ e^-) < 4.7 \times 10^{-12}$ [10] and $\mathcal{B}(\pi^0 \to \mu^+ e^-) < 3.8 \times 10^{-10}$ [11]. The best $\phi$ decay limit, based on 8.5 pb$^{-1}$ of $e^+e^-$ annihilations at center-of-mass energies from $\sqrt{s} = 984 - 1060$ MeV, is obtained by the SND Collaboration: $\mathcal{B}(\phi \to \mu^+ e^-) < 2.0 \times 10^{-6}$ [12]. In the bottomonium system, based on about 20.8 million $\Upsilon(1S)$ events, 9.3 million $\Upsilon(2S)$ events, and 5.9 million $\Upsilon(3S)$ events, the CLEOIII Collaboration presented the most stringent LFV upper limits, $\mathcal{B}(\Upsilon(1S, 2S, 3S) \to \mu\tau) < \mathcal{O}(10^{-6})$ [13]. For charmonium, the best limits come from the BESII Collaboration, who obtained $\mathcal{B}(J/\psi \to \mu e) < 1.1 \times 10^{-6}$ [14], $\mathcal{B}(J/\psi \to e\tau) < 8.3 \times 10^{-6}$ and $\mathcal{B}(J/\psi \to \mu\tau) < 2.0 \times 10^{-6}$ [15] from a sample of 58 million $J/\psi$ events. A recent sample of 225 million $J/\psi$ events [16] collected with the much improved BESIII detector now allows for LFV searches in $J/\psi$ decays with a significant improvement in sensitivity. We present here our results from a blind analysis of $J/\psi \to e^\pm\mu^\mp$.

## II. BESIII DETECTOR AND MONTE CARLO SIMULATIONS

The BESIII detector [17] at the BEPCII collider is a large solid-angle magnetic spectrometer with a geometrical acceptance of 93% of $4\pi$ solid angle consisting of four main components. The innermost is 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 $\mu$m. The resulting charged-particle momentum resolution in our 1.0 T magnetic field is 0.5% at 1.0 GeV, and the resolution on the ionization energy loss information ($dE/dx$) is better than 6%. Next is 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 1.0 GeV. Continuing outward, we have an electromagnetic calorimeter (EMC) consisting of 6240 CsI(Tl) crystals in a cylindrical barrel structure 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). Finally, the muon counter (MUC) consisting of 1000 $m^2$ of Resistive Plate Chambers (RPCs) in nine barrel and eight end-cap layers; it provides a 2 cm position resolution.

Our event selection and sensitivity, including backgrounds, are optimized through Monte Carlo (MC) simulation. The GEANT4-based simulation software BOOST [18] incorporates the geometry implementation simulations and material composition of the BESIII detector, the detector response and digitization models as well as the tracking of the detector running conditions and performances. The generic simulated events are generated by $e^+e^-$ annihilation into a $J/\psi$ meson using the generator KKMC [19] at energies around the center-of-mass energy $\sqrt{s} = 3.097$ GeV. The beam energy and its energy spread are set according to measurements of BEPCII, and initial state radiation (ISR) is implemented in the $J/\psi$ generation. The decays of the $J/\psi$ resonance are generated by EVTGEN [20] for the known modes with branching fractions according to the world-average values [21], and by LUNDCHARM [22] for the remaining unknown decay modes.

## III. EVENT SELECTION

We search for events in which $J/\psi$ decays into an electron and a muon. Candidate signal events are required to have two well-measured tracks with $|\cos\theta| < 0.8$ and zero net charge, consistent with originating from the interaction point. Here, $\theta$ is the polar angle with respect to the beam axis and the closest approach of each track to the interaction point must be less then 5 cm (1 cm) in the beam direction (in the plane perpendicular to the beam). To reject cosmic rays, the TOF difference between the charged tracks must be less than 1.0 ns. The acollinearity and acoplanarity angles between two charged tracks are required to be less than $0.9^\circ$ and $1.4^\circ$, respectively, to reduce other backgrounds.

Photon candidates reconstructed in both the EMC barrel region ($|\cos\theta| < 0.8$) and in the end-caps ($0.86 < |\cos\theta| < 0.92$) must have a minimum energy of 15 MeV. Showers in the angular range between the barrel and end-cap are poorly reconstructed and are not considered. Showers caused by charged particles are eliminated by requiring candidates to be more than 20 degrees away from the extrapolated positions of all charged tracks. Requirements on EMC cluster timing suppress both electronic noise and energy deposits unrelated to the event. In order to suppress the radiative events from $e^+e^- \to \gamma e^+e^-$ and $e^+e^- \to \gamma\mu^+\mu^-$, we veto events with one or more good photon candidates.

The above selection criteria retain events with back-to-back charged tracks and no obvious extra EMC activity. Most of the remaining events originate from the background processes $J/\psi \to e^+e^-, J/\psi \to \mu^+\mu^-, J/\psi \to \pi^+\pi^-, J/\psi \to K^+K^-, e^+e^- \to e^+e^-(\gamma)$ and $e^+e^- \to \mu^+\mu^-(\gamma)$. In order to suppress these background events, we identify electrons and muons based on the information of the MDC, EMC and MUC sub-detectors. The requirements are determined using electron, muon, pion and kaon samples from $J/\psi \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, K^+K^-$ MC events. 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. Also, the absolute value of $\chi^e_{dE/dx}$(the difference between the measured and expected $dE/dx$ for electron hypothesis, normalized to its standard deviation) should be less than 1.8. Fig. 1 shows the $E/p$ and $\chi^e_{dE/dx}$ 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 EMC $0.1 < E < 0.3$ 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 $\chi^2$/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. 2.

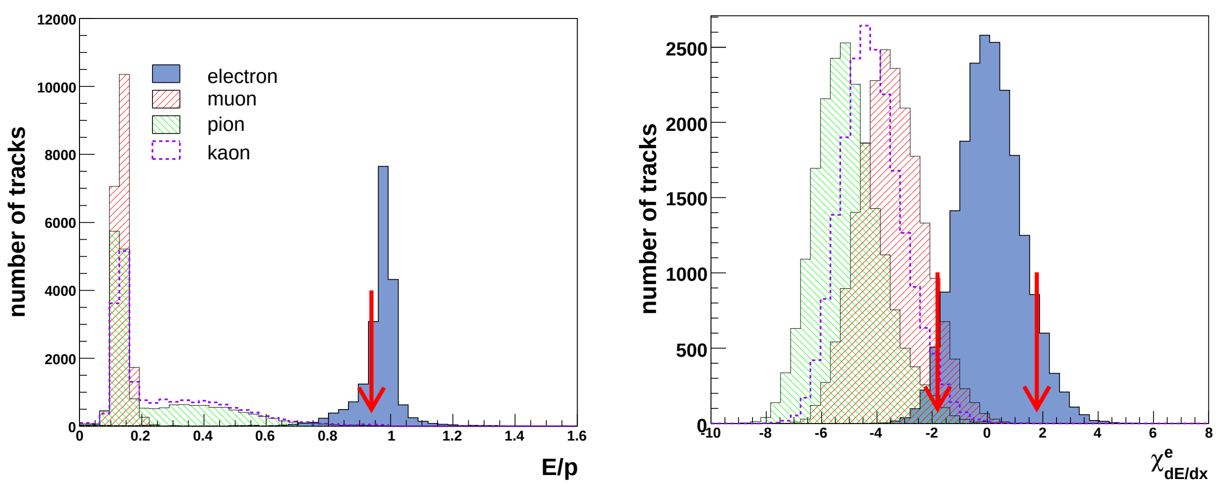


FIG. 1: The distributions of $E/p$ (left) and $\chi^e_{dE/dx}$ (right) for the simulated electron, muon, pion and kaon samples.

Our final analysis of event yields for $J/\psi \to e^+\mu^-$ is performed with the two variables $|\Sigma\vec{p}|/\sqrt{s}$ and $E_{vis}/\sqrt{s}$, where $|\Sigma\vec{p}|$ is the magnitude of the vector sum of the momentum in the event, $E_{vis}$ is the total reconstructed energy and $\sqrt{s}$ is the center-of-mass energy. In the total reconstructed energy, the electron energy is read directly from EMC, and the muon energy is calculated using $\sqrt{p^2 + m^2}$ with each track momentum $p$. Our signal region is defined by $0.93 \leq E_{vis}/\sqrt{s} \leq 1.10$ and $|\Sigma\vec{p}|/\sqrt{s} \leq 0.10$, which correspond in each case to about two standard deviations as determined by MC simulation.

The analysis is done in a blind fashion in order not to bias our choice of selection criteria. Before examining the signal region, all selection criteria were optimized based on simulated samples with a sensitivity figure-of-merit (FOM) defined as a ratio of the detection efficiency to the average upper limit from an ensemble of experiments with the expected background and no signal,

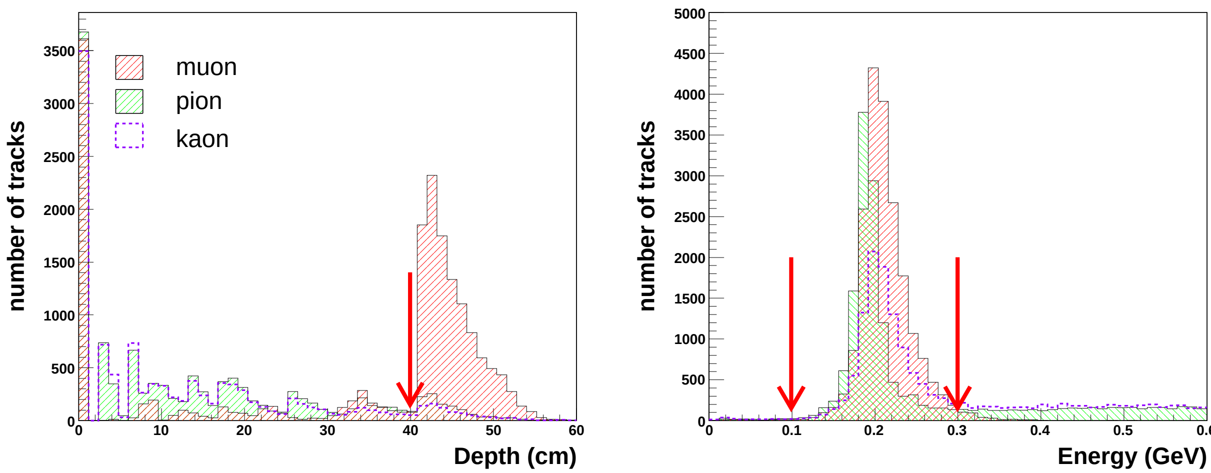


FIG. 2: The distributions of the penetration depth in the MUC (left) and the deposited energy in the EMC (right) for the simulated muon, pion and kaon samples.

$$FOM = \frac{\epsilon}{\sum_{N_{obs}=0}^{\infty} P(N_{obs}|N_{exp}) \cdot UL(N_{obs}|N_{exp})}, \quad (1)$$

where $\epsilon$ is the detection efficiency determined with a sample of 100,000 simulated $J/\psi \to e\mu$ events, $N_{exp}$ is the expected number of background events based on background process simulations, $N_{obs}$ is the number of observed candidate events, $P$ is the Poisson probability, and $UL$ is the upper limit on the signal calculated with the Feldman-Cousins method at 90% C.L. [23]. In addition to the signal MC samples, six background MC samples, each with twice the statistics of the data sample, are employed to optimize the selection criteria. These six background samples correspond to $J/\psi \to e^+e^-$, $J/\psi \to \mu^+\mu^-$, $J/\psi \to \pi^+\pi^-$, $J/\psi \to K^+K^-$, $e^+e^- \to e^+e^-(\gamma)$, and $e^+e^- \to \mu^+\mu^-(\gamma)$.

After applying the optimized selections criteria, four candidate events remain in our signal region, see Fig. 3. The detection efficiency for signal is determined to be $(18.99 \pm 0.12)\%$. Using an inclusive sample of simulated $J/\psi$ decays with four times the size of our data sample, we find nineteen background events surviving in the signal region. This yields a predicted background of $N_{exp} = (4.75 \pm 1.09)$.

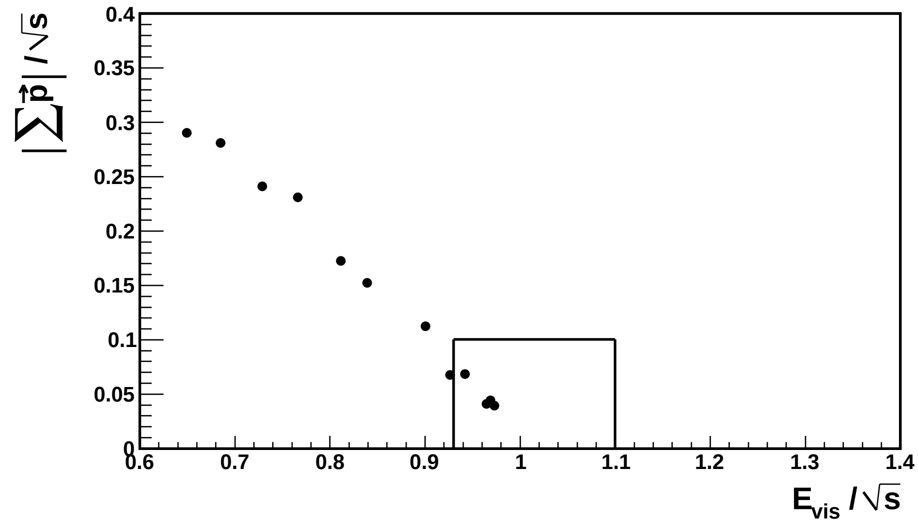


FIG. 3: A scatter plot of $E_{vis}/\sqrt{s}$ versus $|\Sigma\vec{p}|/\sqrt{s}$ for the $J/\psi$ data. The indicated signal region is defined as $0.93 \leq E_{vis}/\sqrt{s} \leq 1.10$ and $|\Sigma\vec{p}|/\sqrt{s} \leq 0.1$.

## IV. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties originate from imperfect knowledge of efficiencies for the electron and muon tracking requirements electron and muon identification, acollinearity and acoplanarity requirements, the photon candidate veto, and the number of $J/\psi$ events.

### A. Tracking efficiency

Control samples of $\psi' \to \pi^+\pi^- J/\psi, J/\psi \to e^+e^-, \mu^+\mu^-$ selected from 106 M $\psi'$ data events and 106 M $\psi'$ inclusive MC events are used to study the possible differences in the tracking efficiency between data and MC events. To determine the tracking efficiency of electrons, we select events with at least three charged tracks. Two tracks with low momentum, $p < 0.5$ GeV/c, and with opposite charge are interpreted as the pions. After requiring the recoiling mass opposite these two pions to satisfy $|M^{recoil}_{\pi^+\pi^-} - 3.097| < 10$ MeV, we obtain $\psi' \to \pi^+\pi^- J/\psi$ candidates. For the $e^-$ selection, at least one track is required to have a negative charge, a momentum in the region from 1.0 GeV/c to 2.0 GeV/c, and a deposited energy in the EMC greater than 1.0 GeV. With these three tagging tracks, $\pi^+$, $\pi^-$, and $e^-$, the total number of $e^+$ tracks, $N^0_{e^+}$, can be determined by fitting the distribution of mass recoiling from the $\pi^+\pi^-e^-$ system, $M_{recoil}^{\pi^+\pi^-e^-}$. In addition, one can obtain the number of detected $e^+$ tracks, $N^1_{e^+}$, by fitting $M_{recoil}^{\pi^+\pi^-e^-}$, after requiring all four charged tracks to be reconstructed. The tracking efficiency of $e^+$ is then obtained as $\epsilon_{e^+} = N^1_{e^+}/N^0_{e^+}$.

Similarly, we can obtain the tracking efficiency for $e^-$, $\mu^+$ and $\mu^-$. The difference between data and MC simulation is found to be about 1.0% in each of these four cases, which is taken as a systematic uncertainty for tracking.

### B. Particle identification

Clean samples of $J/\psi(e^+e^-) \to e^+e^-$ with backgrounds less than 1% selected from data and inclusive MC events are employed to estimate the uncertainty of the $e^\pm$ identification. The event selection criteria for this control sample are identical to those for our signal channel, including two good charged tracks and no good photon. The track with higher momentum is required to satisfy the $e^\pm$ identification criteria described previously, and the other track is used for the $e^\mp$ identification study.

The electron identification efficiency, obtained by comparing the number of events with and without electron identification criteria applied on the selected control sample, is defined by: $\epsilon_{PID} = N_{evt}(w/\ PID)/N_{evt}(w/o\ PID)$, where $N_{evt}$ is the number of events extracted from the control sample. It is found that the average efficiency difference between data and MC simulation is 0.62% for the track momentum range $1.4 - 1.7$ GeV/c, which is taken as the systematic error for electron identification. Applying a similar method, we study the systematic error of the $\mu^\pm$ identification using the control sample $J/\psi(e^+e^-) \to \mu^+\mu^-$. We apply corrections based on data-MC differences, and a residual uncertainty of 0.04% is obtained for the muon identification in the momentum range $1.4 - 1.7$ GeV/c.

### C. Acollinearity and acoplanarity angles

Control samples of $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$ are employed to estimate the uncertainty due to the acollinearity and acoplanarity angle requirements. We obtain the corresponding selection efficiency by comparing the number of events with and without imposing the acollinearity and acoplanarity angle requirements on the the selected control sample. We find efficiency differences between data and MC simulation of 5.36% and 2.83% for electron and muon, respectively. Conservatively, we take 5.36% as a systematic uncertainty for acollinearity and acoplanarity angle requirements.

### D. Photon veto

We expect no good photon candidates to be present in $J/\psi \rightarrow \mu^+\mu^-$, and therefore choose this channel as a suitable control sample. The event selection criteria for this control sample are similar to those in sub-section B. By comparing the numbers of events before and after imposing the $\gamma$-veto criteria on the selected control sample, we can obtain the corresponding selection efficiency. We find that the difference in efficiency between data and MC simulation is 1.19%, which is taken as a systematic uncertainty for photon veto.

The uncertainty in the number of $J/\psi$ is 1.24% [16]. Table I summarizes the systematic error contributions from different sources and the total systematic error is the sum of individual contributions added in quadrature.

TABLE I: Summary of systematic uncertainties (%).

| Sources | Error |
|---|---|
| $e^{\pm}$ tracking | 1.00 |
| $\mu^{\pm}$ tracking | 1.00 |
| $e^{\pm}$ ID | 0.62 |
| $\mu^{\pm}$ ID | 0.04 |
| Acollinearity, acoplanarity | 5.36 |
| Photon veto | 1.19 |
| $N_{J/\psi}$ | 1.24 |
| Total | 5.84 |

## V. RESULTS

We observe four candidate events with an expected background of $4.75 \pm 1.09$, and therefore set an upper limit on the branching fraction of $J/\psi \rightarrow e\mu$, based on the Feldman-Cousins method with systematic uncertainties included. The upper limit on the number of observed signal events at 90% C.L., $N_{obs}^{UL}$, of 6.15 is obtained with the POLE program [25]. Here, the number of expected background events, the number of observed events, and the background uncertainty are used as the input parameters. The upper limit on the branching fraction is given by

$$\mathcal{B}(J/\psi \to e\mu) < \frac{N_{obs}^{UL}}{N_{J/\psi} \cdot \epsilon}, \tag{2}$$

where $N_{J/\psi}$ is the total number of $J/\psi$ events, and $\epsilon$ is the detection efficiency. Combining, we find a 90% C.L. upper limit on the branching fraction of $\mathcal{B}(J/\psi \to e\mu) < 1.6 \times 10^{-7}$, where the efficiency is lowered by a factor of (1-$\sigma_{sys}$).

## VI. SUMMARY

Using $225.3 \pm 2.8 \times 10^6$ $J/\psi$ events collected with the BESIII detector, we have performed a blind analysis searching for the lepton flavor violation process $J/\psi \to e\mu$. We observe four candidate events, consistent with our background expectation. The resulting upper limit on the branching fraction, $\mathcal{B}(J/\psi \to e\mu) < 1.6 \times 10^{-7}$ (90% C.L.), is the most stringent limit obtained thus far for a LFV effect in the heavy quarkonium system.

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