Search for the lepton flavor violating decay $J/\psi \to e\mu$

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Abstract

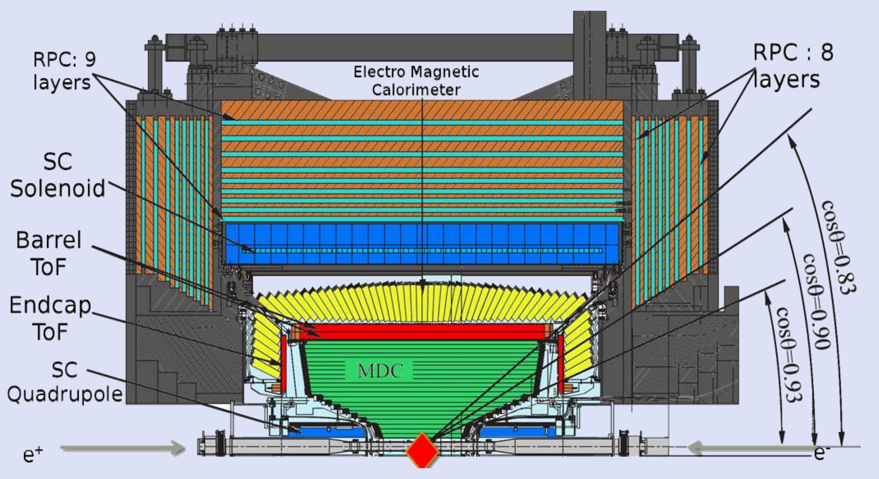
We present a search for the lepton flavor violating decay $J/\psi \to e\mu$ using 8.998×10^9 J/ψ events collected with the BESIII detector at the BEPCII e^+e^- storage ring. No excess of signal above background is observed; we therefore set an upper limit on the branching fraction of $\mathcal{B}(J/\psi \to e\mu) < 4.5 \times 10^{-9}$ at the 90% confidence level. Improving the previous best result by a factor of more than 30, this measurement places the most stringent limit to date on lepton flavor violation in the heavy quarkonium sector.

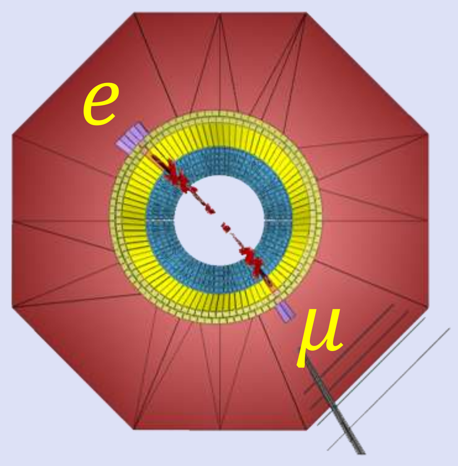
Motivation

Lepton flavor violating (LFV) decays are too small to be detectable in the Standard Model (SM). However, for the LFV decays of charmonium J/ψ, some new physics models can inspire the decay rate up to a detectable level. In experiment, the best upper limits on the branching fractions of $J/\psi \to e\mu$ had been measured by BESIII Collaboration at 90% C. L. based on 225M J/ψ, which is $\mathcal{B}(J/\psi \to e\mu) < 1.6 \times 10^{-7}$. In this work, we analyze about 9 billion J/ψ events, and the upper limit on $\mathcal{B}(J/\psi \to e\mu)$ is expected to be improved by 1~2 orders of magnitude to the level of 10^{-9}.

BEPCII & BESIII

Beijing Electron-Positron Collider (BEPCII) is a double-ring e^+e^- collider operated in the τ-charm energy region. The BESIII detector at the BEPCII is an approximately cylindrically symmetric detector with 93% coverage of the solid angle around the e^+e^- interaction point.





- Main drift chamber (MDC): $\Delta P/P = 0.5\%$
- Time-of-Flight system (TOF): $\sigma_\tau = 60\sim68$ ps
- Electron Calorimeter (EMC): $\Delta E/E = 2.5\%$
- Muon chamber (MUC): $\sigma_{z,\phi} = 2$ cm
- Superconductor (SC): 1.0 Tesla

Data Set

Data Sample :

- 9 billions J/ψ events taken during 2009 to 2019 at $\sqrt{s} = 3.097$ GeV
- e^+e^- collisions collected at $\sqrt{s} = 3.773$ GeV, $\sqrt{s} = 3.510$ GeV, $\sqrt{s} = 3.080$ GeV (to study the continuum background)

Monte Carlo Sample :

- 9 billions J/ψ inclusive MC events (to study the backgrounds from J/ψ decays)
- 0.3 million $J/\psi \to e\mu$ exclusive MC events (to study the signal process)
- Several kinds of exclusive events including $J/\psi \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, K^+K^-, p\bar{p}$, and $e^+e^- \to e^+e^-(\gamma), \mu^+\mu^-(\gamma)$

Event Selection

Each J/ψ candidate is reconstructed with two back-to-back good charged tracks, which will be further identified as electron and muon. The selection criteria are optimized according to the signal MC and inclusive MC.

Electron identification :

- Not associated in the MUC
- $-1.5 < \chi^e_{dE/dx} < 1.5$ ($\chi^e_{dE/dx}$ is defined as the difference between measured and expected dE/dx under the electron hypothesis normalized by the dE/dx resolution)
- $E/p > 0.96$ (E is the deposite energy in the EMC and p is the modulus of the momentum from the MDC)

Muon identification :

- $0.1 < E < 0.3$ GeV, $\chi^e_{dE/dx} < -1.6$
- The penetration depth of the track in the MUC > 40 cm
- Each candidate track must penetrate more than three layers in the MUC, and $\chi^2_{MUC} < 100$

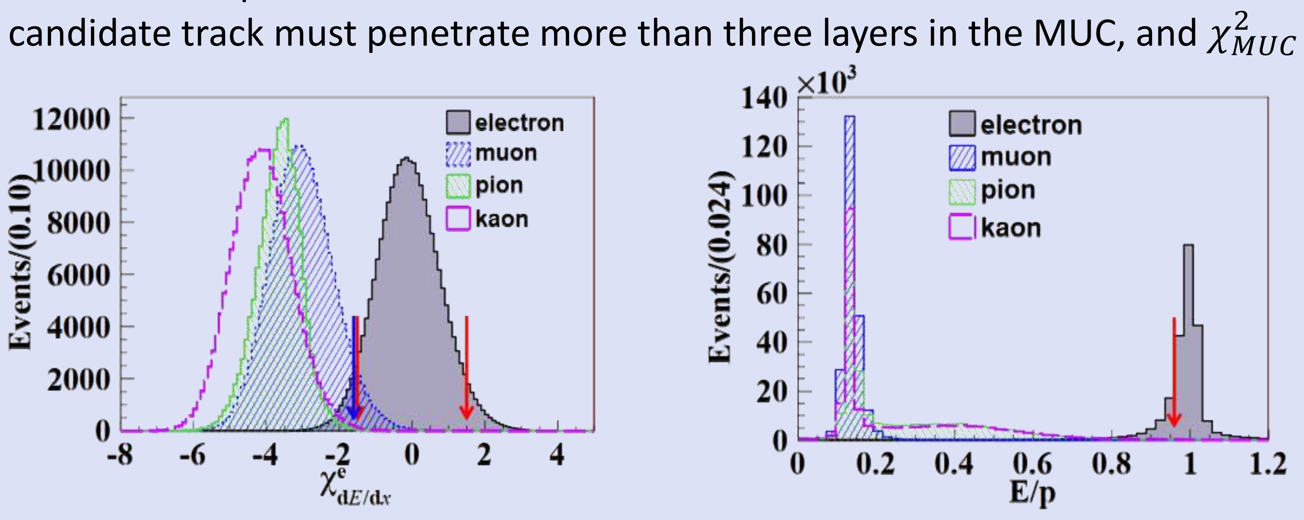


Fig. 1. Distribution of $\chi^e_{dE/dx}$ and E/p from MC simulations.

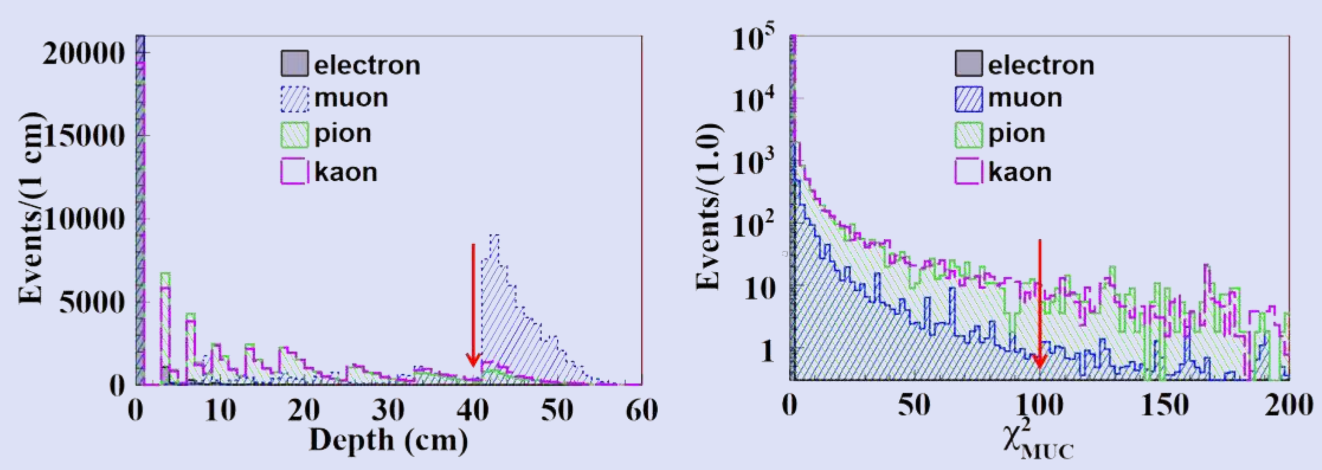


Fig. 2. Distribution of the MUC depth (left) and χ^2_{MUC} (right) of different particle samples from MC simulations.

Event Selection

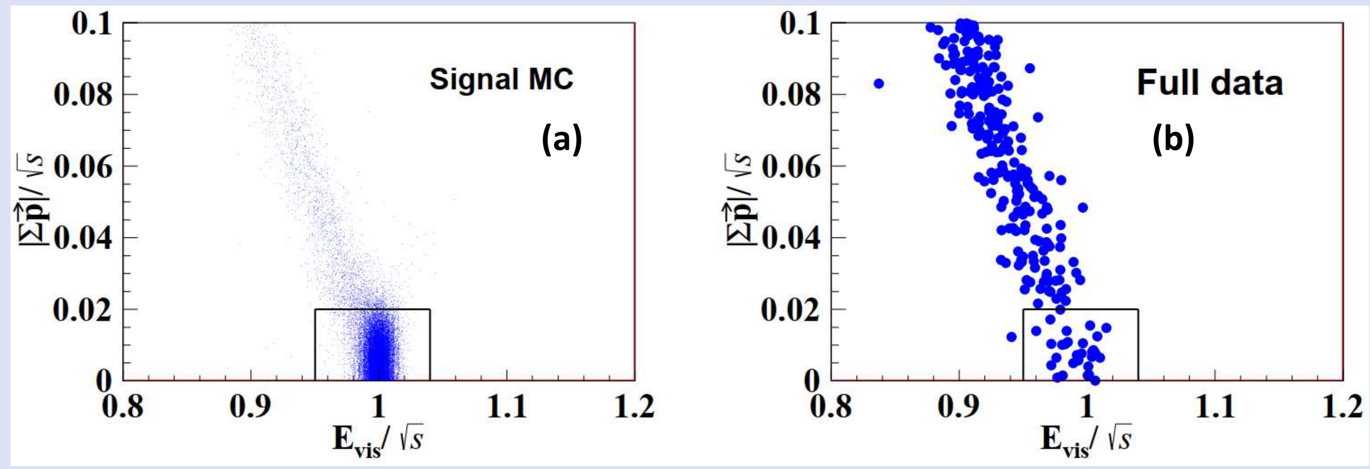


Fig 3. Scatter plots of $|\sum\vec{p}|/\sqrt{s}$ versus $E_{vis}/\sqrt{s}$ for the signal MC sample (left) and the J/ψ full data (right).

The signal region is defined with $|\sum\vec{p}|/\sqrt{s} \le 0.02$ **and** $0.95 \le E_{vis}/\sqrt{s} \le 1.04$, where $|\sum\vec{p}|$ is the magnitude of the vector sum of the momenta and E_{vis} is the total reconstructed energy of e and μ in the event. As shown in the Fig 3.(a), most of the signal events fall into the signal region. By analyzing the full data, **29 candidate events** are observed in the signal region for the $J/\psi \to e\mu$ decays.

Background Study

There are two types of background events that contaminate the signal region.

The first kind of background results from J/ψ decaying into two charged particle tracks, including $J/\psi \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, K^+K^-, p^+p^-$, etc. The dominant background contribution hereby comes from $e-\mu$ misidentification. The normalized background in the signal region N^{norm}_{bkg1} is calculated as,

$$N^{norm}_{bkg1} = N^{J/\psi-MC}_{bkg1} \cdot f_1, \quad f_1 = \frac{N^{data}_{J/\psi}}{N^{MC}_{J/\psi}}$$

- $N^{J/\psi-MC}_{bkg1}$: the number of J/ψ background decays in the J/ψ inclusive and exclusive MC samples
- $N^{data}_{J/\psi}$: the total number of J/ψ events in the data
- $N^{MC}_{J/\psi}$: the total number of equivalent J/ψ events in the J/ψ inclusive and exclusive MC samples

The normalized number in the signal region is estimated to be $N^{norm}_{bkg1} = 24.8 \pm 1.5$.

The other type is continuum background from e^+e^- annihilations into pairs of charged particles, such as $e^+e^- \to e^+e^-(\gamma), \mu^+\mu^-(\gamma)$. This type of background can be estimated using control samples of the e^+e^- collision data at surrounding energy points, such as $\sqrt{s} = 3.773$ GeV, 3.510 GeV, 3.080 GeV. By assuming a $1/s$ energy-dependence of the cross sections, the normalized number of continuum backgrounds at the J/ψ peak, $N^{norm,k}_{bkg2}$, can be obtained by

$$N^{norm,k}_{bkg2} = N^k_{cont} \times f^k_2, \quad f^k_2 = \frac{\mathcal{L}_{J/\psi}}{\mathcal{L}_k} \times \frac{s_k}{s_{J/\psi}}$$

- N^k_{cont} : the number of background events that have survived in the signal region at the energy with index k
- $\mathcal{L}_k, \mathcal{L}_{J/\psi}$: the integrated luminosities at energies k and at the J/ψ peak

The normalized number is estimated to be $N^{norm}_{bkg2} = 12.0 \pm 3.7$.

Systematic Uncertainties

Source	Relative uncertainty(%)
Tracking and PID	13
TOF timing	0.52
Photon veto	0.83
$\lvert\Delta\theta\rvert$ and $\lvert\Delta\phi\rvert$ requirement	2.6
Total	**14**

Result

We observe 29 candidate events in the signal region, while 36.8 ± 4.0 background events are expected. Hence, no excess is observed and an upper limit on the branching fraction $\mathcal{B}(J/\psi \to e\mu)$ is estimated with the profile likelihood method. The upper limit on the branching fraction is found to be

$$\mathcal{B}(J/\psi \to e\mu) < 4.5 \times 10^{-9}$$

at the 90% C. L. by integrating the likelihood curve in the physical region of $\mathcal{B} \ge 0$.

Improving the previous best result by a factor of more than 30, this measurement places the most stringent limit to date on lepton flavor violation in the heavy quarkonium sector.

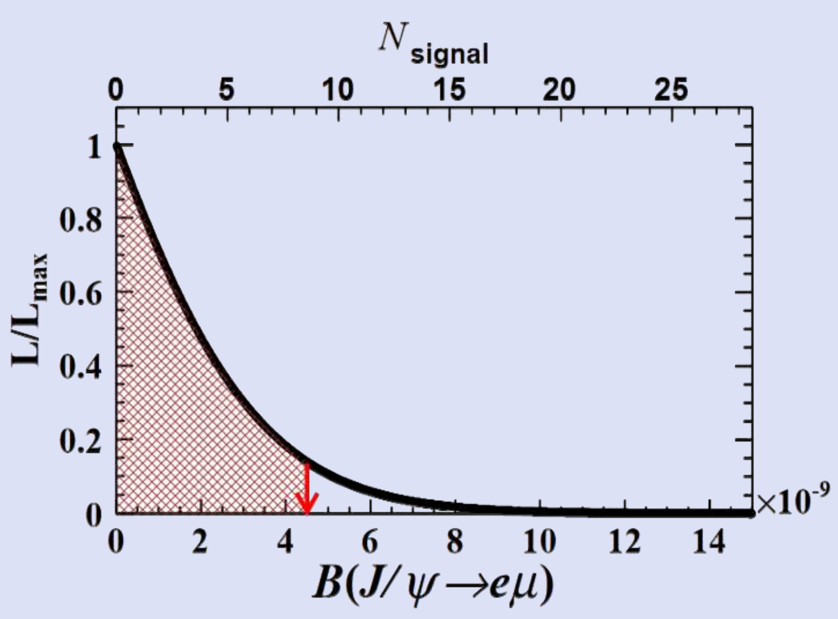


Fig 4. Normalized likelihood distribution as a function of the assumed $\mathcal{B}(J/\psi \to e\mu)$.

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