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Search for Lepton Flavor Violation Process $J/\psi \to e\mu$

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Abstract

Using a sample of $5.8 \times 10^7 J/\psi$ events, the Beijing Spectrometer experiment has searched for the decay $J/\psi \to e\mu$. Four candidates, consistent with the estimated background, are observed, and an upper limit on the branching fraction of $J/\psi \to e\mu$ of 1.1×10^{-6} at the 90 % C.L. is obtained.

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1 Introduction

In the minimal standard model of electroweak theory, the three separate lepton numbers, electron number, muon number, and tau number, are conserved, but this conservation law may be broken in many extensions of the Standard Model, such as grand unified models [1], supersymmetric standard models [2], left-right symmetric models [3] and models where electroweak symmetry is broken dynamically [4]. Recent experimental results from Super-Kamiokande [5], SNO [6] and KamLAND [7] indicate strongly that neutrinos have masses and mix with each other; hence lepton flavor symmetries are broken. There have been many studies both experimentally and theoretically on searching for the lepton flavor violating processes [8], mainly from μ, τ and Z decays [9]. Theoretical studies on the possibility of searching for the lepton flavor violation in decays of charmonium and bottomonium systems are discussed in Refs. [10]-[12]. In this paper we report on a search for lepton flavor violation via the process J/$\psi \to e^{\pm}\mu^{\mp}$ using $5.8 \times 10^7 J/\psi$ events at BEPC/BESII .

2 BES detector

The BEijing Spectrometer (BES) [13] 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 5×10^{30} cm^{-2}s^{-1}. The upgrade from BESI to BESII [14] includes the replacement of the central drift chamber with a straw-tube vertex chamber, composed of 12 tracking layers arranged around a beryllium beam pipe and with a spatial resolution of about 90 μm; a new barrel time-of-flight (TOF) counter with a time resolution of 180 ps; and a new main drift chamber (MDC), which has 40 tracking layers with a dE/dx resolution of $\sigma_{dE/dx} = 8.0\%$ and a momentum resolution of $\sigma_p/p = 1.78\%\sqrt{1+p^2}$ (p in GeV/c) for charged tracks. These upgrades augment the pre-existing calorimeter and muon tracking systems. The barrel shower counter (BSC), which has a total thickness of 12 radiation lengths and covers 80 % of 4π solid angle, has an energy resolution of $\sigma_E/E = 0.21/\sqrt{E}$ (E in GeV) and a spatial resolution of 7.9 mrad in ϕ and 2.3 cm in z. The μ identification system consists of three double layers of proportional tubes interspersed in the iron flux return of the magnet. They provide coordinate measurements along the muon trajectories with resolutions in the outermost layer of 10 cm and 12 cm in $r\phi$ and z, respectively. The absorber thicknesses in front of the three layers are 120, 140, and 140 mm, and the solid angle coverage of the layers is 67 %, 67 %, and 63 % of 4π, respectively.

3 Event selection

The initial selection of $J/\psi \to e^{\pm}\mu^{\mp}$ requires that candidate events have two oppositely charged tracks within the polar angle region, $|\cos\theta| < 0.8$, and fewer than four neutral tracks. A charged track should have a good helix fit; a momentum, P, with 1.45 GeV/$c < P <$ 1.65 GeV/c; and originate from the interaction region, defined by $|x| < 0.015$ m, $|y| < 0.015$ m and $|z| < 0.15$ m. To reject cosmic rays, the TOF time difference of the two charged tracks must be less than 1.2 ns. The invariant mass of the $e\mu$ system, $M_{e\mu}$, must satisfy 2.95 GeV/$c^2 < M_{e\mu} <$ 3.25 GeV/c^2, and the angle between the two charged tracks, θ_{12}, is required to be greater than 178.5°. The θ_{12} distribution is shown in Fig. 1.

Isolated photons are defined as those photons having an energy deposit in the BSC greater than 50 MeV, an angle with any charged track greater than 15°, and an angle between the direction defined by the first layer hit in the BSC and the developing direction of the cluster in the xy-plane less than 18°. There must be no isolated photon in the selected event.

The above criteria select back-to-back, two prong events, such as $J/\psi \to e^+e^-(\gamma), \mu^+\mu^-(\gamma), K^+K^-, \pi^+\pi^-$ and $e^+e^- \to e^+e^-(\gamma)$, etc. To select electrons and muons, the BSC and μ counter information is used. The actual selection criteria are based on distributions determined from data. Fig. 2 shows distributions of E/P, where E is the energy deposited in the shower counter, for candidate electron and muon tracks. To be an electron, a track must have no hits in the muon counter and satisfy $E/P > 0.7$.

To select muon tracks, the differences, $\delta_i (i = x, y, z)$, between the closest muon hit and the projected MDC track in each layer are used. Fig. 3 shows these differences in the third layer of the μ counter. The distributions are Gaussians, and standard deviations, $\sigma_i (i = x, y, z)$, are determined for each layer of the μ counter.

To reduce background, we make a tight cuts on the muon. A good hit in the μ counter requires $|\delta_i| < \sigma_i$ for i = x, y, and z. The total number of layers hit in the μ counter is denoted as μ_{hit} and can range from zero to three. The number of good hits is denoted by μ_{hit}^{good}. A track is considered as a muon if $E/P < 0.3$ and μ_{hit}^{good} is greater than zero if the transverse momentum of the track, P_{xy}, is less than 0.75 GeV/c, $\mu_{hit}^{good} > 1$ if 0.75 GeV/$c < P_{xy} <$ 0.95 GeV/c, or $\mu_{hit}^{good} = 3$ if $P_{xy} >$ 0.95 GeV/c.

Using these selection criteria, four $J/\psi \to e\mu$ candidates are found in $5.8 \times 10^7 J/\psi$ events. The characteristics of these events are listed in Table 1.

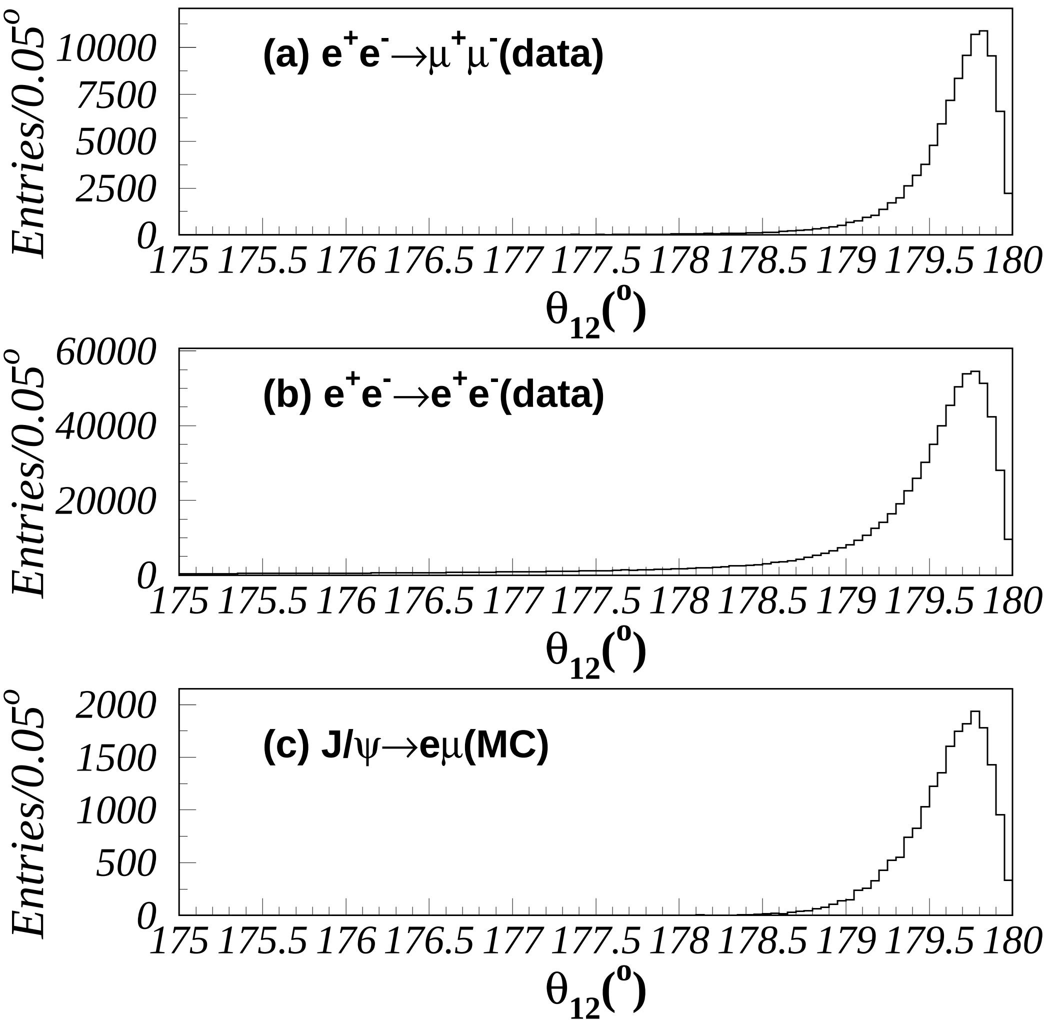

Fig. 1. The opening angle between two charged tracks for (a) $e^+e^- \to \mu^+\mu^-$ (data), (b) $e^+e^- \to e^+e^-$ (data) and (c) $J/\psi \to e\mu$ (Monte Carlo data).

4 Efficiencies and backgrounds

The main backgrounds for $J/\psi \to e\mu$ are nearly back-to-back $J/\psi \to e^+e^-(\gamma)$, $\mu^+\mu^-(\gamma)$, K^+K^-, $\pi^+\pi^-$, $e^+e^- \to e^+e^-(\gamma)$, and $e^+e^- \to \mu^+\mu^-(\gamma)$ events where one or more tracks is misidentified as a μ or e. It is therefore important to determine the μ and e particle identification (PID) misidentification efficiencies for the background channels, as well as the PID efficiencies for the signal channel. In this study, we determine these efficiencies using information from the BSC and muon counters from data. The overall efficiencies include the PID efficiencies and the geometric efficiencies, ϵ_{MC}, determined using our Monte Carlo (MC) program SIMBES (SIMulation at BES), which is based on

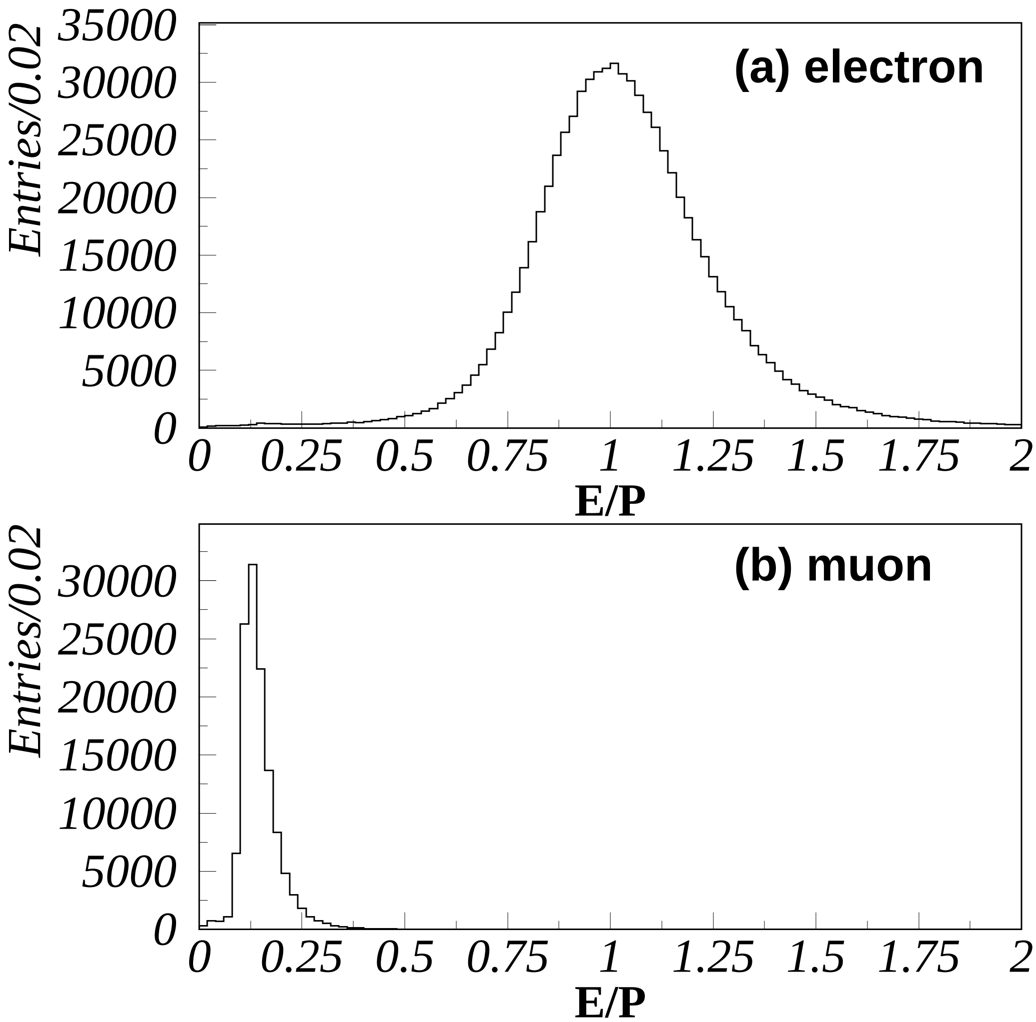

Fig. 2. Distribution of E/P of candidate a.) e and b.) μ tracks. E and P denote the energy deposited in the BSC and the momentum measured in the MDC, respectively.

GEANT3.21. For the signal channel $J/\psi \to e\mu$, the total selection efficiency is then

$$\epsilon_{J/\psi\to e\mu} = \epsilon_{e\mu-MC} \times \epsilon_{e\to e} \times \epsilon_{\mu\to\mu},$$

where $\epsilon_{e\mu-MC}$ is the geometric efficiency, $\epsilon_{e\to e}$ is the electron PID efficiency, and $\epsilon_{\mu\to\mu}$ is the muon PID efficiency. Using 30000 $J/\psi \to e\mu$ Monte Carlo events with an angular distribution of $1+\cos^2\theta$, the geometric efficiency is determined to be $\epsilon_{e\mu-MC} = (53.7 \pm 0.3)\%$.

For the background channels J/ψ $(e^+e^-) \to XX$, where $X = e$, μ, π, K, the efficiency after $J/\psi \to e\mu$ selection is

$$\epsilon_{XX} = \epsilon_{XX-MC} \times \epsilon_{X\to e} \times \epsilon_{X\to\mu} \times 2,$$

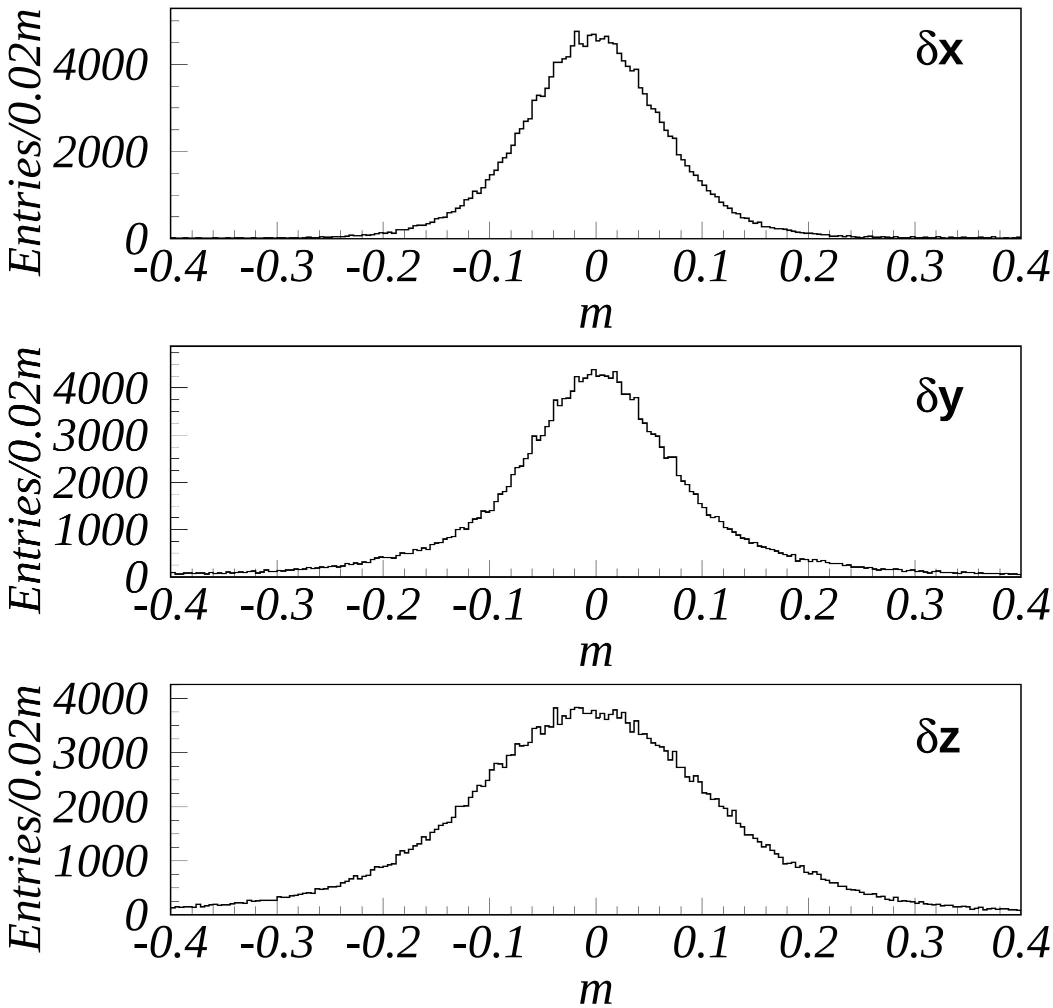

Fig. 3. The differences, δx, δy, and δz, between the closest hit and the extrapolated MDC track in the third layer of the μ system.

where ϵ_{XX-MC} is the Monte Carlo geometric acceptance, shown in Table 2, and $\epsilon_{X\to e}$ and $\epsilon_{X\to\mu}$ are the particle misidentification efficiencies for X being identified as an electron or a muon, respectively.

The e and μ PID efficiencies are determined using e-pair samples of $e^+e^- \to e^+e^-(\gamma)$ (Bhabha, resonance, and continuum production) events and μ-pair samples of $e^+e^- \to \mu^+\mu^-(\gamma)$ (resonance and continuum production) events. The highest momentum track is required to satisfy $1.45 < P < 1.65$ GeV/c and to be identified as an e or μ according to the PID selection criteria. The other track in the event is then assumed to be the same type of lepton, and the fraction of these satisfying the lepton selection determines the efficiency. The PID efficiencies are shown in Table 3, and the total efficiency for $J/\psi \to e\mu$

Table 1
The characteristics of the $J/\psi \to e\mu$ candidates. θ_{12} is the angle between two charged tracks.

RUN No.	14676		16419		18940		19149	
REC No.	16877		26352		27010		9196	
$M_{e\mu}$ (GeV)	3.113		3.117		3.201		3.143	
θ_{12}	179.5		179.8		179.6		179.5	
track	e	μ	e	μ	e	μ	e	μ
P (GeV/c)	1.591	1.522	1.570	1.543	1.587	1.611	1.605	1.535
E/P	0.7188	0.1758	0.8577	0.1778	0.8835	0.1415	0.7155	0.1035
μ_{hit}^{good}	0	3	0	3	0	3	0	3

Table 2
Monte Carlo geometric efficiencies.

channel		MC Efficiency
$J/\psi \to ee$	ϵ_{ee-MC}	(61.47±0.02)%
$J/\psi \to \mu\mu$	$\epsilon_{\mu\mu-MC}$	(58.32±0.02)%
$J/\psi \to \pi\pi$	$\epsilon_{\pi\pi-MC}$	(52.74±0.29)%
$J/\psi \to KK$	ϵ_{KK-MC}	(24.38±0.24)%
$e^+e^- \to e^+e^-(\gamma)$	$\epsilon_{ee(\gamma)-MC}$	(32.51±0.03)%
$e^+e^- \to \mu^+\mu^-(\gamma)$	$\epsilon_{\mu\mu(\gamma)-MC}$	(42.96±0.29)%

is $(9.7 \pm 0.5)\%$.

The misidentification efficiencies between electrons and muons cannot be studied from the data because the events selected for this study are the same as our $J/\psi \to e\mu$ candidates. A rough estimate of this background using a Monte Carlo simulation predicts a total of 7 background events from $e^+e^- \to e^+e^-(\gamma)$ and $e^+e^- \to \mu^+\mu^-(\gamma)$. Since the Monte Carlo simulation is not precise enough to determine this background, we conservatively ignore these backgrounds in the estimation of the upper limit on the branching ratio for $J/\psi \to e\mu$.

For the misidentification efficiencies of hadrons, π and K tracks are selected from $J/\psi \to \rho^{\pm}\pi^{\mp}$ and $K^{*\pm}K^{\mp}$ decays. The track with the highest momentum is considered as the π and K in the respective samples, and a total of 60551 π tracks and 9275 K tracks are selected. The fraction of the tracks above 1.2 GeV/c passing the electron and muon selection criteria are used to obtain the misidentification efficiencies, that are listed in Table 3. The resultant background rates from particle misidentification of $J/\psi \to K^+K^-, \pi^+\pi^-$ events are listed in Table 4, taking into account their branching ratios from

PDG2002 [9].

Table 3
The particle identification/misidentification efficiencies.

	regarded as e	regarded as μ
e sample	95.3%(1±0.02%)	—
μ sample	—	19.0%(1±0.6%)
π	3.6%(1±2.1%)	0.46%(1±5.98%)
K	3.11%(1±5.79%)	0.38%(1±16.8%)

Table 4
The misidentification rates and backgrounds from hadronic channels.

decays	misidentification rate	number of background
$J/\psi \to \pi\pi$	1.74×10^{-4}	1.49
$J/\psi \to KK$	5.77×10^{-5}	0.79
total		2.3

There are a number of sources of systematic error, including the error on the total number of J/ψ (4.7%) events, the errors on the branching ratios from PDG2002 [9], the uncertainties of the muon and electron identification efficiencies, shown in Table 3, and the errors on the hadronic misidentification efficiencies, also shown in Table 3. Table 5 summarizes the errors in the background from the hadronic channels. The total background, ignoring the contributions from $J/\psi \to e^+e^-(\gamma)$ and $\mu^+\mu^-(\gamma)$, is 2.3±0.3 events. Therefore the observed four events are consistent with background.

Table 5
Summary of estimated errors for hadronic background channels.

	N_{total}	BR.	e_{PID}	μ_{PID}	total error	number
$J/\psi \to \pi\pi$	4.7%	15.6%	2.10%	5.98%	17.4%	1.49±0.26
$J/\psi \to KK$	4.7%	13.1%	5.79%	16.8%	22.5%	0.79±0.18

5 Results and discussion

The four observed $J/\psi \to e\mu$ candidates are consistent with the estimated background, hence an upper limit for $J/\psi \to e\mu$ is determined. Only the backgrounds from the hadronic channels are taken into account in the estimation of the upper limit.

There are several ways to determine the upper limit [15] [16] [17]. The following formula is used to calculate the upper limit for $Br(J/\psi \to e\mu)$:

$$Br < \lambda(N_{OB}, N_{BG})/[N_T \times \epsilon_{J/\psi\to e\mu}],$$

where λ is the upper bound of a 90% C.L. for an unknown Poisson signal mean, for total observed events, N_{OB}, and known mean background, N_{BG}. N_T is the total number of J/ψ events, and ϵ is the detection efficiency. $\lambda(N_{OB}, N_{BG})$ can be calculated using the method of Ref. [15].

As a conservative estimation, we take the number of background events as the central value of the number of background events reduced by one standard deviation, $i.e.$ $N_{BG} = 2.0$ and N_{OB}=4, then $\lambda(N_{OB}, N_{BG})$=5.98. Therefore we obtain:

$$Br(J/\psi \to e\mu) < 1.1 \times 10^{-6}.$$

In summary, we searched for $J/\psi \to e\mu$ based on $5.8 \times 10^7 J/\psi$ events and observed four $J/\psi \to e\mu$ candidates passing our selection criteria, which are consistent with the estimated background. The upper limit of $Br(J/\psi \to e\mu)$ is determined to be 1.1×10^{-6} at the 90 % C.L.

6 Acknowledgments

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