Search for the charged lepton flavor violating decay $J/\psi \to e\tau$
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bidden \cite{1, 2}, therefore any significant sign of a signal
charged lepton flavor violating (CLFV) process is for-
BABAR \times 3
pions \cite{12}, kaons \cite{13},
vector mesons, gauge bosons, and the Higgs boson, e.g.,
pions \cite{12}, kaons \cite{13}, B mesons \cite{14, 15}, bottomonium
A search for the charged lepton flavor violating decay \( J/\psi \rightarrow e^\pm \tau^\mp \) with \( \tau^\mp \rightarrow \pi^\mp \pi^0 \nu_\tau \) is
\( 10 \times 10^9 \) \( J/\psi \) events collected with the BESIII detector at the BEPCII. No
significant signal is observed, and an upper limit is set on the branching fraction \( B(J/\psi \rightarrow e^\pm \tau^\mp) < 7.5 \times 10^{-8} \) at the 90% confidence level. This improves the previously published limit by two orders
magnitude.

I. INTRODUCTION

In the Standard Model (SM) of particle physics, the charged lepton flavor violating (CLFV) process is for-
bidden \cite{1, 2}, therefore any significant sign of a signal
could indicate physics beyond the SM. In recent years, there have been active phenomenological exploration of
the sources of lepton flavor symmetry breaking. Many
physics models beyond the SM could allow CLFV pro-
tesses to take place, such as supersymmetry \cite{3, 4}, the
two Higgs doublet model \cite{7, 8}, and models including a
fourth generation of quarks and leptons \cite{5}. The searches have been carried out in a variety of experimental endeavors. For example, the MEG collaboration searched for the decay \( \mu^+ \rightarrow \gamma e^+ \) and set the best upper limit (UL) of
\( B(\mu^+ \rightarrow \gamma e^+) < 4.2 \times 10^{-13} \) \cite{10} up to now, while the \( BABAR \) collaboration found a limit of \( B(\tau^+ \rightarrow \gamma e^+) < 3.3 \times 10^{-8} \) \cite{11}. Meanwhile, many experiments searched for CLFV processes in the decays of pseudoscalar mesons, vector mesons, gauge bosons, and the Higgs boson, e.g.,
pions \cite{12}, kaons \cite{13}, B mesons \cite{14, 15}, bottomonium
states \cite{16, 17}, \( Z^0 \) \cite{18, 19}, and Higgs \cite{20, 21}.

There are various theoretical predictions on CLFV in
the charmonium states using model-independent methods \cite{22, 23}, unparticle physics \cite{24}, and the minimal
supersymmetric model with gauged baryon number and
lepton number \cite{25}, etc. Some of these predictions con-
strain \( B(J/\psi \rightarrow e^\pm \mu^\mp) \) to the order of \( 10^{-13} \), while
\( B(J/\psi \rightarrow e^\pm \tau^\mp) \) and \( B(J/\psi \rightarrow \mu^\pm \tau^\mp) \) to \( 10^{-9} \). With
58 \times 10^6 \( J/\psi \) events, the BES collaboration obtained experimental ULs of various decays of charmonium states, namely
\( B(J/\psi \rightarrow e^\pm \mu^\mp) < 1.1 \times 10^{-6} \) \cite{26}, \( B(J/\psi \rightarrow e^\pm \tau^\mp) < 8.3 \times 10^{-6} \), and \( B(J/\psi \rightarrow \mu^\pm \tau^\mp) < 2.0 \times 10^{-6} \) \cite{27}. More recently and based on 225 \times 10^6 \( J/\psi \) events
collected with BESIII, an UL of \( B(J/\psi \rightarrow e^\pm \mu^\mp) < 1.6 \times 10^{-7} \) was obtained \cite{28}.

In this paper, the CLFV process of \( J/\psi \rightarrow e^\pm \tau^\mp \) with
\( \tau^\mp \rightarrow \pi^\mp \pi^0 \nu_\tau \) is probed based on 10 \times 10^9 \( J/\psi \) events
collected with the BESIII detector. A semiblind analysis is performed to avoid a possible bias. About 10% of
the full data sample are randomly selected. Besides the
selected data, several simulation samples, and inde-
dependent continuum data samples are used to optimize
the event selection criteria, study the background, and
estimate the systematic uncertainties. The final results
are obtained with the full data sample by repeating the
validated analysis strategy. In the rest of this paper,
the charge conjugated channel is implied unless other-
wise specified.

II. BESIII DETECTOR

The BESIII detector is a magnetic spectrometer located at the Beijing Electron Positron Collider (BEPCII). The cylindrical core of the BESIII detector consists of a helium-based multilayer drift chamber (MDC), a plastic scintillator time-of-flight system (TOF), and a CsI(Tl) electromagnetic calorimeter (EMC), which are all enclosed in a superconducting solenoidal magnet providing a 1.0 T(0.9 T in 2012) magnetic field. The solenoid is supported by an octagonal flux-return yoke with resistive plate counter muon identiﬁer modules interleaved with steel. The acceptance of charged particles is 93% over 4π solid angle. The charged-particle momentum resolution at 1 GeV/c is 0.5%, and the dE/dx resolution is 6% for the electrons from Bhabha scattering. The EMC measures photon energies with a resolution of 2.5%(5%) at 1 GeV in the barrel (end cap) region. The time resolution of the TOF barrel part is 68 ps, while that of the end cap part is 110 ps. The end cap TOF system is upgraded in 2015 with a multigap resistive plate chamber technology, providing a time resolution of 60 ps.

III. DATA SAMPLES AND MONTE CARLO SIMULATION

The analysis is based on J/ψ events collected in the years of 2009, 2012, 2018 and 2019 at BESIII. The total number of J/ψ events collected in these years is determined using inclusive J/ψ decays with the method described in Ref. The selected inclusive J/ψ events, the background due to QED processes, beam-gas interactions and cosmic rays is estimated using the continuum data samples at √s = 3.08 GeV. The detection efficiency for the inclusive J/ψ decays is obtained using the experimental data sample of ψ(3686) → π+π−J/ψ. The efficiency difference between the J/ψ produced at rest and the J/ψ from the decay ψ(3686) → π+π−J/ψ is estimated by comparing the corresponding efficiencies in a Monte Carlo (MC) simulation. The uncertainties related to the signal MC model, track reconstruction efficiency, fit to the J/ψ mass peak, background estimation, noise mixing and reconstruction efficiency for the pions recoiling against the J/ψ are studied. Finally, the number of J/ψ events collected at BESIII is determined to be N_{J/ψ} = (10087 ± 44) × 10^6. Among them, in 2009 and 2012, the total J/ψ number is (1310.6 ± 7.0) × 10^6 and this data sample is denoted as “data sample I.” Likewise, the data sample collected in 2018 and 2019 is denoted as “data sample II.”

MC simulated samples produced with the GEANT4-based package, which includes the geometric description of the BESIII detector and the detector response, are used to determine the detection efficiency and to estimate the backgrounds. The simulation takes the beam-energy spread and initial-state radiation in the e+e− annihilations into account, modeled with the generator KKMC. The inclusive MC sample consists of the production of the J/ψ resonance and the continuum processes incorporated in KKMC. The inclusive MC sample contains 1.225 × 10^9 J/ψ events for data sample I and 8.700 × 10^9 J/ψ events for data sample II. The known decay modes are modeled with EVTGEN using branching fractions (BFs) taken from the Particle Data Group (PDG), and the remaining unknown decays from the J/ψ with LUNDCHARM. The final-state radiations (FSR) from charged final-state particles are incorporated with the PHOTOS package. The VLL model, which describes the decay of a vector meson to two charged leptons, is used to generate the process J/ψ → e+e−τ+. The TAUHADNU generator, which describes the τ semileptonic decay with several pions, is used to generate the process τ+ → π+π0ν. This generator is based on conserved vector currents and a chiral Lagrangian model with parameters taken from the paper of the CLEO collaboration. The MC-generated samples simulating signal events, in the following abbreviated as signal MC samples, are generated individually for each data sample and denoted as “signal sample I” and “signal sample II.” To study background contributions, many potential backgrounds of J/ψ decays are generated exclusively with a much larger statistics than each data sample, such as J/ψ → π+π−π0 with Dalitz amplitudes, J/ψ → πντ with helicity amplitudes, as well as J/ψ → ωf2(1270) and πnπ+ with phase space distributions.

IV. EVENT SELECTION

Two charged particles with zero net charge are required to satisfy the polar-angle condition |cos θ| < 0.8 with respect to the beam axis. Their closest approaches to the interaction point are required to be within 10 cm in the beam direction and within 1 cm in the plane perpendicular to the beam. The particle identiﬁcation (PID) is performed by combining the energy-loss measurement, dE/dx, obtained from the MDC and the time-of-ﬂight information from the TOF. PID conﬁdence levels (C.L.) are calculated for the electron (CL_e), pion (CL_π), proton (CL_p), and kaon (CL_K) hypotheses. The electron (pion) candidate requires the electron (pion) hypothesis to have the highest PID conﬁdence levels among the four hypotheses. For electron candidates, the CL_e/(CL_e + CL_π) ratio is required to be larger than 0.95 and the E/p is larger than 0.8 to further improve the electron
Electromagnetic showers in the EMC are identified as photon candidates only if the following criteria are satisfied. The energy deposition is required to be larger than 15 MeV/c² and less than 50 MeV/c² in the end cap (0.86 < |cosθ| < 0.92) regions. To eliminate showers produced by charged particles, the photon candidates are required to be separated from the extrapolated positions of any charged track by more than 10⁻⁶. To suppress electronic noise and unrelated energy depositions, the EMC time deviation from the event start time is required to be within 700 ns. At least two photons satisfying these selection criteria are required in the final state. The π⁰ candidate is reconstructed from photon pairs whose invariant mass M(γγ) is required to satisfy 115 MeV/c² < M(γγ) < 150 MeV/c². To improve the momentum resolution, a kinematic fit is applied by constraining the two-photon invariant mass to the nominal π⁰ mass, and the refined four momenta of the photons are used for further analysis.

The final-state electron from the process J/ψ → e⁻τ⁺ is monochromatic, therefore the momentum of the electron Pₑ and the recoiling mass against the electron Mₑ-recoil are required to be within 1.009 GeV/c < Pₑ < 1.068 GeV/c and 1.742 GeV/c² < Mₑ-recoil < 1.811 GeV/c², respectively. The momentum and recoil-mass resolutions are found, using MC simulations, to be 0.010 and 0.011 GeV/c², respectively. Figure 1 compares the momentum and recoil-mass distributions of the complete data sample with the corresponding signal MC simulation and J/ψ inclusive MC samples. The possible background from continuum process would be discussed in the next section.

The missing energy E_miss is calculated by E_miss = E_CMС - Eₑ - Eπ - Eπ⁰, where E_CMС is the center-of-mass energy of the initial e⁺e⁻ system, while Eₑ, Eπ, and Eπ⁰ are the energies of the electron, charged pion, and neutral pion in the rest frame of the e⁺e⁻ system. The E_miss is required to be larger than 0.43 GeV to suppress the background events whose final states are all detected. The variable Uₜₜ is calculated by Uₜₜ = Eₜₜ - c|Pₜₜ|, is used to define the signal region to have a better resolution than the missing mass. The variable Pₜₜ = P_J/ψ - Pₑ - Pπ - Pπ⁰ is the missing momentum, where P_J/ψ is the corresponding momenta in the rest frame of the e⁺e⁻ system of the particles indicated by the subscript. As the signal events peak near zero with one undetected neutrino, the signal region is defined to be −0.081 GeV < Uₜₜ < 0.112 GeV, which corresponds to three standard deviations of the expected width determined from the signal MC sample. The number of signal candidates for each data sample, N_{obs}, is obtained by counting the number of entries that fall within the signal region. After applying the above selection criteria, the detection efficiency of the signal sample I (II) is determined to be (20.24 ± 0.05)% ((19.37 ± 0.02)%).

V. BACKGROUND STUDY

The dominant background contaminations stem from the continuum process (e.g. radiative Bhabha) and from hadronic J/ψ decays such as J/ψ → π⁺π⁻π⁰.

The continuum background is studied with a 150 pb⁻¹ data sample collected at √s = 3.08 GeV and a 2.93 fb⁻¹ data sample taken at √s = 3.773 GeV. The survived events are dominated by radiative Bhabha process, therefore the normalized background events from the continuum processes are estimated with the assumption of a 1/s dependence of the cross section. Radiative Bhabha MC samples at different energy points are used to evaluate the uncertainty of this assumption to be about 24%. Single electron MC samples are used to study the electron momentum resolution differences at different energy points. The resolution differences are applied to radiative Bhabha MC samples, and the result shows this influence could be negligible in this study. The continuum back-
ground events are estimated to be $5.8 \pm 1.8 \ (37.9 \pm 11.5)$ for data sample I (II) with the uncertainties of statistics and the assumption of 1/s dependence taken into consideration.

The $J/\psi$ decay background is studied with the inclusive MC samples, and only a few events survive. Main background processes from $J/\psi \rightarrow \pi^+ \pi^- \pi^0$, $J/\psi \rightarrow \rho \pi$, $J/\psi \rightarrow \omega f_2(1270)$, and $J/\psi \rightarrow \bar{p} n \pi^+$ are studied with exclusive MC samples. The uncertainty in the $J/\psi$ decay modeling is determined to be about 16% from the inclusive MC samples with and without LUNDCHARM model.

The normalized background events from the $J/\psi$ decays are estimated to be $1.1 \pm 0.8 \ (25.7 \pm 6.4)$ for data sample I (II) with statistical and $J/\psi$ decay modeling uncertainties taken into consideration. The possible cross feed from the CLFV process $J/\psi \rightarrow e^\pm \tau$ whereby the $\tau$ decays to other modes has been studied using a $\tau$ inclusive MC sample modeled by EVTGEN [36] and found to be negligible (0.3%). The background events from $J/\psi$ decay processes are normalized according to the BFs from the PDG [37], the number of $J/\psi$ events, and the detection efficiencies determined from the exclusive MC samples.

The normalized background events from continuum processes and $J/\psi$ decay processes discussed above are utilized to estimate the number of background events left in the signal region. In total, $6.9 \pm 1.9 \ (63.6 \pm 13.2)$ background events are expected for the data sample I (II). Some background events with additional soft tracks contribute near the $U_{miss} = 0$ region. The signal region is opened after completing the optimization of the analysis algorithms and the background study. Figures 2 and 3 depict $U_{miss}$ for the data samples I and II, respectively.

![Figure 2](image-url)

**FIG. 2.** The $U_{miss}$ distribution of data sample I and corresponding background. The dots with error bars are data, while the shaded histogram is from the normalized continuum sample as well as the $J/\psi$ inclusive MC samples. The dashed line shows the arbitrarily scaled signal MC shape extracted from the signal sample I. The areas between the arrows represent the signal region.

![Figure 3](image-url)

**FIG. 3.** Same as Fig. 2 except for data sample II and signal sample II.

### VI. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties mainly come from uncertainties in the total number of $J/\psi$ decays, the quoted intermediate BF, the background estimation, and in efficiencies associated with signal modeling, PID and tracking of charged particles, the photon detection, the $\pi^0$ reconstruction, and kinematic variable requirements. The details of most of sources are described below, while the uncertainties from background estimation have been considered in the Sec. [V].

The uncertainty in the number of $J/\psi$ events is determined to be 0.5% for the data sample I [38], and 0.4% for the data sample II. The uncertainty in the quoted BF of $\tau^+ \rightarrow \pi^- \pi^0 \nu_\tau$ is 0.4% [37]. To estimate the uncertainty in the signal MC model, the generator producing $\tau^+ \rightarrow \pi^- \pi^0 \nu_\tau$ decays is changed to the TauVector generator (for $\tau^+ \rightarrow \rho^+ \nu_\tau$) and the VSS generator (for $\rho^+ \rightarrow \pi^+ \pi^0$) [36]. The TauVector generator simulates the decay of a $\tau$ lepton into a vector particle and a neutrino, while the VSS generator simulates the decay a vector meson into a pair of scalar particles.

The relative change in the detection efficiency of signal sample I, 0.6%, is assigned as the uncertainty. The relative change in the efficiency for sample II is found to be negligible.

The uncertainty in the PID of pions is 1.0% per charged pion, as determined from a study of the control sample of the process $J/\psi \rightarrow \rho \pi$ [42]. The MDC tracking efficiency of charged pions is studied using the control sample of $J/\psi \rightarrow \pi^+ \pi^- pp$ decays, and the difference between the data and MC simulation is 1.0% for each charged pion [43]. The PID and tracking efficiencies of electrons are obtained from a control sample of radiative Bhabha scattering $e^+e^- \rightarrow \gamma e^+e^-$ (including $J/\psi \rightarrow \gamma e^+e^-$) corresponding to the center-of-mass energy of the $J/\psi$ resonance. For the electron-PID study,
the same PID requirements as applied to the dataset of interest are exposed to the control samples. Similarly, for the electron-tracking study, we applied the same conditions for the polar angle and for the closest distance to the interaction point as was used for the data of interest. Differences in PID (tracking) efficiencies between the data and MC simulations are obtained for each bin of a two-dimensional distribution representing the momentum (transverse momentum) versus the polar angle of the electron tracks. These results are subsequently used to determine the overall weighted differences per track for PID (tracking). We obtained PID and tracking uncertainties for electrons of the signal sample I (II) of 0.4% (0.9%) and 0.1% (0.1%) per track, respectively.

The photon detection efficiency is studied with the control sample based on \(J/\psi \rightarrow \pi^+\pi^-\pi^0\), \(\pi^0 \rightarrow \gamma\gamma\) events. The difference between data and MC simulation is 0.5% (1.5%) for a photon in the EMC barrel (end cap) region. The average difference, 0.5% per photon, is taken as systematic uncertainty. The total systematic uncertainty due to uncertainties in the photon-detection efficiency is estimated to be 1.0%. The uncertainty related to the \(\pi^0\) reconstruction is determined to be 1.0% for the two samples using a \(J/\psi \rightarrow \pi^+\pi^-\pi^0\) control sample as described in Ref. 12.

The systematic uncertainties related to \(P_e\) and \(M_{e_recoil}\) requirements are studied with the control sample of the process \(e^+e^- \rightarrow \gamma e^+e^-\) (including \(J/\psi \rightarrow \gamma e^+e^-\)) at the center-of-mass energy of the \(J/\psi\) resonance. The differences in efficiency between the data and MC simulation for these two kinematic variables are studied by varying the event-selection requirement ranges while taking into account the correlation between them. This uncertainty is determined to be 3.0% (3.3%) for sample I (II). The same control sample is used to study the uncertainty associated with \(E_{\text{miss}}\) requirement. The electron with the lowest momentum is assumed to be a missing track, and the data-MC differences of the resulting missing energy are derived as correction factors to be applied to the \(E_{\text{miss}}\) distribution of the signal MC sample. Then the difference in efficiency, 1.0% (0.8%), between the signal MC sample with and without the correction is taken as the systematic uncertainty for data sample I (II).

Table I summarizes all sources of systematic uncertainties discussed above. The total systematic uncertainties of each data sample are obtained by adding these uncertainties in quadrature.

### VII. RESULTS

Table II summarizes the extracted parameters of each sample. The parameters \(N_{\text{exp}}\) and \(\sigma_{\text{bkg}}\) are the expected number of background events and its uncertainty in the signal region determined from the background study; \(\epsilon_{\text{eff}}\) and \(\sigma_{\text{eff}}\) denote the efficiency and its uncertainty determined from signal MC samples and the study of systematic uncertainties.

### TABLE I. Summary of the sources of systematic uncertainties and their estimated magnitudes. The correlated sources are marked with an asterisk, which are added linearly when combining the two data samples. The negligible uncertainty is marked with a dash line.

| Sources                        | sample I | sample II |
|--------------------------------|----------|-----------|
| Number of \(J/\psi\)           | 0.5%     | 0.4%      |
| Quoted BF*                     | 0.4%     | 0.4%      |
| MC model                       | 0.6%     | -         |
| Pion PID*                      | 1.0%     | 1.0%      |
| Pion tracking*                 | 1.0%     | 1.0%      |
| Electron PID                   | 0.4%     | 0.9%      |
| Electron tracking*             | 0.1%     | 0.1%      |
| Photon detection*              | 1.0%     | 1.0%      |
| \(\pi^0\) reconstruction*      | 1.0%     | 1.0%      |
| \(P_e\) and \(M_{e_recoil}\) requirements | 3.0%     | 3.3%      |
| \(E_{\text{miss}}\) requirement | 1.0%     | 0.8%      |
| Total uncertainty              | 3.9%     | 4.1%      |

### TABLE II. A summary of the analysis results. See the text for details.

| Results                  | sample I | sample II |
|--------------------------|----------|-----------|
| \(N_{\text{obs}}\)      | 13       | 69        |
| \(N_{\text{exp}}\)      | 6.9      | 63.6      |
| \(\sigma_{\text{bkg}}\) | 1.9      | 13.2      |
| \(\epsilon_{\text{eff}}\) | 20.24%  | 19.37%    |
| \(\sigma_{\text{eff}}\) | 0.79%    | 0.79%     |
| BF (90% C.L.)            | \(7.5 \times 10^{-8}\) |

Since no significant signal is observed, a maximum likelihood estimator, extended from the profile-likelihood approach, is used to determine the UL on the BF of \(J/\psi \rightarrow e^+e^-\). The likelihood function of each sample which depends on the parameter of interest \(B(J/\psi \rightarrow e^+e^-)\) and the nuisance parameters \(\theta = (\epsilon_{\text{eff}}, N_{\text{bkg}})\) is defined as

\[
L(B(J/\psi \rightarrow e^+e^-), \theta) = P(N_{\text{obs}}, B(J/\psi \rightarrow e^+e^-) \cdot N_{J/\psi} \cdot B_{e^+e^-} \cdot \epsilon_{\text{eff}} + N_{\text{bkg}}) \cdot G(\epsilon_{\text{eff}}, \epsilon_{\text{eff}}^{\text{mc}}) \cdot G(N_{\text{bkg}}, N_{\text{bkg}}^{\text{exp}}, \sigma_{\text{bkg}}^{\text{exp}}),
\]

where the observed events are assumed to follow a Poisson distribution \(P\), while the detection efficiency \(\epsilon_{\text{eff}}\) and the background number \(N_{\text{bkg}}\) follow Gaussian distributions \(G\); \(N_{J/\psi}\) is the number of \(J/\psi\) events.

The likelihood function is treated as the probability function, and the UL on the \(J/\psi \rightarrow e^+e^-\) at 90% C.L. is determined by integrating the likelihood distribution.
in the physical region of $\mathcal{B} \geq 0$ based on the Bayesian method with the ROOSTATS package \cite{29}. The combined likelihood distribution as a function of the BF from the data samples is shown in Fig. 4. The resultant UL is $\mathcal{B}(J/\psi \rightarrow e^\pm \tau^\mp) < 7.5 \times 10^{-8}$ (90\% C.L.), where the detection efficiency, statistical and systematic uncertainties as well as the background estimation are all incorporated.

VIII. SUMMARY

This paper presents a search of the CLFV process $J/\psi \rightarrow e^\pm \tau^\mp$ with $\tau^\mp \rightarrow \pi^\pm \pi^0 \nu_\tau$ using a data sample based upon $10 \times 10^9 J/\psi$ events collected with the BESIII detector. A semiblind analysis found no significant excess in the datasets with respect to the expected background. The UL is determined to be $\mathcal{B}(J/\psi \rightarrow e^\pm \tau^\mp) < 7.5 \times 10^{-8}$ (90\% C.L.), where uncertainties are taken into account. This improves the previous published limits \cite{30} by more than two orders of magnitude and can be used to constrain new physics parameter spaces.

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