Published for SISSA by Springer

Received: *April 15, 2021*
Accepted: *May 28, 2021*
Published: *June 25, 2021*

Search for the rare semi-leptonic decay $J/\psi \to D^-e^+\nu_e + \text{c.c.}$

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Abstract: Using 10.1×10^9 J/ψ events produced by the Beijing Electron Positron Collider (BEPCII) at a center-of-mass energy $\sqrt{s} = 3.097\,\text{GeV}$ and collected with the BESIII detector, we present a search for the rare semi-leptonic decay $J/\psi \to D^-e^+\nu_e + \text{c.c.}$ No excess of signal above background is observed, and an upper limit on the branching fraction $\mathcal{B}(J/\psi \to D^-e^+\nu_e + \text{c.c.}) < 7.1 \times 10^{-8}$ is obtained at 90% confidence level. This is an improvement of more than two orders of magnitude over the previous best limit.

Keywords: e^+-e^- Experiments

ArXiv ePrint: 2104.06628

https://doi.org/10.1007/JHEP06(2021)157

Contents

1 Introduction

The J/ψ meson, which decays primarily through strong and electromagnetic interactions, has been thoroughly studied for decades. However, its weak decays remain elusive. Since the J/ψ mass is below the $D\bar{D}$ threshold, the J/ψ resonance is forbidden to decay into a pair of charmed mesons. However, it can decay into a single charmed meson accompanied by light hadrons or leptons via weak decay of one of the charm quarks. The inclusive branching fraction (BF) of weak decays to a single charmed meson was predicted to be at the order of 10^{-8} or below [1–10] in the Standard Model (SM). Therefore, searching for these decays not only tests the SM prediction [11], but also probes new physics theories beyond the SM, such as the Top-color model, the Minimal Supersymmetric SM with or without R-parity, and the two-Higgs doublet model [12–15], in which these BFs could be significantly larger, reaching values of 10^{-5} [10]. So far, weak decays of the J/ψ meson have not yet been observed [16–20].

In weak semi-leptonic J/ψ decays, the hadronic transition form factor between the initial and final-state mesons can be cleanly decoupled from the weak current [6–10]. Figure 1 shows the tree-level Feynman diagram within the SM for the decays $J/\psi \to D^- l^+ \nu_l$ ($l = e$ or μ). The theoretical predictions for the BF of the rare semi-leptonic decay $J/\psi \to D^- e^+ \nu_e$ within the SM are of the order of 10^{-11} [6–10], as shown in table 1. A previous study of this decay by the BES collaboration reported an upper limit (UL) on the BF of 1.2×10^{-5} at 90% confidence level (CL) based on a sample of 5.8×10^7 J/ψ events [18]. This result reaches down to the level of the expected BF values in several models beyond the SM [14, 15], although it is several orders of magnitude larger than the SM value. To further test the SM predictions and constrain the contributions from new physics models, a new measurement of $\mathcal{B}(J/\psi \to D^- e^+ \nu_e)$ with greater sensitivity is required.

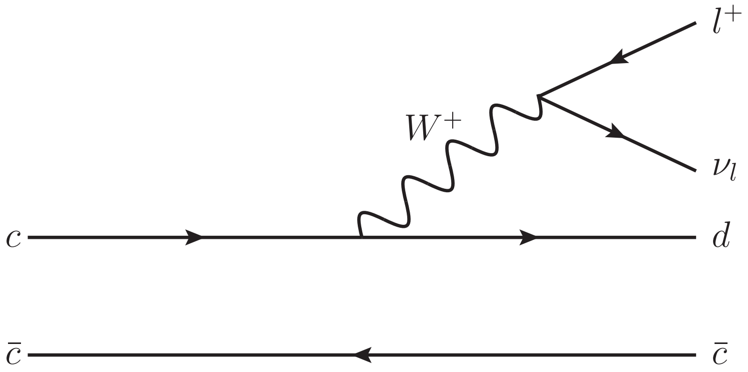

Figure 1. Feynman diagram for $J/\psi \to D^- l^+ \nu_l$ decays at tree-level.

Decay mode	QCDSR [6]	LFQM [7]	BSW [8]	CCQM [9]	BSM [10]
$J/\psi \to D^- e^+ \nu_e$	$0.73^{+0.43}_{-0.22}$	5.1–5.7	$6.0^{+0.8}_{-0.7}$	1.71	$2.03^{+0.29}_{-0.25}$

Table 1. Theoretical results for the BF of the semi-leptonic decay $J/\psi \to D^- e^+ \nu_e$ ($\times 10^{-11}$).

In this paper, we report a search for the semi-leptonic decay $J/\psi \to D^- e^+ \nu_e$+c.c. with $D^\pm \to K^\mp \pi^\pm \pi^\pm$ using 10.1×10^9 J/ψ events collected at the center-of-mass energy $\sqrt{s} = 3.097$ GeV with the BESIII detector [21] operating at the Beijing Electron Positron Collider (BEPCII) [22]. In order to avoid possible bias, we first validate the analysis with about 10% of the full data sample. The final result is obtained with the full data sample by repeating the validated analysis strategy. In addition, Monte Carlo (MC) simulation samples are used to optimize the event selection criteria, determine the signal detection efficiency and study the background. Throughout this paper, the charge-conjugate processes are always implied.

2 BESIII detector and Monte Carlo simulation

The BESIII detector [21] records symmetric e^+e^- collisions provided by the BEPCII storage ring [22], which operates with a peak luminosity of $1 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ in the center-of-mass energy range from 2.0 to 4.95 GeV. BESIII has collected large data samples in this energy region [11]. The cylindrical core of the BESIII detector covers 93% of the full solid angle and 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 identification modules interleaved with steel.

The charged-particle momentum resolution at 1 GeV/c is 0.5%, and the dE/dx resolution is 6% for 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 in the TOF barrel region is 68 ps, while that in the end cap region is 110 ps. The end cap TOF system was upgraded in 2015 using multi-gap resistive plate chamber technology, providing a time resolution of 60 ps [23, 24].

Simulated data samples produced with the GEANT4-based [25] MC package BOOST [26], which includes the geometric and material description of the BESIII detector [27, 28] and the detector response, are used to determine detection efficiencies and to estimate backgrounds. The simulation models the beam energy spread and initial state radiation (ISR) in the e^+e^- annihilations with the generator KKMC [29, 30]. The inclusive MC sample includes both the production of the J/ψ resonance and the continuum processes incorporated in KKMC [29, 30]. By assuming the decay $J/\psi \to D^- e^+ \nu_e$ is governed by the weak interaction via a $c \to d$ charged current process, and ignoring the hadronization effects and quark spin-flip [19], signal MC events are generated in EVTGEN [31, 32]. The known J/ψ decay modes are modelled with EVTGEN [31, 32] using BFs taken from the Particle Data Group [16], and the remaining unknown charmonium decays are modelled with LUNDCHARM [33, 34]. Final state radiation (FSR) from charged final state particles is incorporated using the PHOTOS package [35].

3 Event selection and data analysis

The analysis is performed with the BESIII offline software system (BOSS) [36] which incorporates the detector calibration, event reconstruction and data storage. In the signal process $J/\psi \to D^- e^+ \nu_e$, $D^- \to K^+\pi^-\pi^-$, we detect all final-state particles except the ν_e. Charged tracks detected in the MDC are required to be within a polar angle (θ) range of $|\cos\theta| < 0.93$, where θ is defined with respect to the z-axis. Selected charged tracks are required to satisfy $R_{xy} < 1.0\,\text{cm}$ and $|V_z| < 10\,\text{cm}$, where R_{xy} and $|V_z|$ are the distances of closest approach to the interaction point of the track in the plane perpendicular to the beam and along the beam direction, respectively. We retain the events with exactly four selected charged tracks with zero net charge. Particle identification (PID) for charged tracks combines measurements of the energy deposited in the MDC ($\mathrm{d}E/\mathrm{d}x$) and the flight time in the TOF to form likelihoods $\mathcal{L}(h)$ ($h = p, K, \pi$) for each hadron h hypothesis. The charged kaons and pions are identified by comparing the likelihoods for the kaon and pion hypotheses, $\mathcal{L}(K) > \mathcal{L}(\pi)$ and $\mathcal{L}(\pi) > \mathcal{L}(K)$, respectively. Positron PID uses the measured information in the MDC, TOF and EMC. The combined likelihoods ($\mathcal{L}'$) under the positron, pion, and kaon hypotheses are obtained. Positron candidates are required to satisfy $P_e > 0.001$ and $P_e/(P_\pi + P_K) > 4$, while π (K) candidates fulfil the criteria $P_\pi > P_K$ ($P_K > P_\pi$). To further reduce background from hadrons, the ratio of the deposited energy of the positron candidate in the EMC, E, and its momentum obtained in the MDC, p, is required to be in the range $0.85 < E/p < 1.05$.

Neutral showers deposited in the EMC crystals are identified as photon candidates when the shower energies are larger than 25 MeV in the barrel ($|\cos\theta| < 0.8$) and 50 MeV in the end cap ($0.86 < |\cos\theta| < 0.92$). In order to suppress fake photons due to electronic noise or beam background, the shower clusters are required to be detected within [0, 700] ns from the event start time. In addition, photon candidates must be at least 10° away from any charged tracks to remove fake photons caused by hadronic showers or final state radiations.

The selected charged hadron candidates, $K^+\pi^-\pi^-$, are used to form the D^- meson. Its invariant mass $M_{K\pi\pi}$ is required to be within the range of $[1.85, 1.89]$ GeV$/c^2$, corresponding to ± 3 times the mass resolution around the D^- known mass [16]. A kinematic fit constraining the $K^+\pi^-\pi^-$ invariant mass to the D^- mass [16] is performed and the fit $\chi^2_{1\mathrm{C}}$ value is required to be less than 10. To suppress background contributions from mis-identified events with extra photons, we require the total energy of good photons (E_γ^{tot}) to be less than 0.2 GeV.

Due to conservation of energy and momentum, the undetected neutrino ν_e carries a missing-energy $E_{\mathrm{miss}} = E_{J/\psi} - E_{D^-} - E_{e^+}$ and a missing-momentum $\vec{p}_{\mathrm{miss}} = \vec{p}_{J/\psi} - \vec{p}_{D^-} - \vec{p}_{e^+}$, where E_{D^-} (E_{e^+}) and $\vec{p}_{D^-}$ ($\vec{p}_{e^+}$) are the energy and momentum of the D^- (e^+) in the rest frame of the initial e^+e^- collision. In order to suppress the background contributions from J/ψ hadronic decays in which a pion or a kaon is mis-identified as a positron, $|\vec{p}_{\mathrm{miss}}|$ is required to be larger than 50 MeV$/c$. We extract the yield of the signal decays by examining the variable $U_{\mathrm{miss}} = E_{\mathrm{miss}} - c|\vec{p}_{\mathrm{miss}}|$, in which the signal candidates are expected to peak around zero if the final states of the semi-leptonic decay have been identified correctly.

Figure 2 shows the U_{miss} distribution in data, where no clear enhancement around zero is observed. Using signal MC simulation, the detection efficiency for $J/\psi \to D^-e^+\nu_e$ passing all selection requirements is determined to be $(29.93 \pm 0.10)\%$, where the uncertainty is statistical. The background contributions are investigated using an inclusive MC simulation sample, whose size corresponds to that in data [37]. As shown in figure 2, the U_{miss} distribution in the inclusive MC simulation sample is consistent with that in data and no peaking structure is seen around the signal region.

4 Result

An unbinned extended maximum likelihood fit is used to estimate the signal yield. The probability density function of the signal is derived from the shape of signal MC simulation of the U_{miss} spectrum, while the background shape is modeled with a linear function. As shown in figure 2, a negative signal is obtained, which indicates no signal is found from the fit result. The BF of the signal decay is calculated as

$$\mathcal{B}(J/\psi \to D^-e^+\nu_e + \mathrm{c.c.}) = \frac{N_{\mathrm{signal}}}{N_{J/\psi} \times \epsilon \times \mathcal{B}_{\mathrm{sub}}}, \tag{4.1}$$

where N_{signal} is the number of signal decays, $N_{J/\psi} = (10087 \pm 44) \times 10^6$ is the number of J/ψ events determined with the method described in ref. [38], ϵ is the signal detection efficiency, and $\mathcal{B}_{\mathrm{sub}}$ is the BF of the intermediate decay $D^\pm \to K^\mp\pi^\pm\pi^\pm$ quoted from ref. [16].

To set an UL on the BF via a Bayesian approach [16, 39], we perform a likelihood scan with a series of fits, where the numbers of signal decays N_{signal} are fixed to values from -70 to 70 with a step of 0.1. Since the BF is only meaningful in physical region ($\mathcal{B} \geq 0$), the UL on the BF is calculated in this region. To take into account any uncertainties from the choice of the fit range and the background shape of the U_{miss} distribution, we

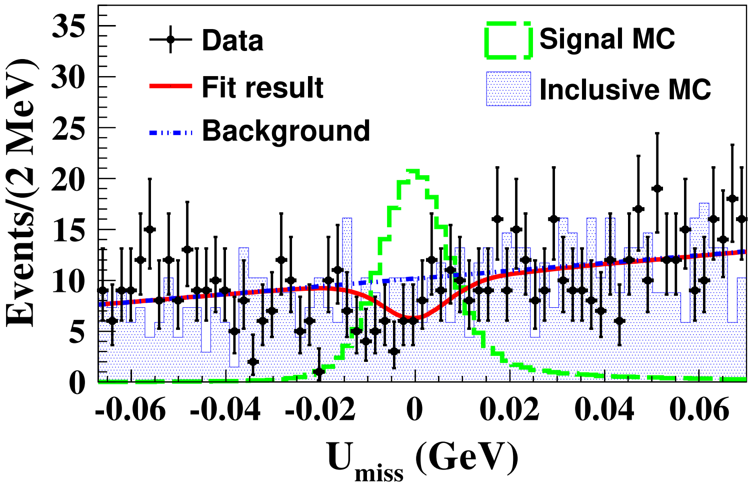

Figure 2. The U_{miss} distributions and the unbinned maximum likelihood fit. The black dots with error bars are data, the red solid line is the total fit result, and the blue dotted-dashed line is the background. The green long-dashed histogram shows the signal MC simulation events and the blue shaded histogram represents the inclusive MC events. Here, the signal MC events histogram is drawn with an arbitrary normalization, while the inclusive MC events histogram and the fit curve are normalized to the data luminosity.

expand the fit range by 6 MeV on either side and simultaneously change the background shape to a second-order polynomial. The largest likelihood value is retained as the most conservative result. Thus, we obtain the likelihood values as a function of the calculated BFs. To incorporate the systematic uncertainties described in the following section, we follow the method in ref. [40] of combining multiple measurements of a BF, where each result can be presented as an upper limit. The distribution of the resulting normalized likelihood values is shown in figure 3. The UL on the BF at the 90% confidence level, obtained by integrating from zero to 90% of the likelihood curve in the physical region ($\mathcal{B} \geq 0$), is $\mathcal{B}(J/\psi \to D^- e^+ \nu_e + \text{c.c.}) < 7.1 \times 10^{-8}$.

5 Systematic uncertainty

The main systematic uncertainties come from the tracking and PID efficiency, the signal MC model, the E_γ^{tot}, E/p and $|\vec{p}_{\mathrm{miss}}|$ requirements, the BF of the $D^- \to K^+\pi^-\pi^-$ decay and the total number of J/ψ events.

- *Tracking and PID efficiency.* The uncertainty due to tracking and PID efficiency for kaons and pions is determined by analyzing doubly-tagged D^+D^- decay events from $\psi(3770)$ [41]. Using partially reconstructed hadronic decays of $D^+ \to K^-\pi^+\pi^+$ and $D^- \to K^+\pi^-\pi^-$ where one π^- or K^+ meson is not reconstructed, the uncertainties are estimated to be 1.0% per track. In addition, the uncertainty from the positron tracking is studied using a control sample of radiative Bhabha events $e^+e^- \to \gamma e^+e^-$ produced at $\sqrt{s} = 3.08\,\mathrm{GeV}$, while the PID uncertainty is studied using a mixed control sample of $e^+e^- \to \gamma e^+e^-$ events and $J/\psi \to e^+e^-(\gamma_{\mathrm{FSR}})$ events produced at

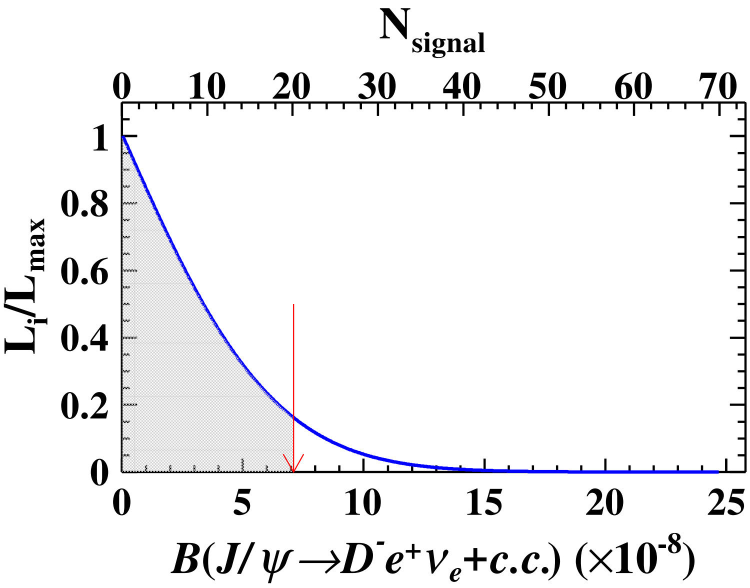

Figure 3. The distribution of the normalized smeared likelihood values (blue solid curve) as a function of the BF ($\mathcal{B}(J/\psi \to D^- e^+ \nu_e + \mathrm{c.c.})$) or the number of signal events ($\mathrm{N_{signal}}$). The shaded area corresponds to the 90% CL region and the red arrow indicates the UL on the BF at 90% CL.

$\sqrt{s} = 3.097\,\mathrm{GeV}$. We quote 1.0% and 1.0% as the systematic uncertainties on the tracking and PID efficiency for the positron, respectively.

- *Signal MC model.* The influence of the assumed signal model on the sensitivity of the result comes from the estimation of the signal efficiency. The difference between the efficiencies estimated with the nominal model and the phase space model is taken as the systematic uncertainty, which is about 3.0%.

- *E_γ^{tot}, E/p, and $|\vec{p}_{\mathrm{miss}}|$ selection requirements.* In order to estimate the systematic uncertainties due to the E_γ^{tot}, E/p, and $|\vec{p}_{\mathrm{miss}}|$ selection requirements, we use a control sample of semi-leptonic signal decays $D^0 \to K^- e^+ \nu_e$ tagged with a $\bar{D}^0 \to K^+ \pi^-$ decay selected from $\psi(3770)$ data [11]. We obtain the overall efficiency from a sample of 200000 signal MC simulation events. We apply the event selection criteria in ref. [42] to the tagging mode, and the selection requirements for the positron and kaon described in section 3 to the signal mode. After applying all the requirements to the $\psi(3770)$ data sample, we get a clean signal sample with 97.8% purity. We perform a fit to the U_{miss} distribution to extract the signal yields and calculate the BF $\mathcal{B}(D^0 \to K^- e^+ \nu_e)$. By comparing the nominal result and the results without one of those requirements, we assign systematic uncertainties of 2.1%, 0.3%, and 0.3% for the E_γ^{tot}, E/p, and $|\vec{p}_{\mathrm{miss}}|$ requirements, respectively.

- *BF of the $D^- \to K^+ \pi^- \pi^-$ decay.* The $\mathcal{B}(D^- \to K^+ \pi^- \pi^-)$ result is used as an input in the baseline analysis, and its uncertainty of 1.7% [16] is propagated as the systematic uncertainty.

Sources	Relative uncertainties
Tracking	4.0
Particle ID	4.0
Signal MC model	3.0
$E_\gamma^{\rm tot}$ requirement	2.1
E/p requirement	0.3
$\lvert\vec{p}_{\rm miss}\rvert$ requirement	0.3
BF of the $D^- \to K^+\pi^-\pi^-$ decay	1.7
Number of J/ψ events	0.5
Total	7.0

Table 2. Summary of the systematic uncertainties in percentage for the measurement of the BF. The total value is calculated by summing up all sources in quadrature.

- *Number of J/ψ events.* We quote a relative uncertainty of 0.5% determined using J/ψ inclusive hadronic decays for $N_{J/\psi}$ as the systematic uncertainty from ref. [38].

All systematic uncertainties are summarized in table 2. They are added in quadrature and their total size is reported as well.

6 Summary

Based upon a sample of 10.1×10^9 J/ψ events collected with the BESIII detector, the BF of the rare semi-leptonic decay $J/\psi \to D^- e^+ \nu_e$ is studied with a semi-blind analysis. No excess of events is observed over the background. The resulting UL on the BF is $\mathcal{B}(J/\psi \to D^- e^+ \nu_e + \text{c.c.}) < 7.1 \times 10^{-8}$ at 90% CL, when systematic uncertainties are taken into account. Our result improves this limit [18] by a factor of 170. This is the most sensitive search for the $J/\psi \to D^- e^+ \nu_e$ decay. This measurement is compatible with the SM theoretical predictions [6–10], and puts a stringent constraint on the parameter spaces for different new physics models predicting BFs of the order of 10^{-5} [10].

Acknowledgments

The BESIII collaboration thanks the staff of BEPCII and the IHEP computing center for their strong support. This work is supported in part by National Key Research and Development Program of China under Contracts Nos. 2020YFA0406400, 2020YFA0406300; Joint Large-Scale Scientific Facility Funds of the National Natural Science Foundation of China (NSFC) and Chinese Academy of Sciences (CAS) under Contracts Nos. U1932101, U1732263, U1832207; State Key Laboratory of Nuclear Physics and Technology, PKU under Grant No. NPT2020KFY04; NSFC under Contracts Nos. 11625523, 11635010, 11675275, 11735014, 11822506, 11835012, 11935015, 11935016, 11935018, 11961141012, 11975021, 12022510, 12035009, 12035013, 12061131003; the CAS Center for Excellence in Particle Physics (CCEPP); the CAS Large-Scale Scientific Facility Program; CAS Key Research Program of Frontier Sciences under Contract No. QYZDJ-SSW-SLH040; 100 Talents Program of CAS; Fundamental Research Funds for the Central Universities; INPAC and Shanghai Key Laboratory for Particle Physics and Cosmology; ERC under Contract No. 758462; European Union Horizon 2020 research and innovation programme under Contract No. Marie Sklodowska-Curie grant agreement No. 894790; German Research Foundation DFG under Contracts Nos. 443159800, Collaborative Research Center CRC 1044, FOR 2359, FOR 2359, GRK 214; Istituto Nazionale di Fisica Nucleare, Italy; Ministry of Development of Turkey under Contract No. DPT2006K-120470; National Science and Technology fund; Olle Engkvist Foundation under Contract No. 200-0605; STFC (U.K.); The Knut and Alice Wallenberg Foundation (Sweden) under Contract No. 2016.0157; The Royal Society, U.K. under Contracts Nos. DH140054, DH160214; The Swedish Research Council; U.S. Department of Energy under Contracts Nos. DE-FG02-05ER41374, DE-SC-0012069.

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