# Search for the weak decays $J/\psi \to D_s^{(*)-} e^+ \nu_e + c.c.$

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Using a sample of $2.25 \times 10^8$ $J/\psi$ events collected with the BESIII detector at the BEPCII collider, we search for the $J/\psi$ semileptonic weak decay $J/\psi \to D_s^- e^+ \nu_e + c.c.$ with a much higher sensitivity than previous searches. We also perform the first search for $J/\psi \to D_s^{*-} e^+ \nu_e + c.c.$ No significant excess of a signal above background is observed in either channel. At the 90% confidence level, the upper limits are determined to be $\mathcal{B}(J/\psi \to D_s^- e^+ \nu_e + c.c.) < 1.3 \times 10^{-6}$ and $\mathcal{B}(J/\psi \to D_s^{*-} e^+ \nu_e + c.c.) < 1.8 \times 10^{-6}$, respectively. Both are consistent with Standard Model predictions.

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## I. INTRODUCTION

The $J/\psi$ particle, lying below the open charm threshold, cannot decay into a pair of charmed mesons. However, the $J/\psi$ can decay into a single charmed meson

via the weak interaction [1]. Weak decays of the $J/\psi$ are rare processes, and the inclusive branching fractions of $J/\psi$ decays to single $D$ or $D_s$ mesons are predicted to be of the order of $10^{-8}$ or less [2] in the Standard Model (SM). Figure. 1 shows the tree-level Feynman diagram within the SM for the decays $J/\psi \to D_s^{(*)} l\nu$ ($l = e$ or $\mu$). Most recent theoretical calculations predict the $J/\psi \to D_s^{(*)} l\nu$ branching fractions to be $\simeq 10^{-10}$ by using QCD sum rules and employing the covariant light-front quark model [3]. However, as mentioned in Refs. [4–7], the branching fractions of $J/\psi \to D(\bar{D})X$ (with $X$ denoting any hadrons) could be enhanced when new interaction couplings are considered, such as in the top-color models, the minimal super-symmetric SM with R-parity violation, or the two-Higgs-doublet model. It is interesting to note that the ratio between $J/\psi \to D_s^* l\nu$ and $D_s l\nu$ is predicted to be $1.5 \sim 3.1$ in Ref. [2, 3], where part of the theoretical uncertainties cancel.

The BES collaboration has studied several weak decays, including semileptonic and nonleptonic weak decays of the $J/\psi$. With a $5.8 \times 10^7$ $J/\psi$ events sample, the upper limit for $\mathcal{B}(J/\psi \to D_s^- e^+\nu_e + c.c.)$ was found to be $3.6 \times 10^{-5}$ at the 90% C.L. [8], while the $J/\psi \to D_s^{*-} e^+\nu_e + c.c.$ has never been studied in experiments before. When we refer to $+c.c.$, we mean the combination of $J/\psi \to D_s^{(*)-} e^+\nu_e$ and the charge conjugated modes $J/\psi \to D_s^{(*)+} e^-\bar{\nu_e}$. In the following, the signals are the sum of both modes and charge conjugation is implied unless otherwise specified. Using a sample of $2.25 \times 10^8$ $J/\psi$ events collected with the BESIII detector at the Beijing Electron Positron Collider (BEPCII) [9], we search for the weak decays $J/\psi \to D_s^- e^+\nu_e$ and $J/\psi \to D_s^{*-} e^+\nu_e$. The $D_s^-$ meson is reconstructed via four decay modes: $D_s^- \to K^+K^-\pi^-$, $D_s^- \to K^+K^-\pi^-\pi^0$, $D_s^- \to K_S^0 K^-$, and $D_s^- \to K_S^0 K^+\pi^-\pi^-$, where the $\pi^0$ and $K_S^0$ mesons are reconstructed from their $\gamma\gamma$ and $\pi^+\pi^-$ decays, respectively. The $D_s^*$ candidate is reconstructed from its radiative transitions to $D_s$. A 478 pb$^{-1}$ data sample collected at the center-of-mass energy $\sqrt{s} = 4.009$ GeV [10] is used to study systematic uncertainties.

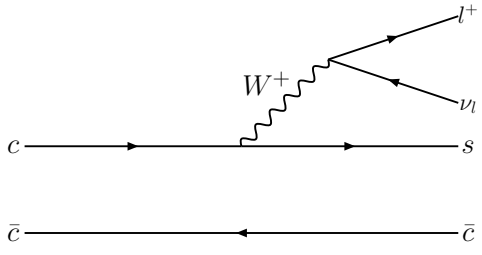


FIG. 1. Feynman diagrams for $J/\psi \to D_s^{(*)-} l^+\nu_l$ at the tree level.

## II. BESIII EXPERIMENT

The BESIII detector is a magnetic spectrometer [11] located at BEPCII, which is a double-ring $e^+e^-$ collider with a design peak luminosity of $10^{33}$ cm$^{-2}$ s$^{-1}$ at a center-of-mass energy of 3.773 GeV. The cylindrical core of the BESIII detector consists of a helium-based main 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 magnetic field. The solenoid is supported by an octagonal flux-return yoke with modules of resistive plate muon counters interleaved with steel. The acceptance for charged particles and photons is 93% over a $4\pi$ solid angle. The momentum resolution for a charged particle at 1 GeV/c is 0.5%, and the ionization energy loss per unit path-length ($dE/dx$) resolution is 6%. The EMC measures photon energies with a resolution of 2.5% (5%) at 1 GeV in the barrel (end caps). The time resolution for the TOF is 80 ps in the barrel and 110 ps in the end caps.

Monte Carlo (MC) simulations are used to determine the detection efficiency, study backgrounds and optimize event selection criteria. A GEANT4-based [12] simulation is used to simulate the BESIII detector response. Electron-positron annihilation into a $J/\psi$ resonance is simulated at energies around $\sqrt{s} = 3.097$ GeV, while the beam energy and its energy spread are set according to measurements of the Beam Energy Measurement System [13]. The production of the $J/\psi$ resonance is implemented with the generator KKMC [14]. The signal channels are generated with a new generator implemented in EVTGEN [15], and we assume the process $J/\psi \to D_s^{(*)-} e^+\nu_e$ is dominated by the weak interaction, i.e. via the $c \to s$ charged current process, while the effects of hadronization and quark spin flip are ignored. The known decay modes of the $J/\psi$ resonance are generated by EVTGEN [15] with branching fractions set according to the world average values of the Particle Data Group [16], while the unknown decays are generated by LUNDCHARM [17]. A sample of $2.25 \times 10^8$ generic $J/\psi$ decays ("inclusive MC") is used to identify potential background channels.

## III. EVENT SELECTION AND DATA ANALYSIS

Tracks from charged particles are reconstructed using hit information from the MDC. We select tracks in the polar angle range $|\cos\theta| < 0.93$ and require that they pass within $\pm 10$ cm from the interaction point (IP) along the beam and within $\pm 1$ cm transverse to the beam direction. The charged particle identification (PID) is based on a combination of $dE/dx$ and TOF information, and the probability of each particle hypothesis ($P(i)$ with $i = e/\pi/K$) is calculated. A pion candidate is required to satisfy $P(\pi) > 0.001$ and $P(\pi) > P(K)$; for kaons,

$P(K) > 0.001$ and $P(K) > P(\pi)$ are required; and for electrons or positrons, we require the track from charged particles to satisfy $P(e) > 0.001$ and $P(e) > P(K)$ and $P(e) > P(\pi)$ as well as $0.80 < E/p < 1.05$, where $E/p$ is the ratio of the energy deposited in the EMC to the momentum of the track measured by the MDC.

The $K^0_S$ candidates are reconstructed from pairs of oppositely charged tracks, which are assumed to be pions without a PID requirement, and where the IP requirements are relaxed to 20 cm in the direction along the beam. For each pair of tracks, a primary vertex fit and a secondary vertex fit are performed and the $K^0_S$ decay length is required to be two times larger than its fit error. The resulting track parameters from the secondary vertex fit are used to calculate the invariant mass $M(\pi^+\pi^-)$. The $\pi^+\pi^-$ combinations with an invariant mass $0.487\ \mathrm{GeV/c^2} < M(\pi^+\pi^-) < 0.511\ \mathrm{GeV/c^2}$ are kept as $K^0_S$ candidates. Multiple $K^0_S$ candidates are allowed in one event.

Photon candidates are reconstructed based on the showers in both the EMC barrel region ($|\cos\theta| < 0.8$) and the end cap regions ($0.86 < |\cos\theta| < 0.92$). Showers from the barrel region must have a minimum energy of 25 MeV, while those in the end caps must have at least 50 MeV. To exclude showers from charged particles, a photon candidate must be separated by at least 20° from any charged particle track with respect to the interaction point. The EMC timing information ($0\ \mathrm{ns} \leqslant T \leqslant 700\ \mathrm{ns}$) is used to further suppress electronic noise and energy depositions unrelated to the event.

The $\pi^0$ candidates are reconstructed from pairs of photons. A kinematic fit is performed constraining the invariant mass of the photon pair to the known $\pi^0$ mass [16]. The combination with the minimum $\chi^2$ from the kinematic fit that satisfies $\chi^2 < 100$, and $0.115\ \mathrm{GeV/c^2} < M(\gamma\gamma) < 0.150\ \mathrm{GeV/c^2}$ is kept for further analysis. The $\pi^0$ candidates with both photons from the end cap regions are excluded due to poor resolution in this region of the detector.

With the previously described charged and neutral particle candidates, the $D_s^-$ candidates can be reconstructed through the four decay modes mentioned in the Introduction; we name them $KK\pi$, $KK\pi\pi$, $K^0_SK$ and $K^0_SK\pi\pi$, and number each as the $k$th ($k = 1...4$) decay mode, in sequence. Since the resolution of the reconstructed $D_s^-$ mass is different for each decay mode, the invariant mass of $D_s^-$ candidates is required to be in different mass windows, which are taken as three times the respective resolution ($\pm 3\sigma$ around its central value). For $J/\psi \to D_s^{*-}e^+\nu_e$ , the $D_s^-$ and an additional photon candidate are combined to reconstruct $D_s^{*-}$ candidates, and the invariant mass difference ($\Delta M$) between $D_s^-\gamma$ and $D_s^-$ is required to satisfy $0.125\ \mathrm{GeV/c^2} < \Delta M < 0.150\ \mathrm{GeV/c^2}$. To avoid bias, we set no requirement to select the best $D_s^-$ or $D_s^{*-}$ candidate, and multiple $D_s^-$ or $D_s^{*-}$ candidates are allowed in one event. According to the MC simulations, after all selection criteria are applied, events with multiple candidates occur in about 0.1% cases for each mode in $J/\psi \to D_s^-e^+\nu_e$ and about 0.2% for each mode in $J/\psi \to D_s^{*-}e^+\nu_e$. For real data, only a few events are observed and no events with multiple candidates are found, so the effect of the multiplicity of candidates can be safely ignored.

Once a $D_s^-$ or $D_s^{*-}$ is reconstructed, the signal event candidate is required to contain a positron track. Events that include charged particles other than those from the $D_s^-$ and the positron candidate are vetoed. To reduce background contributions from misidentified events with extra photons, we require the total energy of those extra neutral particles be less than 0.2 or 0.3 GeV for $D_s^-$ or $D_s^{*-}$ in the modes of $K^+K^-\pi^-$, $K^0_SK^-$ and $K^0_SK^+\pi^-\pi^-$, respectively, and 0.15 or 0.2 GeV for the $K^+K^-\pi^-\pi^0$ mode. These selection criteria are chosen by optimizing the ratio $S/\sqrt{B}$, where $S$ and $B$ are the numbers of signal events from the signal MC sample and expected background events from the inclusive MC sample, respectively.

For a $J/\psi \to D_s^{(*)-}e^+\nu_e$ candidate, the undetected neutrino leads to a missing energy $E_{miss} = E_{J/\psi} - E_{D_s^{(*)-}} - E_{e^+}$ and a missing momentum $\vec{p}_{miss} = \vec{p}_{J/\psi} - \vec{p}_{D_s^{(*)-}} - \vec{p}_{e^+}$, where $E_{D_s^{(*)-}}$ and $\vec{p}_{D_s^{(*)-}}$ ($E_{e^+}$ and $\vec{p}_{e^+}$) are the energy and momentum of the $D_s^{(*)-}$ (positron). We require $|\vec{p}_{miss}|$ to be larger than 50 MeV to suppress the background contributions from $J/\psi$ hadronic decays in which a pion is misidentified as a positron. The $J/\psi$ semileptonic decay events are extracted using the variable $U_{\rm miss} = E_{miss} - |\vec{p}_{miss}|$. If the decay products of the $J/\psi$ semileptonic decay have been correctly identified, $U_{\rm miss}$ is expected to peak around zero. The $U_{\rm miss}$ distributions of $J/\psi \to D_s^-e^+\nu_e$ and $J/\psi \to D_s^{*-}e^+\nu_e$ candidates are shown in Figs. 2 and 3, respectively. The signal shapes obtained from MC simulations are shown with dashed curves. No significant excess of signal above background is observed in either mode.

From a MC study, we find that background events are mostly from those decay modes where a pion is misidentified as an electron/positron. For example, the process $J/\psi \to K^+K^-\pi^-\pi^+$ would be one potential background of $J/\psi \to D_s^-e^+\nu_e$, $D_s^- \to K^+K^-\pi^-$. Background channels from inclusive MC simulations are shown in Figs. 2 and 3 with filled histograms. No peaking background is found, and the expected background from MC is consistent with data.

For each $D_s^-$ decay mode, 100,000 exclusive signal MC events are generated, and the detection efficiencies are determined to be $(24.46 \pm 0.17)\%$, $(11.08 \pm 0.13)\%$, $(29.90 \pm 0.19)\%$ and $(13.74 \pm 0.12)\%$ for $KK\pi$, $KK\pi\pi^0$, $K^0_SK$ and $K^0_SK\pi\pi$ modes of $J/\psi \to D_s^-e^+\nu_e$ , and $(16.59 \pm 0.17)\%$, $(7.40 \pm 0.15)\%$, $(19.62 \pm 0.17)\%$ and $(8.20 \pm 0.11)\%$ for $KK\pi$, $KK\pi\pi^0$, $K^0_SK$ and $K^0_SK\pi\pi$ modes of $J/\psi \to D_s^{*-}e^+\nu_e$ , respectively.

A simultaneous unbinned maximum likelihood fit is used to determine the event yields of the four $D_s$ decay modes. The Bayesian method [16] with a uniform prior is used to estimate the upper limits on the num-

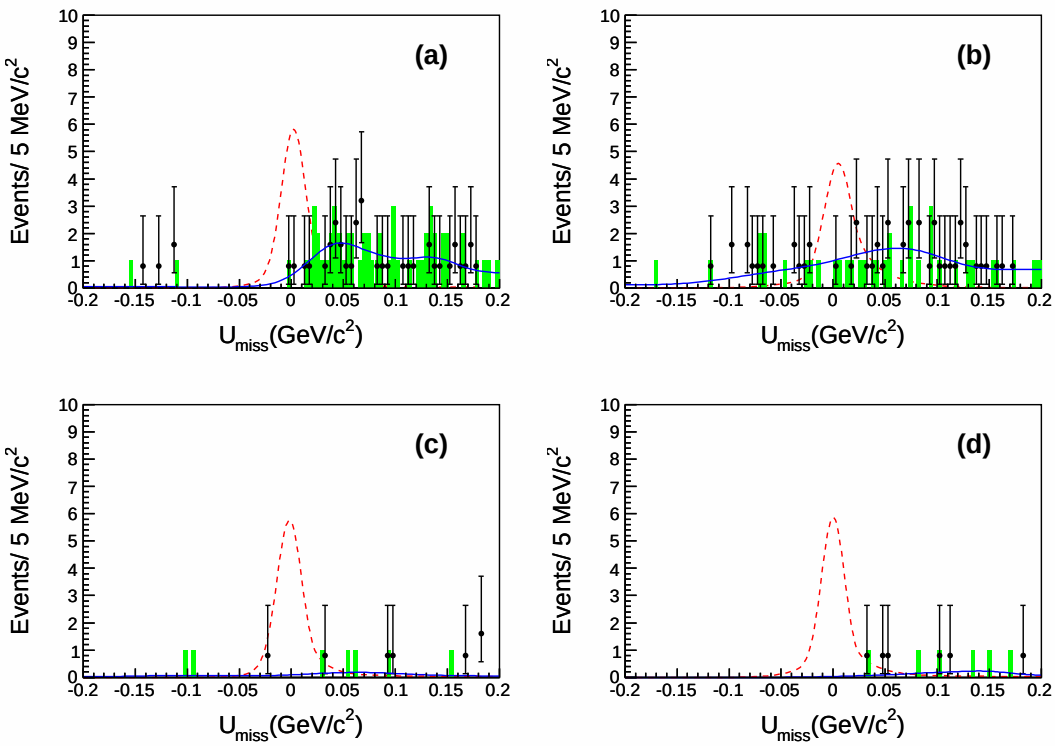


FIG. 2. $U_{\rm miss}$ distributions for $J/\psi \to D_s^- e^+ \nu_e$ : (a) $D_s^- \to K^+K^-\pi^-$; (b) $D_s^- \to K^+K^-\pi^-\pi^0$; (c) $D_s^- \to K_S^0 K^-$; (d) $D_s^- \to K_S^0 K^+\pi^-\pi^-$. Data are shown by dots with error bars, the signal shapes are shown with dashed curves, the background contributions from inclusive MC simulations are shown with filled histograms, and the results of simultaneous fit are shown with solid curves. Here the signal shape is drawn with arbitrary normalization, while the shapes of inclusive MC and fit are normalized to the data luminosity.

ber of signal events since no significant signals are observed for either $J/\psi$ weak decay mode. We choose $-0.2$ GeV/c$^2$ $< U_{\rm miss} <$ 0.2 GeV/c$^2$ as the fitting range. The signal events are described by a sum of a Gaussian and a Crystal Ball function [18] with the parameters obtained from a fit to the signal MC sample. The background shape is obtained from the inclusive $J/\psi$ MC sample and modeled with a probability density function that represents the shape of an external unbinned data set as a superposition of Gaussians [19]. The likelihood for the $k$th $D_s^-$ decay mode is constructed as

$$\mathcal{L}_k = \prod_{i=1}^{N_k} \frac{N_{\rm total}\mathcal{B}_k\epsilon_k\mathcal{P}_{i,k}^{\rm sig} + N_k^{\rm bkg}\mathcal{P}_{i,k}^{\rm bkg}}{N_{\rm total}\mathcal{B}_k\epsilon_k + N_k^{\rm bkg}} \ , \qquad (1)$$

where $N_{\rm total}$ is the total number of produced $J/\psi \to D_s^{(*)-}e^+\nu_e$ events in data, $\mathcal{B}_k$ is the world average branching fraction of the $k$th $D_s^-$ decay mode [16], $\epsilon_k$ is the detection efficiency of the $k$th $D_s^-$ decay mode, and $N_k^{\rm bkg}$ is the number of background events in the $k$th $D_s^-$ decay mode. $N_k$ is the total number of selected events in the fit region for the $k$th $D_s^-$ decay mode. $\mathcal{P}_{i,k}^{\rm sig}$ is the probability density function of signal for the $k$th $D_s^-$ decay mode evaluated at the $i$th event; similarly, $\mathcal{P}_{i,k}^{\rm bkg}$ is that of background. The total likelihood $\mathcal{L}$ is the product of likelihoods for each $D_s^-$ decay mode. A simultaneous unbinned fit with floating amplitudes of signal and background is performed. No significant signal is found by the fit as expected, and the fitting results are shown in the Figs. 2 and 3 as solid curves.

We calculate the 90% C.L. upper limit yield from the fit, $N_{\rm total}^{\rm up}$, using

$$\frac{\int_0^{N_{\rm total}^{\rm up}} \mathcal{L}(N_{\rm total})dN_{\rm total}}{\int_0^{\infty} \mathcal{L}(N_{\rm total})dN_{\rm total}} = 0.90 \ , \qquad (2)$$

where $\mathcal{L}(N_{\rm total})$ is the total likelihood $\mathcal{L}$ at fixed $N_{\rm total}$.

In each fit, the likelihood value is obtained and the corresponding probabilities are calculated as shown in Fig. 4. Figure. 4 also shows the numbers of $N_{\rm total}$ corresponding to 90% of the accumulated areas below the likelihood curves, which are then quoted as the upper limits on the number of signal events at the 90% C.L. The limits are 244 and 335 for the $J/\psi \to D_s^- e^+\nu_e$ and $J/\psi \to D_s^{*-} e^+\nu_e$ decay modes, respectively.

## IV. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties in this analysis are divided into two sets. The dominant one is from the uncertainty

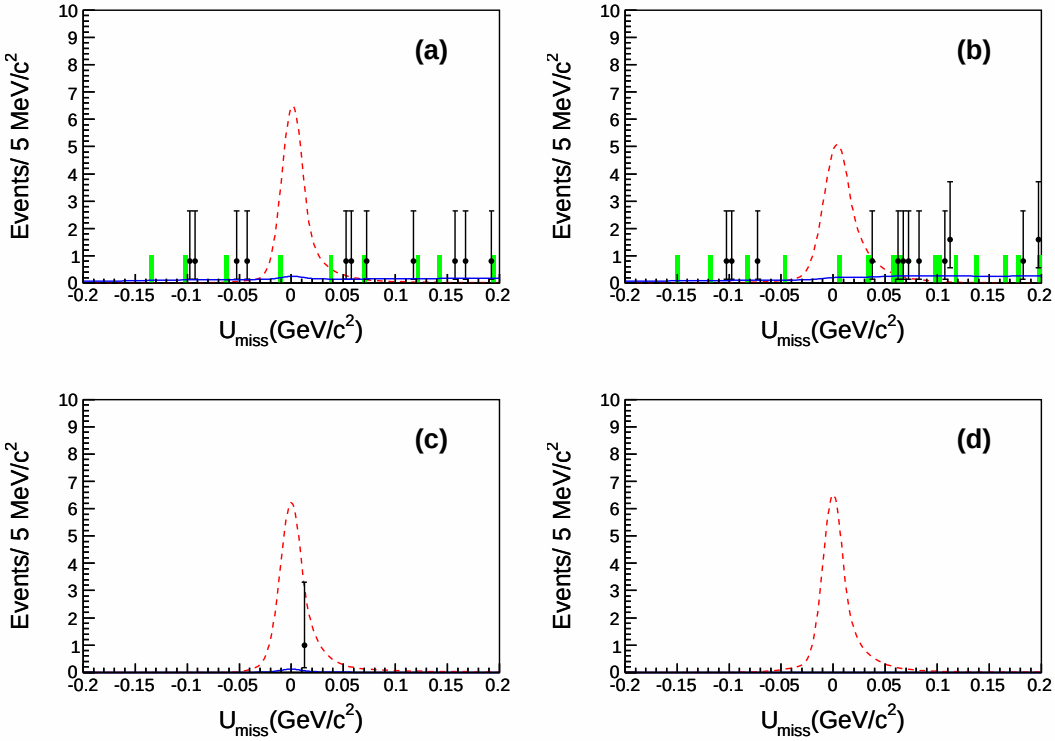


FIG. 3. $U_{\rm miss}$ distributions for $J/\psi \to D_s^{*-}e^+\nu_e$ : (a) $D_s^- \to K^+K^-\pi^-$; (b) $D_s^- \to K^+K^-\pi^-\pi^0$; (c) $D_s^- \to K_S^0K^-$; (d) $D_s^- \to K_S^0K^+\pi^-\pi^-$. Data are shown by dots with error bars, the signal shapes are shown with dashed curves, the background contributions from inclusive MC simulations are shown with filled histograms, and the results of simultaneous fit are shown with solid curves. Here the signal shape is drawn with arbitrary normalization, while the shapes of inclusive MC and fit are normalized with to the data luminosity.

of the efficiency corrected signal yield. The others are common uncertainties, including the physics model, electron tracking, electron PID, $E/p$ cut, total number of $J/\psi$ events, and trigger efficiency, as well as the photon efficiency and $\mathcal{B}(D_s^{*-} \to D_s^-\gamma)$ for the $D_s^*$ mode.

### A. Systematic uncertainty of efficiency corrected signal yield for each channel

The systematic uncertainties caused by charged and neutral particle reconstruction efficiencies, $K$ and $\pi$ PID efficiencies, the $\pi^0$ reconstruction efficiency, the $K_S^0$ reconstruction efficiency, and $D_s$ mass resolutions are all considered together as the systematic error due to the reconstruction efficiency of the $D_s$. It is the dominant uncertainty in this analysis and is studied using a control sample of $\psi(4040) \to D_s^+D_s^-$, in which a 478 pb$^{-1}$ $\psi(4040)$ data sample taken at 4.009 GeV is used [10]. In this study, one $D_s$ is tagged using eight $D_s$ hadronic decays modes, and the other $D_s$ is reconstructed in the same way as in the $J/\psi \to D_s^{(*)-}e^+\nu_e$ analysis. The differences of the $D_s$ reconstruction efficiencies of MC and data are quoted as the systematic uncertainties in the $D_s$ reconstruction and are listed in Tables. I and II. The uncertainties on the $D_s$ decay branching fractions are separated from the reconstruction uncertainty deliberately by squared subtraction.

The systematic uncertainty of background shapes is estimated by varying the shapes of background. These new background shapes are obtained by smoothing the bin contents of the histograms, that are extracted from the inclusive MC sample. By convolution with a Guassian function, we repeat this process till the maximum difference between the contents of any two adjacent bins is less than 25%.

The systematic uncertainty due to the choice of fitting ranges is determined by varying the ranges of the $U_{\rm miss}$ distributions from $[-0.2, 0.2]$ to $[-0.25, 0.25]$ GeV/c$^2$, and the difference is taken as this systematic uncertainty.

The systematic uncertainty contributions studied above and the uncertainty due to MC statistics are summarized in Tables I and II. The total uncertainty is obtained by summing in quadrature the individual uncertainties quadratically.

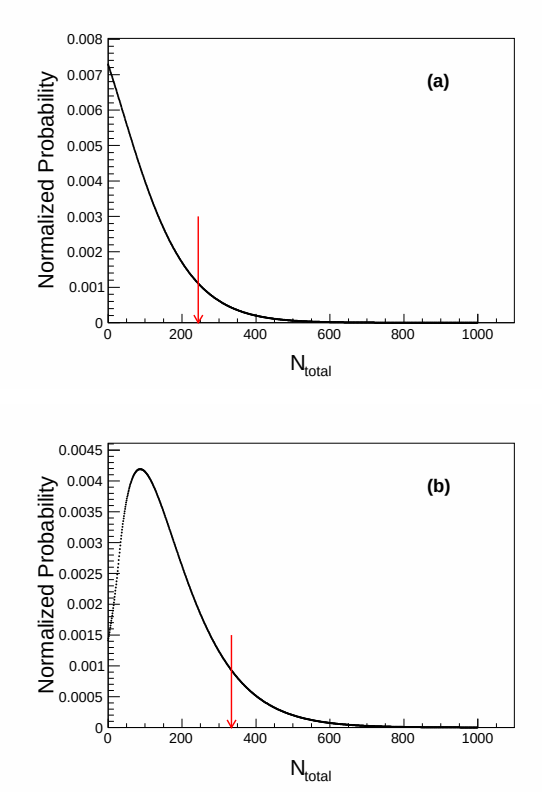


FIG. 4. Normalized probabilities as a function of $N_{\rm total}$ in the (a) $J/\psi \to D_s^- e^+ \nu_e$ and (b) $J/\psi \to D_s^{*-} e^+ \nu_e$ decay modes. The red arrows indicate where 90% of the area is accumulated below the curves.

TABLE I. Summary of systematic uncertainties of the efficiency corrected signal yield in the measurement of $J/\psi \to D_s^- e^+ \nu_e$ in %.

| Sources\modes | $K^+K^-\pi^-$ | $K^+K^-\pi^-\pi^0$ | $K_S^0K^-$ | $K_S^0K^-\pi^+\pi^-$ |
|---|---|---|---|---|
| Reconstruction $\epsilon$ | 6.8 | 16.2 | 16.6 | 18.6 |
| $\mathcal{B}(D_s^- \to X)$ | 3.9 | 11.1 | 4.0 | 6.6 |
| Background shape | 2.3 | 2.4 | 3.2 | 2.9 |
| Fitting range | 0.3 | 0.4 | 0.5 | 0.6 |
| MC statistic | 0.7 | 1.2 | 0.6 | 0.9 |
| Total | 8.2 | 19.8 | 17.4 | 20.0 |

TABLE II. Summary of systematic uncertainties of the efficiency corrected signal yield in the measurement of $J/\psi \to D_s^{*-} e^+ \nu_e$ in %.

| Sources\modes | $K^+K^-\pi^-$ | $K^+K^-\pi^-\pi^0$ | $K_S^0K^-$ | $K_S^0K^-\pi^+\pi^-$ |
|---|---|---|---|---|
| Reconstruction $\epsilon$ | 6.8 | 16.2 | 16.6 | 18.6 |
| $\mathcal{B}(D_s^- \to X)$ | 3.9 | 11.1 | 4.0 | 6.6 |
| Background shape | 2.5 | 2.5 | 2.7 | 3.2 |
| Fitting range | 0.2 | 0.6 | 0.4 | 0.4 |
| MC statistic | 1.0 | 1.9 | 0.9 | 1.4 |
| Total | 8.3 | 20.0 | 17.4 | 20.1 |

### B. Common uncertainties

The difference of the efficiencies based on phase space and the new generator used in this analysis is taken as the systematic uncertainty of the physics model.

The systematic uncertainty of the resolutions has been estimated by smearing the MC simulations. The simulation of the photon reconstruction has been studied with a control sample of the well-understood decays $J/\psi \to \rho^0\pi^0$ in Ref. [20], and we smear the resolution of the photon energy deposited in the EMC at the 1% level by a convolution with a Gaussian function. For the tracks from charged particles, we smear the helix parameters of each track as described in Ref. [21]. The difference in the final yields between before and after smearing is taken as the systematic uncertainty. The variable $U_{\rm miss}$ is associated with the energy and momentum resolutions of detected tracks. Thus, the systematic uncertainty of the signal shape has been taken into account implicitly.

The electrons from the signal are in a low momentum region, which causes a systematic uncertainty of 2.1% in the MDC tracking efficiency and 1.0% in the PID efficiency [22]. A radiative Bhabha sample, normalized with respect to the momentum, is used as a control sample to estimate the systematic uncertainty caused by the $E/p$ requirement, i.e. $0.80 < E/p < 1.05$. The difference in efficiency between the MC simulation and the data is quoted as the systematic uncertainty caused by this requirement. Since the electron momentum in the $J/\psi \to D_s^{*-} e^+ \nu_e$ decay is lower, the uncertainty caused by the $E/p$ requirement of $J/\psi \to D_s^{*-} e^+ \nu_e$ is larger than that of $J/\psi \to D_s^- e^+ \nu_e$ correspondingly.

The total number of $J/\psi$ events is determined by using $J/\psi$ inclusive decays [9], and the value 1.2% is quoted as the systematic uncertainty of the total number of $J/\psi$ events.

According to Ref. [23], the trigger efficiency is very high since there are four to six tracks from charged particles in addition to possible neutral particles within the barrel regions in the final states. Therefore, the systematic uncertainty of the trigger efficiency is negligible.

Since the $D_s^*$ mesons are only reconstructed by $D_s^{*-} \to D_s^-\gamma$, we deal with most of the systematic uncertainties of $J/\psi \to D_s^{*-} e^+ \nu_e$ in the same way as those of $J/\psi \to D_s^- e^+ \nu_e$ , and with two additional uncertainties in $D_s^*$ than in the $D_s$ mode. One is a 1% uncertainty from the additional photon detecting efficiency [24]. The other one is the input branching fraction $\mathcal{B}(D_s^{*-} \to D_s^-\gamma)$ in MC simulation. Since the world average value is $(94.2 \pm 0.7)\%$ [16], this leads to a 0.7% uncertainty. All of the common systematic uncertainties are listed in Table III.

### C. Upper limit calculation

Taking the systematic uncertainties into account, the upper limits on the branching fractions are calculated

TABLE III. Summary of common systematic uncertainties in the measurement of $J/\psi \to D_s^- e^+ \nu_e$ and $J/\psi \to D_s^{*-} e^+ \nu_e$ .

| Source | $J/\psi \to D_s^- e^+ \nu_e$ (%) | $J/\psi \to D_s^{*-} e^+ \nu_e$ (%) |
|---|---|---|
| Physics model | 0.9 | 0.8 |
| Resolutions | 1.6 | 1.8 |
| $e$ tracking | 2.1 | 2.1 |
| $e$ PID | 1.0 | 1.0 |
| $E/p$ cut | 0.6 | 1.7 |
| Photon efficiency | - | 1.0 |
| $\mathcal{B}(D_s^{*-} \to D_s^- \gamma)$ | - | 0.7 |
| $J/\psi$ events | 1.2 | 1.2 |
| Trigger | Negligible | Negligible |
| Total | 3.3 | 3.9 |

TABLE IV. Upper limits of the branching fractions of $J/\psi \to D_s^- e^+ \nu_e$ and $J/\psi \to D_s^{*-} e^+ \nu_e$ after considering the systematic uncertainties.

| | $J/\psi \to D_s^- e^+ \nu_e$ | $J/\psi \to D_s^{*-} e^+ \nu_e$ |
|---|---|---|
| $\bar{N}^{\rm up}_{\rm total}$ | 244 | 335 |
| $\sigma_{\rm total}$ | 31 | 43 |
| $N^{\rm up\ \prime}_{\rm total}$ | 275 | 378 |
| $\sigma^{\rm sys}_{\rm common}$ | 3.3% | 3.9% |
| $N_{J/\psi}$ | $2.25 \times 10^8$ | |
| $\mathcal{B}$(90%C.L.) | $< 1.3 \times 10^{-6}$ | $< 1.8 \times 10^{-6}$ |

using

$$\mathcal{B} < \frac{N^{\rm up\ \prime}_{\rm total}}{(1-\sigma^{\rm sys}_{\rm common})N_{J/\psi}} \quad , \tag{3}$$

where $N^{\rm up\ \prime}_{\rm total}$ is the corrected $N^{\rm up}_{\rm total}$ after considering the systematic uncertainties of the signal efficiency, as described below, and $\sigma^{\rm sys}_{\rm common}$ is the total common systematic uncertainty.

From Eqs. (1) and (2), $N^{\rm up}_{\rm total}$ depends on the signal efficiencies of all decay channels in a complex way, and there is no simple analytic method to calculate the final effect due to those efficiency uncertainties. To study this dependence, we obtain an $N^{\rm up}_{\rm total}$ distribution by sampling each signal efficiency by a Gaussian function of which mean value and standard deviation are set as the normal signal efficiency and the systematic uncertainty obtained before, respectively. This new $N^{\rm up}_{\rm total}$ distribution can be described by a Gaussian function. A sum of the mean value ($\bar{N}^{\rm up}_{\rm total}$) and one standard deviation ($\sigma_{\rm total}$) of this Gaussian function is quoted as the $N^{\rm up\ \prime}_{\rm total}$. All the numerical results are summarized in Table IV.

## V. SUMMARY

With a sample of $2.25 \times 10^8$ $J/\psi$ events collected with the BESIII detector, we have searched for the weak decays $J/\psi \to D_s^- e^+ \nu_e$ and $J/\psi \to D_s^{*-} e^+ \nu_e$ . No significant excess of signal is observed. At the 90% C.L., the upper limits of the branching fractions are: $\mathcal{B}(J/\psi \to D_s^- e^+ \nu_e + c.c.) < 1.3 \times 10^{-6}$ and $\mathcal{B}(J/\psi \to D_s^{*-} e^+ \nu_e + c.c.) < 1.8 \times 10^{-6}$. The upper limit on the branching fraction $\mathcal{B}(J/\psi \to D_s^{*-} e^+ \nu_e + c.c.)$ is set for the first time and the upper limit on the branching fraction $\mathcal{B}(J/\psi \to D_s^- e^+ \nu_e + c.c.)$ is 30 times more strict than the previously result [16]. The results are within the SM prediction, but more data will be helpful to test the branching fraction of semileptonic decays of the $J/\psi$ to the order of $10^{-8}$. The results would also be applied to constrain the parameter spaces of some BSM models if direct calculations of these processes are carried out in the future.

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