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Search for the charmonium weak decays $J/\psi \to D_s^- \rho^+$ + c.c. and $J/\psi \to D_s^- \pi^+$ + c.c.

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Abstract: Based on $(10087 \pm 44) \times 10^6$ J/ψ events recorded with the BESIII detector, we search for the rare charmonium weak decays $J/\psi \to D_s^- \rho^+ + \text{c.c.}$ and $J/\psi \to D_s^- \pi^+ + \text{c.c.}$ No signal is observed, and upper limits on the branching fractions at the 90% confidence level are set as $\mathcal{B}(J/\psi \to D_s^- \rho^+ + \text{c.c.}) < 8.0 \times 10^{-7}$ and $\mathcal{B}(J/\psi \to D_s^- \pi^+ + \text{c.c.}) < 4.1 \times 10^{-7}$. Our results provide the most stringent experimental constraints on these decays.

Keywords: Branching fraction, e^+-e^- Experiments, Quarkonium, Rare Decay

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Contents

1 Introduction

As the mass of the J/ψ lies below the $D\bar{D}$ threshold, its decay to $D\bar{D}$ is forbidden. However, weak decays of the J/ψ to a charmed meson D or D_s accompanied by a light meson, such as a ρ or π, are allowed in the Standard Model (SM). Compared with the extensively studied decays of J/ψ caused by the strong and electromagnetic interactions, weak decays of the J/ψ are rarely mentioned. The inclusive branching fraction (BF) of charmonium rare weak decays is predicted to be of the order of 10^{-8} in the SM [1–12]. The BFs of exclusive decays $J/\psi \to D_s^- \rho^+$ and $J/\psi \to D_s^- \pi^+$ are predicted to be $(12.6 - 51.1) \times 10^{-10}$ and $(2.0 - 7.5) \times 10^{-10}$ [5, 7, 8, 11] in the SM, respectively, as shown in table 1. Figure 1 shows an example of the Feynman diagram at the tree level for the charmonium SM weak decays $J/\psi \to D_s^- \rho^+$ and $J/\psi \to D_s^- \pi^+$. These J/ψ weak decays are mediated via the spectator mechanism in which one of the charm (anti-charm) quarks decays and the other does not (i.e., is a spectator). The ratio between the expectation of the D_s channel and the D channel $\frac{\mathcal{B}_{SM}(J/\psi \to D_s^- \rho^+(\pi^+))}{\mathcal{B}_{SM}(J/\psi \to D^- \rho^+(\pi^+))}$ is approximately 20 because the D_s channel is Cabibbo favored within the SM [5, 8, 11]. The decays $J/\psi \to D_s^- \rho^+$ and $J/\psi \to D_s^- \pi^+$ are two of the charmonium weak decays involving a $D_{(s)}$ meson that have the largest BFs expected in the SM [11], making them the most sensitive for observing a SM signal.

Many hadronic weak decays of the J/ψ have been studied in theory, such as several branching ratios for $J/\psi \to SS, VS$ decays (S and V represent a scalar, or a pseudoscalar, and a vector meson, respectively). The decay rates of $J/\psi \to D_s M$ (M represents a meson) are given by

$$\Gamma_{J/\psi \to D_s M} = \frac{1}{3}\frac{1}{8\pi}|\mathcal{A}(J/\psi \to D_s M)|^2 \frac{|\vec{p}_{D_s}|}{m_{J/\psi}^2}, \tag{1.1}$$

where $\vec{p}_{D_s}$ is the three-momentum of the D_s meson, the factor $\frac{1}{3}$ is from the spin average of the J/ψ, and $\mathcal{A}(J/\psi \to D_s M)$ is the decay amplitude which can be calculated based on the three-point QCD sum rules (QCDSR) [5]. The BF ratio for the hadronic weak decays $J/\psi \to D_s^- \rho^+$

Model	QCDSR [5]	BSW [8]	CLFQM [7]	CLFQM [11]
$\mathcal{B}(J/\psi \to D_s^- \rho^+)$ ($\times 10^{-10}$)	$12.6^{+3.0}_{-1.2}$	$51.1^{+7.6}_{-6.0}$	28^{+0}_{-9}	$29.5^{+0.6+1.1+1.5}_{-0.5-1.4-1.9}$
$\mathcal{B}(J/\psi \to D_s^- \pi^+)$ ($\times 10^{-10}$)	$2.0^{+0.4}_{-0.2}$	$7.41^{+0.13}_{-0.23}$	$2.5^{+0.0}_{-0.1}$	$3.64^{+0.06+0.34+0.78}_{-0.06-0.38-0.96}$

Table 1. Theoretical predictions for the BFs of the weak decays $J/\psi \to D_s^- \rho^+$ and $J/\psi \to D_s^- \pi^+$ within the SM, where QCDSR is the QCD sum rule model, BSW is the Bauer-Stech-Wirbel model, and CLFQM is the covariant light-front quark model.

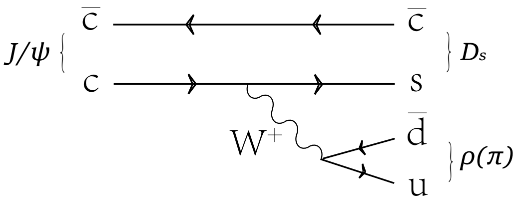


Figure 1. Feynman diagram for both $J/\psi \to D_s^- \rho^+$ and $J/\psi \to D_s^- \pi^+$ decays at the tree-level.

and $J/\psi \to D_s^- \pi^+$ is predicted to be approximately 4.2 by using a factorization scheme [4]. The experimental results of known charmonium rare weak decays are shown in table 2 [13–23].

Meanwhile, various new physics models beyond the SM, including the top-color model [24], the minimal super-symmetric SM with or without R-parity [25], and the two-Higgs doublet model [26] allow the J/ψ weak decay inclusive BFs to be enhanced up to 10^{-5} [27]. Most new physics models enhance J/ψ weak decays either via flavor-changing neutral-current (FCNC) processes or through the exchange of a charged boson. Furthermore, several models, such as the two-Higgs doublet model, predict a larger enhancement for the D_s channel than for the D channel [28]. The processes $J/\psi \to D_s^- \rho^+$ and $J/\psi \to D_s^- \pi^+$ provide a unique opportunity to search for new physics beyond the SM [13, 14]. If a signal for either of these two decays is observed with BFs in the range of 10^{-8} to 10^{-6}, it would indicate new physics beyond the SM.

In this paper, we search for the charmonium weak decays $J/\psi \to D_s^- \rho^+$ and $J/\psi \to D_s^- \pi^+$ using $(10087 \pm 44) \times 10^6$ J/ψ events collected at the BESIII detector [29]. Throughout this paper, charge-conjugate processes are always implied unless explicitly specified.

2 BESIII detector and Monte Carlo simulation

The BESIII detector [30] records symmetric e^+e^- collisions provided by the BEPCII storage ring [31] in the center-of-mass energy range from 1.84 to 4.95 GeV, with a peak luminosity of 1.1×10^{33} cm^{-2}s^{-1} achieved at $\sqrt{s} = 3.773$ GeV. BESIII has collected large data samples in this energy region [13, 32–34]. 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 magnetic field. The magnetic field was 0.9 T in 2012, which affects 11% of the total J/ψ data. 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

Experiment	Decay (+c.c)	$N_{J/\psi}$ or $N_{\psi(3686)}$	UL at 90% C.L.	Year
BESII	$J/\psi \to D_s^- \pi^+$	58×10^6	1.4×10^{-4}	2008 [15]
BESII	$J/\psi \to D^0 K^0$	58×10^6	1.7×10^{-4}	2008 [15]
BESIII	$J/\psi \to D_s^- \rho^+$	225×10^6	1.3×10^{-5}	2014 [16]
BESIII	$J/\psi \to D^0 K^{*0}$	225×10^6	2.5×10^{-6}	2014 [16]
BESIII	$J/\psi \to D_s^- e^+ \nu_e$	225×10^6	1.3×10^{-6}	2014 [17]
BESIII	$J/\psi \to D_s^{*-} e^+ \nu_e$	225×10^6	1.8×10^{-6}	2014 [17]
BESIII	$J/\psi \to D^0 e^+ e^-$	1310.6×10^6	8.5×10^{-8}	2017 [18]
BESIII	$\psi(3686) \to D^0 e^+ e^-$	1310.6×10^6	1.4×10^{-7}	2017 [18]
BESIII	$J/\psi \to D^- e^+ \nu_e$	10087×10^6	7.1×10^{-8}	2021 [19]
BESIII	$\psi(3686) \to \Lambda_c^+ \bar{\Sigma}^-$	448.1×10^6	4.7×10^{-7}	2023 [20]
BESIII	$J/\psi \to D^- \mu^+ \nu_\mu$	10087×10^6	5.6×10^{-7}	2024 [21]
BESIII	$J/\psi \to D^- \rho^+$	10087×10^6	6.0×10^{-7}	2024 [22]
BESIII	$J/\psi \to D^- \pi^+$	10087×10^6	7.0×10^{-8}	2024 [22]
BESIII	$J/\psi \to \bar{D}^0 \rho^0$	10087×10^6	5.2×10^{-7}	2024 [22]
BESIII	$J/\psi \to \bar{D}^0 \eta$	10087×10^6	6.8×10^{-7}	2024 [22]
BESIII	$J/\psi \to \bar{D}^0 \pi^0$	10087×10^6	4.7×10^{-7}	2024 [22]
BESIII	$J/\psi \to D^0 \mu^+ \mu^-$	10087×10^6	1.1×10^{-7}	2025 [23]

Table 2. Summary of studies of charmonium weak decays, listing the decay mode, the total number of J/ψ or $\psi(3686)$ events, and the upper limits (ULs) on the BFs at the 90% confidence level (C.L.).

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 multigap resistive plate chamber technology, providing a time resolution of 60 ps, for 87% of the data used in this analysis [35–37].

Monte Carlo (MC) simulated data samples produced with a GEANT4-based [38] software package, which includes the geometric description of the BESIII detector [39–43] 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 in the e^+e^- annihilations with the generator KKMC [44, 45]. The inclusive MC sample includes both the production of the J/ψ resonance and the continuum processes incorporated in KKMC [44, 45]. All particle decays are modeled with EVTGEN [46, 47] using BFs either taken from the Particle Data Group (PDG) [48], when available, or otherwise estimated with LUNDCHARM [49, 50]. Final state radiation from charged final state particles is incorporated using the PHOTOS package [51]. The signal MC sample for the decay $J/\psi \to D_s^- \rho^+$ is generated with the VVS_PWAVE model [46, 47] for the initial decay while the $J/\psi \to D_s^- \pi^+$ sample is generated with the VSS model [46, 47]. The subsequent $D_s^- \to \phi e^- \bar{\nu}_e$ decay is generated with the PHOTOS ISGW2 model while $\phi \to K^+K^-$ and $\rho^+ \to \pi^+\pi^0$ use the VSS model [46, 47].

3 Event selection and data analysis

The analysis is conducted using the BESIII offline software system [52]. Full reconstruction of D_s mesons with non-leptonic-decay modes does not offer good sensitivity due to the large hadronic background from J/ψ inclusive decays. Therefore, D_s candidates are reconstructed via the semi-leptonic decay $D_s^- \to \phi e^- \bar{\nu}_e$ with $\phi \to K^+K^-$, which has a large BF of $(2.39 \pm 0.16)\%$ and low background [48]. For the ρ^+ side, the subsequent signal decays are $\rho^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma\gamma$. For both decays $J/\psi \to D_s^-\rho^+$ and $J/\psi \to D_s^-\pi^+$, the net charge of the tracks $\sum Q = 0$ and the number of charged tracks must be four. Four charged tracks in both decays must be detected in the MDC within the range of $|\cos\theta| < 0.93$, where θ is the polar angle with respect to the axis of symmetry of the MDC. The distance of closest approach from the interaction point is required to satisfy R_z <10 cm along the beam direction, and R_{xy} <1 cm in the plane perpendicular to the beam axis.

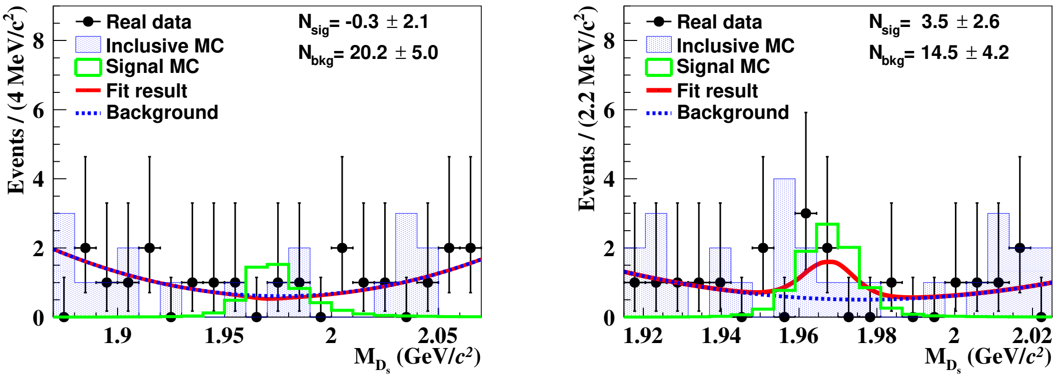
Particle identification (PID) is applied by combining the measurements of $\mathrm{d}E/\mathrm{d}x$ in the MDC and the time-of-flight in the TOF to obtain the likelihoods for each hadron hypothesis $\mathcal{L}_h$ $(h = K, \pi, e)$. The π candidates require $\mathcal{L}(\pi) > 0$, $\mathcal{L}(\pi) > \mathcal{L}(K)$, and $\mathcal{L}(\pi) > \mathcal{L}(e)$. The K candidates require $\mathcal{L}(K) > 0$ and $\mathcal{L}(K) > \mathcal{L}(\pi)$. The e candidates require $\mathcal{L}(e) > 0.001$ and $\mathcal{L}(e)/(\mathcal{L}(e) + \mathcal{L}(\pi) + \mathcal{L}(K)) > 0.8$. One π candidate, two K candidates, and one e candidate are required for each event.

Photon candidates are selected from showers deposited in the EMC with energies of $E_\gamma > 25\,\mathrm{MeV}$ in the barrel ($|\cos\theta| < 0.80$) and $E_\gamma > 50\,\mathrm{MeV}$ in the end-cap ($0.86 < |\cos\theta| < 0.92$). Showers must be separated from the extrapolated positions of any charged track by at least 10° and occur within 700 ns after the event start time. Events with at least two photon candidates are kept in the selection of $J/\psi \to D_s^-\rho^+$.

The $D_s^- \to \phi e^- \bar{\nu}_e$ reconstruction requires one e candidate and one ϕ candidate. To suppress the backgrounds from hadron misidentification, the following requirements for e^- candidates are used: $0.83 < E/p < 1.11$ for $J/\psi \to D_s^-\rho^+$ and $0.87 < E/p < 1.14$ for $J/\psi \to D_s^-\pi^+$. Here E/p is the ratio of the EMC deposited energy, E, and the MDC momentum, p; these criteria have been optimized according to the Punzi significance [53]. One K^+ and one K^- candidate are used to reconstruct the ϕ candidate, whose invariant mass, M_{KK}, must lie within $(1.01, 1.03)\,\mathrm{GeV}/c^2$.

For $J/\psi \to D_s^-\rho^+$, the ρ^+ candidates are reconstructed from one π^+ candidate and one π^0 candidate. The π^0 candidates are selected by looping over all pairs of good photon candidates to select the one with the minimum $\chi^2_{\gamma\gamma}$ from a kinematic fit constraining their invariant mass to the known π^0 mass [48]; this minimum must also satisfy $\chi^2_{\gamma\gamma} < 200$. The updated π^0 four-vector from the fit is used in later kinematic calculations. To select the ρ^+ candidates, $|M_{\pi\pi} - M_\rho^{\mathrm{PDG}}| < 0.15\,\mathrm{GeV}/c^2$ is required, where $M_{\pi\pi}$ is the $\pi^+\pi^0$ invariant mass and M_ρ^{PDG} is the PDG resonance mass [48]. The total energy (E_γ^{rest}) of photons, except for the two photons that are used to reconstruct the π^0, must be less than 0.22 GeV to reduce backgrounds with extra photons.

Neutrinos are not directly detectable and are inferred from the missing energy and momentum. To suppress the backgrounds from J/ψ hadronic decays without a missing particle, we require the missing momentum $|\vec{p}_{\mathrm{miss}}| = |\vec{p}_{J/\psi} - \vec{p}_{K^+} - \vec{p}_{K^-} - \vec{p}_{e^-} - \vec{p}_{\rho^+(\pi^+)}|$ to be larger than $0.15\,\mathrm{GeV}/c$ for $J/\psi \to D_s^-\rho^+$ and $0.10\,\mathrm{GeV}/c$ for $J/\psi \to D_s^-\pi^+$, where $\vec{p}_{J/\psi}$,



(a) (b)

Figure 2. The M_{D_s} distributions of the (a) $J/\psi \to D_s^- \rho^+$ and (b) $J/\psi \to D_s^- \pi^+$ candidate events. The black dots with error bars are data; the blue histograms are the inclusive MC samples; the green solid lines are the signal MC samples, scaled to the obtained 90% UL BFs. The red line is the total fit result with the signal shape and the blue background shape dotted line.

$\vec{p}_{K^+}$, $\vec{p}_{K^-}$, $\vec{p}_{e^-}$ and $\vec{p}_{\rho^+(\pi^+)}$ are the momenta of J/ψ, K^+, K^-, e^-, and ρ^+ (π^+), respectively. To remove the background from $J/\psi \to K^+K^-\pi^+\pi^-$ and multi-π^0/γ in final states, we apply a requirement $|\mathrm{U}_{\mathrm{miss}}| < 0.04\,\mathrm{GeV}$, with $\mathrm{U}_{\mathrm{miss}}$ defined as:

$$\mathrm{U}_{\mathrm{miss}} = E_{\mathrm{miss}} - |\vec{p}_{\mathrm{miss}}|c, \tag{3.1}$$

$$E_{\mathrm{miss}} = E_{J/\psi} - E_{K^+} - E_{K^-} - E_{e^-} - E_{\rho^+(\pi^+)}, \tag{3.2}$$

where $E_{J/\psi}$, E_{K^+}, E_{K^-}, E_{e^-}, and $E_{\rho^+(\pi^+)}$ are the energies of J/ψ, K^+, K^-, e^-, and ρ^+ (π^+), respectively.

After the above selection, most background events are removed according to inclusive MC sample results. To study the remaining background sources, we analyze the MC truth information for background events passing the selections. Most background events contain a π^- being misidentified as an e^- candidate. Thus, we further require for e^- candidates that $\chi_{\pi}^{\mathrm{track}\ e} < 3.0$ and $\chi_{e}^{\mathrm{track}\ e} > -1.0$ for $J/\psi \to D_s^- \rho^+$, and $\chi_{\pi}^{\mathrm{track}\ e} < 2.6$ for $J/\psi \to D_s^- \pi^+$, in which $\chi_{\pi(e)}^{\mathrm{track}\ e}$ is the normalized deviation of the measured $\mathrm{d}E/\mathrm{d}x$ from the expected value under π (e) hypothesis. These requirements are optimized according to the Punzi significance [53].

The D_s^- candidates are identified by the mass recoiling against the ρ^+ (π^+) candidates. Specifically, the signal variable M_{D_s} is the signature of signal events, which is defined by

$$M_{D_s} = \sqrt{E_{D_s}^2/c^4 - |\vec{p}_{D_s}|^2/c^2}, \tag{3.3}$$

with

$$E_{D_s} = E_{J/\psi} - E_{\rho^+(\pi^+)}\,, \quad \vec{p}_{D_s} = \vec{p}_{J/\psi} - \vec{p}_{\rho^+(\pi^+)}. \tag{3.4}$$

The signal will appear as a peak with a central value around the known D_s mass [48].

4 Result

Unbinned extended maximum likelihood fits are performed to the distributions of M_{D_s} to determine the signal yields, as shown in figure 2. The signal probability density function (PDF) is derived from the shape of signal MC simulation. The background shape is described with a second-order polynomial function.

The results indicate no significant excess of observed signal above the backgrounds. Therefore, we set the ULs on $\mathcal{B}(J/\psi \to D_s^- \rho^+)$ and $\mathcal{B}(J/\psi \to D_s^- \pi^+)$ at the 90% C.L. after considering the systematic uncertainties. The branching fraction $\mathcal{B}$ is calculated by

$$\mathcal{B} = \frac{\mathrm{N}_{\mathrm{sig}}}{\mathrm{N}_{J/\psi}\, \epsilon\, \mathcal{B}_{\mathrm{inter}}}, \tag{4.1}$$

where $\mathrm{N}_{\mathrm{sig}}$, $\mathrm{N}_{J/\psi}$, ϵ, and $\mathcal{B}_{\mathrm{inter}}$ are the fitted signal yield, the total number of J/ψ events, the signal efficiency, and the intermediate decay BF, respectively. We scan the $J/\psi \to D_s^- \rho^+$ ($J/\psi \to D_s^- \pi^+$) signal yields 200 (300) times by varying the number of events with a step size of 0.1 to obtain the likelihood $\mathcal{L}_i$ at each step i. The relative likelihood $\mathcal{L}$ is defined as

$$\mathcal{L} = \frac{\mathcal{L}_i}{\mathcal{L}_{\mathrm{max}}}, \tag{4.2}$$

where $\mathcal{L}_{\mathrm{max}}$ is the maximum value of all $\mathcal{L}_i$ in the scan. A Gaussian fit is performed to the dependence of the relative likelihood on the BF. The fitting function is

$$\mathcal{L}(\mathcal{B})_{\mathrm{fit}} \propto \exp\left[-\frac{(\mathcal{B}-\hat{\mathcal{B}})^2}{2\sigma_{\mathcal{B}}^2}\right], \tag{4.3}$$

where $\hat{\mathcal{B}}$ and $\sigma_{\mathcal{B}}$ are the fitted mean value and uncertainty of the BF. Following a method which incorporates the systematic uncertainties into the UL of the BF [54], we obtain the smeared likelihood function by convolving with a Gaussian function:

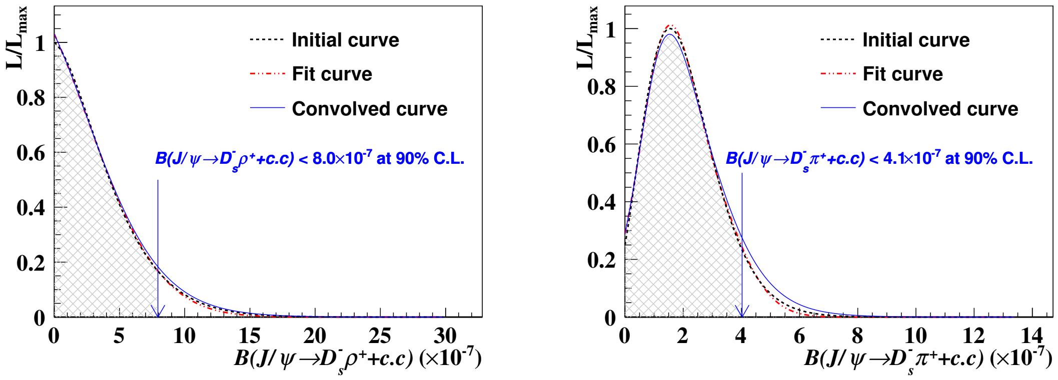
$$\mathcal{L}(\mathcal{B})_{\mathrm{smear}} \propto \int_0^1 \exp\left[-\frac{(\epsilon\mathcal{B}/\hat{\epsilon}-\hat{\mathcal{B}})^2}{2\sigma_{\mathcal{B}}^2}\right] \frac{1}{\sqrt{2\pi}\sigma_\epsilon} \exp\left[-\frac{(\epsilon-\hat{\epsilon})^2}{2\sigma_\epsilon^2}\right] \mathrm{d}\epsilon, \tag{4.4}$$

where $\hat{\epsilon}$ is the nominal efficiency, $\sigma_\epsilon = \sigma_{\mathrm{sys}}\,\epsilon$ is the systematic uncertainty of efficiency. For the $D_s^- \pi^+$ channel, the $\mathcal{L}(\mathcal{B})_{\mathrm{fit}}$ distribution is asymmetrical and is fitted with a double Gaussian before smearing is applied.

To ensure a conservative assessment of the impact of fluctuations resulting from the fit range of M_{D_s}, we have systematically varied the fit ranges multiple times. Additionally, to account for the influence of fluctuations introduced by the background fit shape of M_{D_s}, we have employed a first-order polynomial function to replace the initial second-order polynomial function. We choose the most conservative ULs $\mathcal{B}(J/\psi \to D_s^- \rho^+ + \mathrm{c.c.}) < 8.0 \times 10^{-7}$ and $\mathcal{B}(J/\psi \to D_s^- \pi^+ + \mathrm{c.c.}) < 4.1 \times 10^{-7}$ at the 90% C.L., as shown in figure 3.

5 Systematic uncertainty

The systematic uncertainties in the BF measurement of $J/\psi \to D_s^- \rho^+$ and $J/\psi \to D_s^- \pi^+$ mainly come from the signal MC model, particle tracking and PID, intermediate BFs, the



(a) (b)

Figure 3. The distributions of the likelihood scan values for (a) $J/\psi \to D_s^- \rho^+$ and (b) $J/\psi \to D_s^- \pi^+$. The dotted-dashed black line is the initial curve, the dotted-dashed red line is the fit curve with a Gaussian function, and the solid blue line is the fit curve convolved with a Gaussian for systematic uncertainties. The blue arrows indicate the ULs on BFs at the 90% C.L.

total number of J/ψ events, MC statistics, and the requirements imposed on M_ϕ, $|\vec{p}_{\rm miss}|$, $\mathrm{U}_{\rm miss}$, E/p, and $\chi_\pi^{{\rm track}\ e}$. In addition, photon detection efficiency and the requirements on $\chi_e^{{\rm track}\ e}$, M_ρ, and $E_\gamma^{\rm rest}$ are sources of the systematic uncertainties in the BF measurement of $J/\psi \to D_s^- \rho^+$. The influence of fluctuations introduced by the background fit shape of M_{D_s} is discussed in section 4. The systematic uncertainties from different sources are studied in the following items and summarized in table 3. The quadratic sum of all the uncertainties is taken as the total systematic uncertainty.

- *MC generator model.* To estimate the systematic uncertainty due to the MC generator model, signal MC samples generated with alternative phase space (PHSP) models are compared to the nominal signal MC samples. The efficiency differences between the alternative and nominal signal MC samples are assigned as the systematic uncertainties: 10.5% and 13.1%, for $J/\psi \to D_s^- \rho^+$ and $J/\psi \to D_s^- \pi^+$, respectively.
- *Tracking and PID efficiencies.* The uncertainties of the tracking and PID efficiencies for $K^\pm$ and $\pi^\pm$ have been studied by analyzing $\psi(3770) \to D^0 \bar{D}^0$ ($D^+ D^-$) decay events. The hadronic decays of $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$ versus $\bar{D}^0 \to K^+\pi^-$, $K^+\pi^-\pi^-\pi^+$, and $D^+ \to K^-\pi^+\pi^+$ versus $D^- \to K^+\pi^-\pi^-$, are used as control samples for missing-particle studies. The electron tracking and PID efficiencies of the datasets are studied using control samples of the process $e^+e^- \to e^+e^-\gamma$ (including $J/\psi \to e^+e^-\gamma$) from MC simulation at 3.097 GeV and the corresponding data. We calculate the systematic uncertainties of K, π, e tracking and K, π, e PID, accounting for the momentum distributions of K, π, e in data. The total systematic uncertainties from tracking are 2.6% for $J/\psi \to D_s^- \rho^+$ and 2.7% for $J/\psi \to D_s^- \pi^+$. The total systematic uncertainties from PID are 1.1% for $J/\psi \to D_s^- \rho^+$ and 1.3% for $J/\psi \to D_s^- \pi^+$.
- *Intermediate BFs.* The uncertainty of the intermediate decay BFs quoted from the PDG [48] is 6.8% for both $J/\psi \to D_s^- \rho^+$ and $J/\psi \to D_s^- \pi^+$.

Sources	$\Delta_{sys}(J/\psi \to D_s\rho)$ (%)	$\Delta_{sys}(J/\psi \to D_s\pi)$ (%)
MC generator model	10.5	13.1
Tracking	2.6	2.7
Particle ID	1.1	1.3
Intermediate BFs	6.8	6.8
Total number of J/ψ	0.5	0.5
MC statistics	0.6	0.4
M_ϕ requirement	5.2	5.2
$\lvert\vec{p}_{\rm miss}\rvert$ requirement	4.1	2.6
$\mathrm{U}_{\rm miss}$ requirement	5.7	5.7
E/p requirement	1.5	1.8
$\chi_\pi^{\rm track\ e}$ requirement	5.7	5.0
$\chi_e^{\rm track\ e}$ requirement	2.9	–
M_ρ requirement	2.8	–
$E_\gamma^{\rm rest}$ requirement	3.3	–
γ detection	2.0	–
Total	17.5	17.9

Table 3. Summary of the systematic uncertainties for the BF measurements. A "–" indicates a non-applicable source. The total value is calculated by summing up all sources in quadrature.

- *Number of J/ψ events.* The total number of J/ψ events is $\mathrm{N}_{J/\psi} = (10087 \pm 44) \times 10^6$ [29], where the uncertainty is systematic and the statistical one is negligible. We take 0.5% as the systematic uncertainty.

- *MC statistics.* The systematic uncertainties due to MC statistics are 0.6% for $J/\psi \to D_s^-\rho^+$ and 0.4% for $J/\psi \to D_s^-\pi^+$.

- *M_ϕ requirement.* The systematic uncertainty of the M_ϕ requirement is estimated as 5.2% via a control sample of $J/\psi \to \phi\phi\gamma$ with $\phi \to K^+K^-$.

- *$\lvert\vec{p}_{\rm miss}\rvert$, $U_{\rm miss}$, E/p, $\chi_\pi^{track\ e}$, and $\chi_e^{track\ e}$ requirements.* To estimate the systematic uncertainties caused by the requirements on these quantities, we use a control sample of $D^0 \to K^+e^-\bar{\nu}$. The systematic uncertainties for $J/\psi \to D_s^-\rho^+$ are 4.1%, 5.7%, 1.5%, 5.7%, and 2.9%, respectively. For $J/\psi \to D_s^-\pi^+$, only the first four quantities are relevant and the obtained uncertainties are 2.6%, 5.7%, 1.8%, and 5.0%.

- *M_ρ and $E_\gamma^{\rm rest}$ requirements.* The systematic uncertainties on the M_ρ and $E_\gamma^{\rm rest}$ requirements are estimated as 2.8% and 3.3% using a control sample of $J/\psi \to \rho^+\pi^-$ with $\rho^+ \to \pi^+\pi^0$.

- *γ detection.* The uncertainty due to γ detection is assigned as 1% per γ by using $J/\psi \to \rho^0\pi^0$ and $e^+e^- \to \gamma\gamma$ samples [55].

The total systematic uncertainties are 17.5% for $J/\psi \to D_s^-\rho^+$ and 17.9% for $J/\psi \to D_s^-\pi^+$.

6 Summary

The rare charmonium weak decays $J/\psi \to D_s^- \rho^+$ and $J/\psi \to D_s^- \pi^+$ are searched for based on $(10087 \pm 44) \times 10^6$ J/ψ events collected with the BESIII detector. No significant signal is observed, and ULs on their BFs are set at $\mathcal{B}(J/\psi \to D_s^- \rho^+) < 8.0 \times 10^{-7}$ and $\mathcal{B}(J/\psi \to D_s^- \pi^+) < 4.1 \times 10^{-7}$ at the 90% C.L. In comparison to the previous best limits, the UL for $J/\psi \to D_s^- \rho^+$ has been improved by about an order of magnitude, and the UL for $J/\psi \to D_s^- \pi^+$ has been improved by about three orders of magnitude. These results are consistent with the SM-based predictions [5, 7, 8, 11].

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JHEP12(2025)077

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