Search for $h_c \to \pi^+\pi^- J/\psi$ via $\psi(3686) \to \pi^0 h_c$

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Using $(2712.4 \pm 14.3) \times 10^6$ $\psi(3686)$ events collected with the BESIII detector operating at the BEPCII collider, we search for the hadronic transition $h_c \to \pi^+\pi^- J/\psi$ via $\psi(3686) \to \pi^0 h_c$. No significant signal is observed. We set the most stringent upper limits to date on the branching fractions $\mathcal{B}(\psi(3686) \to \pi^0 h_c) \times \mathcal{B}(h_c \to \pi^+\pi^- J/\psi)$ and $\mathcal{B}(h_c \to \pi^+\pi^- J/\psi)$ at the 90% confidence level, which are determined to be 6.7×10^{-7} and 9.4×10^{-4}, respectively.

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I. INTRODUCTION

The study of charmonium decays is crucial to elucidate the mechanism of quantum chromodynamics (QCD), as these states lie in the transition region between nonperturbative and perturbative QCD. Although QCD has successfully explained many aspects of strong interactions, some known charmonium decay mechanisms remain challenging, as documented in Ref. [1].

Following identification of spin-singlet P-wave charmonium state $h_c(^1P_1)$ in 2005 [2,3], extensive theoretical and experimental efforts have been made to understand its characteristics. The study of h_c remains difficult due to its relatively low branching fraction (BF), because its production through 1^{--} charmonia is suppressed [4].

The first evidence for the h_c state was reported by E835 at Fermilab in the $p\bar{p} \to h_c \to \gamma\eta_c$ process [5]. Subsequently, the CLEO experiment presented the first observation of the h_c in a study of the cascade decay $\psi(3686) \to \pi^0 h_c, h_c \to \gamma\eta_c$ [6], measured its mass [7], and provided evidence for its multipion decay modes [8]. The BESIII collaboration made the first measurement of the absolute BFs, $\mathcal{B}(\psi(3686) \to \pi^0 h_c)$ and $\mathcal{B}(h_c \to \gamma\eta_c)$ [9], which were later confirmed by CLEO [10]. With a larger $\psi(3686)$ data sample, recent experimental measurements give $\mathcal{B}(\psi(3686) \to \pi^0 h_c) = (7.32 \pm 0.34 \pm 0.41) \times 10^{-4}$ and $\mathcal{B}(h_c \to \gamma\eta_c) = (57.66^{+3.62}_{-3.50} \pm 0.58)\%$ [11]. These indicate that the sum of the h_c hadronic decay modes is comparable to its radiative transition rate.

The hadronic transitions of h_c provide a valuable opportunity to investigate the spin-spin interaction between heavy quarks [12]. The Feynman diagram of the hadronic transition $h_c \to \pi^+\pi^- J/\psi$ is depicted in Fig. 1. According to theoretical predictions based on a QCD multipole expansion, the BF of $h_c \to \pi\pi J/\psi$ (including charged and neutral modes) is predicted to be 2% [13]. However, when nonlocality in time is neglected, the predicted BF decreases significantly to 0.05% [14]. Additionally, Ref. [15] suggests that the BF for $h_c \to \pi^+\pi^- J/\psi$ is approximately 40 times smaller than that for $h_c \to \pi^0 J/\psi$.

In 2018, the BESIII collaboration searched for the hadronic transition of $h_c \to \pi^+\pi^- J/\psi$ using a dataset of (448.1 ± 0.8) million $\psi(3686)$ events [16]. The upper limit on the product of BFs, $\mathcal{B}(\psi(3686) \to \pi^0 h_c) \times \mathcal{B}(h_c \to \pi^+\pi^- J/\psi)$, was determined to be 2.0×10^{-6} at the 90% confidence level (CL) [17], which is in better agreement with the theoretical prediction presented in Ref. [14]. Four years later, the BESIII Collaboration reported the upper limit on $\mathcal{B}(h_c \to \pi^0 J/\psi)$ which was determined to be 4.7×10^{-4} at the 90% CL, utilizing 11 fb^{-1} of e^+e^- collision data taken at center-of-mass energies between 4.189 and 4.437 GeV [18]. According to

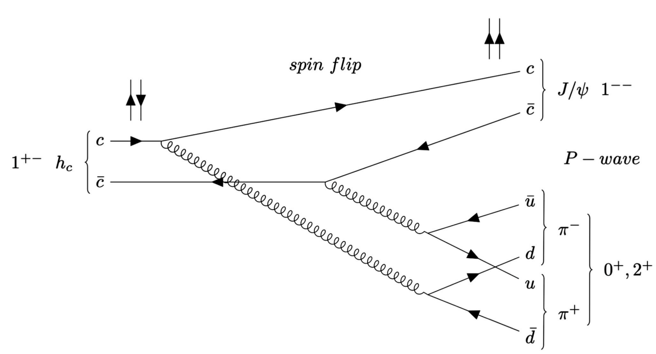

FIG. 1. The Feynman diagram for the spin flip hadronic transition $h_c \to \pi^+\pi^- J/\psi$.

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Ref. [15], this result suggests that $\mathcal{B}(h_c \to \pi^+\pi^- J/\psi)$ could be smaller than 1.2×10^{-5}.

In this paper, based on $(2712.4 \pm 14.3) \times 10^6$ $\psi(3686)$ events [16,19], we present an updated analysis of a search for the hadronic transition $h_c \to \pi^+\pi^- J/\psi$.

II. BESIII DETECTOR AND MONTE CARLO SIMULATION

The BESIII detector [20] records symmetric e^+e^- collisions provided by the BEPCII storage ring [21] in the center-of-mass energy range from 1.84 to 4.95 GeV, with a peak luminosity of 1.1×10^{33} $\mathrm{cm^{-2}\,s^{-1}}$ achieved at $\sqrt{s} = 3.773$ GeV. BESIII has collected large data samples in this energy region [22–24]. 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 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 (MUC) interleaved with steel. 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 energy with a resolution of 2.5% (5%) at 1 GeV in the barrel (end-cap) region. The time resolution of the plastic scintillator TOF barrel part is 68 ps, while that of the end-cap part 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, which benefits ~83% of the data used in this analysis [25–27].

Monte Carlo (MC) simulated data samples produced with GEANT4-based [28] software, which includes the geometric description of the BESIII detector and the detector response, are used to optimize the event selection criteria and estimate the signal efficiency and level of background. The simulation models the beam-energy spread and initial-state radiation in the e^+e^- annihilation using the generator KKMC [29,30]. The inclusive MC sample includes the production of the $\psi(3686)$ resonance, the initial-state radiation production of the J/ψ meson, and the continuum processes incorporated in KKMC. All particle decays are modeled with EVTGEN [31,32] using BFs either taken from the Particle Data Group (PDG) [4], when available, or otherwise estimated with LUNDCHARM [33,34]. Final-state radiation from charged final-state particles is incorporated using PHOTOS [35].

Corresponding to the total number of $\psi(3686)$ events collected in different years, 2,712,400 signal MC events are generated with $\psi(3686) \to \pi^0 h_c$ and $J/\psi \to e^+e^-/\mu^+\mu^-$ modeled by PARTWAVE and PHOTOS VLL simulations [31,32], respectively. Additionally, $\pi^0 \to \gamma\gamma$ and $h_c \to \pi^+\pi^- J/\psi$ are modeled with a phase space (PHSP) model.

III. EVENT SELECTION

The final-state particles in this analysis include $\pi^+\pi^-\gamma\gamma\mu^+\mu^-$ and $\pi^+\pi^-\gamma\gamma e^+e^-$. 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, which is the symmetry axis of the MDC. For charged tracks, the distance of closest approach to the interaction point (IP) must be less than 10 cm along the z-axis, $|V_z|$, and less than 1 cm in the transverse plane, $|V_{xy}|$.

Photon candidates are identified using isolated showers in the EMC. The deposited energy of each shower must be more than 25 MeV in the barrel region ($|\cos\theta| < 0.80$) and more than 50 MeV in the end-cap region ($0.86 < |\cos\theta| < 0.92$). To exclude showers that originate from charged tracks, the angle subtended by the EMC shower and the position of the closest charged track at the EMC must be greater than 10 degrees as measured from the IP. To suppress electronic noise and showers unrelated to the event, the difference between the EMC time and the event start time is required to be within [0, 700] ns.

The number of good charged tracks is required to be four with zero net charge. The three-momenta in the laboratory frame is used to separate leptons and pions. Charged tracks with momentum below 1 GeV/c are assumed to be pions, while those with momentum above 1 GeV/c are taken as leptons. A pair of pions with opposite charge and a pair of leptons with the same flavor and opposite charge are required. Muons and electrons are separated based on their energy deposits in the EMC. Electrons and positrons must have energy deposits greater than 1.0 GeV, while muons have energy deposits less than 0.4 GeV.

The J/ψ candidates are reconstructed from e^+e^- and $\mu^+\mu^-$ pairs with invariant mass in the J/ψ mass region, defined as $3.085 < M(l^+l^-) < 3.108$ GeV/c^2, ($l \equiv e, \mu$), which is about three times the standard deviation obtained from the fit to the distribution of the l^+l^- invariant mass $M(l^+l^-)$ of data.

To suppress background, a five-constraint (5C) kinematic fit is performed, constraining the four-momentum of the final state particles to that of the initial system and the invariant mass of the $\gamma\gamma$ pair to the π^0 mass [4]. The four-momenta from the kinematic fit are used in the following analysis.

To suppress background from the decay $\psi(3686) \to \eta J/\psi, \eta \to \pi^+\pi^-\pi^0$ and other background decays to different final states, we optimize two selection criteria, which are the requirements on $\chi^2_{5\mathrm{C}}$ and on the $\pi^+\pi^-\pi^0$ invariant mass, $M_{\pi^+\pi^-\pi^0}$, by maximizing a figure-of-merit given by $\epsilon_{\mathrm{sig}}/(\alpha/2 + \sqrt{B})$. Here the signal efficiency (ϵ_{sig}) is determined with the signal MC sample, the background yield (B) is estimated using the inclusive MC sample, and α is the significance level, which is set to be 3.0. Based on the optimization, the optimal requirements of $\chi^2_{5\mathrm{C}} < 15$ and $|M_{\pi^+\pi^-\pi^0} - M_\eta| > 24.5$ MeV/c^2 are applied, where M_η is

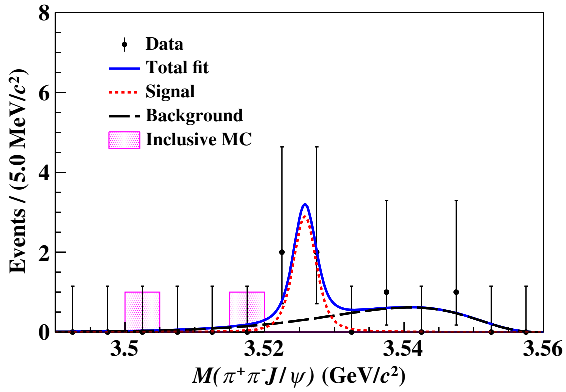

FIG. 2. The fit to the $M(\pi^+\pi^- J/\psi)$ distribution. The points with errors bar are data, the blue solid curve is the fit result, the black solid dashed line is the background, the red dotted curve is the signal and the purple bars are the remaining inclusive MC events.

the η mass [4]. Additionally, a requirement of $M(\pi^+\pi^-) > 0.3\ \mathrm{GeV}/c^2$ has been applied to reduce the background from the decay $\psi(3686) \to \pi^0\pi^0 J/\psi$ with γ converting into an e^+e^- pair in the beam pipe or inner wall of the MDC and the e^+e^- pair is misidentified as $\pi^+\pi^-$ pair. After applying the above selection criteria, only two background events from $\psi(3686) \to \eta J/\psi, \eta \to \pi^+\pi^-\pi^0$ survive, which are shown as the purple bars in Fig. 2.

IV. SIGNAL YIELDS

To determine the signal yield, we perform an unbinned likelihood fit to the $M(\pi^+\pi^- J/\psi)$ distribution of the accepted candidates, as shown in Fig. 2. The h_c signal is described using the shape obtained from signal MC events, while the combinatorial background shape is described by an ARGUS function [36]. The signal yield determined from the fit is $N_{\mathrm{sig}}^{\mathrm{obs}} = 2.7 \pm 2.1$. The statistical significance of the h_c signal is 1.6σ, by comparing the log-likelihood values of the fits with and without signal component ($\Delta \ln L = 1.26$) and taking the change in the number of degrees of freedom into account.

Since no significant signal of $\psi(3686) \to \pi^0 h_c, h_c \to \pi^+\pi^- J/\psi$ is observed, the upper limit on the product BFs is calculated as

$$[\mathcal{B}(\psi(3686) \to \pi^0 h_c) \times \mathcal{B}(h_c \to \pi^+\pi^- J/\psi)]_{\mathrm{upper}} = \frac{N_{\mathrm{sig}}^{\mathrm{up}}}{N_{\psi(3686)} \times \epsilon_{\mathrm{sig}} \times \mathcal{B}(J/\psi \to l^+l^-) \times \mathcal{B}(\pi^0 \to \gamma\gamma)}. \quad (1)$$

Here, $N_{\psi(3686)}$ is the number of $\psi(3686)$ events and $N_{\mathrm{sig}}^{\mathrm{up}}$ is the upper limit of h_c signal events obtained from a Bayesian method [37] with a prior density p, where $p = 0$ for $N_{\mathrm{sig}} < 0$, and $p = 1$ for $N_{\mathrm{sig}} \geq 0$. The detection efficiency of the signal mode is $\epsilon_{\mathrm{sig}} = 3.74\%$. The BFs of the intermediate states, $\mathcal{B}(\pi^0 \to \gamma\gamma)$ and $\mathcal{B}(J/\psi \to l^+l^-)$, are taken from the PDG [4]. The upper limit on $\mathcal{B}(\psi(3686) \to \pi^0 h_c) \times \mathcal{B}(h_c \to \pi^+\pi^- J/\psi)$ is determined to be 6.7×10^{-7} incorporating the systematic uncertainties that will be addressed in Sec. V.

V. SYSTEMATIC UNCERTAINTIES

The systematic uncertainty for the upper limit of the BF includes multiplicative and additive sources. The multiplicative systematic uncertainties are from the number of $\psi(3686)$ events, tracking, photon detection, kinematic fit, quoted BFs, mass windows, and the signal model. Details of the systematic uncertainties are discussed below:

(i) Number of $\psi(3686)$ events: The uncertainty on the number of $\psi(3686)$ events, determined with inclusive hadronic $\psi(3686)$ decays, is 0.5% [16,19].

(ii) Tracking: The uncertainties of the tracking efficiencies for charged pions and leptons are estimated with a control sample of $\psi(3686) \to \pi^+\pi^- J/\psi, J/\psi \to e^+e^-(\mu^+\mu^-)$. The MC simulation is re-weighted in two-dimensional $(\cos\theta, p_t)$ bins according to the efficiencies obtained from the control sample, where θ is the polar angle and p_t is the transverse momentum of the charged pions and leptons. The corrected detection efficiency is taken as the nominal result. The difference in efficiencies before and after the correction is taken as the systematic uncertainty due to tracking. It is assigned to be 0.4% for each pion and 0.1% for each lepton, resulting in a total tracking uncertainty of 1.0%.

(iii) Photon detection: The photon detection efficiency has been studied using a control sample of $e^+e^- \to \gamma\mu^+\mu^-$. The difference between data and MC simulation is found to be 0.5% for each photon. Therefore, the total systematic uncertainty for two photons is assigned as 1.0%.

(iv) π^0 reconstruction: Using a high purity control sample of $J/\psi \to \pi^0 p\bar{p}$, the systematic uncertainty from π^0 reconstruction is determined to be 1.0% [38].

(v) Kinematic fit: ϵ_{sig} is the efficiency obtained from the signal MC sample after the helix parameter correction. The systematic uncertainty related to the kinematic fit is evaluated by comparing the efficiencies with and without this correction [39]. Half of their difference, 0.7%, is taken as the associated uncertainty.

(vi) Quoted BFs: The quoted BFs of $J/\psi \to e^+e^-$, $J/\psi \to \mu^+\mu^-$, and $\pi^0 \to \gamma\gamma$ are taken from the PDG [4], with uncertainties of 0.5%, 0.6%, and 0.03%, respectively.

(vii) Mass windows: To evaluate the systematic uncertainty associated with the choice of mass windows, we perform a Barlow test [40] to examine the deviation in significance (ζ) between the baseline selection and that used for the systematic test. The deviation in significance is defined as

$$\zeta = \frac{|V_{\text{nominal}} - V_{\text{test}}|}{\sqrt{|\sigma^2_{V\text{nominal}} - \sigma^2_{V\text{test}}|}}, \qquad (2)$$

where V is $N^{\text{up}}_{\text{sig}}/\epsilon_{\text{sig}}$; σ_V is the statistical uncertainty on V. The mass windows applied on $M(\pi^+\pi^-)$ and $M(\pi^0\pi^+\pi^-)$ are varied between $(0.270, 0.330)\ \text{GeV}/c^2$ and $(0.225, 0.305)\ \text{GeV}/c^2$ with steps of $3.0\ \text{MeV}/c^2$ and $4.0\ \text{MeV}/c^2$, respectively. As the ζ values are always smaller than 2, the corresponding systematic uncertainties are ignored.

(viii) Signal mode: Due to the limited knowledge of the $M(\pi^+\pi^-)$ distribution in the decay $h_c \to \pi^+\pi^- J/\psi$, the signal MC sample is generated uniformly in phase space without considering the angular distribution in the nominal analysis. To account for the potential systematic bias of the theoretical model, an alternative signal MC sample is generated. In this model, pure P-wave production between the two-pion system (S-wave) and J/ψ is assumed, specifically $h_c \to f_0(500)J/\psi$, which is described by the helicity amplitude model in EVTGEN [31,32]. The decay $f_0(500) \to \pi^+\pi^-$ is generated using a phase space model. The efficiency difference between these two models, 6.3%, is assigned as the systematic uncertainty.

The multiplicative systematic uncertainties are summarized in Table I. The total systematic uncertainty is obtained by adding all contributions in quadrature under the assumption that they are independent.

The additive systematic uncertainties stem from the determination of the signal yield, which depends on the fit range and signal and background shapes. Since these additive systematic uncertainties are correlated, we simultaneously change these three fit conditions and choose the most conservative upper limit. The contributions to the systematic uncertainties are discussed below.

TABLE I. Multiplicative systematic uncertainties (%).

Source	Uncertainty
Number of $\psi(3686)$ events	0.5
Tracking	1.0
Photon detection	1.0
π^0 reconstruction	1.0
Kinematic fit	0.7
$M(\pi^+\pi^-)$ mass window	Neglected
$M(\pi^+\pi^-\pi^0)$ mass window	Neglected
$\mathcal{B}(\pi^0 \to \gamma\gamma)$	Neglected
$\mathcal{B}(J/\psi \to e^+e^-)$	0.5
$\mathcal{B}(J/\psi \to \mu^+\mu^-)$	0.6
Signal model	6.3
Total	6.6

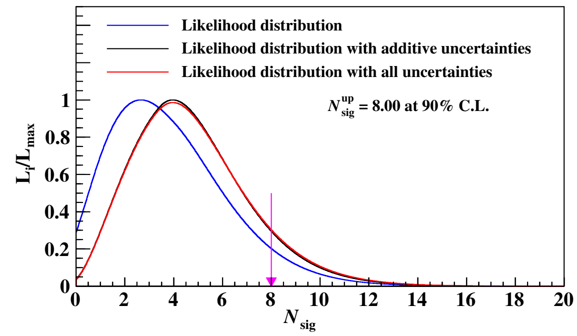

FIG. 3. The normalized likelihood distribution for $\psi(3686) \to \pi^0 h_c, h_c \to \pi^+\pi^- J/\psi$. The result obtained without accounting for any systematic uncertainties is depicted in blue, another with additive systematic uncertainties in black, and the third considering all systematic uncertainties in red. The arrow indicates the upper limit on the signal yield at the 90% confidence level after accounting for all systematic uncertainties.

(i) Fit range: The systematic uncertainty arising from the fit range is evaluated by varying the fit range, adjusting both left and right limits by $\pm 10\ \text{MeV}/c^2$.

(ii) Signal shape: The systematic uncertainty from the signal shape is estimated by using the MC-simulated shape convolved with a Gaussian function. The parameters of the Gaussian function are $M_{\text{Gaussian}} = -0.4 \pm 0.3$ MeV and $\sigma_{\text{Gaussian}} = 0.7 \pm 1.0$ MeV, taken from $e^+e^- \to \eta h_c, h_c \to \gamma\eta_c$ [41].

(iii) Background shape: The systematic uncertainty due to the background shape is estimated by replacing the ARGUS function [36] with a 0th-order polynomial function, or by fixing the background yield to the remaining inclusive MC sample.

The multiplicative and additive systematic uncertainties are incorporated into the calculation of the upper limit via [42,43]

$$L'(N) = \int_{\epsilon=0}^{1} L\left(\frac{\epsilon}{\epsilon_{\text{sig}}} N\right) \exp\left[-\frac{(\epsilon - \epsilon_{\text{sig}})^2}{2\sigma_\epsilon^2}\right] d\epsilon, \qquad (3)$$

where $L(N)$ is the likelihood distribution as a function of signal yield, N; ϵ is the expected efficiency and ϵ_{sig} is the nominal efficiency; σ_ϵ is its multiplicative systematic uncertainty as summarized in Table I. The likelihood distribution is shown in Fig. 3, note that the shift of the peak value is mostly due to the signal line shape uncertainty. The signal yield of the process $\psi(3686) \to \pi^0 h_c, h_c \to \pi^+\pi^- J/\psi$ at the 90% CL, is taken as the upper limit ($N^{\text{up}}_{\text{sig}} = 8.00$), and used for the calculation of the upper limit of BF.

VI. SUMMARY

A search for the hadronic transition $h_c \to \pi^+\pi^- J/\psi$ is performed by analyzing $(2712.4 \pm 14.3) \times 10^6$ $\psi(3686)$

events collected at the BESIII experiment, no significant signal is observed. The upper limit on the product of BFs, that is $\mathcal{B}(\psi(3686) \to \pi^0 h_c) \times \mathcal{B}(h_c \to \pi^+\pi^- J/\psi)$, at the 90% CL is determined to be 6.7×10^{-7}.

Using the PDG value of $\mathcal{B}(\psi(3686) \to \pi^0 h_c) = (7.4 \pm 0.5) \times 10^{-4}$ and incorporating the additional uncertainty of 6.8% [4], the upper limit for $\mathcal{B}(h_c \to \pi^+\pi^- J/\psi)$ at the 90% CL is estimated to be 9.4×10^{-4}. This result is above the predicted upper limit of $\mathcal{B}(h_c \to \pi^+\pi^- J/\psi)$ of 1.2×10^{-5} obtained from the latest result of $\mathcal{B}(h_c \to \pi^0 J/\psi)$ [18] as proposed by Voloshin [15].

Neglecting the small difference between phase space for charged and neutral $\pi\pi$ modes, we obtain $\mathcal{B}(h_c \to \pi\pi J/\psi) < 1.41 \times 10^{-3}$ (including charged and neutral modes) at the 90% CL by considering isospin symmetry. The upper limit on the BF of $h_c \to \pi\pi J/\psi$ presented in this paper is about 3 times lower than that from the previous study [17]. In comparison with theoretical predictions, our result is an order of magnitude smaller than the BF predicted by Kuang *et al.* (about 2%) [13], and closer to the prediction calculated by Pyungwon Ko (0.05%) [14].

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