

RECEIVED: November 30, 2021

REVISED: March 23, 2022

ACCEPTED: April 8, 2022

PUBLISHED: May 2, 2022

## Search for the decay $h_c \rightarrow \pi^0 J/\psi$

---



The BESIII collaboration

*E-mail:* [besiii-publications@ihep.ac.cn](mailto:besiii-publications@ihep.ac.cn)

**ABSTRACT:** A search for the decay  $h_c \rightarrow \pi^0 J/\psi$  is performed using a sample of  $h_c$  produced in the reaction  $e^+e^- \rightarrow \pi^+\pi^-h_c$ . The data samples were collected with the BESIII detector at center-of-mass energies between 4.189 and 4.437 GeV, corresponding to a total integrated luminosity of  $11 \text{ fb}^{-1}$ . No significant signal is observed. Upper limits on the branching ratio  $\mathcal{B}(h_c \rightarrow \pi^0 J/\psi)/\mathcal{B}(h_c \rightarrow \gamma\eta_c \rightarrow \gamma K^+ K^- \pi^0)$  and on the branching fraction  $\mathcal{B}(h_c \rightarrow \pi^0 J/\psi)$  are determined to be  $7.5 \times 10^{-2}$  and  $4.7 \times 10^{-4}$  at 90% confidence level, respectively. The latter is derived from the former using the measured branching fraction of the normalization channel. This is the first determination of the upper limit of the decay  $h_c \rightarrow \pi^0 J/\psi$ .

**KEYWORDS:** Branching fraction,  $e^+e^-$  Experiments, Quarkonium

ARXIV EPRINT: [2111.13915](https://arxiv.org/abs/2111.13915)

---

**Contents**

<b>1</b>	<b>Introduction</b>	<b>1</b>
<b>2</b>	<b>BESIII detector and Monte Carlo simulation</b>	<b>2</b>
<b>3</b>	<b>Event selection</b>	<b>2</b>
<b>4</b>	<b>Branching fraction measurement</b>	<b>3</b>
<b>5</b>	<b>Systematic uncertainty</b>	<b>5</b>
<b>6</b>	<b>Summary and discussion</b>	<b>7</b>
	<b>The BESIII collaboration</b>	<b>11</b>

---

**1 Introduction**

Charmonium, the bound state of a charm quark and anticharm quark ( $c\bar{c}$ ), plays an important role in our understanding of quantum chromodynamics (QCD), which is the fundamental theory of the strong interaction. Low energy QCD remains a field of high interest both experimentally and theoretically. All charmonium states below the open-charm ( $D\bar{D}$ ) threshold have been observed experimentally and can be well described by QCD inspired models [1]. However, knowledge is still sparse on the  $P$ -wave spin-singlet state,  $h_c(1P)$  [2]. So far, only a few decay modes of the  $h_c$  have been observed, such as  $h_c \rightarrow \gamma\eta_c(\eta')$  [2]. Searches for new decay modes of the  $h_c$  can provide useful information to constrain theoretical models in the charmonium region.

In 1992, the E760 Collaboration reported an evidence of the  $h_c$  in the  $\pi^0 J/\psi$  decay mode [3]. The decay  $h_c \rightarrow \pi^0 J/\psi$  was not confirmed by the successor experiment E835 with higher statistics in 2005 [4], but E835 Collaboration found the evidence for  $h_c$  in another decay mode  $\gamma\eta_c$ . More measurements are thus needed for clarification. In addition, several theoretical articles have addressed the decay  $h_c \rightarrow \pi^0 J/\psi$ , with predictions for the partial width around several keV [5–8]. Until now, there is no experimental result to confirm this.

Many studies of the  $h_c$  have been performed using the reaction  $\psi(3686) \rightarrow \pi^0 h_c$  from the  $\psi(3686)$  data sample at BESIII [9–11]. However, it is hard to search for the decay  $h_c \rightarrow \pi^0 J/\psi$  using the  $\psi(3686)$  data sample due to the large background from  $\psi(3686) \rightarrow \pi^0 \pi^0 J/\psi$ . BESIII has observed a sizeable cross section for the process  $e^+e^- \rightarrow \pi^+\pi^-h_c$  between 4.189 and 4.437 GeV [12]. This process is advantageous in the search for the decay  $h_c \rightarrow \pi^0 J/\psi$ , because it avoids the dominant background of  $\psi(3686) \rightarrow \pi^0 \pi^0 J/\psi$  present in the  $\psi(3686)$  decay.

In this paper, a search for  $h_c \rightarrow \pi^0 J/\psi$  is reported using  $e^+e^- \rightarrow \pi^+\pi^-h_c$  events from data samples collected at center-of-mass energies between 4.189 and 4.437 GeV with the BESIII detector [13] with a total integrated luminosity of  $11 \text{ fb}^{-1}$ . The  $J/\psi$  is reconstructed in its decay to a  $\ell^+\ell^-$  pair ( $\ell = e$  or  $\mu$ ), and the  $\pi^0$  is reconstructed via the decay  $\pi^0 \rightarrow \gamma\gamma$ . Additionally, the decay  $h_c \rightarrow \gamma\eta_c$  with  $\eta_c \rightarrow K^+K^-\pi^0$  is used as the normalization channel.

## 2 BESIII detector and Monte Carlo simulation

The BESIII detector [13] records symmetric  $e^+e^-$  collisions provided by the BEPCII storage ring [14], which operates with a peak luminosity of  $1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$  in the center-of-mass energy range from 2.0 to 4.95 GeV. BESIII has collected large data samples in this energy region [15]. 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 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 [16–18]. About 70% of the data sample used here was taken after this upgrade.

Simulated data samples produced with a GEANT4-based [19] Monte Carlo (MC) package, which includes the geometric description of the BESIII detector 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 [20, 21]. The inclusive MC sample includes the production of open charm processes, the ISR production of vector charmonium(-like) states, and the continuum processes incorporated in KKMC [20, 21]. The known decay modes are modelled with EVTGEN [22, 23] using branching fractions taken from the Particle Data Group (PDG) [2], and the remaining unknown charmonium decays are modelled with LUNDCHARM [24, 25]. Final state radiation (FSR) from charged final state particles is incorporated using PHOTOS [26]. Signal MC samples for  $e^+e^- \rightarrow \pi^+\pi^-h_c$  are generated using isotropic phase space populations at each center-of-mass energy point, assuming that the input line-shape follows a coherent sum of  $Y(4220)$  and  $Y(4390)$  Breit-Wigner functions, whose parameters are fixed to the measured values in ref. [12]. The subsequent  $h_c \rightarrow \pi^0 J/\psi$  decay is generated uniformly in phase space, and the transition  $h_c \rightarrow \gamma\eta_c$  is generated with an angular distribution of  $1 + \cos^2\theta^*$ , where  $\theta^*$  is the angle of the photon with respect to the  $h_c$  helicity direction in the  $h_c$  rest frame. Furthermore, the three-body process  $\eta_c \rightarrow K^+K^-\pi^0$  is simulated according to the measured two-body invariant-mass distributions [10].

## 3 Event selection

For each charged track, the distance of closest approach to the interaction point is required to be within  $\pm 10$  cm in the beam direction and within 1 cm in the plane perpendicular to the beam direction. The polar angle ( $\theta$ ) of the charged tracks must be within the fiducial volume of the MDC ( $|\cos\theta| < 0.93$ ). Photons are reconstructed from isolated showers in

the EMC, which are at least  $10^\circ$  away from the nearest charged track. The photon energy is required to be at least 25 MeV in the barrel region ( $|\cos\theta| < 0.80$ ) or 50 MeV in the end cap region ( $0.86 < |\cos\theta| < 0.92$ ). To suppress electronic noise and energy depositions unrelated to the event, the time at which the photon is recorded in the EMC is required to be within 700 ns of the event start time.

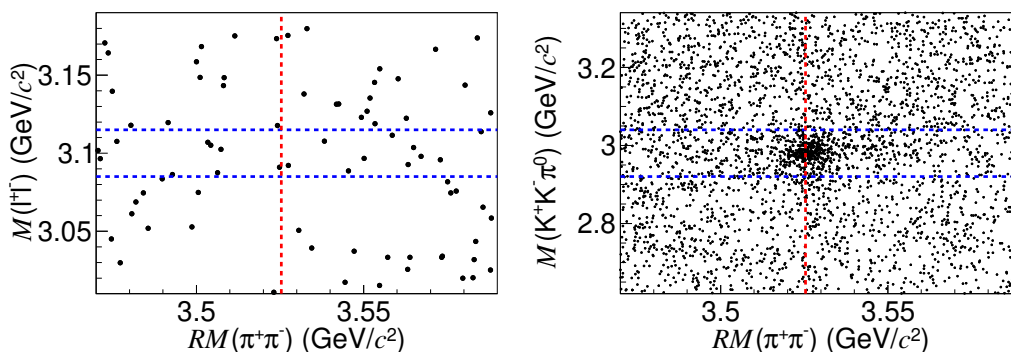
Since the decays  $h_c \rightarrow \pi^0 J/\psi$  and  $h_c \rightarrow \gamma\eta_c$  result in the final states  $\gamma\gamma\pi^+\pi^-\ell^+\ell^-$  and  $\gamma\gamma\pi^+\pi^-K^+K^-$ , respectively, candidate events are required to have four charged tracks with zero net charge, at least two photons for  $h_c \rightarrow \pi^0 J/\psi$ , and at least three for  $h_c \rightarrow \gamma\eta_c$ . For the  $h_c \rightarrow \pi^0 J/\psi$  decay, tracks with momenta larger than 1.0 GeV/c are assigned to be leptons from  $J/\psi$  decay. Otherwise, they are considered as pions. Leptons from the  $J/\psi$  decay with an energy deposited in the EMC larger than 1.0 GeV are identified as electrons, and those with less than 0.4 GeV as muons. For the  $h_c \rightarrow \gamma\eta_c$  decay, information from TOF and  $dE/dx$  measurements is combined to form particle identification (PID) likelihoods for the  $\pi$ ,  $K$  and  $p$  hypotheses. Each track is assigned with a particle type corresponding to the hypothesis of the highest PID likelihood. Exactly two oppositely charged  $\pi$  and  $K$  each are required in each event. To reduce the background contributions and to improve the mass resolution, a five-constraint kinematic fit is performed for the two channels. The total four-momentum is constrained to the initial four-momentum of the  $e^+e^-$  system. Additionally, the invariant mass of the two photons from the  $\pi^0$  decay is constrained to the  $\pi^0$  mass taken from the PDG [2]. If there is more than one candidate in an event, the one with the smallest  $\chi^2$  of the kinematic fit is selected. The  $\chi^2$  is required to be less than 30 for  $h_c \rightarrow \pi^0 J/\psi$  or 40 for  $h_c \rightarrow \gamma\eta_c$ .

To remove backgrounds from  $\eta/\omega \rightarrow \pi^+\pi^-\pi^0$  in the  $h_c \rightarrow \pi^0 J/\psi$  decay, events with invariant mass  $M(\pi^+\pi^-\pi^0)$  in regions around the mass of the  $\eta$  or  $\omega$ , namely  $[0.51, 0.58]$  GeV/ $c^2$  or  $[0.75, 0.81]$  GeV/ $c^2$ , respectively, are excluded. The  $J/\psi$  signal region is chosen as the range  $[3.085, 3.115]$  GeV/ $c^2$  in  $M(\ell^+\ell^-)$ , and sideband regions for studying the non-resonant backgrounds are defined as the ranges  $[3.00, 3.06]$  and  $[3.14, 3.20]$  GeV/ $c^2$ . The  $\eta_c$  signal region is chosen to be  $[2.92, 3.04]$  GeV/ $c^2$  in  $M(K^+K^-\pi^0)$ , and sideband regions are the ranges  $[2.59, 2.71]$  GeV/ $c^2$  and  $[3.25, 3.37]$  GeV/ $c^2$ .

## 4 Branching fraction measurement

Distributions of the invariant mass of  $\ell^+\ell^-$  (or  $K^+K^-\pi^0$ ),  $M(\ell^+\ell^-)$  (or  $M(K^+K^-\pi^0)$ ), versus the recoil mass of  $\pi^+\pi^-$ ,  $RM(\pi^+\pi^-)$  for  $h_c \rightarrow \pi^0 J/\psi$  (or  $\gamma\eta_c$ ) are shown in figure 1. Here,  $RM(\pi^+\pi^-) = \sqrt{(P_{e^+e^-} - P_{\pi^+} - P_{\pi^-})^2}$ , where  $P_{e^+e^-}$  and  $P_{\pi^\pm}$  are the four-momenta of the initial  $e^+e^-$  system and the  $\pi^\pm$ , respectively. No significant signal is observed for the  $h_c \rightarrow \pi^0 J/\psi$  decay. As expected, a high-density area can be observed originating from the  $h_c \rightarrow \gamma\eta_c$  decay.

Figure 2 shows the distributions of  $RM(\pi^+\pi^-)$  for the decays  $h_c \rightarrow \pi^0 J/\psi$  and  $h_c \rightarrow \gamma\eta_c$  for data in the  $J/\psi$  and  $\eta_c$  signal regions. No significant signal is seen for the  $h_c \rightarrow \pi^0 J/\psi$  decay, while a clear peak is present for the  $h_c \rightarrow \gamma\eta_c$  decay. The green shaded histograms correspond to the normalized events from the  $J/\psi$  and  $\eta_c$  sideband regions. No significant peaks are found in sideband events, and the sideband is not used in the following



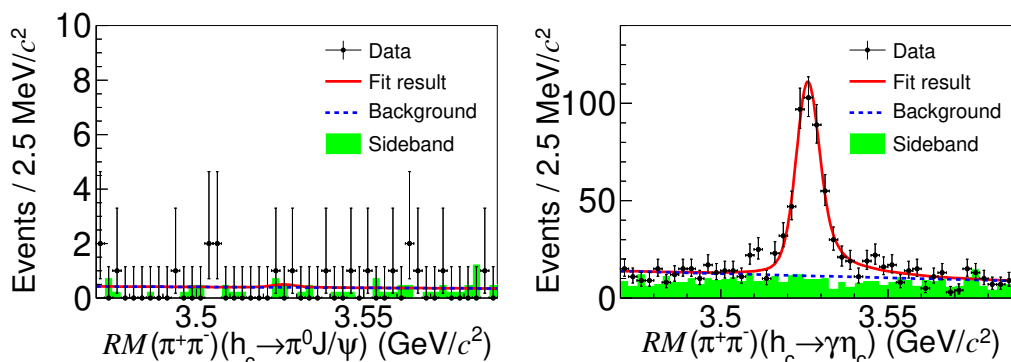
**Figure 1.** Distributions of  $M(\ell^+\ell^-)$  versus  $RM(\pi^+\pi^-)$  for  $h_c \rightarrow \pi^0 J/\psi$  (left panel) and  $M(K^+K^-\pi^0)$  versus  $RM(\pi^+\pi^-)$  for  $h_c \rightarrow \gamma\eta_c$  (right panel). The horizontal dashed lines denote the signal regions of the  $J/\psi$  (left) and  $\eta_c$  (right), and the vertical dashed lines mark the nominal  $h_c$  mass.

fit. A detailed study of the inclusive MC sample indicates that there are no peaking background contributions in the  $h_c$  signal region [27]. In order to extract the  $h_c$  signal yield, a simultaneous unbinned maximum-likelihood fit to the  $RM(\pi^+\pi^-)$  in two decay channels is performed. The signal shape of  $RM(\pi^+\pi^-)$  is modeled by a shape obtained from the simulation convolved with a Gaussian function. The mean value and width of the Gaussian function are allowed to float, but are constrained to be the same for the two channels in the simultaneous fit. The background is described by a first-order polynomial function. The solid curves in figure 2 show the fit results. The  $h_c$  signal yields are  $0.5 \pm 1.6$  and  $451.6 \pm 26.7$  for the decays  $h_c \rightarrow \pi^0 J/\psi$  and  $h_c \rightarrow \gamma\eta_c$ , respectively. Since no significant signal is observed for the  $h_c \rightarrow \pi^0 J/\psi$  decay, an upper limit at 90% confidence level (C.L.) using the Bayesian method is given. With the fit function described above, the  $h_c \rightarrow \pi^0 J/\psi$  signal yield is scanned to obtain the likelihood distribution, which is then convolved with the systematic uncertainty. The upper limit on the  $h_c \rightarrow \pi^0 J/\psi$  signal yield  $N_{\pi^0 J/\psi}^{\text{up}}$  at 90% C.L. is obtained by solving the equation  $\int_0^{N_{\pi^0 J/\psi}^{\text{up}}} F(x)dx / \int_0^\infty F(x)dx = 0.90$ , where  $x$  is  $h_c \rightarrow \pi^0 J/\psi$  signal yield and  $F(x)$  is the probability density function of the likelihood distribution. The upper limit  $N_{\pi^0 J/\psi}^{\text{up}}$  is determined to be 4.8.

The branching ratio  $\mathcal{B}(h_c \rightarrow \pi^0 J/\psi) / \mathcal{B}(h_c \rightarrow \gamma\eta_c \rightarrow \gamma K^+ K^- \pi^0)$  is calculated with

$$\frac{\mathcal{B}(h_c \rightarrow \pi^0 J/\psi)}{\mathcal{B}(h_c \rightarrow \gamma\eta_c \rightarrow \gamma K^+ K^- \pi^0)} = \frac{N_{\pi^0 J/\psi}}{N_{\gamma\eta_c}} \frac{\sum_i \mathcal{L}_i \sigma_i (1 + \delta_i) \epsilon_i^{\gamma\eta_c}}{\sum_i \mathcal{L}_i \sigma_i (1 + \delta_i) \epsilon_i^{\pi^0 J/\psi}} \frac{1}{\mathcal{B}(J/\psi \rightarrow \ell^+\ell^-)}, \quad (4.1)$$

where  $N$  is the yield of signal events,  $\mathcal{L}$  is the integrated luminosity [28],  $\sigma$  is the cross section of  $e^+e^- \rightarrow \pi^+\pi^-h_c$  [12],  $1 + \delta$  is the radiative correction factor [20, 21, 29],  $\epsilon$  is the efficiency,  $\mathcal{B}(J/\psi \rightarrow \ell^+\ell^-)$  is the branching fraction of  $J/\psi \rightarrow \ell^+\ell^-$  from the PDG [2], and  $i$  denotes each energy point. Table 1 shows the luminosity, cross section, radiative correction factor and efficiency at each center-of-mass energy. So the ratio  $\sum_i \mathcal{L}_i \sigma_i (1 + \delta_i) \epsilon_i^{\gamma\eta_c} / \sum_i \mathcal{L}_i \sigma_i (1 + \delta_i) \epsilon_i^{\pi^0 J/\psi}$  is 0.847, and the upper limit on the branching



**Figure 2.** Results of the simultaneous fit to the  $RM(\pi^+\pi^-)$  distributions from the decays  $h_c \rightarrow \pi^0 J/\psi$  (left panel) and  $h_c \rightarrow \gamma\eta_c$  (right panel). The red solid lines are the total fit results and the blue dashed lines are the background components. The green shaded histograms correspond to the normalized events from the  $J/\psi$  and  $\eta_c$  sideband regions.

ratio  $\mathcal{B}(h_c \rightarrow \pi^0 J/\psi)/\mathcal{B}(h_c \rightarrow \gamma\eta_c \rightarrow \gamma K^+ K^- \pi^0)$  at 90% C.L. is determined to be  $\mathcal{B}(h_c \rightarrow \pi^0 J/\psi)/\mathcal{B}(h_c \rightarrow \gamma\eta_c \rightarrow \gamma K^+ K^- \pi^0) < 7.5 \times 10^{-2}$ . With the world averages of  $\mathcal{B}(h_c \rightarrow \gamma\eta_c)$  and  $\mathcal{B}(\eta_c \rightarrow K^+ K^- \pi^0)$  from the PDG [2], which is  $\mathcal{B}(h_c \rightarrow \gamma\eta_c) = (51 \pm 6)\%$  and  $\mathcal{B}(\eta_c \rightarrow K^+ K^- \pi^0) = \mathcal{B}(\eta_c \rightarrow KK\pi)/6 = (1.217 \pm 0.067)\%$  according to the isospin symmetry, an upper limit on the branching fraction  $\mathcal{B}(h_c \rightarrow \pi^0 J/\psi)$  at 90% C.L. can be determined to be  $\mathcal{B}(h_c \rightarrow \pi^0 J/\psi) < 4.7 \times 10^{-4}$ . The systematic uncertainties have been considered in these upper limit calculations.

## 5 Systematic uncertainty

The sources of systematic uncertainty related to the branching ratio  $\mathcal{B}(h_c \rightarrow \pi^0 J/\psi)/\mathcal{B}(h_c \rightarrow \gamma\eta_c \rightarrow \gamma K^+ K^- \pi^0)$  and branching fraction  $\mathcal{B}(h_c \rightarrow \pi^0 J/\psi)$  are summarized in table 2, where the uncertainties associated with the charged track PID efficiencies and normalization channel yields, as well as the branching fraction of the normalization channel used to obtain the absolute branching fraction of  $h_c \rightarrow \pi^0 J/\psi$ .

The uncertainty in the photon efficiency and charged track PID efficiency is 1% per photon or per track [30–32]. The uncertainty due to the kinematic fit is estimated by correcting the helix parameters of charged tracks, and the difference between the results with and without this correction is taken as the uncertainty [33]. To estimate the uncertainty related to the input line-shape of the process  $e^+e^- \rightarrow \pi^+\pi^-h_c$ , the input line-shape is changed to a flat line-shape and the difference is taken as the uncertainty.

The process  $e^+e^- \rightarrow \pi^+\pi^-h_c$  is generated by a three-body phase-space model. The uncertainty related to the MC decay model is obtained by substitution with a model  $e^+e^- \rightarrow \pi^\pm Z_c(4020)^\mp \rightarrow \pi^+\pi^-h_c$ . The angular distribution of  $h_c \rightarrow \pi^0 J/\psi$  is varied from phase space to  $1 \pm \cos^2\theta^{**}$ , where  $\theta^{**}$  is the angle of the  $\pi^0$  with respect to the  $h_c$  helicity direction in the  $h_c$  rest frame. These two items are combined as the total uncertainty from the MC decay model.

$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb $^{-1}$ )	$\sigma$ (pb)	$1 + \delta$	$\epsilon^{\pi^0 J/\psi}$ (%)	$\epsilon^{\gamma\eta_c}$ (%)
4.189	570	15.315	0.705	17.60	15.07
4.199	526	25.183	0.706	17.68	15.25
4.209	572	38.706	0.712	17.58	15.33
4.219	570	51.740	0.725	17.59	15.27
4.226	1101	57.072	0.740	18.41	15.62
4.236	530	57.956	0.766	17.80	15.38
4.244	594	55.185	0.786	17.62	15.40
4.258	828	49.053	0.817	17.58	15.04
4.267	531	46.002	0.831	16.94	15.03
4.278	176	43.657	0.842	16.85	14.47
4.288	502	42.757	0.847	16.38	14.10
4.312	546	44.609	0.845	16.79	14.36
4.338	505	51.729	0.834	17.29	14.45
4.358	544	58.972	0.829	17.74	14.83
4.378	579	63.700	0.835	17.99	14.63
4.397	508	61.392	0.857	17.42	14.42
4.416	1091	52.183	0.898	17.12	14.03
4.437	570	39.299	0.960	15.85	13.34

**Table 1.** The luminosity  $\mathcal{L}$ , cross section  $\sigma$ , radiative correction factor  $1 + \delta$  and efficiency  $\epsilon$  at each center-of-mass energy  $\sqrt{s}$ .

The uncertainty from the  $J/\psi$  mass window requirement is estimated using  $e^+e^- \rightarrow \gamma_{ISR}\psi(3686) \rightarrow \gamma_{ISR}\pi^+\pi^-J/\psi$  events [34]. The efficiency difference between data and MC simulation is taken as the systematic uncertainty, which arises from the different mass resolutions in the data and the simulation. The uncertainty from the  $\eta_c$  mass window requirement is obtained by shifting the  $\eta_c$  mass window by  $\pm 10$  MeV/ $c^2$ , and we take the difference of  $\mathcal{B}(h_c \rightarrow \gamma\eta_c \rightarrow \gamma K^+K^-\pi^0)$  to the nominal one as the systematic uncertainty. These two items are combined as the total uncertainty of the mass window.

The number of events for the normalization channel  $h_c \rightarrow \gamma\eta_c$  is determined to be  $N_{\gamma\eta_c} = 451.6 \pm 26.7$ . The uncertainty from the yield of the normalization channel is thus 5.9%. The uncertainties from the branching fractions  $\mathcal{B}(J/\psi \rightarrow l^+l^-)$ ,  $\mathcal{B}(h_c \rightarrow \gamma\eta_c)$  and  $\mathcal{B}(\eta_c \rightarrow K^+K^-\pi^0)$  are taken from the PDG [2].

The overall systematic uncertainties except for the fit procedure are obtained by adding all sources of systematic uncertainties in quadrature, assuming they are uncorrelated, and are summarized in table 2.

The sources of uncertainty in the fit procedure include the fit range and background shape. The limit of the fit range is varied by  $\pm 5$  MeV/ $c^2$ , and the background shape is replaced from the first-order polynomial to a constant function or a second-order polynomial function. For the uncertainty from the fit procedure for the upper limit measurement, different combinations of fit range and background shape are used to get the upper limits, and the largest upper limit is chosen as the nominal one. Then the likelihood distribution

Source	$\mathcal{B}(h_c \rightarrow \pi^0 J/\psi)/\mathcal{B}(h_c \rightarrow \gamma\eta_c \rightarrow \gamma K^+ K^- \pi^0)$	$\mathcal{B}(h_c \rightarrow \pi^0 J/\psi)$
Photon efficiency	1.0	1.0
PID efficiency	4.0	4.0
Kinematic fit	2.0	2.0
Input line-shape	1.2	1.2
MC decay model	1.6	1.6
Mass window	2.4	2.4
Normalization channel yield	5.9	5.9
$\mathcal{B}(J/\psi \rightarrow l^+ l^-)$	0.6	0.6
$\mathcal{B}(h_c \rightarrow \gamma\eta_c)$	—	11.8
$\mathcal{B}(\eta_c \rightarrow K^+ K^- \pi^0)$	—	5.5
Sum	8.1	15.3

**Table 2.** Relative systematic uncertainties (in %) on the branching ratio  $\mathcal{B}(h_c \rightarrow \pi^0 J/\psi)/\mathcal{B}(h_c \rightarrow \gamma\eta_c \rightarrow \gamma K^+ K^- \pi^0)$  and the branching fraction  $\mathcal{B}(h_c \rightarrow \pi^0 J/\psi)$ . Dashes are used when sources of uncertainty are not applicable.

of the nominal upper limit is convolved with the above overall systematic uncertainties to get the final upper limit.

## 6 Summary and discussion

The decay  $h_c \rightarrow \pi^0 J/\psi$  is searched for using the process  $e^+e^- \rightarrow \pi^+\pi^-h_c$  with data samples collected at center-of-mass energies between 4.189 and 4.437 GeV with the BESIII detector corresponding to a total integrated luminosity of  $11 \text{ fb}^{-1}$ . No significant signal is observed for the decay channel  $h_c \rightarrow \pi^0 J/\psi$ . The upper limits on the branching ratio  $\mathcal{B}(h_c \rightarrow \pi^0 J/\psi)/\mathcal{B}(h_c \rightarrow \gamma\eta_c \rightarrow \gamma K^+ K^- \pi^0)$  and the branching fraction  $\mathcal{B}(h_c \rightarrow \pi^0 J/\psi)$  at 90% confidence level are determined to be  $7.5 \times 10^{-2}$  and  $4.7 \times 10^{-4}$ , respectively. The latter is derived from the former using the measured branching fraction of the normalization channel. This is the first upper limit measurement of the branching fraction for the decay  $h_c \rightarrow \pi^0 J/\psi$ . The measured results are not consistent with the measurements by the E760 Collaboration [3], while in agreement with the E835 Collaboration [4]. The  $h_c$  total width is  $0.7 \pm 0.4 \text{ MeV}$  from the PDG [2], and we take 1.1 MeV as the  $h_c$  total width conservatively. Therefore, the upper limit on the partial width for  $h_c \rightarrow \pi^0 J/\psi$  is conservatively determined to be  $\Gamma(h_c \rightarrow \pi^0 J/\psi) < 0.52 \text{ keV}$ , which is one order-of-magnitude lower than the current theoretical predictions (several keV) [5–8].

## 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 R&D Program of China under Contracts Nos. 2020YFA0406300, 2020YFA0406400; National Natural Science Foundation of China (NSFC) under Contracts Nos. 11905179, 11625523, 11635010,



11735014, 11822506, 11835012, 11935015, 11935016, 11935018, 11961141012, 12022510, 12025502, 12035009, 12035013, 12061131003; the Chinese Academy of Sciences (CAS) Large-Scale Scientific Facility Program; Joint Large-Scale Scientific Facility Funds of the NSFC and CAS under Contracts Nos. U1732263, U1832207; CAS Key Research Program of Frontier Sciences under Contract No. QYZDJ-SSW-SLH040; 100 Talents Program of CAS; INPAC and Shanghai Key Laboratory for Particle Physics and Cosmology; ERC under Contract No. 758462; Nanhu Scholars Program for Young Scholars of Xinyang Normal University; European Union Horizon 2020 research and innovation programme under Contract No. Marie Skłodowska-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 (United Kingdom); 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.

**Open Access.** This article is distributed under the terms of the Creative Commons Attribution License ([CC-BY 4.0](https://creativecommons.org/licenses/by/4.0/)), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited.

## References

- [1] S. Godfrey and N. Isgur, *Mesons in a relativized quark model with chromodynamics*, *Phys. Rev. D* **32** (1985) 189 [[INSPIRE](#)].
- [2] PARTICLE DATA GROUP collaboration, *Review of Particle Physics*, *PTEP* **2020** (2020) 083C01 [[INSPIRE](#)].
- [3] T.A. Armstrong et al., *Observation of the  $^1P_1$  state of charmonium*, *Phys. Rev. Lett.* **69** (1992) 2337 [[INSPIRE](#)].
- [4] M. Andreotti et al., *Results of a search for the  $h_c(^1P_1)$  state of charmonium in the  $\eta_c\gamma$  and  $J/\psi\pi^0$  decay modes*, *Phys. Rev. D* **72** (2005) 032001 [[INSPIRE](#)].
- [5] Y.-P. Kuang, S.F. Tuan and T.-M. Yan, *Hadronic transitions and  $^1P_1$  states of heavy quarkonia*, *Phys. Rev. D* **37** (1988) 1210 [[INSPIRE](#)].
- [6] P. Ko, *Radiative and hadronic transitions of the charmonium  $^1P_1$  state*, *Phys. Rev. D* **47** (1993) 2837 [[INSPIRE](#)].
- [7] P. Ko, *Search for  $\eta'_c$  and  $h_c(^1P_1)$  states in  $e^+e^-$  annihilation*, *Phys. Rev. D* **52** (1995) 1710 [[hep-ph/9505299](#)] [[INSPIRE](#)].
- [8] M.B. Voloshin, *Pion transitions from  $\chi_{cJ}$  to  $\eta_c$* , *Phys. Rev. D* **86** (2012) 074033 [[arXiv:1209.3716](#)] [[INSPIRE](#)].
- [9] BESIII collaboration, *Measurements of  $h_c(^1P_1)$  in  $\psi'$  Decays*, *Phys. Rev. Lett.* **104** (2010) 132002 [[arXiv:1002.0501](#)] [[INSPIRE](#)].
- [10] BESIII collaboration, *Study of  $\psi(3686) \rightarrow \pi^0 h_c$ ,  $h_c \rightarrow \gamma \eta_c$  via  $\eta_c$  exclusive decays*, *Phys. Rev. D* **86** (2012) 092009 [[arXiv:1209.4963](#)] [[INSPIRE](#)].

- [11] BESIII collaboration, *Observation of  $h_c$  Radiative Decay  $h_c \rightarrow \gamma\eta'$  and Evidence for  $h_c \rightarrow \gamma\eta$* , *Phys. Rev. Lett.* **116** (2016) 251802 [[arXiv:1603.04936](#)] [[INSPIRE](#)].
- [12] BESIII collaboration, *Evidence of Two Resonant Structures in  $e^+e^- \rightarrow \pi^+\pi^-h_c$* , *Phys. Rev. Lett.* **118** (2017) 092002 [[arXiv:1610.07044](#)] [[INSPIRE](#)].
- [13] BESIII collaboration, *Design and construction of the BESIII detector*, *Nucl. Instrum. Meth. A* **614** (2010) 345 [[arXiv:0911.4960](#)] [[INSPIRE](#)].
- [14] C.H. Yu et al., *BEPCII Performance and Beam Dynamics Studies on Luminosity*, in *Proceedings of IPAC2016*, Busan, Korea 2016, [[DOI](#)].
- [15] BESIII collaboration, *Future Physics Programme of BESIII*, *Chin. Phys. C* **44** (2020) 040001 [[arXiv:1912.05983](#)] [[INSPIRE](#)].
- [16] X. Li et al., *Study of MRPC technology for BESIII endcap-TOF upgrade*, *Radiat. Detect. Technol. Methods* **1** (2017) 13.
- [17] Y.X. Guo et al., *The study of time calibration for upgraded end cap TOF of BESIII*, *Radiat. Detect. Technol. Methods* **1** (2017) 15.
- [18] P. Cao et al., *Design and construction of the new BESIII endcap Time-of-Flight system with MRPC Technology*, *Nucl. Instrum. Meth. A* **953** (2020) 163053.
- [19] GEANT4 collaboration, *GEANT4 — a simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250 [[INSPIRE](#)].
- [20] S. Jadach, B.F.L. Ward and Z. Was, *Coherent exclusive exponentiation for precision Monte Carlo calculations*, *Phys. Rev. D* **63** (2001) 113009 [[hep-ph/0006359](#)] [[INSPIRE](#)].
- [21] S. Jadach, B.F.L. Ward and Z. Was, *The precision Monte Carlo event generator KK for two-fermion final states in  $e^+e^-$  collisions*, *Comput. Phys. Commun.* **130** (2000) 260 [[hep-ph/9912214](#)] [[INSPIRE](#)].
- [22] D.J. Lange, *The EvtGen particle decay simulation package*, *Nucl. Instrum. Meth. A* **462** (2001) 152 [[INSPIRE](#)].
- [23] R.-G. Ping, *Event generators at BESIII*, *Chin. Phys. C* **32** (2008) 599 [[INSPIRE](#)].
- [24] J.C. Chen, G.S. Huang, X.R. Qi, D.H. Zhang and Y.S. Zhu, *Event generator for  $J/\psi$  and  $\psi(2S)$  decay*, *Phys. Rev. D* **62** (2000) 034003 [[INSPIRE](#)].
- [25] R.-L. Yang, R.-G. Ping and H. Chen, *Tuning and Validation of the Lundcharm Model with  $J/\psi$  Decays*, *Chin. Phys. Lett.* **31** (2014) 061301 [[INSPIRE](#)].
- [26] E. Richter-Was, *QED bremsstrahlung in semileptonic  $B$  and leptonic  $\tau$  decays*, *Phys. Lett. B* **303** (1993) 163 [[INSPIRE](#)].
- [27] X. Zhou, S. Du, G. Li and C. Shen, *TopoAna: A generic tool for the event type analysis of inclusive Monte-Carlo samples in high energy physics experiments*, *Comput. Phys. Commun.* **258** (2021) 107540.
- [28] BESIII collaboration, *Precision measurement of the integrated luminosity of the data taken by BESIII at center-of-mass energies between 3.810 GeV and 4.600 GeV*, *Chin. Phys. C* **39** (2015) 093001 [[arXiv:1503.03408](#)] [[INSPIRE](#)].
- [29] E.A. Kuraev and V.S. Fadin, *On Radiative Corrections to  $e^+e^-$  Single Photon Annihilation at High-Energy*, *Sov. J. Nucl. Phys.* **41** (1985) 466 [[INSPIRE](#)].

- [30] BESIII collaboration, *Cross section measurements of  $e^+e^- \rightarrow \omega\chi_{c0}$  from  $\sqrt{s} = 4.178$  to  $4.278$  GeV*, *Phys. Rev. D* **99** (2019) 091103 [[arXiv:1903.02359](#)] [[INSPIRE](#)].
- [31] BESIII collaboration, *Search for new decay modes of the  $\psi_2(3823)$  and the process  $e^+e^- \rightarrow \pi^0\pi^0\psi_2(3823)$* , *Phys. Rev. D* **103** (2021) L091102 [[arXiv:2102.10845](#)] [[INSPIRE](#)].
- [32] G0 collaboration, *Study of  $e^+e^- \rightarrow \pi^0 X(3872)\gamma$  and search for  $Z_c(4020)^0 \rightarrow X(3872)\gamma$* , *Phys. Rev. Lett.* **104** (2010) 012001 [[arXiv:0909.5107](#)] [[INSPIRE](#)].
- [33] BESIII collaboration, *Search for hadronic transition  $\chi_{cJ} \rightarrow \eta_c\pi^+\pi^-$  and observation of  $\chi_{cJ} \rightarrow K\bar{K}\pi\pi\pi$* , *Phys. Rev. D* **87** (2013) 012002 [[arXiv:1208.4805](#)] [[INSPIRE](#)].
- [34] BESIII collaboration, *Cross section measurement of  $e^+e^- \rightarrow \eta' J/\psi$  from  $\sqrt{s} = 4.178$  to  $4.600$  GeV*, *Phys. Rev. D* **101** (2020) 012008 [[arXiv:1911.00885](#)] [[INSPIRE](#)].

## The BESIII collaboration

M. Ablikim<sup>1</sup>, M.N. Achasov<sup>10,b</sup>, P. Adlarson<sup>68</sup>, S. Ahmed<sup>14</sup>, M. Albrecht<sup>4</sup>, R. Aliberti<sup>28</sup>, A. Amoroso<sup>67A,67C</sup>, M.R. An<sup>32</sup>, Q. An<sup>64,50</sup>, X.H. Bai<sup>58</sup>, Y. Bai<sup>49</sup>, O. Bakina<sup>29</sup>, R. Baldini Ferroli<sup>23A</sup>, I. Balossino<sup>24A</sup>, Y. Ban<sup>39,h</sup>, K. Begzsuren<sup>26</sup>, N. Berger<sup>28</sup>, M. Bertani<sup>23A</sup>, D. Bettoni<sup>24A</sup>, F. Bianchi<sup>67A,67C</sup>, J. Bloms<sup>61</sup>, A. Bortone<sup>67A,67C</sup>, I. Boyko<sup>29</sup>, R.A. Briere<sup>5</sup>, H. Cai<sup>69</sup>, X. Cai<sup>1,50</sup>, A. Calcaterra<sup>23A</sup>, G.F. Cao<sup>1,55</sup>, N. Cao<sup>1,55</sup>, S.A. Cetin<sup>54A</sup>, J.F. Chang<sup>1,50</sup>, W.L. Chang<sup>1,55</sup>, G. Chelkov<sup>29,a</sup>, D.Y. Chen<sup>6</sup>, G. Chen<sup>1</sup>, H.S. Chen<sup>1,55</sup>, M.L. Chen<sup>1,50</sup>, S.J. Chen<sup>35</sup>, X.R. Chen<sup>25</sup>, Y.B. Chen<sup>1,50</sup>, Z.J. Chen<sup>20,i</sup>, W.S. Cheng<sup>67C</sup>, G. Cibinetto<sup>24A</sup>, F. Cossio<sup>67C</sup>, X.F. Cui<sup>36</sup>, H.L. Dai<sup>1,50</sup>, J.P. Dai<sup>71</sup>, X.C. Dai<sup>1,55</sup>, A. Dbeyssi<sup>14</sup>, R. E. de Boer<sup>4</sup>, D. Dedovich<sup>29</sup>, Z.Y. Deng<sup>1</sup>, A. Denig<sup>28</sup>, I. Denysenko<sup>29</sup>, M. Destefanis<sup>67A,67C</sup>, F. De Mori<sup>67A,67C</sup>, Y. Ding<sup>33</sup>, C. Dong<sup>36</sup>, J. Dong<sup>1,50</sup>, L.Y. Dong<sup>1,55</sup>, M.Y. Dong<sup>1,50,55</sup>, X. Dong<sup>69</sup>, S.X. Du<sup>73</sup>, Y.L. Fan<sup>69</sup>, J. Fang<sup>1,50</sup>, S.S. Fang<sup>1,55</sup>, Y. Fang<sup>1</sup>, R. Farinelli<sup>24A</sup>, L. Fava<sup>67B,67C</sup>, F. Feldbauer<sup>4</sup>, G. Felici<sup>23A</sup>, C.Q. Feng<sup>64,50</sup>, J.H. Feng<sup>51</sup>, M. Fritsch<sup>4</sup>, C.D. Fu<sup>1</sup>, Y. Gao<sup>64,50</sup>, Y. Gao<sup>39,h</sup>, Y.G. Gao<sup>6</sup>, I. Garzia<sup>24A,24B</sup>, P.T. Ge<sup>69</sup>, C. Geng<sup>51</sup>, E.M. Gersabeck<sup>59</sup>, A. Gilman<sup>62</sup>, K. Goetzen<sup>11</sup>, L. Gong<sup>33</sup>, W.X. Gong<sup>1,50</sup>, W. Gradl<sup>28</sup>, M. Greco<sup>67A,67C</sup>, L.M. Gu<sup>35</sup>, M.H. Gu<sup>1,50</sup>, C.Y. Guan<sup>1,55</sup>, A.Q. Guo<sup>22</sup>, A.Q. Guo<sup>25</sup>, L.B. Guo<sup>34</sup>, R.P. Guo<sup>41</sup>, Y.P. Guo<sup>9,f</sup>, A. Guskov<sup>29,a</sup>, T.T. Han<sup>42</sup>, W.Y. Han<sup>32</sup>, X.Q. Hao<sup>15</sup>, F.A. Harris<sup>57</sup>, K.L. He<sup>1,55</sup>, F.H. Heinsius<sup>4</sup>, C.H. Heinz<sup>28</sup>, Y.K. Heng<sup>1,50,55</sup>, C. Herold<sup>52</sup>, M. Himmelreich<sup>11,d</sup>, T. Holtmann<sup>4</sup>, G.Y. Hou<sup>1,55</sup>, Y.R. Hou<sup>55</sup>, Z.L. Hou<sup>1</sup>, H.M. Hu<sup>1,55</sup>, J.F. Hu<sup>48,j</sup>, T. Hu<sup>1,50,55</sup>, Y. Hu<sup>1</sup>, G.S. Huang<sup>64,50</sup>, L.Q. Huang<sup>65</sup>, X.T. Huang<sup>42</sup>, Y.P. Huang<sup>1</sup>, Z. Huang<sup>39,h</sup>, T. Hussain<sup>66</sup>, N. Hüsken<sup>22,28</sup>, W. Ikegami Andersson<sup>68</sup>, W. Imoehl<sup>22</sup>, M. Irshad<sup>64,50</sup>, S. Jaeger<sup>4</sup>, S. Janchiv<sup>26</sup>, Q. Ji<sup>1</sup>, Q.P. Ji<sup>15</sup>, X.B. Ji<sup>1,55</sup>, X.L. Ji<sup>1,50</sup>, Y.Y. Ji<sup>42</sup>, H.B. Jiang<sup>42</sup>, X.S. Jiang<sup>1,50,55</sup>, J.B. Jiao<sup>42</sup>, Z. Jiao<sup>18</sup>, S. Jin<sup>35</sup>, Y. Jin<sup>58</sup>, M.Q. Jing<sup>1,55</sup>, T. Johansson<sup>68</sup>, N. Kalantar-Nayestanaki<sup>56</sup>, X.S. Kang<sup>33</sup>, R. Kappert<sup>56</sup>, M. Kavatsyuk<sup>56</sup>, B.C. Ke<sup>44,1</sup>, I.K. Keshk<sup>4</sup>, A. Khoukaz<sup>61</sup>, P. Kiese<sup>28</sup>, R. Kiuchi<sup>1</sup>, R. Kliemt<sup>11</sup>, L. Koch<sup>30</sup>, O.B. Kolcu<sup>54A</sup>, B. Kopf<sup>4</sup>, M. Kuemmel<sup>4</sup>, M. Kuessner<sup>4</sup>, A. Kupsc<sup>37,68</sup>, M. G. Kurth<sup>1,55</sup>, W. Kühn<sup>30</sup>, J.J. Lane<sup>59</sup>, J.S. Lange<sup>30</sup>, P. Larin<sup>14</sup>, A. Lavania<sup>21</sup>, L. Lavezzi<sup>67A,67C</sup>, Z.H. Lei<sup>64,50</sup>, H. Leithoff<sup>28</sup>, M. Lellmann<sup>28</sup>, T. Lenz<sup>28</sup>, C. Li<sup>40</sup>, C.H. Li<sup>32</sup>, Cheng Li<sup>64,50</sup>, D.M. Li<sup>73</sup>, F. Li<sup>1,50</sup>, G. Li<sup>1</sup>, H. Li<sup>64,50</sup>, H. Li<sup>44</sup>, H.B. Li<sup>1,55</sup>, H.J. Li<sup>15</sup>, H.N. Li<sup>48,j</sup>, J.L. Li<sup>42</sup>, J.Q. Li<sup>4</sup>, J.S. Li<sup>51</sup>, Ke Li<sup>1</sup>, L.K. Li<sup>1</sup>, Lei Li<sup>3</sup>, P.R. Li<sup>31,k,l</sup>, S.Y. Li<sup>53</sup>, W.D. Li<sup>1,55</sup>, W.G. Li<sup>1</sup>, X.H. Li<sup>64,50</sup>, X.L. Li<sup>42</sup>, Xiaoyu Li<sup>1,55</sup>, Z.Y. Li<sup>51</sup>, H. Liang<sup>64,50</sup>, H. Liang<sup>1,55</sup>, H. Liang<sup>27</sup>, Y.F. Liang<sup>46</sup>, Y.T. Liang<sup>25</sup>, G.R. Liao<sup>12</sup>, L.Z. Liao<sup>1,55</sup>, J. Libby<sup>21</sup>, A. Limphirat<sup>52</sup>, C.X. Lin<sup>51</sup>, D.X. Lin<sup>25</sup>, T. Lin<sup>1</sup>, B.J. Liu<sup>1</sup>, C.X. Liu<sup>1</sup>, D. Liu<sup>14,64</sup>, F.H. Liu<sup>45</sup>, Fang Liu<sup>1</sup>, Feng Liu<sup>6</sup>, G.M. Liu<sup>48,j</sup>, H.M. Liu<sup>1,55</sup>, Huanhuan Liu<sup>1</sup>, Huihui Liu<sup>16</sup>, J.B. Liu<sup>64,50</sup>, J.L. Liu<sup>65</sup>, J.Y. Liu<sup>1,55</sup>, K. Liu<sup>1</sup>, K.Y. Liu<sup>33</sup>, Ke Liu<sup>17,m</sup>, L. Liu<sup>64,50</sup>, M.H. Liu<sup>9,f</sup>, P.L. Liu<sup>1</sup>, Q. Liu<sup>55</sup>, Q. Liu<sup>69</sup>, S.B. Liu<sup>64,50</sup>, T. Liu<sup>1,55</sup>, T. Liu<sup>9,f</sup>, W.M. Liu<sup>64,50</sup>, X. Liu<sup>31,k,l</sup>, Y. Liu<sup>31,k,l</sup>, Y.B. Liu<sup>36</sup>, Z.A. Liu<sup>1,50,55</sup>, Z.Q. Liu<sup>42</sup>, X.C. Lou<sup>1,50,55</sup>, F.X. Lu<sup>51</sup>, H.J. Lu<sup>18</sup>, J.D. Lu<sup>1,55</sup>, J.G. Lu<sup>1,50</sup>, X.L. Lu<sup>1</sup>, Y. Lu<sup>1</sup>, Y.P. Lu<sup>1,50</sup>, C.L. Luo<sup>34</sup>, M.X. Luo<sup>72</sup>, P.W. Luo<sup>51</sup>, T. Luo<sup>9,f</sup>, X.L. Luo<sup>1,50</sup>, X.R. Lyu<sup>55</sup>, F.C. Ma<sup>33</sup>, H.L. Ma<sup>1</sup>, L.L. Ma<sup>42</sup>, M.M. Ma<sup>1,55</sup>, Q.M. Ma<sup>1</sup>, R.Q. Ma<sup>1,55</sup>, R.T. Ma<sup>55</sup>, X.X. Ma<sup>1,55</sup>, X.Y. Ma<sup>1,50</sup>, F.E. Maas<sup>14</sup>, M. Maggiora<sup>67A,67C</sup>, S. Maldaner<sup>4</sup>, S. Malde<sup>62</sup>, Q.A. Malik<sup>66</sup>, A. Mangoni<sup>23B</sup>, Y.J. Mao<sup>39,h</sup>, Z.P. Mao<sup>1</sup>, S. Marcello<sup>67A,67C</sup>, Z.X. Meng<sup>58</sup>, J.G. Messchendorp<sup>56</sup>, G. Mezzadri<sup>24A</sup>, T.J. Min<sup>35</sup>, R.E. Mitchell<sup>22</sup>, X.H. Mo<sup>1,50,55</sup>, N. Yu. Muchnoi<sup>10,b</sup>, H. Muramatsu<sup>60</sup>, S. Nakhoul<sup>11,d</sup>, Y. Nefedov<sup>29</sup>, F. Nerling<sup>11,d</sup>, I.B. Nikolaev<sup>10,b</sup>, Z. Ning<sup>1,50</sup>, S. Nisar<sup>8,g</sup>, S.L. Olsen<sup>55</sup>, Q. Ouyang<sup>1,50,55</sup>, S. Pacetti<sup>23B,23C</sup>, X. Pan<sup>9,f</sup>, Y. Pan<sup>59</sup>, A. Pathak<sup>1</sup>, A. Pathak<sup>27</sup>, P. Patteri<sup>23A</sup>, M. Pelizaeus<sup>4</sup>, H.P. Peng<sup>64,50</sup>, K. Peters<sup>11,d</sup>, J. Pettersson<sup>68</sup>, J.L. Ping<sup>34</sup>, R.G. Ping<sup>1,55</sup>, S. Pogodin<sup>29</sup>, R. Poling<sup>60</sup>, V. Prasad<sup>64,50</sup>, H. Qi<sup>64,50</sup>, H.R. Qi<sup>53</sup>, M. Qi<sup>35</sup>, T.Y. Qi<sup>9</sup>, S. Qian<sup>1,50</sup>, W.B. Qian<sup>55</sup>, Z. Qian<sup>51</sup>, C.F. Qiao<sup>55</sup>, J.J. Qin<sup>65</sup>, L.Q. Qin<sup>12</sup>, X.P. Qin<sup>9</sup>, X.S. Qin<sup>42</sup>, Z.H. Qin<sup>1,50</sup>, J.F. Qiu<sup>1</sup>, S.Q. Qu<sup>36</sup>, K.H. Rashid<sup>66</sup>, K. Ravindran<sup>21</sup>, C.F. Redmer<sup>28</sup>, A. Rivetti<sup>67C</sup>, V. Rodin<sup>56</sup>, M. Rolo<sup>67C</sup>, G. Rong<sup>1,55</sup>, Ch. Rosner<sup>14</sup>, M. Rump<sup>61</sup>, H.S. Sang<sup>64</sup>, A. Sarantsev<sup>29,c</sup>, Y. Schelhaas<sup>28</sup>,

C. Schnier<sup>4</sup>, K. Schoenning<sup>68</sup>, M. Scodeggio<sup>24A,24B</sup>, W. Shan<sup>19</sup>, X.Y. Shan<sup>64,50</sup>, J.F. Shangguan<sup>47</sup>, M. Shao<sup>64,50</sup>, C.P. Shen<sup>9</sup>, H.F. Shen<sup>1,55</sup>, X.Y. Shen<sup>1,55</sup>, H.C. Shi<sup>64,50</sup>, R.S. Shi<sup>1,55</sup>, X. Shi<sup>1,50</sup>, X.D. Shi<sup>64,50</sup>, J.J. Song<sup>42</sup>, J.J. Song<sup>15</sup>, W.M. Song<sup>27,1</sup>, Y.X. Song<sup>39,h</sup>, S. Sosio<sup>67A,67C</sup>, S. Spataro<sup>67A,67C</sup>, K.X. Su<sup>69</sup>, P.P. Su<sup>47</sup>, F.F. Sui<sup>42</sup>, G.X. Sun<sup>1</sup>, H.K. Sun<sup>1</sup>, J.F. Sun<sup>15</sup>, L. Sun<sup>69</sup>, S.S. Sun<sup>1,55</sup>, T. Sun<sup>1,55</sup>, W.Y. Sun<sup>27</sup>, X. Sun<sup>20,i</sup>, Y.J. Sun<sup>64,50</sup>, Y.Z. Sun<sup>1</sup>, Z.T. Sun<sup>1</sup>, Y.H. Tan<sup>69</sup>, Y.X. Tan<sup>64,50</sup>, C.J. Tang<sup>46</sup>, G.Y. Tang<sup>1</sup>, J. Tang<sup>51</sup>, J.X. Teng<sup>64,50</sup>, V. Thoren<sup>68</sup>, W.H. Tian<sup>44</sup>, Y.T. Tian<sup>25</sup>, I. Uman<sup>54B</sup>, B. Wang<sup>1</sup>, C.W. Wang<sup>35</sup>, D.Y. Wang<sup>39,h</sup>, H.J. Wang<sup>31,k,l</sup>, H.P. Wang<sup>1,55</sup>, K. Wang<sup>1,50</sup>, L.L. Wang<sup>1</sup>, M. Wang<sup>42</sup>, M.Z. Wang<sup>39,h</sup>, Meng Wang<sup>1,55</sup>, S. Wang<sup>9,f</sup>, W. Wang<sup>51</sup>, W.H. Wang<sup>69</sup>, W.P. Wang<sup>64,50</sup>, X. Wang<sup>39,h</sup>, X.F. Wang<sup>31,k,l</sup>, X.L. Wang<sup>9,f</sup>, Y. Wang<sup>51</sup>, Y.D. Wang<sup>38</sup>, Y.F. Wang<sup>1,50,55</sup>, Y.Q. Wang<sup>1</sup>, Y.Y. Wang<sup>31,k,l</sup>, Z. Wang<sup>1,50</sup>, Z.Y. Wang<sup>1</sup>, Ziyi Wang<sup>55</sup>, Zongyuan Wang<sup>1,55</sup>, D.H. Wei<sup>12</sup>, F. Weidner<sup>61</sup>, S.P. Wen<sup>1</sup>, D.J. White<sup>59</sup>, U. Wiedner<sup>4</sup>, G. Wilkinson<sup>62</sup>, M. Wolke<sup>68</sup>, L. Wollenberg<sup>4</sup>, J.F. Wu<sup>1,55</sup>, L.H. Wu<sup>1</sup>, L.J. Wu<sup>1,55</sup>, X. Wu<sup>9,f</sup>, X.H. Wu<sup>27</sup>, Z. Wu<sup>1,50</sup>, L. Xia<sup>64,50</sup>, H. Xiao<sup>9,f</sup>, S.Y. Xiao<sup>1</sup>, Z.J. Xiao<sup>34</sup>, X.H. Xie<sup>39,h</sup>, Y.G. Xie<sup>1,50</sup>, Y.H. Xie<sup>6</sup>, T.Y. Xing<sup>1,55</sup>, C.J. Xu<sup>51</sup>, G.F. Xu<sup>1</sup>, Q.J. Xu<sup>13</sup>, W. Xu<sup>1,55</sup>, X.P. Xu<sup>47</sup>, Y.C. Xu<sup>55</sup>, F. Yan<sup>9,f</sup>, L. Yan<sup>9,f</sup>, W.B. Yan<sup>64,50</sup>, W.C. Yan<sup>73</sup>, H.J. Yang<sup>43,e</sup>, H.X. Yang<sup>1</sup>, L. Yang<sup>44</sup>, S.L. Yang<sup>55</sup>, Y.X. Yang<sup>12</sup>, Yifan Yang<sup>1,55</sup>, Zhi Yang<sup>25</sup>, M. Ye<sup>1,50</sup>, M.H. Ye<sup>7</sup>, J.H. Yin<sup>1</sup>, Z.Y. You<sup>51</sup>, B.X. Yu<sup>1,50,55</sup>, C.X. Yu<sup>36</sup>, G. Yu<sup>1,55</sup>, J.S. Yu<sup>20,i</sup>, T. Yu<sup>65</sup>, C.Z. Yuan<sup>1,55</sup>, L. Yuan<sup>2</sup>, X.Q. Yuan<sup>39,h</sup>, Y. Yuan<sup>1</sup>, Z.Y. Yuan<sup>51</sup>, C.X. Yue<sup>32</sup>, A.A. Zafar<sup>66</sup>, X. Zeng Zeng<sup>6</sup>, Y. Zeng<sup>20,i</sup>, A.Q. Zhang<sup>1</sup>, B.X. Zhang<sup>1</sup>, Guangyi Zhang<sup>15</sup>, H. Zhang<sup>64</sup>, H.H. Zhang<sup>51</sup>, H.H. Zhang<sup>27</sup>, H.Y. Zhang<sup>1,50</sup>, J.L. Zhang<sup>70</sup>, J.Q. Zhang<sup>34</sup>, J.W. Zhang<sup>1,50,55</sup>, J.Y. Zhang<sup>1</sup>, J.Z. Zhang<sup>1,55</sup>, Jianyu Zhang<sup>1,55</sup>, Jiawei Zhang<sup>1,55</sup>, L.M. Zhang<sup>53</sup>, L.Q. Zhang<sup>51</sup>, Lei Zhang<sup>35</sup>, S. Zhang<sup>51</sup>, S.F. Zhang<sup>35</sup>, Shulei Zhang<sup>20,i</sup>, X.D. Zhang<sup>38</sup>, X.Y. Zhang<sup>42</sup>, Y. Zhang<sup>62</sup>, Y. T. Zhang<sup>73</sup>, Y.H. Zhang<sup>1,50</sup>, Yan Zhang<sup>64,50</sup>, Yao Zhang<sup>1</sup>, Z.Y. Zhang<sup>69</sup>, G. Zhao<sup>1</sup>, J. Zhao<sup>32</sup>, J.Y. Zhao<sup>1,55</sup>, J.Z. Zhao<sup>1,50</sup>, Lei Zhao<sup>64,50</sup>, Ling Zhao<sup>1</sup>, M.G. Zhao<sup>36</sup>, Q. Zhao<sup>1</sup>, S.J. Zhao<sup>73</sup>, Y.B. Zhao<sup>1,50</sup>, Y.X. Zhao<sup>25</sup>, Z.G. Zhao<sup>64,50</sup>, A. Zhemchugov<sup>29,a</sup>, B. Zheng<sup>65</sup>, J.P. Zheng<sup>1,50</sup>, Y.H. Zheng<sup>55</sup>, B. Zhong<sup>34</sup>, C. Zhong<sup>65</sup>, L.P. Zhou<sup>1,55</sup>, Q. Zhou<sup>1,55</sup>, X. Zhou<sup>69</sup>, X.K. Zhou<sup>55</sup>, X.R. Zhou<sup>64,50</sup>, X.Y. Zhou<sup>32</sup>, A.N. Zhu<sup>1,55</sup>, J. Zhu<sup>36</sup>, K. Zhu<sup>1</sup>, K.J. Zhu<sup>1,50,55</sup>, S.H. Zhu<sup>63</sup>, T.J. Zhu<sup>70</sup>, W.J. Zhu<sup>36</sup>, W.J. Zhu<sup>9,f</sup>, Y.C. Zhu<sup>64,50</sup>, Z.A. Zhu<sup>1,55</sup>, B.S. Zou<sup>1</sup>, J.H. Zou<sup>1</sup>

<sup>1</sup> Institute of High Energy Physics, Beijing 100049, People's Republic of China

<sup>2</sup> Beihang University, Beijing 100191, People's Republic of China

<sup>3</sup> Beijing Institute of Petrochemical Technology, Beijing 102617, People's Republic of China

<sup>4</sup> Bochum Ruhr-University, D-44780 Bochum, Germany

<sup>5</sup> Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, U.S.A.

<sup>6</sup> Central China Normal University, Wuhan 430079, People's Republic of China

<sup>7</sup> China Center of Advanced Science and Technology, Beijing 100190, People's Republic of China

<sup>8</sup> COMSATS University Islamabad, Lahore Campus, Defence Road, Off Raiwind Road, 54000 Lahore, Pakistan

<sup>9</sup> Fudan University, Shanghai 200443, People's Republic of China

<sup>10</sup> G.I. Budker Institute of Nuclear Physics SB RAS (BINP), Novosibirsk 630090, Russia

<sup>11</sup> GSI Helmholtzcentre for Heavy Ion Research GmbH, D-64291 Darmstadt, Germany

<sup>12</sup> Guangxi Normal University, Guilin 541004, People's Republic of China

<sup>13</sup> Hangzhou Normal University, Hangzhou 310036, People's Republic of China

<sup>14</sup> Helmholtz Institute Mainz, Staudinger Weg 18, D-55099 Mainz, Germany

<sup>15</sup> Henan Normal University, Xinxiang 453007, People's Republic of China

<sup>16</sup> Henan University of Science and Technology, Luoyang 471003, People's Republic of China

<sup>17</sup> Henan University of Technology, Zhengzhou 450001, People's Republic of China

<sup>18</sup> Huangshan College, Huangshan 245000, People's Republic of China

<sup>19</sup> Hunan Normal University, Changsha 410081, People's Republic of China

<sup>20</sup> Hunan University, Changsha 410082, People's Republic of China

- 21 *Indian Institute of Technology Madras, Chennai 600036, India*
- 22 *Indiana University, Bloomington, Indiana 47405, U.S.A.*
- 23 *INFN Laboratori Nazionali di Frascati, <sup>(A)</sup>INFN Laboratori Nazionali di Frascati, I-00044, Frascati, Italy; <sup>(B)</sup>INFN Sezione di Perugia, I-06100, Perugia, Italy; <sup>(C)</sup>University of Perugia, I-06100, Perugia, Italy*
- 24 *INFN Sezione di Ferrara, <sup>(A)</sup>INFN Sezione di Ferrara, I-44122, Ferrara, Italy; <sup>(B)</sup>University of Ferrara, I-44122, Ferrara, Italy*
- 25 *Institute of Modern Physics, Lanzhou 730000, People's Republic of China*
- 26 *Institute of Physics and Technology, Peace Ave. 54B, Ulaanbaatar 13330, Mongolia*
- 27 *Jilin University, Changchun 130012, People's Republic of China*
- 28 *Johannes Gutenberg University of Mainz, Johann-Joachim-Becher-Weg 45, D-55099 Mainz, Germany*
- 29 *Joint Institute for Nuclear Research, 141980 Dubna, Moscow region, Russia*
- 30 *Justus-Liebig-Universitaet Giessen, II. Physikalisches Institut, Heinrich-Buff-Ring 16, D-35392 Giessen, Germany*
- 31 *Lanzhou University, Lanzhou 730000, People's Republic of China*
- 32 *Liaoning Normal University, Dalian 116029, People's Republic of China*
- 33 *Liaoning University, Shenyang 110036, People's Republic of China*
- 34 *Nanjing Normal University, Nanjing 210023, People's Republic of China*
- 35 *Nanjing University, Nanjing 210093, People's Republic of China*
- 36 *Nankai University, Tianjin 300071, People's Republic of China*
- 37 *National Centre for Nuclear Research, Warsaw 02-093, Poland*
- 38 *North China Electric Power University, Beijing 102206, People's Republic of China*
- 39 *Peking University, Beijing 100871, People's Republic of China*
- 40 *Qufu Normal University, Qufu 273165, People's Republic of China*
- 41 *Shandong Normal University, Jinan 250014, People's Republic of China*
- 42 *Shandong University, Jinan 250100, People's Republic of China*
- 43 *Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China*
- 44 *Shanxi Normal University, Linfen 041004, People's Republic of China*
- 45 *Shanxi University, Taiyuan 030006, People's Republic of China*
- 46 *Sichuan University, Chengdu 610064, People's Republic of China*
- 47 *Soochow University, Suzhou 215006, People's Republic of China*
- 48 *South China Normal University, Guangzhou 510006, People's Republic of China*
- 49 *Southeast University, Nanjing 211100, People's Republic of China*
- 50 *State Key Laboratory of Particle Detection and Electronics, Beijing 100049, Hefei 230026, People's Republic of China*
- 51 *Sun Yat-Sen University, Guangzhou 510275, People's Republic of China*
- 52 *Suranaree University of Technology, University Avenue 111, Nakhon Ratchasima 30000, Thailand*
- 53 *Tsinghua University, Beijing 100084, People's Republic of China*
- 54 *Turkish Accelerator Center Particle Factory Group, <sup>(A)</sup>Istinye University, 34010, Istanbul, Turkey; <sup>(B)</sup>Near East University, Nicosia, North Cyprus, Mersin 10, Turkey*
- 55 *University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China*
- 56 *University of Groningen, NL-9747 AA Groningen, The Netherlands*
- 57 *University of Hawaii, Honolulu, Hawaii 96822, U.S.A.*
- 58 *University of Jinan, Jinan 250022, People's Republic of China*
- 59 *University of Manchester, Oxford Road, Manchester, M13 9PL, United Kingdom*
- 60 *University of Minnesota, Minneapolis, Minnesota 55455, U.S.A.*
- 61 *University of Muenster, Wilhelm-Klemm-Str. 9, 48149 Muenster, Germany*
- 62 *University of Oxford, Keble Rd, Oxford, U.K. OX13RH*
- 63 *University of Science and Technology Liaoning, Anshan 114051, People's Republic of China*
- 64 *University of Science and Technology of China, Hefei 230026, People's Republic of China*
- 65 *University of South China, Hengyang 421001, People's Republic of China*
- 66 *University of the Punjab, Lahore-54590, Pakistan*

- <sup>67</sup> *University of Turin and INFN, <sup>(A)</sup> University of Turin, I-10125, Turin, Italy; <sup>(B)</sup> University of Eastern Piedmont, I-15121, Alessandria, Italy; <sup>(C)</sup> INFN, I-10125, Turin, Italy*
- <sup>68</sup> *Uppsala University, Box 516, SE-75120 Uppsala, Sweden*
- <sup>69</sup> *Wuhan University, Wuhan 430072, People's Republic of China*
- <sup>70</sup> *Xinyang Normal University, Xinyang 464000, People's Republic of China*
- <sup>71</sup> *Yunnan University, Kunming 650500, People's Republic of China*
- <sup>72</sup> *Zhejiang University, Hangzhou 310027, People's Republic of China*
- <sup>73</sup> *Zhengzhou University, Zhengzhou 450001, People's Republic of China*
- <sup>a</sup> *Also at the Moscow Institute of Physics and Technology, Moscow 141700, Russia*
- <sup>b</sup> *Also at the Novosibirsk State University, Novosibirsk, 630090, Russia*
- <sup>c</sup> *Also at the NRC "Kurchatov Institute", PNPI, 188300, Gatchina, Russia*
- <sup>d</sup> *Also at Goethe University Frankfurt, 60323 Frankfurt am Main, Germany*
- <sup>e</sup> *Also at Key Laboratory for Particle Physics, Astrophysics and Cosmology, Ministry of Education; Shanghai Key Laboratory for Particle Physics and Cosmology; Institute of Nuclear and Particle Physics, Shanghai 200240, People's Republic of China*
- <sup>f</sup> *Also at Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) and Institute of Modern Physics, Fudan University, Shanghai 200443, People's Republic of China*
- <sup>g</sup> *Also at Harvard University, Department of Physics, Cambridge, MA, 02138, U.S.A.*
- <sup>h</sup> *Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, People's Republic of China*
- <sup>i</sup> *Also at School of Physics and Electronics, Hunan University, Changsha 410082, China*
- <sup>j</sup> *Also at Guangdong Provincial Key Laboratory of Nuclear Science, Institute of Quantum Matter, South China Normal University, Guangzhou 510006, China*
- <sup>k</sup> *Also at Frontiers Science Center for Rare Isotopes, Lanzhou University, Lanzhou 730000, People's Republic of China*
- <sup>l</sup> *Also at Lanzhou Center for Theoretical Physics, Lanzhou University, Lanzhou 730000, People's Republic of China*
- <sup>m</sup> *Henan University of Technology, Zhengzhou 450001, People's Republic of China*