

Observation of Charmonium h_c Radiative Decays to Multiple Light Hadrons and the Tensor State $f_2(1270)$

M. Ablikim *et al.*^{*}
(BESIII Collaboration)

 (Received 26 January 2025; revised 1 June 2025; accepted 4 June 2025; published 17 June 2025)

Using $\psi(3686) \rightarrow \pi^0 h_c$ decays from a data sample of $(27.12 \pm 0.14) \times 10^8$ $\psi(3686)$ events collected by the BESIII detector at the BEPCII collider, h_c radiative decays to multiple light hadrons below $2.8 \text{ GeV}/c^2$ — $\gamma\pi^+\pi^-$, $\gamma\pi^+\pi^-\eta$, $\gamma 2(\pi^+\pi^-)$, and $\gamma p\bar{p}$ —are observed for the first time, each with a significance greater than 5σ . The corresponding branching fractions are measured. Furthermore, intermediate states are investigated, leading to the first observation of the decay process of $h_c \rightarrow \gamma f_2(1270) \rightarrow \gamma\pi^+\pi^-$ with a significance of 5.1σ . This observation represents the first instance of h_c radiative decay to a tensor state.

DOI: [10.1103/v4hf-s8x8](https://doi.org/10.1103/v4hf-s8x8)

The study of charmonium radiative decay provides a unique opportunity to deepen our understanding of quantum chromodynamics (QCD) by testing theoretical predictions with experimental observations. Of particular interest, enhanced glueball production is expected in OZI-suppressed processes, such as J/ψ radiative decay, where the $c\bar{c}$ must annihilate to gluons before hadronizing into the final state. The radiative decays of the P-wave triplet charmonium (χ_{cJ}) [1,2] have been investigated to test our theoretical understanding of their decay dynamics [3]. However, the study of the radiative decay of the P-wave singlet h_c charmonium state to light hadrons is limited due to its predominantly suppressed production through $\psi(3686)$ [4]. Only three $h_c \rightarrow \gamma + 1^1S_0$ decays have been observed, namely $h_c \rightarrow \gamma\eta_c$ [5], $h_c \rightarrow \gamma\eta'$, and $h_c \rightarrow \gamma\eta$ [6]. The branching fraction $\mathcal{B}(h_c \rightarrow \gamma + 2g)$, where g represents the gluon, is estimated to be approximately 5.5% with a QCD model [7]. However, the measured total branching fraction of h_c decay to a photon and a light hadron(η/η') is only about 0.2% [6], indicating that a substantial portion of $h_c \rightarrow \gamma + 2g$ decay modes remain to be seen.

Studying J/ψ and $\psi(3686)$ radiative photon recoil spectra and comparing their decay rates has proven to be quite informative [8–14]. Many channels, including $\gamma\pi^+\pi^-$, $\gamma\pi^+\pi^-\eta$, $\gamma 2(\pi^+\pi^-)$, and $\gamma p\bar{p}$, have been studied to search for exotic states [8–11], such as the $p\bar{p}$ near-threshold invariant-mass enhancement in $J/\psi \rightarrow \gamma p\bar{p}$ [11]. Among these, the $f_2(1270)$ state has generated particular interest,

with various theoretical models being proposed for its description, including the standard $q\bar{q}$ pair model, a $\rho - \rho$ molecule [15], or a mixture between the $q\bar{q}$ component and the glueball component [16]. The h_c has the same C-parity as the J/ψ but different orbital angular momentum, and its unique properties provide an opportunity for improving our understanding of charmonium radiative decays and for searching for exotic particles.

In this Letter, we present the first measurements of four h_c radiative decays into multiple light hadrons, based on a dataset of $(27.12 \pm 0.14) \times 10^8$ $\psi(3686)$ events [17] collected by the BESIII detector [18]. We measure the branching fractions of radiative decays to I: $\pi^+\pi^-$, II: $\pi^+\pi^-\eta$, III: $2(\pi^+\pi^-)$, and IV: $p\bar{p}$ in radiative decays and investigate intermediate states to search for potential exotic states.

The BESIII detector records symmetric e^+e^- collisions at the BEPCII collider [19]. Details of the BESIII detector can be found in Ref. [18]. Simulated data samples produced with GEANT4-based [20] Monte Carlo (MC) software, which includes the geometric description of the BESIII detector and the detector response, are used to determine the detection efficiency and to estimate the background contributions. The simulation includes the beam energy spread and initial-state radiation (ISR) in the e^+e^- annihilations modeled with the generator KKMC [21]. The inclusive MC sample includes the production of the $\psi(3686)$ resonance, the ISR production of the J/ψ , and the continuum processes incorporated in KKMC [21]. All particle decays are modeled with EVTGEN [22] using branching fractions either taken from the Particle Data Group (PDG) [5], when available, or otherwise estimated with LUNDCHARM [23]. Final-state radiation from charged final-state particles is incorporated using PHOTOS [24]. The signal MC samples for the decay $\psi(3686) \rightarrow \pi^0 h_c$ are

^{*}Full author list given at the end of the Letter.

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International](https://creativecommons.org/licenses/by/4.0/) license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

generated using a helicity amplitude model. The h_c exclusive decays are simulated using a phase-space (PHSP) model [22], except for the process of $h_c \rightarrow \gamma f_2(1270)$, which is modeled with an angular distribution of $1 + \cos^2(\theta)$, where θ is the polar angle of the radiative photon in the rest frame of the h_c . Subsequently, $f_2(1270) \rightarrow \pi^+\pi^-$ is generated according to the TSS model [22], which describes the decay of a tensor particle into a pair of scalar mesons.

Charged tracks and photon candidates are selected based on standard BESIII criteria [25]. The number of candidate charged tracks must exactly match the number of charged particles in final states, while the number of photons must be no less than the number required by each decay mode. The h_c meson is produced by the isospin-violating decay $\psi(3686) \rightarrow \pi^0 h_c$, and the π^0 mass acceptance window is set to be $[0.10, 0.16]$ GeV/ c^2 in the event preselection. To reduce background contributions and improve the mass resolution, a five-constraint (5C) kinematic fit is performed with four constraints (4C), requiring that the total four-momentum of final states is equal to the initial $\psi(3686)$ momentum and an additional π^0 mass [5] constraint. The one with the minimum χ^2_{5C} value is selected in all possible photon combinations. For the $\psi(3686) \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma \pi^+\pi^-\eta$ process where the $\eta \rightarrow \gamma\gamma$ decay is utilized, at least five photons are required. The two photons with an invariant mass closest to the η mass [5] are taken as originating from the η . The η signal region is defined as $[0.513, 0.583]$ GeV/ c^2 , while the sideband regions, $[0.400, 0.470]$ and $[0.626, 0.696]$ GeV/ c^2 , are used to estimate the non- η background. For the process of $h_c \rightarrow \gamma p \bar{p}$, particle identification (PID) is used for the charged particles. The flight time in the time-of-flight system (TOF) and the dE/dx information in the multilayer drift chamber (MDC) are combined to calculate PID likelihoods for the π , K , and p hypotheses. For this channel, the likelihood of a proton hypothesis is required to be larger than those for both the kaon and pion hypotheses.

To suppress backgrounds with the wrong number of photons compared to the signal mode, $\chi^2_{4C,n\gamma} < \chi^2_{4C,(n-1)\gamma}$ and $\chi^2_{4C,n\gamma} < \chi^2_{4C,(n+1)\gamma}$ are required for Modes I, III, and IV. For Mode II, only $\chi^2_{4C,n\gamma} < \chi^2_{4C,(n+1)\gamma}$ is used, because the inclusion of $\chi^2_{4C,n\gamma} < \chi^2_{4C,(n-1)\gamma}$ does not significantly improve the purity of the signal. Here, $\chi^2_{4C,n\gamma}$ is the χ^2 value of the 4C kinematic fit with the hypothesis of the same photon combination selected with the minimum χ^2_{5C} , where n includes photons from π^0 and h_c decays in the process of $\psi(3686) \rightarrow \pi^0 h_c$. And $\chi^2_{4C,(n-1)\gamma}$ and $\chi^2_{4C,(n+1)\gamma}$ are the minimum χ^2 values obtained from the 4C fits method with one less and one more photon compared to the signal process, respectively.

To reduce the peaking background of $h_c \rightarrow \gamma \eta_c$ with $\eta_c \rightarrow X$ and X are $\pi^+\pi^-\eta$, $\pi^+\pi^-\pi^+\pi^-$, and $p \bar{p}$, the invariant

mass of X is required to be less than 2.8 GeV/ c^2 . Additionally, for Mode II, $M(\pi^+\pi^-\eta) > 1.0$ GeV/ c^2 is required to reject the peaking background from $h_c \rightarrow \gamma \eta'$. After applying all the above selection criteria, two types of peaking backgrounds remain: $h_c \rightarrow \pi^0 + X$ with a γ missing from the π^0 and $h_c \rightarrow \gamma \eta_c$ [with $\eta_c \rightarrow X$ and $M(X) < 2.8$ GeV/ c^2]. The contribution from the first type is estimated using a MC simulation according to the measured $h_c \rightarrow \pi^0 X$ branching fractions [26,27]. For the second one, the contribution of $h_c \rightarrow \gamma \eta_c$ is obtained by fitting $M(X)$ in the range $[2.40, 3.07]$ GeV/ c^2 . A Breit-Wigner function convolved with a Gaussian function is used to describe the signal yield in the fit, with parameters fixed to the η_c nominal values [5]. The smooth background shape is modeled by a second-order polynomial function. The number of remaining η_c events with $M(X) < 2.8$ GeV/ c^2 is then determined to be less than 2%. For Mode II, there is no peaking background from the η sideband region.

For nonpeaking backgrounds, the following specific requirements are imposed. Mode I: the criterion $\cos \theta_{\pi^+\pi^-} > -0.98$, where $\theta_{\pi^+\pi^-}$ is the angle between the two pions, is used to suppress the processes of two leptons produced by the e^+e^- collision. The invariant mass of $\pi^+\pi^-\pi^0$ is required to be outside the ω and ϕ mass regions by 3σ , where σ is the corresponding invariant mass resolution, with values of 9.8 and 9.1 MeV/ c^2 for ω and ϕ , respectively. Also, $M(\pi^0\gamma)$ is required to be outside the ω mass region by 3σ ($\sigma = 12.1$ MeV/ c^2) to reject the background from $\omega \rightarrow \pi^0\gamma$. To remove the photon combinatorial background, $M(\gamma_H\gamma)$ is required to be outside the π^0 mass window $[0.10, 0.16]$ GeV/ c^2 , where γ_H is the higher-energy photon from π^0 decay and γ is the photon from h_c radiative decay. The background from $\psi(3686) \rightarrow \pi^0\pi^0 J/\psi$ is suppressed by $M(\pi^+\pi^-) < 2.8$ GeV/ c^2 . Mode II: the photon combinatorial background is removed by requiring that $M(\gamma\gamma)_{\text{mix}}$ does not fall within the π^0 mass window, where $M(\gamma\gamma)_{\text{mix}}$ denotes the invariant mass of all possible two-photon pairs, which are not from the same π^0 or η candidate. Events with $\pi^+\pi^-$ recoil mass greater than 3.085 GeV/ c^2 are removed to veto the background from $\psi(3686) \rightarrow \pi^+\pi^- J/\psi$. Mode III: the $\pi^+\pi^-\pi^0$ invariant mass must be outside the η ($[0.537, 0.558]$ GeV/ c^2) and ω ($[0.762, 0.804]$ GeV/ c^2) mass regions, and the $\pi^+\pi^-$ recoil mass should not fall within the J/ψ mass region $[3.091, 3.103]$ GeV/ c^2 .

The signal yields are determined by fits to the $M(\gamma X)$ invariant mass distributions, which are shown in Fig. 1 for all decay modes. The signal shape is described by the MC-simulated shape convolved with a Gaussian function with free parameters to account for the resolution difference between data and MC. The peaking backgrounds are fixed to the estimated numbers and described by the corresponding MC shapes. The smooth background is modeled by an

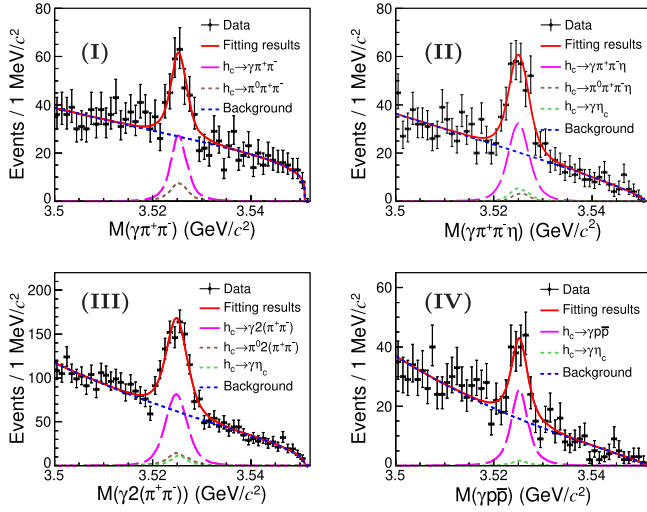


FIG. 1. Fits to the $M(\gamma X)$ invariant mass distributions, where X represents (I) $\pi^+\pi^-$, (II) $\pi^+\pi^-\eta$, (III) $2(\pi^+\pi^-)$, and (IV) $p\bar{p}$. The dots with error bars are data, the red solid line is the fitting result, the pink dashed line is the signal shape, the blue dashed line is the smooth background, and the other dashed lines represent the peaking backgrounds.

ARGUS function [28], where the threshold parameter is fixed to $3.551 \text{ GeV}/c^2$. The statistical significance of each decay mode is larger than 5σ , which is estimated by comparing the log-likelihood values of the fits with and without the signal component and considering the change of degrees of freedom.

To search for possible intermediate states, the invariant mass distributions of light hadrons are examined within the h_c signal region $[3.52, 3.53] \text{ GeV}/c^2$. Figure 2 (top) shows the $M(\pi^+\pi^-)$ distribution of $h_c \rightarrow \gamma\pi^+\pi^-$ below $2.8 \text{ GeV}/c^2$ from this region. An excess of events around $1.3 \text{ GeV}/c^2$ is observed, suggesting a potential resonance, assumed to be the $f_2(1270)$ state. The statistical significance of the $f_2(1270)$ signal is determined to be 5.5σ , and after including systematic uncertainties (see below), the significance is 5.1σ .

To determine the number of $f_2(1270)$ signal events, we perform a simultaneous fit to the $\pi^+\pi^-$ mass spectra in the h_c signal region and sideband regions $([3.50, 3.51] \cup [3.54, 3.55] \text{ GeV}/c^2)$. Included in the fit of the signal region are the $h_c \rightarrow \gamma f_2(1270)$ signal process, nonresonant $h_c \rightarrow \gamma\pi^+\pi^-$ described by phase space, and the following background processes: the $\psi(3686) \rightarrow \omega f_2(1270)$ peaking background, $h_c \rightarrow \pi^+\pi^-\pi^0$, and a smooth background. The shapes of these components are described by MC shapes, except the $f_2(1270)$ signal is described by its MC shape convolved with a Gaussian function with free parameters, and the smooth background is described by a function $F_{BG}(m) = (m - m_t)^c e^{-d \cdot m - e \cdot m^2}$, where m_t is the threshold mass for $\pi^+\pi^-$, and c , d , and e are free parameters. The number of $\psi(3686) \rightarrow \omega f_2(1270)$ peaking background

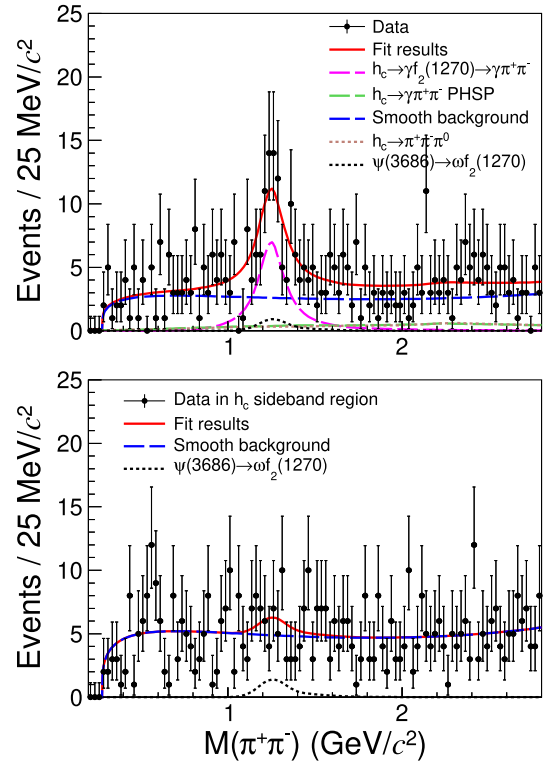


FIG. 2. Fit to the $M(\pi^+\pi^-)$ invariant mass distribution for the process of $h_c \rightarrow \gamma\pi^+\pi^-$ for events in the (top) h_c signal region and (bottom) h_c sideband regions. The dots with error bars are data, the red solid line is the total fitting result, the pink dashed line is the signal of $h_c \rightarrow \gamma f_2(1270)$, and the green dashed line is the phase-space process of $h_c \rightarrow \gamma\pi^+\pi^-$. The blue dashed line denotes the smooth background, and the brown dashed line is the background from $h_c \rightarrow \pi^+\pi^-\pi^0$. The black dashed line is the $\psi(3686) \rightarrow \omega f_2(1270)$ peaking background.

events is fixed to 9.0 according to a MC study, and the number of background events from $h_c \rightarrow \pi^+\pi^-\pi^0$ is fixed to 35.4 according to Ref. [26]. Two potential peaking background processes, $\psi(3686) \rightarrow \gamma\pi^0 f_2(1270)$ and $\psi(3686) \rightarrow \pi^0 f_2(1270)$, have been investigated. The former is evaluated using h_c sideband data and found to be negligible. The latter, being forbidden by C-parity conservation, is expected to be highly suppressed and thus neglected in this analysis.

The fit to the sideband includes the $\psi(3686) \rightarrow \omega f_2(1270)$ peaking background, described by the MC shape, and the smooth background, described by $F_{BG}(m)$. The two fit functions share the smooth background $F_{BG}(m)$, and the number of smooth background events in the h_c signal region is scaled by a scale factor from the number of smooth background events in the h_c sideband region. The number of phase space and signal events are floated in the fitting process, but the interference between them is not considered due to the low statistics. The fits in the h_c signal and sideband regions are shown in Fig. 2.

TABLE I. The numerical results for four h_c decay channels, where the first uncertainty is statistical, the second systematic, and the third from the branching fraction of $\psi(3686) \rightarrow \pi^0 h_c$. The significance is estimated, taking systematic uncertainties into account.

Decay model	Branching fraction	Signal yield	Efficiency (%)	Significance (σ)
$h_c \rightarrow \gamma \pi^+ \pi^-$	$(3.06 \pm 0.54 \pm 0.37 \pm 0.21) \times 10^{-4}$	127.0 ± 22.2	20.9	5.4
$h_c \rightarrow \gamma f_2(1270) \rightarrow \gamma \pi^+ \pi^-$	$(1.81 \pm 0.35 \pm 0.19 \pm 0.12) \times 10^{-4}$	71.8 ± 13.8	20.0	5.1
$h_c \rightarrow \gamma \pi^+ \pi^- \eta$	$(3.52 \pm 0.50 \pm 0.30 \pm 0.24) \times 10^{-3}$	191.6 ± 27.1	7.0	7.5
$h_c \rightarrow \gamma 2(\pi^+ \pi^-)$	$(2.19 \pm 0.20 \pm 0.16 \pm 0.15) \times 10^{-3}$	494.9 ± 44.5	11.4	11.8
$h_c \rightarrow \gamma p \bar{p}$	$(3.34 \pm 0.53 \pm 0.33 \pm 0.23) \times 10^{-4}$	127.4 ± 20.1	19.3	6.4

The branching fractions of $h_c \rightarrow \gamma X$ ($X = \pi^+ \pi^-, \pi^+ \pi^- \eta, 2(\pi^+ \pi^-), p \bar{p}$) are calculated by

$$\mathcal{B}(h_c \rightarrow \gamma X) = \frac{N^{\text{sig}}}{N^{\text{tot}} \cdot \mathcal{B}(\psi(3686) \rightarrow \pi^0 h_c) \prod_i \mathcal{B}_i \epsilon},$$

where N^{sig} is the number of signal events; $\prod_i \mathcal{B}_i$ is the product of branching fractions of the intermediate states, e.g., $\mathcal{B}(\pi^0 \rightarrow \gamma \gamma)$ [5] or $\mathcal{B}(\pi^0 \rightarrow \gamma \gamma) \cdot \mathcal{B}(\eta \rightarrow \gamma \gamma)$ [5]; ϵ is the detection efficiency; and N^{tot} is the number of $\psi(3686)$ events. For the $h_c \rightarrow \gamma \pi^+ \pi^-$ process, the total detection efficiency is estimated by combining the PHSP and intermediate-state $f_2(1270)$ processes. The ratio between these two components is determined based on this Letter.

For $h_c \rightarrow \gamma \pi^+ \pi^- \eta$ and $h_c \rightarrow \gamma p \bar{p}$, no obvious intermediate state is found. We find that $h_c \rightarrow \gamma 2(\pi^+ \pi^-)$ is dominated by $h_c \rightarrow \gamma \rho^0 \rho^0$; therefore, $h_c \rightarrow \gamma 2(\pi^+ \pi^-)$ is simulated by $h_c \rightarrow \gamma \rho^0 \rho^0 \rightarrow \gamma 2(\pi^+ \pi^-)$ cascade decay. Table I summarizes the branching fraction, signal yield, efficiency, and significance for each decay mode.

Systematic uncertainties of these decay branching fractions are listed in Table II. The overall systematic uncertainties are obtained by adding all sources in quadrature, assuming they are independent.

The uncertainty arising from the pion tracking efficiency is 1.0% per track according to the study of a control sample

of $\psi(3686) \rightarrow \pi^+ \pi^- J/\psi$, $J/\psi \rightarrow \ell^+ \ell^-$ ($\ell = e, \mu$) [29]. Similarly, the tracking efficiencies of protons and antiprotons are studied with the control sample of $\psi(3686) \rightarrow p \bar{p} \pi^+ \pi^-$. The uncertainty associated with the proton (antiproton) tracking efficiency is 0.7% (1.0%) per track [30]. The uncertainty due to PID is 1.3% per proton and 1.6% per antiproton, based on the study of $J/\psi \rightarrow p \bar{p} \pi^+ \pi^-$ [26].

The uncertainty of the photon detection efficiency is 0.5% per photon, obtained from the study of the $e^+ e^- \rightarrow \gamma \mu^+ \mu^-$ process. The uncertainty of the π^0 reconstruction efficiency is estimated using its momentum distribution based on the control sample of $\psi(3686) \rightarrow \pi^0 \pi^0 J/\psi$ and $e^+ e^- \rightarrow \omega \pi^0$ at $\sqrt{s} = 3.773$ GeV. MC events are weighted according to the relative difference between data and MC, which is described by a linear function $((0.06 - 2.41 \times p)\%)$, where p is the momentum of π^0 . The uncertainty due to the η mass window is determined to be 1% through a study of the control sample of $J/\psi \rightarrow p \bar{p} \eta$ [29].

The uncertainty due to the kinematic fit requirements is estimated by correcting the helix parameters of charged tracks according to the method described in Ref. [31]. The difference between detection efficiencies obtained from MC samples with and without this correction is taken as the uncertainty.

TABLE II. Relative systematic uncertainties (%), where a dash (–) indicates that a systematic effect is not applicable.

Source	$h_c \rightarrow \gamma \pi^+ \pi^-$	$h_c \rightarrow \gamma \pi^+ \pi^- \eta$	$h_c \rightarrow \gamma 2(\pi^+ \pi^-)$	$h_c \rightarrow \gamma p \bar{p}$	$h_c \rightarrow \gamma f_2(1270) \rightarrow \gamma \pi^+ \pi^-$
Tracking	2.0	2.0	4.0	1.7	2.0
Photon reconstruction	1.5	2.5	1.5	1.5	1.5
PID	–	–	–	2.9	–
π^0 reconstruction	0.5	0.5	0.5	0.5	0.5
η mass window	–	1.0	–	–	–
Kinematic fit	1.5	0.6	2.1	0.6	1.3
Intermediate states	2.0	0.1	0.6	–	–
Background veto	2.0	2.2	–	–	2.0
Peaking background	8.7	4.3	1.5	0.6	2.7
Fitting procedure	7.5	6.0	5.3	9.1	9.7
Branching fractions	6.8	6.8	6.8	6.8	6.8
Number of $\psi(3686)$	0.5	0.5	0.5	0.5	0.5
Total	14.0	10.9	10.0	12.0	12.7

Possible intermediate states are considered in the simulations of the $h_c \rightarrow \gamma\pi^+\pi^-$, $h_c \rightarrow \gamma\pi^+\pi^-\eta$, and $h_c \rightarrow \gamma 2(\pi^+\pi^-)$ modes. For $h_c \rightarrow \gamma\pi^+\pi^-$, the detection efficiency is estimated based on the ratio of the PHSP and intermediate-state $f_2(1270)$ processes. The covariance matrix obtained from this Letter is used to regenerate multidimensional Gaussian samples to get the uncertainty of the average efficiency. For $h_c \rightarrow \gamma\pi^+\pi^-\eta$, we reweighted the PHSP MC sample according to distributions of $M(\pi^+\pi^-)$, $M(\pi^+\eta)$, and $M(\pi^-\eta)$ in the data. In the case of $h_c \rightarrow \gamma 2(\pi^+\pi^-)$, the distribution of $M(\pi^+\pi^-)$ in the data is used to weight the $h_c \rightarrow \gamma\rho^0\rho^0$ three-body PHSP MC. The efficiency differences between the PHSP MC and the weighted MC are taken as uncertainties.

For the π^0 background veto, the photon energy resolution difference between data and MC can affect the distribution of $M(\gamma\gamma)$. To address this, we adjust the energy resolution by 4% [32], and the difference between the efficiencies with or without this correction is regarded as the systematic uncertainty. For the uncertainty caused by other background vetoes, we perform a Barlow test [33] to examine the significance deviation (ζ) between the nominal fit and the systematic test. We change the background veto region in 10 different intervals. If ζ is less than 2 at all times (or very close to 2), we treat the systematic uncertainty as negligible. Otherwise, we take the maximum difference as the systematic uncertainty for a conservative estimation.

There are three sources of peaking background. For the $\psi(3686) \rightarrow \omega f_2(1270)$ and $h_c \rightarrow \pi^0 X$ peaking backgrounds, the systematic uncertainties are estimated based on the uncertainties of measured branching fractions [5,26,27]. For $h_c \rightarrow \gamma\eta_c$, the fitting results are varied within one standard deviation, and the differences between the varied and nominal values are taken as the systematic uncertainties.

The uncertainty from the fitting procedure is determined by varying the fitting range, background shape, and signal shape. The uncertainty caused by the fitting range is estimated by changing the left side of the range by $\pm 10 \text{ MeV}/c^2$ [6,26]. The difference in the fitting results is taken as the systematic uncertainty. To estimate the systematic uncertainty related to the background shape, the ARGUS function is changed to a function $(m_t - m)^a e^{-bm - cm^2}$ [34], where $m_t = 3.551 \text{ GeV}/c^2$, and a , b , and c are free parameters. The uncertainty of the signal shape is estimated by replacing the nominal fit with a Breit-Wigner function convolved with a Gaussian function with free parameters, where the parameters of the Breit-Wigner function are fixed to the values in the PDG [5]. The uncertainty in the fitting procedure is determined by the differences in the final results added in quadrature.

For the $h_c \rightarrow \gamma f_2(1270) \rightarrow \gamma\pi^+\pi^-$ process, the uncertainty of the fitting procedure involves the background from $h_c \rightarrow \pi^+\pi^-\pi^0$, the h_c signal region and h_c sideband regions, and the h_c sideband scale factor. The uncertainty

of the background from $h_c \rightarrow \pi^+\pi^-\pi^0$ is estimated by varying the background contribution within its uncertainty. To estimate the uncertainties related to the choice of signal and sideband regions, the h_c signal region is varied by $\pm 1 \text{ MeV}/c^2$ at both boundaries, and the h_c sideband regions are shifted to the left or right by $\pm 2 \text{ MeV}/c^2$. The h_c sideband scale factor is determined according to the fit results of $M(\gamma\pi^+\pi^-)$. To estimate the uncertainty, we recalculate the scale factor using the covariance matrix from the fit results. Five thousand sets of fitting parameters are generated using multidimensional Gaussian sampling to recalculate the h_c sideband scaling factor. The standard deviation of the resultant number of $f_2(1270)$ events is taken as the systematic uncertainty. The uncertainty in the fitting procedure is determined by differences in the final results added in quadrature.

The systematic uncertainties arising from the branching fractions, including $\mathcal{B}(\psi(3686) \rightarrow \pi^0 h_c)$, $\mathcal{B}(\eta \rightarrow \gamma\gamma)$, and $\mathcal{B}(\pi^0 \rightarrow \gamma\gamma)$, are from the PDG [5]. The number of $\psi(3686)$ is determined by measuring the inclusive hadronic events, as described in Ref. [17]. The uncertainty is estimated to be 0.5%.

In summary, using a data sample of $(27.12 \pm 0.14) \times 10^8$ $\psi(3686)$ events collected by the BESIII detector, four modes of h_c radiative decays to multiple light hadrons are studied via $\psi(3686) \rightarrow \pi^0 h_c$ ($h_c \rightarrow \gamma X$) for the first time. The processes of $h_c \rightarrow \gamma X$ [$X = \pi^+\pi^-$, $\pi^+\pi^-\eta$, $2(\pi^+\pi^-)$, and $p\bar{p}$] are observed with a significance larger than 5σ . The sum of known branching fractions of the h_c radiative decay including the results of this analysis is approximately 0.8%, which is significantly lower than the predicted value 5.5% of $\mathcal{B}(h_c \rightarrow \gamma + 2g)$ in Ref. [7]. This discrepancy highlights the need for further exploration of h_c radiative decays. Moreover, h_c radiative decay to $f_2(1270)$ is observed with a significance of 5.1σ including the systematic uncertainty. This is the first observation of h_c radiative decay to a tensor state. The branching fraction of $h_c \rightarrow \gamma f_2(1270) \rightarrow \gamma\pi^+\pi^-$ is an order of magnitude smaller than that in J/ψ decay [35]. This measurement could be employed to investigate the quark and glueball mixing parameters of $f_2(1270)$ from the method as outlined in Ref. [16].

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 No. 2020YFA0406300, No. 2020YFA0406400, and No. 2023YFA1606000; National Natural Science Foundation of China (NSFC) under Contracts No. 12375070, No. 11635010, No. 11735014, No. 11935015, No. 11935016, No. 11935018, No. 12025502, No. 12035009, No. 12035013, No. 12061131003, No. 12192260, No. 12192261, No. 12192262, No. 12192263, No. 12192264,

No. 12192265, No. 12221005, No. 12225509, No. 12235017, and No. 12361141819; the Chinese Academy of Sciences (CAS) Large-Scale Scientific Facility Program; the CAS Center for Excellence in Particle Physics (CCEPP); the Shanghai Leading Talent Program of Eastern Talent Plan under Contract No. JLH5913002; the Joint Large-Scale Scientific Facility Funds of the NSFC and CAS under Contracts No. U2032108 and No. U1832207; the 100 Talents Program of CAS; the Institute of Nuclear and Particle Physics (INPAC) and Shanghai Key Laboratory for Particle Physics and Cosmology; the German Research Foundation DFG under Contract No. FOR5327; Istituto Nazionale di Fisica Nucleare, Italy; the Knut and Alice Wallenberg Foundation under Contracts No. 2021.0174 and No. 2021.0299; the Ministry of Development of Turkey under Contract No. DPT2006K-120470; the National Research Foundation of Korea under Contract No. NRF-2022R1A2C1092335; the National Science and Technology fund of Mongolia; the National Science Research and Innovation Fund (NSRF) via the Program Management Unit for Human Resources & Institutional Development, Research, and Innovation of Thailand under Contracts No. B16F640076, and No. B50G670107; the Polish National Science Centre under Contract No. 2019/35/O/ST2/02907; the Swedish Research Council under Contract No. 2019.04595; the Swedish Foundation for International Cooperation in Research and Higher Education under Contract No. CH2018-7756; and the U.S. Department of Energy under Contract No. DE-FG02-05ER41374.

Data availability—The data that support the findings of this Letter are not publicly available. The data are available from the authors upon reasonable request.

[1] J. V. Bennett *et al.* (CLEO Collaboration), *Phys. Rev. Lett.* **101**, 151801 (2008).
 [2] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. D* **83**, 112005 (2011).
 [3] Y. J. Gao, Y. J. Zhang, and K. T. Chao, *Chin. Phys. Lett.* **23**, 2376 (2006).
 [4] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. D* **106**, 072007 (2022).
 [5] S. Navas *et al.* (Particle Data Group), *Phys. Rev. D* **110**, 030001 (2024).
 [6] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. Lett.* **116**, 251802 (2016); M. Ablikim *et al.* (BESIII Collaboration), *J. High Energy Phys.* **08** (2024) 180.
 [7] S. Godfrey and J. L. Rosner, *Phys. Rev. D* **66**, 014012 (2002).
 [8] A. V. Sarantsev, I. Denisenko, U. Thoma, and E. Klempt, *Phys. Lett.* **86B**, 136227 (2021).
 [9] J. Z. Bai *et al.* (BES Collaboration), *Phys. Lett. B* **446**, 356 (1999).

[10] R. M. Baltrusaitis *et al.* (Mark III Collaboration), *Phys. Rev. D* **33**, 1222 (1986).
 [11] J. Z. Bai *et al.* (BES Collaboration), *Phys. Rev. Lett.* **91**, 022001 (2003).
 [12] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. Lett.* **129**, 042001 (2022).
 [13] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. Lett.* **129**, 192002 (2022).
 [14] M. Ablikim *et al.* (BES Collaboration), *Phys. Rev. Lett.* **99**, 011802 (2007).
 [15] R. Molina, D. Nicmorus, and E. Oset, *Phys. Rev. D* **78**, 114018 (2008).
 [16] Q. X. Shen and H. Yu, *Phys. Rev. D* **40**, 1517 (1989).
 [17] M. Ablikim *et al.* (BESIII Collaboration), *Chin. Phys. C* **42**, 023001 (2013); M. Ablikim *et al.* (BESIII Collaboration), *Chin. Phys. C* **48**, 093001 (2024).
 [18] M. Ablikim *et al.* (BESIII Collaboration), *Nucl. Instrum. Methods Phys. Res., Sect. A* **614**, 345 (2010); M. Ablikim *et al.* (BESIII Collaboration), *Chin. Phys. C* **44**, 040001 (2020).
 [19] C. H. Yu *et al.*, *Proceedings of IPAC2016, Busan, Korea* (2016), [10.18429/JACoW-IPAC2016-TUYA01](#).
 [20] S. Agostinelli *et al.* (GEANT4 Collaboration), *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003).
 [21] S. Jadach, B. F. L. Ward, and Z. Was, *Phys. Rev. D* **63**, 113009 (2001); *Comput. Phys. Commun.* **130**, 260 (2000).
 [22] D. J. Lange, *Nucl. Instrum. Methods Phys. Res., Sect. A* **462**, 152 (2001); R. G. Ping, *Chin. Phys. C* **32**, 599 (2008).
 [23] J. C. Chen, G. S. Huang, X. R. Qi, D. H. Zhang, and Y. S. Zhu, *Phys. Rev. D* **62**, 034003 (2000); R. L. Yang, R. G. Ping, and H. Chen, *Chin. Phys. Lett.* **31**, 061301 (2014).
 [24] E. Richter-Was, *Phys. Lett. B* **303**, 163 (1993).
 [25] M. Ablikim *et al.* (BESIII Collaboration), *J. High Energy Phys.* **05** (2022) 108.
 [26] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. D* **99**, 072008 (2019).
 [27] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. D* **102**, 112007 (2020).
 [28] H. Albrecht *et al.* (ARGUS Collaboration), *Phys. Lett. B* **340**, 217 (1994).
 [29] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. Lett.* **105**, 261801 (2010).
 [30] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. D* **99**, 032006 (2019).
 [31] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. D* **87**, 012002 (2013).
 [32] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. Lett.* **104**, 132002 (2010).
 [33] O. Behnke, K. Kroninger, G. Schott, and T. H. Schorner Sadenius, *Data Analysis in High Energy Physics: A Practical Guide to Statistical Methods* (Wiley-VCH, Berlin, Germany, 2013).
 [34] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. D* **87**, 092006 (2013).
 [35] S. Dobbs, A. Tomaradze, T. Xiao, and K. K. Seth, *Phys. Rev. D* **91**, 052006 (2015).

M. Ablikim,¹ M. N. Achasov,^{4,c} P. Adlarson,⁷⁶ X. C. Ai,⁸¹ R. Aliberti,³⁵ A. Amoroso,^{75a,75c} Q. An,^{72,58,a} Y. Bai,⁵⁷
 O. Bakina,³⁶ Y. Ban,^{46,h} H.-R. Bao,⁶⁴ V. Batzskaya,^{1,44} K. Begzsuren,³² N. Berger,³⁵ M. Berlowski,⁴⁴ M. Bertani,^{28a}
 D. Bettoni,^{29a} F. Bianchi,^{75a,75c} E. Bianco,^{75a,75c} A. Bortone,^{75a,75c} I. Boyko,³⁶ R. A. Briere,⁵ A. Brueggemann,⁶⁹ H. Cai,⁷⁷
 M. H. Cai,^{38,k,l} X. Cai,^{1,58} A. Calcaterra,^{28a} G. F. Cao,^{1,64} N. Cao,^{1,64} S. A. Cetin,^{62a} X. Y. Chai,^{46,h} J. F. Chang,^{1,58}
 G. R. Che,⁴³ Y. Z. Che,^{1,58,64} G. Chelkov,^{36,b} C. Chen,⁴³ C. H. Chen,⁹ Chao Chen,⁵⁵ G. Chen,¹ H. S. Chen,^{1,64} H. Y. Chen,²⁰
 M. L. Chen,^{1,58,64} S. J. Chen,⁴² S. L. Chen,⁴⁵ S. M. Chen,⁶¹ T. Chen,^{1,64} X. R. Chen,^{31,64} X. T. Chen,^{1,64} Y. B. Chen,^{1,58}
 Y. Q. Chen,³⁴ Z. J. Chen,^{25,i} S. K. Choi,¹⁰ X. Chu,^{12,g} G. Cibinetto,^{29a} F. Cossio,^{75c} J. J. Cui,⁵⁰ H. L. Dai,^{1,58} J. P. Dai,⁷⁹
 A. Dbeyssi,¹⁸ R. E. de Boer,³ D. Dedovich,³⁶ C. Q. Deng,⁷³ Z. Y. Deng,¹ A. Denig,³⁵ I. Denysenko,³⁶ M. Destefanis,^{75a,75c}
 F. De Mori,^{75a,75c} B. Ding,^{67,1} X. X. Ding,^{46,h} Y. Ding,³⁴ Y. Ding,⁴⁰ Y. X. Ding,³⁰ J. Dong,^{1,58} L. Y. Dong,^{1,64}
 M. Y. Dong,^{1,58,64} X. Dong,⁷⁷ M. C. Du,¹ S. X. Du,⁸¹ Y. Y. Duan,⁵⁵ Z. H. Duan,⁴² P. Egorov,^{36,b} G. F. Fan,⁴² J. J. Fan,¹⁹
 Y. H. Fan,⁴⁵ J. Fang,^{1,58} J. Fang,⁵⁹ S. S. Fang,^{1,64} W. X. Fang,¹ Y. Q. Fang,^{1,58} R. Farinelli,^{29a} L. Fava,^{75b,75c} F. Feldbauer,³
 G. Felici,^{28a} C. Q. Feng,^{72,58} J. H. Feng,⁵⁹ Y. T. Feng,^{72,58} M. Fritsch,³ C. D. Fu,¹ J. L. Fu,⁶⁴ Y. W. Fu,^{1,64} H. Gao,⁶⁴
 X. B. Gao,⁴¹ Y. N. Gao,¹⁹ Y. N. Gao,^{46,h} Y. Y. Gao,³⁰ Yang Gao,^{72,58} S. Garbolino,^{75c} I. Garzia,^{29a,29b} P. T. Ge,¹⁹ Z. W. Ge,⁴²
 C. Geng,⁵⁹ E. M. Gersabeck,⁶⁸ A. Gilman,⁷⁰ K. Goetzen,¹³ L. Gong,⁴⁰ W. X. Gong,^{1,58} W. Gradl,³⁵ S. Gramigna,^{29a,29b}
 M. Greco,^{75a,75c} M. H. Gu,^{1,58} Y. T. Gu,¹⁵ C. Y. Guan,^{1,64} A. Q. Guo,³¹ L. B. Guo,⁴¹ M. J. Guo,⁵⁰ R. P. Guo,⁴⁹ Y. P. Guo,^{12,g}
 A. Guskov,^{36,b} J. Gutierrez,²⁷ K. L. Han,⁶⁴ T. T. Han,¹ F. Hanisch,³ K. D. Hao,^{72,58} X. Q. Hao,¹⁹ F. A. Harris,⁶⁶ K. K. He,⁵⁵
 K. L. He,^{1,64} F. H. Heinsius,³ C. H. Heinz,³⁵ Y. K. Heng,^{1,58,64} C. Herold,⁶⁰ T. Holtmann,³ P. C. Hong,³⁴ G. Y. Hou,^{1,64}
 X. T. Hou,^{1,64} Y. R. Hou,⁶⁴ Z. L. Hou,¹ B. Y. Hu,⁵⁹ H. M. Hu,^{1,64} J. F. Hu,^{56,j} Q. P. Hu,^{72,58} S. L. Hu,^{12,g} T. Hu,^{1,58,64} Y. Hu,¹
 G. S. Huang,^{72,58} K. X. Huang,⁵⁹ L. Q. Huang,^{31,64} P. Huang,⁴² X. T. Huang,⁵⁰ Y. P. Huang,¹ Y. S. Huang,⁵⁹ T. Hussain,⁷⁴
 N. Hüsken,³⁵ N. in der Wiesche,⁶⁹ J. Jackson,²⁷ S. Janchiv,³² Q. Ji,¹ Q. P. Ji,¹⁹ W. Ji,^{1,64} X. B. Ji,^{1,64} X. L. Ji,^{1,58} Y. Y. Ji,⁵⁰
 Z. K. Jia,^{72,58} D. Jiang,^{1,64} H. B. Jiang,⁷⁷ P. C. Jiang,^{46,h} S. J. Jiang,⁹ T. J. Jiang,¹⁶ X. S. Jiang,^{1,58,64} Y. Jiang,⁶⁴ J. B. Jiao,⁵⁰
 J. K. Jiao,³⁴ Z. Jiao,²³ S. Jin,⁴² Y. Jin,⁶⁷ M. Q. Jing,^{1,64} X. M. Jing,⁶⁴ T. Johansson,⁷⁶ S. Kabana,³³ N. Kalantar-Nayestanaki,⁶⁵
 X. L. Kang,⁹ X. S. Kang,⁴⁰ M. Kavatsyuk,⁶⁵ B. C. Ke,⁸¹ V. Khachatryan,²⁷ A. Khoukaz,⁶⁹ R. Kiuchi,¹ O. B. Kolcu,^{62a}
 B. Kopf,³ M. Kuessner,³ X. Kui,^{1,64} N. Kumar,²⁶ A. Kupsc,^{44,76} W. Kühn,³⁷ Q. Lan,⁷³ W. N. Lan,¹⁹ T. T. Lei,^{72,58}
 Z. H. Lei,^{72,58} M. Lellmann,³⁵ T. Lenz,³⁵ C. Li,⁴³ C. Li,⁴⁷ C. H. Li,³⁹ C. K. Li,²⁰ Cheng Li,^{72,58} D. M. Li,⁸¹ F. Li,^{1,58} G. Li,¹
 H. B. Li,^{1,64} H. J. Li,¹⁹ H. N. Li,^{56,j} Hui Li,⁴³ J. R. Li,⁶¹ J. S. Li,⁵⁹ K. Li,¹ K. L. Li,¹⁹ K. L. Li,^{38,k,l} L. J. Li,^{1,64} Lei Li,⁴⁸
 M. H. Li,⁴³ M. R. Li,^{1,64} P. L. Li,⁶⁴ P. R. Li,^{38,k,l} Q. M. Li,^{1,64} Q. X. Li,⁵⁰ R. Li,^{17,31} T. Li,⁵⁰ T. Y. Li,⁴³ W. D. Li,^{1,64} W. G. Li,^{1,a}
 X. Li,^{1,64} X. H. Li,^{72,58} X. L. Li,⁵⁰ X. Y. Li,^{1,8} X. Z. Li,⁵⁹ Y. Li,¹⁹ Y. G. Li,^{46,h} Z. J. Li,⁵⁹ Z. Y. Li,⁷⁹ C. Liang,⁴² H. Liang,^{72,58}
 Y. F. Liang,⁵⁴ Y. T. Liang,^{31,64} G. R. Liao,¹⁴ Y. P. Liao,^{1,64} J. Libby,²⁶ A. Limphirat,⁶⁰ C. C. Lin,⁵⁵ C. X. Lin,⁶⁴ D. X. Lin,^{31,64}
 L. Q. Lin,³⁹ T. Lin,¹ B. J. Liu,¹ B. X. Liu,⁷⁷ C. Liu,³⁴ C. X. Liu,¹ F. Liu,¹ F. H. Liu,⁵³ Feng Liu,⁶ G. M. Liu,^{56,j} H. Liu,^{38,k,l}
 H. B. Liu,¹⁵ H. H. Liu,¹ H. M. Liu,^{1,64} Huihui Liu,²¹ J. B. Liu,^{72,58} J. J. Liu,²⁰ K. Liu,⁷³ K. Liu,^{38,k,l} K. Y. Liu,⁴⁰ Ke Liu,²²
 L. Liu,^{72,58} L. C. Liu,⁴³ Lu Liu,⁴³ M. H. Liu,^{12,g} P. L. Liu,¹ Q. Liu,⁶⁴ S. B. Liu,^{72,58} T. Liu,^{12,g} W. K. Liu,⁴³ W. M. Liu,^{72,58}
 W. T. Liu,³⁹ X. Liu,^{38,k,l} X. Liu,³⁹ X. Y. Liu,⁷⁷ Y. Liu,⁸¹ Y. Liu,⁸¹ Y. Liu,^{38,k,l} Y. B. Liu,⁴³ Z. A. Liu,^{1,58,64} Z. D. Liu,⁹
 Z. Q. Liu,⁵⁰ X. C. Lou,^{1,58,64} F. X. Lu,⁵⁹ H. J. Lu,²³ J. G. Lu,^{1,58} Y. Lu,⁷ Y. H. Lu,^{1,64} Y. P. Lu,^{1,58} Z. H. Lu,^{1,64} C. L. Luo,⁴¹
 J. R. Luo,⁵⁹ J. S. Luo,^{1,64} M. X. Luo,⁸⁰ T. Luo,^{12,g} X. L. Luo,^{1,58} X. R. Lyu,^{64,p} Y. F. Lyu,⁴³ Y. H. Lyu,⁸¹ F. C. Ma,⁴⁰ H. Ma,⁷⁹
 H. L. Ma,¹ J. L. Ma,^{1,64} L. L. Ma,⁵⁰ L. R. Ma,⁶⁷ Q. M. Ma,¹ R. Q. Ma,^{1,64} R. Y. Ma,¹⁹ T. Ma,^{72,58} X. T. Ma,^{1,64} X. Y. Ma,^{1,58}
 Y. M. Ma,³¹ F. E. Maas,¹⁸ I. MacKay,⁷⁰ M. Maggiora,^{75a,75c} S. Malde,⁷⁰ Y. J. Mao,^{46,h} Z. P. Mao,¹ S. Marcello,^{75a,75c}
 Y. H. Meng,⁶⁴ Z. X. Meng,⁶⁷ J. G. Messchendorp,^{13,65} G. Mezzadri,^{29a} H. Miao,^{1,64} T. J. Min,⁴² R. E. Mitchell,²⁷
 X. H. Mo,^{1,58,64} B. Moses,²⁷ N. Yu. Muchnoi,^{4,c} J. Muskalla,³⁵ Y. Nefedov,³⁶ F. Nerling,^{18,e} L. S. Nie,²⁰ I. B. Nikolaev,^{4,c}
 Z. Ning,^{1,58} S. Nisar,^{11,m} Q. L. Niu,^{38,k,l} S. L. Olsen,^{10,64} Q. Ouyang,^{1,58,64} S. Pacetti,^{28b,28c} X. Pan,⁵⁵ Y. Pan,⁵⁷ A. Pathak,¹⁰
 Y. P. Pei,^{72,58} M. Pelizaeus,³ H. P. Peng,^{72,58} Y. Y. Peng,^{38,k,l} K. Peters,^{13,e} J. L. Ping,⁴¹ R. G. Ping,^{1,64} S. Plura,³⁵ V. Prasad,³³
 F. Z. Qi,¹ H. R. Qi,⁶¹ M. Qi,⁴² S. Qian,^{1,58} W. B. Qian,⁶⁴ C. F. Qiao,⁶⁴ J. H. Qiao,¹⁹ J. J. Qin,⁷³ J. L. Qin,⁵⁵ L. Q. Qin,¹⁴
 L. Y. Qin,^{72,58} P. B. Qin,⁷³ X. P. Qin,^{12,g} X. S. Qin,⁵⁰ Z. H. Qin,^{1,58} J. F. Qiu,¹ Z. H. Qu,⁷³ C. F. Redmer,³⁵ A. Rivetti,^{75c}
 M. Rolo,^{75c} G. Rong,^{1,64} S. S. Rong,^{1,64} Ch. Rosner,¹⁸ M. Q. Ruan,^{1,58} S. N. Ruan,⁴³ N. Salone,⁴⁴ A. Sarantsev,^{36,d}
 Y. Schelhaas,³⁵ K. Schoenning,⁷⁶ M. Scodeggio,^{29a} K. Y. Shan,^{12,g} W. Shan,²⁴ X. Y. Shan,^{72,58} Z. J. Shang,^{38,k,l}
 J. F. Shangguan,¹⁶ L. G. Shao,^{1,64} M. Shao,^{72,58} C. P. Shen,^{12,g} H. F. Shen,^{1,8} W. H. Shen,⁶⁴ X. Y. Shen,^{1,64} B. A. Shi,⁶⁴
 H. Shi,^{72,58} J. L. Shi,^{12,g} J. Y. Shi,¹ S. Y. Shi,⁷³ X. Shi,^{1,58} H. L. Song,^{72,58} J. J. Song,¹⁹ T. Z. Song,⁵⁹ W. M. Song,^{34,1}

Y. J. Song,^{12,g} Y. X. Song,^{46,h,n} S. Sosio,^{75a,75c} S. Spataro,^{75a,75c} F. Stieler,³⁵ S. S. Su,⁴⁰ Y. J. Su,⁶⁴ G. B. Sun,⁷⁷ G. X. Sun,¹
 H. Sun,⁶⁴ H. K. Sun,¹ J. F. Sun,¹⁹ K. Sun,⁶¹ L. Sun,⁷⁷ S. S. Sun,^{1,64} T. Sun,^{51,f} Y. Sun,⁴⁸ Y. C. Sun,⁷⁷ Y. H. Sun,³⁰
 Y. J. Sun,^{72,58} Y. Z. Sun,¹ Z. Q. Sun,^{1,64} Z. T. Sun,⁵⁰ C. J. Tang,⁵⁴ G. Y. Tang,¹ J. Tang,⁵⁹ L. F. Tang,³⁹ M. Tang,^{72,58}
 Y. A. Tang,⁷⁷ L. Y. Tao,⁷³ M. Tat,⁷⁰ J. X. Teng,^{72,58} V. Thoren,⁷⁶ J. Y. Tian,^{72,58} W. H. Tian,⁵⁹ Y. Tian,³¹ Z. F. Tian,⁷⁷
 I. Uman,^{62b} B. Wang,¹ Bo Wang,^{72,58} C. Wang,¹⁹ D. Y. Wang,^{46,h} H. J. Wang,^{38,k,l} J. J. Wang,⁷⁷ K. Wang,^{1,58} L. L. Wang,¹
 L. W. Wang,³⁴ M. Wang,^{72,58} M. Wang,⁵⁰ N. Y. Wang,⁶⁴ S. Wang,^{38,k,l} S. Wang,^{12,g} T. Wang,^{12,g} T. J. Wang,⁴³ W. Wang,⁵⁹
 W. Wang,⁷³ W. P. Wang,^{35,58,72,o} X. Wang,^{46,h} X. F. Wang,^{38,k,l} X. J. Wang,³⁹ X. L. Wang,^{12,g} X. N. Wang,¹ Y. Wang,⁶¹
 Y. D. Wang,⁴⁵ Y. F. Wang,^{1,58,64} Y. H. Wang,^{38,k,l} Y. L. Wang,¹⁹ Y. N. Wang,⁷⁷ Y. Q. Wang,¹ Yaqian Wang,¹⁷ Yi Wang,⁶¹
 Yuan Wang,^{17,31} Z. Wang,^{1,58} Z. L. Wang,⁷³ Z. Y. Wang,^{1,64} D. H. Wei,¹⁴ F. Weidner,⁶⁹ S. P. Wen,¹ Y. R. Wen,³⁹ U. Wiedner,³
 G. Wilkinson,⁷⁰ M. Wolke,⁷⁶ C. Wu,³⁹ J. F. Wu,^{1,8} L. H. Wu,¹ L. J. Wu,^{1,64} Lianjie Wu,¹⁹ S. G. Wu,^{1,64} S. M. Wu,⁶⁴ X. Wu,^{12,g}
 X. H. Wu,³⁴ Y. J. Wu,³¹ Z. Wu,^{1,58} L. Xia,^{72,58} X. M. Xian,³⁹ B. H. Xiang,^{1,64} T. Xiang,^{46,h} D. Xiao,^{38,k,l} G. Y. Xiao,⁴²
 H. Xiao,⁷³ Y. L. Xiao,^{12,g} Z. J. Xiao,⁴¹ C. Xie,⁴² K. J. Xie,^{1,64} X. H. Xie,^{46,h} Y. Xie,⁵⁰ Y. G. Xie,^{1,58} Y. H. Xie,⁶ Z. P. Xie,^{72,58}
 T. Y. Xing,^{1,64} C. F. Xu,^{1,64} C. J. Xu,⁵⁹ G. F. Xu,¹ M. Xu,^{72,58} Q. J. Xu,¹⁶ Q. N. Xu,³⁰ W. L. Xu,⁶⁷ X. P. Xu,⁵⁵ Y. Xu,⁴⁰
 Y. C. Xu,⁷⁸ Z. S. Xu,⁶⁴ F. Yan,^{12,g} H. Y. Yan,³⁹ L. Yan,^{12,g} W. B. Yan,^{72,58} W. C. Yan,⁸¹ W. P. Yan,¹⁹ X. Q. Yan,^{1,64}
 H. J. Yang,^{51,f} H. L. Yang,³⁴ H. X. Yang,¹ J. H. Yang,⁴² R. J. Yang,¹⁹ T. Yang,¹ Y. Yang,^{12,g} Y. F. Yang,⁴³ Y. Q. Yang,⁹
 Y. X. Yang,^{1,64} Y. Z. Yang,¹⁹ M. Ye,^{1,58} M. H. Ye,⁸ Junhao Yin,⁴³ Z. Y. You,⁵⁹ B. X. Yu,^{1,58,64} C. X. Yu,⁴³ G. Yu,¹³ J. S. Yu,^{25,i}
 M. C. Yu,⁴⁰ T. Yu,⁷³ X. D. Yu,^{46,h} Y. C. Yu,⁸¹ C. Z. Yuan,^{1,64} H. Yuan,^{1,64} J. Yuan,³⁴ J. Yuan,⁴⁵ L. Yuan,² S. C. Yuan,^{1,64}
 Y. Yuan,^{1,64} Z. Y. Yuan,⁵⁹ C. X. Yue,³⁹ Ying Yue,¹⁹ A. A. Zafar,⁷⁴ S. H. Zeng,⁶³ X. Zeng,^{12,g} Y. Zeng,^{25,i} Y. J. Zeng,^{1,64}
 Y. J. Zeng,⁵⁹ X. Y. Zhai,³⁴ Y. H. Zhan,⁵⁹ A. Q. Zhang,^{1,64} B. L. Zhang,^{1,64} B. X. Zhang,¹ D. H. Zhang,⁴³ G. Y. Zhang,¹⁹
 G. Y. Zhang,^{1,64} H. Zhang,^{72,58} H. Zhang,⁸¹ H. C. Zhang,^{1,58,64} H. H. Zhang,⁵⁹ H. Q. Zhang,^{1,58,64} H. R. Zhang,^{72,58}
 H. Y. Zhang,^{1,58} J. Zhang,⁵⁹ J. Zhang,⁸¹ J. J. Zhang,⁵² J. L. Zhang,²⁰ J. Q. Zhang,⁴¹ J. S. Zhang,^{12,g} J. W. Zhang,^{1,58,64}
 J. X. Zhang,^{38,k,l} J. Y. Zhang,¹ J. Z. Zhang,^{1,64} Jianyu Zhang,⁶⁴ L. M. Zhang,⁶¹ Lei Zhang,⁴² N. Zhang,⁸¹ P. Zhang,^{1,64}
 Q. Zhang,¹⁹ Q. Y. Zhang,³⁴ R. Y. Zhang,^{38,k,l} S. H. Zhang,^{1,64} Shulei Zhang,^{25,i} X. M. Zhang,¹ X. Y. Zhang,⁴⁰ X. Y. Zhang,⁵⁰
 Y. Zhang,⁷³ Y. Zhang,¹ Y. T. Zhang,⁸¹ Y. H. Zhang,^{1,58} Y. M. Zhang,³⁹ Z. D. Zhang,¹ Z. H. Zhang,¹ Z. L. Zhang,⁵⁵
 Z. L. Zhang,³⁴ Z. X. Zhang,¹⁹ Z. Y. Zhang,⁷⁷ Z. Y. Zhang,⁴³ Z. Z. Zhang,⁴⁵ Zh. Zh. Zhang,¹⁹ G. Zhao,¹ J. Y. Zhao,^{1,64}
 J. Z. Zhao,^{1,58} L. Zhao,¹ Lei Zhao,^{72,58} M. G. Zhao,⁴³ N. Zhao,⁷⁹ R. P. Zhao,⁶⁴ S. J. Zhao,⁸¹ Y. B. Zhao,^{1,58} Y. L. Zhao,⁵⁵
 Y. X. Zhao,^{31,64} Z. G. Zhao,^{72,58} A. Zhemchugov,^{36,b} B. Zheng,⁷³ B. M. Zheng,³⁴ J. P. Zheng,^{1,58} W. J. Zheng,^{1,64}
 X. R. Zheng,¹⁹ Y. H. Zheng,^{64,p} B. Zhong,⁴¹ X. Zhong,⁵⁹ H. Zhou,^{35,50,o} J. Y. Zhou,³⁴ S. Zhou,⁶ X. Zhou,⁷⁷ X. K. Zhou,⁶
 X. R. Zhou,^{72,58} X. Y. Zhou,³⁹ Y. Z. Zhou,^{12,g} Z. C. Zhou,²⁰ A. N. Zhu,⁶⁴ J. Zhu,⁴³ K. Zhu,¹ K. J. Zhu,^{1,58,64} K. S. Zhu,^{12,g}
 L. Zhu,³⁴ L. X. Zhu,⁶⁴ S. H. Zhu,⁷¹ T. J. Zhu,^{12,g} W. D. Zhu,⁴¹ W. J. Zhu,¹ W. Z. Zhu,¹⁹ Y. C. Zhu,^{72,58} Z. A. Zhu,^{1,64}
 X. Y. Zhuang,⁴³ J. H. Zou,¹ and J. Zu^{72,58}

(BESIII Collaboration)

¹*Institute of High Energy Physics, Beijing 100049, People's Republic of China*

²*Beihang University, Beijing 100191, People's Republic of China*

³*Bochum Ruhr-University, D-44780 Bochum, Germany*

⁴*Budker Institute of Nuclear Physics SB RAS (BINP), Novosibirsk 630090, Russia*

⁵*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*

⁶*Central China Normal University, Wuhan 430079, People's Republic of China*

⁷*Central South University, Changsha 410083, People's Republic of China*

⁸*China Center of Advanced Science and Technology, Beijing 100190, People's Republic of China*

⁹*China University of Geosciences, Wuhan 430074, People's Republic of China*

¹⁰*Chung-Ang University, Seoul, 06974, Republic of Korea*

¹¹*COMSATS University Islamabad, Lahore Campus, Defence Road, Off Raiwind Road, 54000 Lahore, Pakistan*

¹²*Fudan University, Shanghai 200433, People's Republic of China*

¹³*GSI Helmholtzcentre for Heavy Ion Research GmbH, D-64291 Darmstadt, Germany*

¹⁴*Guangxi Normal University, Guilin 541004, People's Republic of China*

¹⁵*Guangxi University, Nanning 530004, People's Republic of China*

¹⁶*Hangzhou Normal University, Hangzhou 310036, People's Republic of China*

¹⁷*Hebei University, Baoding 071002, People's Republic of China*

- ¹⁸Helmholtz Institute Mainz, Staudinger Weg 18, D-55099 Mainz, Germany
- ¹⁹Henan Normal University, Xinxiang 453007, People's Republic of China
- ²⁰Henan University, Kaifeng 475004, People's Republic of China
- ²¹Henan University of Science and Technology, Luoyang 471003, People's Republic of China
- ²²Henan University of Technology, Zhengzhou 450001, People's Republic of China
- ²³Huangshan College, Huangshan 245000, People's Republic of China
- ²⁴Hunan Normal University, Changsha 410081, People's Republic of China
- ²⁵Hunan University, Changsha 410082, People's Republic of China
- ²⁶Indian Institute of Technology Madras, Chennai 600036, India
- ²⁷Indiana University, Bloomington, Indiana 47405, USA
- ^{28a}INFN Laboratori Nazionali di Frascati, INFN Laboratori Nazionali di Frascati, I-00044, Frascati, Italy
- ^{28b}INFN Sezione di Perugia, I-06100, Perugia, Italy
- ^{28c}University of Perugia, I-06100, Perugia, Italy
- ^{29a}INFN Sezione di Ferrara, INFN Sezione di Ferrara, I-44122, Ferrara, Italy
- ^{29b}University of Ferrara, I-44122, Ferrara, Italy
- ³⁰Inner Mongolia University, Hohhot 010021, People's Republic of China
- ³¹Institute of Modern Physics, Lanzhou 730000, People's Republic of China
- ³²Institute of Physics and Technology, Peace Avenue 54B, Ulaanbaatar 13330, Mongolia
- ³³Instituto de Alta Investigación, Universidad de Tarapacá, Casilla 7D, Arica 1000000, Chile
- ³⁴Jilin University, Changchun 130012, People's Republic of China
- ³⁵Johannes Gutenberg University of Mainz, Johann-Joachim-Becher-Weg 45, D-55099 Mainz, Germany
- ³⁶Joint Institute for Nuclear Research, 141980 Dubna, Moscow region, Russia
- ³⁷Justus-Liebig-Universität Giessen, II. Physikalisches Institut, Heinrich-Buff-Ring 16, D-35392 Giessen, Germany
- ³⁸Lanzhou University, Lanzhou 730000, People's Republic of China
- ³⁹Liaoning Normal University, Dalian 116029, People's Republic of China
- ⁴⁰Liaoning University, Shenyang 110036, People's Republic of China
- ⁴¹Nanjing Normal University, Nanjing 210023, People's Republic of China
- ⁴²Nanjing University, Nanjing 210093, People's Republic of China
- ⁴³Nankai University, Tianjin 300071, People's Republic of China
- ⁴⁴National Centre for Nuclear Research, Warsaw 02-093, Poland
- ⁴⁵North China Electric Power University, Beijing 102206, People's Republic of China
- ⁴⁶Peking University, Beijing 100871, People's Republic of China
- ⁴⁷Qufu Normal University, Qufu 273165, People's Republic of China
- ⁴⁸Renmin University of China, Beijing 100872, People's Republic of China
- ⁴⁹Shandong Normal University, Jinan 250014, People's Republic of China
- ⁵⁰Shandong University, Jinan 250100, People's Republic of China
- ⁵¹Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China
- ⁵²Shanxi Normal University, Linfen 041004, People's Republic of China
- ⁵³Shanxi University, Taiyuan 030006, People's Republic of China
- ⁵⁴Sichuan University, Chengdu 610064, People's Republic of China
- ⁵⁵Soochow University, Suzhou 215006, People's Republic of China
- ⁵⁶South China Normal University, Guangzhou 510006, People's Republic of China
- ⁵⁷Southeast University, Nanjing 211100, People's Republic of China
- ⁵⁸State Key Laboratory of Particle Detection and Electronics, Beijing 100049, Hefei 230026, People's Republic of China
- ⁵⁹Sun Yat-Sen University, Guangzhou 510275, People's Republic of China
- ⁶⁰Suranaree University of Technology, University Avenue 111, Nakhon Ratchasima 30000, Thailand
- ⁶¹Tsinghua University, Beijing 100084, People's Republic of China
- ^{62a}Turkish Accelerator Center Particle Factory Group, Istinye University, 34010, Istanbul, Turkey
- ^{62b}Near East University, Nicosia, North Cyprus, 99138, Mersin 10, Turkey
- ⁶³University of Bristol, H H Wills Physics Laboratory, Tyndall Avenue, Bristol, BS8 1TL, United Kingdom
- ⁶⁴University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China
- ⁶⁵University of Groningen, NL-9747 AA Groningen, The Netherlands
- ⁶⁶University of Hawaii, Honolulu, Hawaii 96822, USA
- ⁶⁷University of Jinan, Jinan 250022, People's Republic of China
- ⁶⁸University of Manchester, Oxford Road, Manchester, M13 9PL, United Kingdom
- ⁶⁹University of Muenster, Wilhelm-Klemm-Strasse 9, 48149 Muenster, Germany
- ⁷⁰University of Oxford, Keble Road, Oxford OX13RH, United Kingdom
- ⁷¹University of Science and Technology Liaoning, Anshan 114051, People's Republic of China
- ⁷²University of Science and Technology of China, Hefei 230026, People's Republic of China
- ⁷³University of South China, Hengyang 421001, People's Republic of China

⁷⁴*University of the Punjab, Lahore-54590, Pakistan*

^{75a}*University of Turin and INFN, University of Turin, I-10125, Turin, Italy*

^{75b}*University of Eastern Piedmont, I-15121, Alessandria, Italy*

^{75c}*INFN, I-10125, Turin, Italy*

⁷⁶*Uppsala University, Box 516, SE-75120 Uppsala, Sweden*

⁷⁷*Wuhan University, Wuhan 430072, People's Republic of China*

⁷⁸*Yantai University, Yantai 264005, People's Republic of China*

⁷⁹*Yunnan University, Kunming 650500, People's Republic of China*

⁸⁰*Zhejiang University, Hangzhou 310027, People's Republic of China*

⁸¹*Zhengzhou University, Zhengzhou 450001, People's Republic of China*

^aDeceased.

^bAlso at the Moscow Institute of Physics and Technology, Moscow 141700, Russia.

^cAlso at the Novosibirsk State University, Novosibirsk, 630090, Russia.

^dAlso at the NRC "Kurchatov Institute," PNPI, 188300, Gatchina, Russia.

^eAlso at Goethe University Frankfurt, 60323 Frankfurt am Main, Germany.

^fAlso 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.

^gAlso 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.

^hAlso at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, People's Republic of China.

ⁱAlso at School of Physics and Electronics, Hunan University, Changsha 410082, China.

^jAlso at Guangdong Provincial Key Laboratory of Nuclear Science, Institute of Quantum Matter, South China Normal University, Guangzhou 510006, China.

^kAlso at MOE Frontiers Science Center for Rare Isotopes, Lanzhou University, Lanzhou 730000, People's Republic of China.

^lAlso at Lanzhou Center for Theoretical Physics, Lanzhou University, Lanzhou 730000, People's Republic of China.

^mAlso at the Department of Mathematical Sciences, IBA, Karachi 75270, Pakistan.

ⁿAlso at Ecole Polytechnique Federale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland.

^oAlso at Helmholtz Institute Mainz, Staudinger Weg 18, D-55099 Mainz, Germany.

^pAlso at Hangzhou Institute for Advanced Study, University of Chinese Academy of Sciences, Hangzhou 310024, China.