

Observation of $\chi_{cJ}(J = 0, 1, 2) \rightarrow p\bar{p}\eta\eta$



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ABSTRACT: Using $(2712.4 \pm 14.3) \times 10^6$ $\psi(3686)$ candidates collected by the BESIII detector operating at the BEPCII storage ring, the decays $\chi_{cJ}(J = 0, 1, 2) \rightarrow p\bar{p}\eta\eta$ are observed for the first time through the radiative transition $\psi(3686) \rightarrow \gamma\chi_{cJ}$. The statistical significances for χ_{cJ} signals are all larger than 5σ . The branching fractions of $\chi_{c0,1,2} \rightarrow p\bar{p}\eta\eta$ are determined to be $(5.75 \pm 0.59 \pm 0.42) \times 10^{-5}$, $(1.40 \pm 0.33 \pm 0.17) \times 10^{-5}$, and $(2.64 \pm 0.40 \pm 0.27) \times 10^{-5}$, respectively, where the first uncertainties are statistical and the second systematic. No evident resonant structures are found in the $p\bar{p}$ and $p\eta/\bar{p}\eta$ systems.

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

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1 Introduction

In the quark model, the $\chi_{cJ}(J = 0, 1, 2)$ mesons are identified as 1^3P_J charmonium states. Because of parity conservation, they can only be produced in a two-photon exchange in direct e^+e^- collisions, which are suppressed. The direct production $e^+e^- \rightarrow \chi_{c1}$ was observed by the BESIII Collaboration [1]. However, the radiative decays of $\psi(3686)$ into χ_{cJ} occur with significant branching fractions of approximately 10% each [2]. Since 2008, BESIII has collected a large $\psi(3686)$ data sample [3], thereby providing an opportunity to further investigate the decays of χ_{cJ} .

An intriguing enhancement near the $p\bar{p}$ threshold, referred to as the $X(p\bar{p})$, was discovered by the BES Collaboration in the radiative decay of $J/\psi \rightarrow \gamma p\bar{p}$ [4] and subsequently confirmed by CLEO [5] and BESIII [6]. However, no similar enhancement is found in the radiative decay $\Upsilon(1S) \rightarrow \gamma p\bar{p}$ [7] nor in the decay $J/\psi \rightarrow \omega p\bar{p}$ [8]. Many theories have been proposed to interpret the nature of this structure, including the quasibound nuclear baryonium [9, 10], a multiquark resonance [11], or an effect caused by final state interaction [12, 13] near the $p\bar{p}$ production threshold. Therefore, further searches for an enhancement at this threshold in other hadronic final states are helpful to understand its properties.

Charmonium decays also provide an excellent venue to study some excited baryons, such as $N(1535)$ with $I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$, which is observed with a mass close to the one predicted from the quark model [14]. However, its unexpectedly large branching fraction for $N(1535) \rightarrow p\eta$ remains puzzling [15, 16]. BESIII has observed the $N(1535)$ via the decay of $\psi(3686) \rightarrow p\bar{p}\eta$ [16]. A search for $N(1535)$ via other charmonia, such as χ_{cJ} decays, can help understand the property of the $N(1535)$.

In this study, we present the first search for the decays $\chi_{cJ} \rightarrow p\bar{p}\eta\eta$ ($J = 0, 1, 2$) via the radiative transition $\psi(3686) \rightarrow \gamma\chi_{cJ}$, based on an analysis of $(2712.4 \pm 14.3) \times 10^6$ $\psi(3686)$ candidates [3]. Furthermore, the intermediate states in the $p\bar{p}\eta\eta$ system are investigated.

2 BESIII detector and Monte Carlo simulation

The BESIII detector [17] records e^+e^- collisions provided by the BEPCII storage ring [18]. 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 magnet is supported by an octagonal flux-return yoke with modules of resistive plate muon counters (MUC) interleaved with steel. The charged-particle momentum resolution at 1 GeV/ c is 0.5%, and the dE/dx resolution is 6% for electrons from Bhabha scattering at 1 GeV. The EMC measures photon energy with a resolution of 2.5% (5%) at 1 GeV in the barrel (end-cap) region. The time resolution of the TOF barrel part is 68 ps, while that of the end-cap part is 110 ps. The end-cap TOF system was upgraded in 2015 using multi-gap resistive plate chamber technology, providing a time resolution of 60 ps, which benefits 86% of data [19–21].

Monte Carlo (MC) simulated data samples are produced with a GEANT4-based [22] software package, which includes the geometric description [23] of the BESIII detector and the detector response. These samples are used to optimize the event selection criteria, estimate the signal efficiency, and determine the level of background. The simulation models the beam energy spread and initial-state radiation in the e^+e^- annihilation using the generator KKMC [24, 25]. The inclusive MC sample includes the production of the $\psi(3686)$ resonance, the initial-state radiation production of the J/ψ meson, and the continuum processes incorporated in KKMC. Particle decays are generated by EVTGEN [26, 27] for the known decay modes with branching fractions taken from the Particle Data Group (PDG) [2] and LUNDCHARM [28, 29] for the unknown ones. Final-state radiation from charged final-state particles is included using the PHOTOS package [30].

The signal MC samples are generated by using the phase space (PHSP) and P2GC0/1/2 models. The P2GC0/1/2 generator models are set according to the quantum number and angular distribution of $\psi(3686) \rightarrow \gamma\chi_{cJ} (J = 0, 1, 2)$, respectively [31, 32]. The other processes are generated by the PHSP model.

3 Event selection

In this analysis, the η candidate is reconstructed from a $\gamma\gamma$ final state. Therefore, the final state of interest is $p\bar{p}5\gamma$. Hence, at least one positively charged and one negatively charged track are required. Charged tracks are required to originate within 10 cm from the interaction point in the z direction and less than 1 cm in the plane perpendicular to the beam, and be within a range of $|\cos\theta| < 0.93$, where θ is the polar angle with respect to the MDC symmetry axis. The combined information of the dE/dx and TOF is used to calculate particle identification (PID) probabilities for the pion, kaon, and proton hypothesis, respectively, and the particle type with the highest probability is assigned to the corresponding track. Finally, the events with exactly two charged tracks, one proton and one anti-proton, are retained.

Photon candidates are selected using showers in the EMC. The deposited energy of each shower must be greater than 25 MeV in the barrel region ($|\cos\theta| < 0.80$) or greater than 50 MeV in the end-cap region ($0.86 < |\cos\theta| < 0.92$). To suppress electronic noise and energy

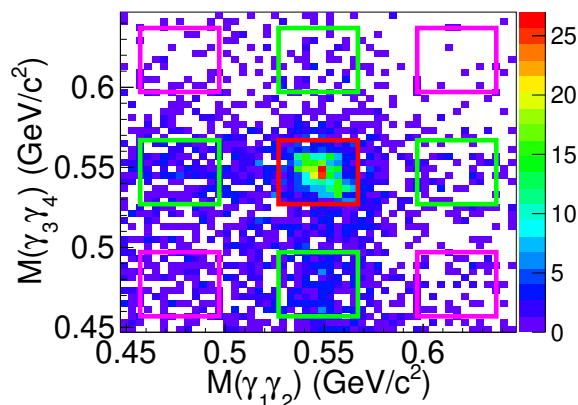


Figure 1. The scatter plot of $M(\gamma_1\gamma_2)$ versus $M(\gamma_3\gamma_4)$ for data. The red box marks the $\eta\eta$ signal region, the green boxes mark the single- η sideband regions and the purple boxes mark the non- η sideband regions.

deposition not associated to the event, the EMC cluster timing from the reconstructed event start time is further required to satisfy $0 \leq t \leq 700$ ns. The number of photon candidates is required to be at least five.

In order to suppress the remaining background and to improve the mass resolution, a four-constraint (4C) kinematic fit is performed with the $\psi(3686) \rightarrow 5\gamma p\bar{p}$ hypothesis by constraining the total four-momentum of the final state particles to that of the colliding beams. If there is more than one combination surviving the 4C kinematic fit, the one with the least χ^2 is chosen. Furthermore, the χ^2 of the 4C kinematic fit is required to be less than 35, which is obtained by optimizing the figure-of-merit $FOM = S/\sqrt{S+B}$ [33], where S is the number of MC signal events normalized to the data from $\chi_{c0} \rightarrow p\bar{p}\eta\eta$ and B is obtained from the normalized inclusive MC sample. Moreover, in order to suppress the background from the final states with a non-nominal photon number, we perform a 4C kinematic fit by looping over all the four, five, and six-photon combinations, respectively. Four-photon final state are a background when they are combined with an additional fake photon, which can easily be produced by the EMC of BESIII. The combinations with the least χ^2 are chosen for different photon number hypotheses. Then, we require $\chi^2(5\gamma p\bar{p}) < \chi^2(4\gamma p\bar{p})$ and $\chi^2(5\gamma p\bar{p}) < \chi^2(6\gamma p\bar{p})$. To suppress background with a final state that contains a π^0 , such as $\chi_{cJ} \rightarrow p\bar{p}\pi^0\pi^0$, the invariant mass for all $\gamma\gamma$ combinations is required to be out of the π^0 mass window, i.e., $|M(\gamma\gamma) - m_{\pi^0}| > 15 \text{ MeV}/c^2$, where m_{π^0} is the π^0 nominal mass [2] and $15 \text{ MeV}/c^2$ is about three standard deviations of the resolution for the π^0 .

After applying all the above selection criteria, the $\eta\eta$ pair is selected from all four-photon combinations by minimizing $\Delta = \sqrt{(M(\gamma_1\gamma_2) - m_\eta)^2 + (M(\gamma_3\gamma_4) - m_\eta)^2}$, where m_η is the η nominal mass, and the subscripts are assigned to discriminate the different photon candidates. Figure 1 shows the two dimensional (2D) distribution of the invariant masses of the photon pairs. A clear $\eta\eta$ signal is seen in the central region. The signal region (the red box) is defined as $|M(\gamma_1\gamma_2) - m_\eta| < 20 \text{ MeV}/c^2$ and $|M(\gamma_3\gamma_4) - m_\eta| < 20 \text{ MeV}/c^2$. The single- η sideband (SD1) regions are offset by $\pm 70 \text{ MeV}/c^2$ along each axis (4 green squares) and the non- η sideband (SD2) regions are shifted by $\pm 70 \text{ MeV}/c^2$ along both axis simultaneously (4 purple squares).

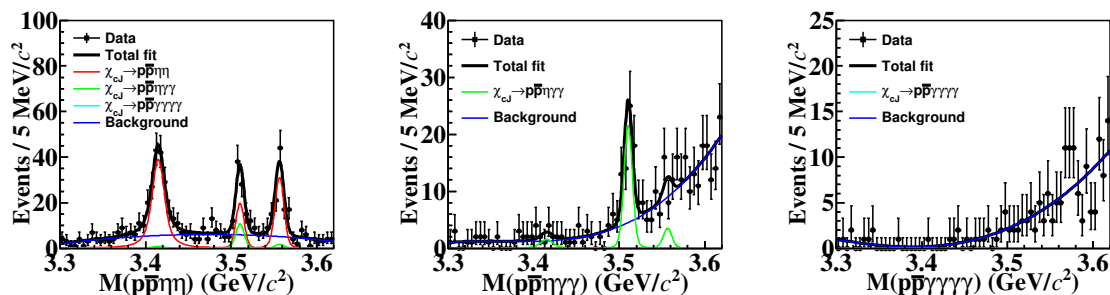


Figure 2. Simultaneous fit to the $M(p\bar{p}\eta\eta)$ (left), $M(p\bar{p}\eta\gamma\gamma)$ (middle) and $M(p\bar{p}\gamma\gamma\gamma)$ (right) distributions of accepted candidate events in the χ_{cJ} mass region for $\eta\eta$ signal region (left), SD1 region (middle) and SD2 region (right).

Figure 2 shows the $M(p\bar{p}\eta\eta)$, $M(p\bar{p}\eta\gamma\gamma)$ and $M(p\bar{p}\gamma\gamma\gamma)$ distributions of the survival event candidates in the $\eta\eta$, SD1 and SD2 regions. Significant χ_{cJ} signals are seen for the events in the $\eta\eta$ signal region, while there is also χ_{cJ} peaking background for the sideband events from SD1 region, but there is no significant χ_{cJ} peaking background for the sideband events from SD2 region. The potential remaining background from $\psi(3686)$ decays is investigated with the $\psi(3686)$ inclusive MC samples, using the event-type analysis tool TopoAna [34]. It is found that although there are some surviving backgrounds from other $\psi(3686)$ decays, the distribution is smooth without significant χ_{cJ} peaks. To investigate the continuum background from direct e^+e^- collisions without through $\psi(3686)$ decays, the same selection criteria are applied to the data samples collected at the center-of-mass energy of 3.650 GeV, 3.682 GeV, and 3.773 GeV. The total integrated luminosity of these samples amounts to 3931 pb^{-1} , while the $\psi(3686)$ data sample corresponds to an integrated luminosity of 3877 pb^{-1} . Only a few events are found, which is less than one percent of the selected candidates, so the continuum background is negligible. Therefore, the contribution from the χ_{cJ} peaking background can be estimated using normalized sideband events.

4 Signal yields

The signal yields for $\chi_{c0,1,2}$ are obtained by performing a simultaneous fit to the mass spectrums of $M(p\bar{p}\eta\eta)$, $M(p\bar{p}\eta\gamma\gamma)$, $M(p\bar{p}\gamma\gamma\gamma)$ for the $\eta\eta$ signal and both sideband regions (SD1 and SD2). The signal shape of the χ_{cJ} is described by Breit-Wigner (BW) functions $\text{BW}(m, \Gamma)$ convolved with a Gaussian function accounting for the detector resolution whose parameters are left as free and shared by all χ_{cJ} signals. The mass (m) and width (Γ) in the BW function are fixed to those in the PDG [2]. The smooth background is described with a 2nd-order Chebychev polynomial function due to its smooth shape. The χ_{cJ} signals from SD1 and SD2 are also described by BW functions $\text{BW}(m, \Gamma)$ convolved with a Gaussian function, whose parameters are the same as those used above. The number of χ_{cJ} peaking background events in the signal region is estimated to be $\frac{1}{2}N(\text{SD1}) - \frac{1}{4}N(\text{SD2})$ by assuming the single- η and non- η peaking background to be a linear distribution, where $N(\text{SD1})$ and $N(\text{SD2})$ are the number of χ_{cJ} events in the SD1 and SD2 regions, respectively. The $\chi_{cJ} \rightarrow p\bar{p}\eta\eta$ signal yield $N_{\chi_{cJ}}^{\text{obs}}$, $N(\text{SD1})$, $N(\text{SD2})$ for each of the χ_{cJ} and the smooth background in each region are floated in the fit. The fit results are shown in figure 2 and summarized in table 1.

	$N_{\chi_{cJ}}^{\text{obs}}$	$N(\text{SD1})$	$N(\text{SD2})$	$S(\sigma)$	$\epsilon(\%)$	$\mathcal{B}(\chi_{cJ} \rightarrow p\bar{p}\eta\eta)(\times 10^{-5})$
χ_{c0}	180.4 ± 18.4	7.2 ± 5.6	0.0 ± 1.4	13.4	7.64	$5.75 \pm 0.59 \pm 0.42$
χ_{c1}	50.9 ± 11.9	55.4 ± 9.6	0.0 ± 4.0	5.4	8.88	$1.40 \pm 0.33 \pm 0.17$
χ_{c2}	87.3 ± 13.3	9.8 ± 7.8	0.0 ± 14.3	9.6	8.42	$2.64 \pm 0.40 \pm 0.27$

Table 1. The $\chi_{cJ} \rightarrow p\bar{p}\eta\eta$ signal yield $N_{\chi_{cJ}}^{\text{obs}}$, $N(\text{SD1})$, $N(\text{SD2})$, significance (S), efficiency (ϵ), and branching fractions $\mathcal{B}(\chi_{cJ} \rightarrow p\bar{p}\eta\eta)$. The first uncertainties are statistical and the second systematic.

The statistical significances of χ_{c0} , χ_{c1} , and χ_{c2} decays are determined to be 13.4σ , 5.4σ , and 9.6σ , respectively, by comparing the difference of the likelihood with and without the respective signal component in the fit. The effect from the systematic uncertainty has been considered in determining the signal significance.

Figure 3 shows the distributions for both data and signal MC, no significant structures are observed in all mass spectrums. There are χ_{cJ} peaking background and smooth background when selecting signal candidates from data, so in these distributions for data, the χ_{cJ} peaking background is estimated by generating the exclusive MC of the χ_{cJ} peaking background and normalizing it to the data, and the smooth background is estimated by extracting events from the χ_{cJ} sideband region in $M(p\bar{p}\eta\eta)$ and normalizing them to the signal region. Since there are two η candidates, the ones with higher and lower momenta are distinguished by subscripts ‘‘H’’ and ‘‘L’’. Then the background subtracted $p\bar{p}$, $p\eta/\bar{p}\eta$ and $\eta\eta$ distributions of data are examined for possible intermediate structures, as shown in figure 3.

5 Numerical results

The branching fractions of $\chi_{c0,1,2} \rightarrow p\bar{p}\eta\eta$ are determined as:

$$\mathcal{B}(\chi_{cJ} \rightarrow p\bar{p}\eta\eta) = \frac{N_{\chi_{cJ}}^{\text{obs}}}{N_{\psi(3686)} \mathcal{B}(\psi(3686) \rightarrow \gamma\chi_{cJ}) \mathcal{B}^2(\eta \rightarrow \gamma\gamma) \epsilon},$$

where $N_{\chi_{cJ}}^{\text{obs}}$ is the $\chi_{cJ} \rightarrow p\bar{p}\eta\eta$ signal yield, $N_{\psi(3686)}$ is the number of $\psi(3686)$ candidates in data [3], and ϵ denotes the detection efficiency obtained from MC simulations. The branching fractions related to the intermediate states are taken from the PDG [2]. The measured branching fractions are summarized in table 1.

6 Systematic uncertainties

The sources of the systematic uncertainty are listed below:

- (i) **Tracking:** the uncertainty of the tracking for proton or anti-proton is estimated to be 1.0% for each track by the control sample $J/\psi \rightarrow p\bar{p}\pi^+\pi^-$ [35].
- (ii) **Photon reconstruction:** the uncertainty originating from the photon reconstruction is studied using the control sample $J/\psi \rightarrow \rho^0\pi^0$, and is determined to be 1.0% per photon [36].

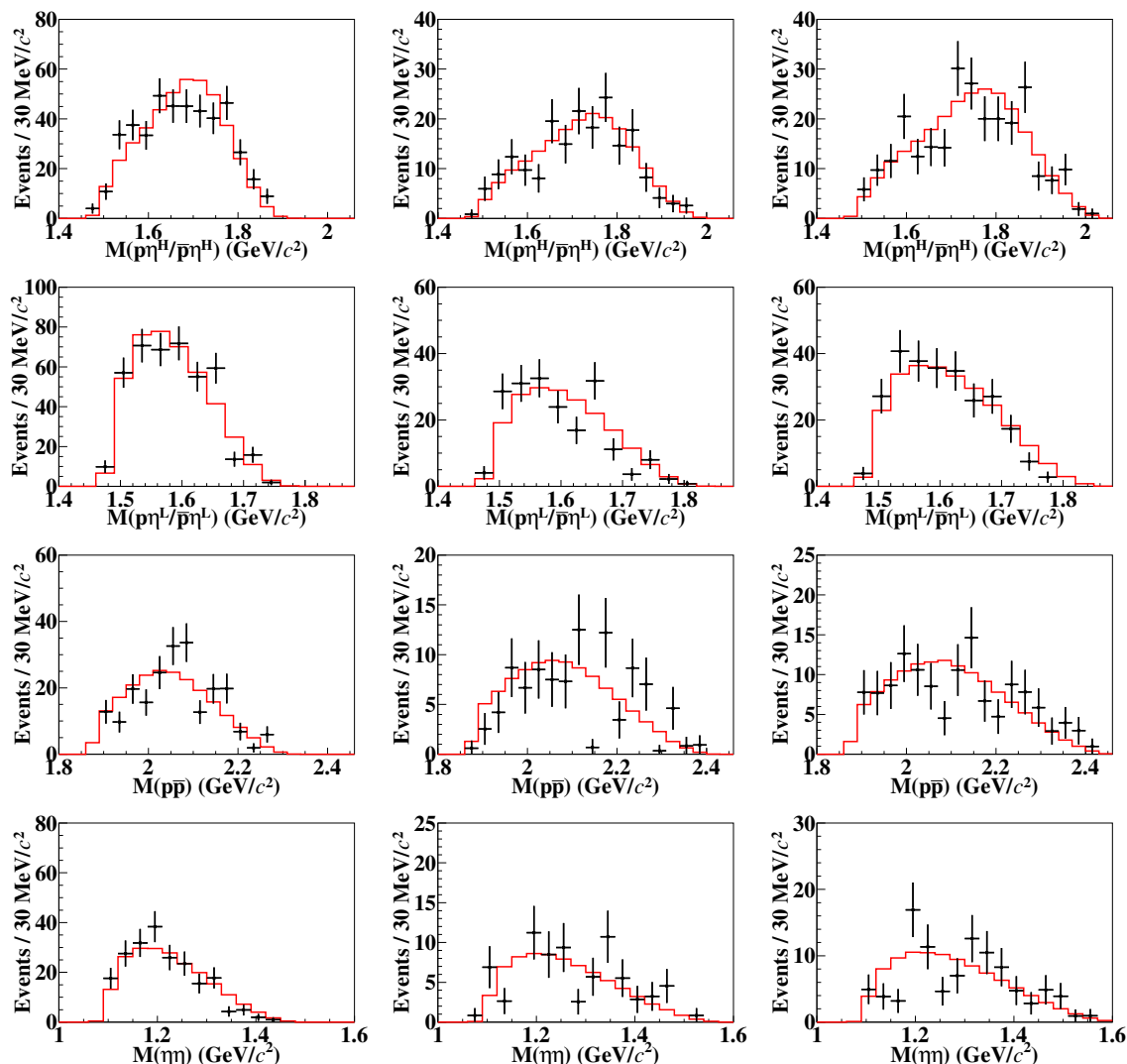


Figure 3. Invariant mass distributions of $p\eta/\bar{p}\eta$, $p\bar{p}$, and $\eta\eta$ for χ_{c0} (left), χ_{c1} (middle), and χ_{c2} (right). The points with error bars are data and the histograms are signal MC simulations.

- (iii) **PID:** the uncertainty from the PID for proton or anti-proton is determined to be 1.0% for each particle by the control sample $J/\psi \rightarrow p\bar{p}\pi^+\pi^-$ [35].
- (iv) **Kinematic fit:** the systematic uncertainty due to the 4C kinematic fit is estimated by comparing the efficiency before and after applying the helix correction [37]. The correction factors are obtained by studying the control sample $\psi(3686) \rightarrow p\bar{p}\pi^0$. The systematic uncertainties are 1.4%, 1.0% and 1.1% for $\chi_{c0,1,2}$ channels, respectively.
- (v) **π^0 mass window:** to evaluate the uncertainty, we perform a Barlow test [38] to examine the significant deviation (ζ) between the nominal fit and the systematic test. The variable ζ is defined as,

$$\zeta = \frac{|V_{\text{nominal}} - V_{\text{test}}|}{\sqrt{|\sigma_{V_{\text{nominal}}}^2 - \sigma_{V_{\text{test}}}^2|}}, \quad (6.1)$$

where V denotes the measured branching fraction and σ_V^2 is the statistical error of V . To obtain the ζ distribution, we vary the mass window of π^0 from $|M(\gamma\gamma) - m_{\pi^0}| > 13 \text{ MeV}/c^2$ to $|M(\gamma\gamma) - m_{\pi^0}| > 17 \text{ MeV}/c^2$ with a step size of $0.5 \text{ MeV}/c^2$. Since the values of ζ are greater than 2, the largest differences relative to the nominal results are taken as the systematic uncertainties, which are 3.1%, 8.8% and 7.2% for $\chi_{c0,1,2} \rightarrow p\bar{p}\eta\eta$, respectively.

- (vi) **η sideband:** to estimate the uncertainty from the non- $\eta\eta$ background subtraction via the η sideband, we also perform a similar Barlow test [38] as above. To obtain the ζ distribution, we change the interval between the signal and the sideband region from 2.5σ to 3.5σ with a step size of 0.1σ . The largest differences relative to the nominal results are taken as the systematic uncertainties, which are 1.2%, 5.5%, and 2.5% for $\chi_{c0,1,2} \rightarrow p\bar{p}\eta\eta$, respectively.
- (vii) **Signal shape:** to estimate the uncertainty caused by the signal shape, we alternatively apply another BW function ($E_\gamma^3 \times BW(m) \times f_d(E_\gamma)$) $\otimes G(\delta m, \sigma)$ to describe the signal shape, where $E_\gamma = (m_{\psi(3686)}^2 - M_{p\bar{p}\eta\eta}^2)/2m_{\psi(3686)}$ [39] is the energy of the transition photon in the $\psi(3686)$ rest frame and $m_{\psi(3686)}$ is the $\psi(3686)$ nominal mass. The function $f_d(E_\gamma)$ damps the diverging tail raised by E_γ^3 , expressed as $E_0^2/(E_\gamma E_0 + (E_\gamma - E_0)^2)$ [40]. The difference relative to the nominal BW function is taken as the systematic uncertainty.
- (viii) **Background shape:** the uncertainty due to the background shape is estimated by replacing the 2nd-order polynomial function with a 3rd-order polynomial function. The difference between two background functions is taken as the systematic uncertainty.
- (ix) **Intermediate branching fractions:** the branching fractions of the intermediate states are obtained from the PDG [2].
- (x) **$N_{\psi(3686)}$:** the uncertainty due to the number of $\psi(3686)$ candidates in data is determined to be 0.5% [3].

All the systematic uncertainties on the branching fractions are summarized in table 2. The total systematic uncertainties are obtained by summing each systematic uncertainty in quadrature under the assumption that they are independent.

7 Summary

Based on $(2712.4 \pm 14.3) \times 10^6$ $\psi(3686)$ candidates, the decays $\chi_{cJ}(J = 0, 1, 2) \rightarrow p\bar{p}\eta\eta$ are observed for the first time with a statistical significances of 13.4σ , 5.4σ , and 9.6σ , respectively. The branching fractions of $\chi_{c0,1,2} \rightarrow p\bar{p}\eta\eta$ are determined to be $(5.75 \pm 0.59 \pm 0.42) \times 10^{-5}$, $(1.40 \pm 0.33 \pm 0.17) \times 10^{-5}$, and $(2.64 \pm 0.40 \pm 0.27) \times 10^{-5}$, respectively, where the first uncertainties are statistical and the second systematic. No obvious intermediate states are found in the $p\eta/\bar{p}\eta$, $p\bar{p}$, and $\eta\eta$ systems. In order to further understand the characteristics of χ_{cJ} mesons and excited baryons, the theoretical study of the decay channels of χ_{cJ} remains a key focus of future research.

Source	$\Delta_{\chi_{c0}}(\%)$	$\Delta_{\chi_{c1}}(\%)$	$\Delta_{\chi_{c2}}(\%)$
Tracking	2.0	2.0	2.0
Photon reconstruction	5.0	5.0	5.0
PID	2.0	2.0	2.0
Kinematic fit	1.4	1.0	1.1
π^0 mass window	3.1	8.8	7.2
η sideband	1.2	5.5	2.5
Signal shape	0.9	0.3	0.1
Background shape	0.6	1.6	1.6
Intermediate branching fractions	2.4	2.8	2.5
$N_{\psi(3686)}$	0.5	0.5	0.5
Total	7.3	12.3	10.1

Table 2. Relative systematic uncertainties in the measurements of the branching fractions of $\chi_{cJ} \rightarrow p\bar{p}\eta\eta$.

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Code Availability Statement. This article has no associated code or the code will not be deposited.

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