

Observation of the χ_{cJ} decays into $pK^-\bar{\Lambda}\eta + \text{c.c.}$

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By analyzing $(2712.4 \pm 14.3) \times 10^6$ $\psi(3686)$ events collected with the BESIII detector operating at the BEPCII collider, the decays $\chi_{cJ} \rightarrow pK^-\bar{\Lambda}\eta + \text{c.c.}$ ($J = 0, 1, 2$) are observed for the first time, with statistical significances exceeding 5σ for all three χ_{cJ} states. The measured branching fractions are $\mathcal{B}(\chi_{c0} \rightarrow pK^-\bar{\Lambda}\eta + \text{c.c.}) = (5.3 \pm 0.7 \pm 0.5) \times 10^{-5}$, $\mathcal{B}(\chi_{c1} \rightarrow pK^-\bar{\Lambda}\eta + \text{c.c.}) = (9.8 \pm 0.6 \pm 0.6) \times 10^{-5}$, and $\mathcal{B}(\chi_{c2} \rightarrow pK^-\bar{\Lambda}\eta + \text{c.c.}) = (9.3 \pm 0.6 \pm 0.6) \times 10^{-5}$, where the first uncertainties are statistical and the second are systematic. Structures consistent with the known hyperon resonances $\Lambda(1520)$ and $\bar{\Lambda}(1690)$ are seen in the pK^- and $\bar{\Lambda}\eta$ invariant mass spectra, respectively. The reported branching fractions include both resonant and nonresonant contributions. These results provide new experimental information on hadronic decays of P -wave charmonium states and contribute to the understanding of baryon production and hadronization dynamics in the nonperturbative QCD regime.

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I. INTRODUCTION

In the quark model, the χ_{cJ} states ($J = 0, 1, 2$) correspond to the 3P_J charmonium states. Their quantum numbers are incompatible with those of a single virtual photon, and therefore they cannot be produced through single-photon exchange in e^+e^- annihilation [1]. The χ_{cJ} states are efficiently produced via the radiative transitions $\psi(3686) \rightarrow \gamma\chi_{cJ}$, whose branching fractions are about 9% for each χ_{cJ} state [2]. These transitions make $\psi(3686)$ decays an excellent laboratory for studying the hadronic decay properties of χ_{cJ} states and for testing the predictions of nonperturbative quantum chromodynamics (QCD) [3]. Hadronic decays of χ_{cJ} proceed predominantly through the annihilation of a $c\bar{c}$ pair into gluons, followed by hadronization into multihadron final states. Such processes are sensitive to intermediate resonant structures and final-state interactions, thereby providing valuable information on hadronization dynamics and baryon production mechanisms [4].

In the previous studies at the BES and BESIII experiments, a near-threshold enhancement in the $p\bar{\Lambda}$ invariant-mass spectrum was observed in decay channels of J/ψ and $\psi(3686)$ [5], and similar behavior was also reported in $\chi_{cJ} \rightarrow pK^-\bar{\Lambda}$ decays [6]. This structure has attracted

considerable interest in hadron spectroscopy, and has been interpreted in terms of possible baryoniumlike states [7], strong final-state interactions [8], or interference effects from excited kaon contributions [9]. Extending such investigations to more χ_{cJ} decay modes can help further clarify the role of similar effects in P -wave charmonium transitions, where the gluon hadronization dynamics may differ from those in S -wave decays.

Given the considerations discussed above, the decays $\chi_{cJ} \rightarrow pK^-\bar{\Lambda}\eta$ provide a unique opportunity to study baryon-antibaryon threshold behavior and hyperon excitation dynamics. The final state contains both a baryon-antibaryon pair and pseudoscalar mesons, making it particularly sensitive to potential excited Λ hyperon contributions in the pK^- and $\bar{\Lambda}\eta$ subsystems. In this paper, by analyzing $(2712.4 \pm 14.3) \times 10^6$ $\psi(3686)$ events collected with the BESIII detector [10], we present the first observation of the decays $\chi_{cJ} \rightarrow pK^-\bar{\Lambda}\eta$ and measure their corresponding branching fractions. Charge-conjugate modes are implied throughout this paper.

II. BESIII DETECTOR AND MONTE CARLO SIMULATION

The BESIII detector [11] records symmetric e^+e^- collisions provided by the BEPCII storage ring [12] in the center-of-mass energy range from 1.84 to 4.95 GeV, with a peak luminosity of $1.1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ achieved at $\sqrt{s} = 3.773 \text{ GeV}$. 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 (TI) electromagnetic calorimeter (EMC), which are all

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enclosed in a superconducting solenoidal magnet providing a 1.0 T magnetic field, except for the data taken in 2012, for which the magnetic field was 0.9 T. 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 was 110 ps. The end cap TOF system was upgraded in 2015 using multigap resistive plate chamber technology, providing a time resolution of 60 ps [13–15]. Around 83% of the data used in this analysis benefits from this upgrade.

Simulated data samples produced with a Geant4-based [16] Monte Carlo (MC) package, which includes the geometric description [17–20] 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 [21]. An inclusive MC sample containing 2.7×10^9 generic $\psi(3686)$ events is used to study potential backgrounds. The inclusive MC sample includes the production of the $\psi(3686)$ resonance. Known particle decays are modeled with EvtGen [22,23] using branching fractions taken from the Particle Data Group (PDG) [2], while unknown decays are modeled with Lundcharm [24]. Final-state radiation from charged final state particles is incorporated using the Photos package [25].

To account for the effect of intermediate resonance structures on the detection efficiency, each of the $\chi_{c0,1,2}$ decays is modeled using 5.04 million mixed signal MC samples. The dominant decay modes include intermediate resonances such as $\Lambda(1520)$ and $\bar{\Lambda}(1690)$, corresponding to the pK^- and $\bar{\Lambda}\eta$ systems, respectively. These components are generated using a phase-space (PHSP) model employed in EvtGen. These samples are then mixed with four-body PHSP signal MC samples. The mixing ratios are determined by examining the corresponding invariant mass spectra, as discussed in Sec. V.

III. EVENT SELECTION

We study the process $\psi(3686) \rightarrow \gamma\chi_{cJ}$ followed by $\chi_{cJ} \rightarrow pK^-\bar{\Lambda}\eta$, with $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ and $\eta \rightarrow \gamma\gamma$. Charged tracks (p , K^- , $\bar{p}$, and π^+) and photons are reconstructed with the standard BESIII algorithms. Candidate events are required to have at least four charged tracks with zero net charge. Tracks reconstructed in the MDC must satisfy $|\cos\theta| < 0.93$, where θ is the polar angle with respect to the MDC z axis. For charged tracks originating directly from the χ_{cJ} decay, the distances of closest approach to the interaction point (IP) are required to satisfy $|V_z| < 10$ cm

and $|V_{xy}| < 1$ cm, where V_z and V_{xy} denote the distances along the beam and transverse directions, respectively. No IP-vertex requirement is imposed on the daughter tracks from the $\bar{\Lambda}$ decay.

The PID information combines the dE/dx measurements in the MDC and the TOF information to form likelihoods $\mathcal{L}(h)$ for $h \in \{p, K, \pi\}$. A track is identified as a proton if $\mathcal{L}(p) > \mathcal{L}(K)$ and $\mathcal{L}(p) > \mathcal{L}(\pi)$, and as a kaon if $\mathcal{L}(K) > \mathcal{L}(p)$ and $\mathcal{L}(K) > \mathcal{L}(\pi)$. Tracks failing both criteria are treated as pion candidates.

Photon candidates are identified using isolated showers in the EMC. At least three good photon candidates are required. The deposited energy must exceed 25 MeV in the barrel region ($|\cos\theta| < 0.80$) and 50 MeV in the end cap region ($0.86 < |\cos\theta| < 0.92$). The EMC time is required to be within $[0, 700]$ ns relative to the event start time to suppress noise and beam backgrounds. To reduce contamination from hadronic interactions or bremsstrahlung, clusters within a cone of 20° around the extrapolated EMC position of a $\bar{p}$ track and within 10° of any other charged track are rejected.

The $\bar{\Lambda}$ candidates are reconstructed from pairs of oppositely charged tracks excluding the selected proton and kaon candidates, under the $\bar{p}\pi^+$ mass hypothesis, without applying PID requirements to the daughter tracks. The two tracks are required to satisfy $|\cos\theta| < 0.93$ and $|V_z| < 20$ cm; no requirement is imposed on V_{xy} due to the displaced decay vertex of the long-lived $\bar{\Lambda}$ baryon. The two tracks are subjected to a common secondary-vertex fit, and combinations with fit $\chi^2_{\text{vtx}} < 200$ are retained. To suppress combinatorial background, the decay length of the $\bar{\Lambda}$ candidate is required to satisfy $L/\sigma_L > 2$, where L is the distance between the reconstructed decay vertex and the IP, and σ_L is the uncertainty of the decay length L . The $\bar{\Lambda}$ signal region is defined as $|M_{\bar{p}\pi^+} - m_{\bar{\Lambda}}| < 0.015$ GeV/ c^2 , while the sidebands are $0.020 < |M_{\bar{p}\pi^+} - m_{\bar{\Lambda}}| < 0.050$ GeV/ c^2 , where $m_{\bar{\Lambda}}$ is the known $\bar{\Lambda}$ mass [2]; the distributions and windows are shown in Fig. 1.

To improve the mass resolution and suppress combinatorial background, a four-constraint (4C) kinematic fit is performed under the hypothesis $e^+e^- \rightarrow pK^-\bar{\Lambda}\gamma\gamma$, imposing conservation of the total energy and the three-momentum components. If multiple combinations are found, the one with the smallest fit χ^2_{4C} is retained. The requirement on χ^2_{4C} is optimized using a figure-of-merit (FOM) procedure, where the FOM is defined as $\text{FOM} = S/\sqrt{S+B}$ with S and B denoting the signal and background yields extracted from the signal MC and inclusive MC samples normalized to data. This yields the nominal selection $\chi^2_{4C} < 35$.

The η meson candidate is reconstructed from photon pairs formed from the three selected photons. The three photons are ordered by energy, $E_{\gamma_1} > E_{\gamma_2} > E_{\gamma_3}$. Studies with signal MC indicate that the $(\gamma_2\gamma_3)$ combination is found to contain a negligible η signal and is therefore

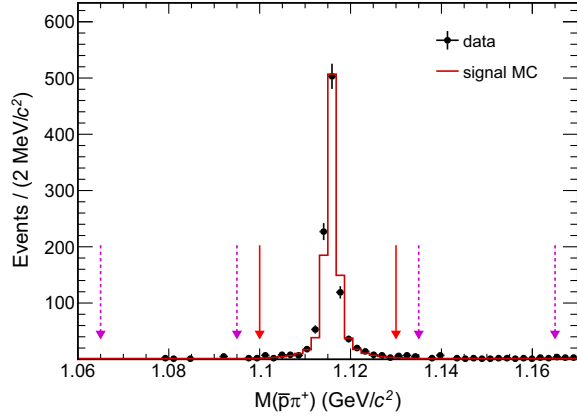


FIG. 1. Invariant mass spectrum of $\bar{p}\pi^+$ candidates. Data are shown as black points with error bars, and the signal MC distribution is shown as the red histogram. The $\bar{\Lambda}$ signal window $[1.100, 1.130]$ GeV/c^2 is indicated by red solid arrows, and the sideband windows $[1.065, 1.095]$ GeV/c^2 (left) and $[1.135, 1.165]$ GeV/c^2 (right) are indicated by magenta dashed arrows.

discarded; the η candidate is formed from either the $\gamma_1\gamma_2$ or $\gamma_1\gamma_3$ combination. The $M_{\gamma\gamma}$ distribution is fitted with a double-Gaussian signal function and a polynomial background function, as shown in Fig. 2. The η signal window is defined as $0.525 < M_{\gamma\gamma} < 0.570$ GeV/c^2 , and the lower (upper) sideband region is defined as $0.458 < M_{\gamma\gamma} < 0.503$ GeV/c^2 ($0.592 < M_{\gamma\gamma} < 0.637$ GeV/c^2). If both $M_{\gamma_1\gamma_2}$ and $M_{\gamma_1\gamma_3}$ fall within the η signal window in the same event, the event is excluded from further analysis to

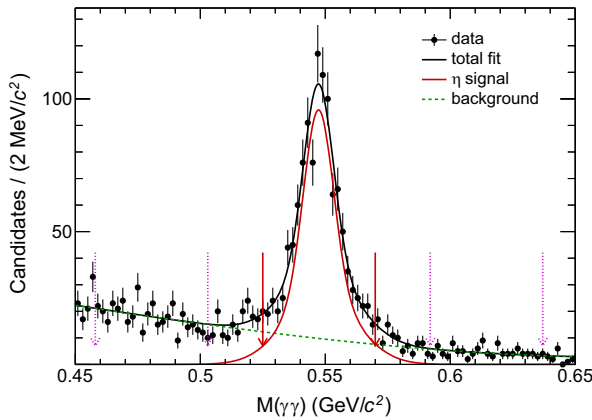


FIG. 2. Invariant mass spectrum of $\gamma\gamma$ combinations for η candidates in data. The total fit is shown by the black solid curve, while the red solid curve represents the η signal component and the green dashed curve denotes the background contribution. The η signal region $[0.525, 0.570]$ GeV/c^2 is indicated by red solid arrows, and the sideband regions $[0.458, 0.503]$ GeV/c^2 (left) and $[0.592, 0.637]$ GeV/c^2 (right) are indicated by magenta dashed arrows.

avoid double counting, at the loss of about 4% of the η signal yield.

To suppress $\pi^0 \rightarrow \gamma\gamma$ contamination, photon-pair veto windows around the known π^0 mass m_{π^0} [2] are applied, $|M_{\gamma_1\gamma_2} - m_{\pi^0}| > 0.013 \text{ GeV}/c^2$, $|M_{\gamma_1\gamma_3} - m_{\pi^0}| > 0.018 \text{ GeV}/c^2$, and $|M_{\gamma_2\gamma_3} - m_{\pi^0}| > 0.009 \text{ GeV}/c^2$, due to the different π^0 invariant-mass resolutions of the three photon combinations. These requirements, together with all other veto selections described below, are optimized using the same FOM procedure, based on the signal and inclusive MC samples normalized to data. Backgrounds from $\psi(3686) \rightarrow \eta J/\psi$ with $J/\psi \rightarrow pK^-\bar{\Lambda} + \text{c.c.}$ are suppressed by vetoing events whose η recoil mass lies near the known J/ψ mass $m_{J/\psi}$ [2]. The recoil mass is calculated using the reconstructed $\eta \rightarrow \gamma\gamma$ candidate as $RM_\eta = \sqrt{(E_{\text{cm}} - E_\eta)^2 - |\vec{p}_\eta|^2}$, where E_{cm} is the center-of-mass energy, while E_η and $\vec{p}_\eta$ denote the energy and three-momentum of the η candidate in the center-of-mass frame. Using the same FOM optimization procedure, the requirement $|RM_\eta - m_{J/\psi}| > 0.007 \text{ GeV}/c^2$ is chosen. In addition, contributions from $\bar{\Sigma}^0 \rightarrow \bar{\Lambda}\gamma$ are suppressed with a veto around the $\bar{\Sigma}^0$ mass region. The photon not used in the selected $\eta \rightarrow \gamma\gamma$ candidate is combined with the $\bar{\Lambda}$ candidate. The requirement $|M_{\bar{\Lambda}\gamma} - m_{\Sigma^0}| > 0.018 \text{ GeV}/c^2$ is optimized using the FOM procedure, where m_{Σ^0} is the known Σ^0 mass [2].

IV. BACKGROUND ANALYSIS

Potential background contributions surviving the event selection are investigated using the inclusive $\psi(3686)$ MC sample. The decay chains of the candidate background events are identified with the TopoAna package [26]. The dominant decay chains can be categorized into three classes: (i) $\psi(3686) \rightarrow \eta J/\psi$ with $\eta \rightarrow \gamma\gamma$, (ii) $\psi(3686) \rightarrow \gamma\chi_{cJ}$ followed by $\chi_{cJ} \rightarrow \gamma J/\psi$ or hadronic decays, and (iii) multibody direct decays possibly involving $K^*(892)$, Λ , or $\Sigma^*(1385)$ resonances.

For the selected inclusive MC sample, the $M_{pK^-\bar{\Lambda}\eta}$ distribution exhibits a broad, nonpeaking structure, indicating that the background predominantly originates from nonresonant processes and combinatorial contributions. A mild enhancement is found near $3.5 \text{ GeV}/c^2$, which is mainly attributed to cascade decays such as $\psi(3686) \rightarrow \gamma\chi_{c1}$ followed by $\chi_{c1} \rightarrow \gamma J/\psi$ with $J/\psi \rightarrow pK^-(892)\bar{\Lambda}$ or $J/\psi \rightarrow pK^-\bar{\Sigma}^{*0}(1385)$. Dedicated exclusive MC studies show that the expected residual contributions from these two processes are 1 and 3 events, respectively. Therefore, their contributions are negligible and are not included in the final fit.

The possible quantum electrodynamics (QED) contribution from the process $e^+e^- \rightarrow \gamma\chi_{cJ}$ is evaluated with the continuum data at $\sqrt{s} = 3.650 \text{ GeV}$, corresponding to an

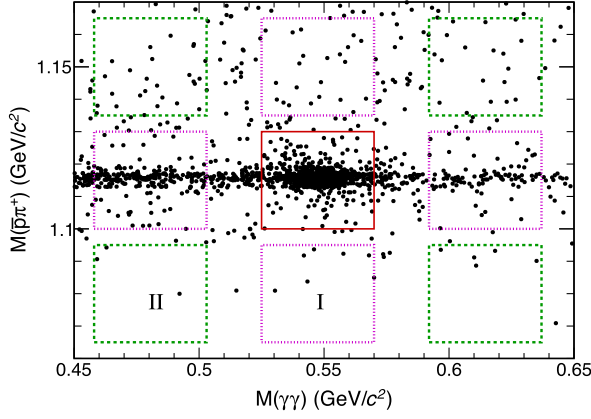


FIG. 3. Two-dimensional distribution of $M_{p\pi^+}$ versus $M_{\gamma\gamma}$ for the accepted events in data. The red solid rectangle denotes the η signal region, the magenta dot-dashed rectangles denote the $\bar{\Lambda}$ and η sideband I regions, and the green dashed rectangles denote the $\bar{\Lambda}$ and η sideband II regions.

integrated luminosity of 401.0 pb⁻¹ [10]. Applying the same event selection criteria as for the $\psi(3686)$ data, no surviving event is found. Hence, the QED background is negligible in this analysis.

V. BRANCHING FRACTIONS

To determine the signal yields, we perform an unbinned maximum-likelihood fit to the $M_{pK^-\bar{\Lambda}\eta}$ spectrum of accepted candidates. The fit is carried out simultaneously in the signal region and in the sideband regions, defined by events

satisfying both the $\bar{\Lambda}$ and η signal windows, and in the $\bar{\Lambda}$ and η sideband control samples shown in Fig. 3 (the sideband window definitions follow Sec. III). This constrains backgrounds from misreconstructed $\bar{\Lambda}$ or η candidates.

In the simultaneous fit to $M_{pK^-\bar{\Lambda}\eta}$, the three χ_{cJ} peaks ($J = 0, 1, 2$) are described by Breit-Wigner functions with parameters determined from exclusive signal MC samples. Each Breit-Wigner function is convolved with a single Gaussian function to account for the possible difference in mass resolution between data and MC simulation. The Gaussian parameters are allowed to float and are common between the signal and sideband samples for a given J . The combinatorial background in both regions is described with a first-order Chebyshev polynomial. Sideband normalizations are fixed by the geometric scale factors determined from their window widths. The net signal yield obtained from the fitted χ_{cJ} peaking yields is $N_{\text{net}} = N_{\text{sig}} - \frac{1}{2} \cdot N_{\text{sideband I}} + \frac{1}{4} \cdot N_{\text{sideband II}}$. Here, N_{sig} denotes the χ_{cJ} peaking yield in the signal region. The net yields for each signal decay are summarized in Table I. The statistical significances are computed from the change in log-likelihood with respect to the zero-signal hypothesis, $\Delta(\ln \mathcal{L}) = \ln \mathcal{L}_{\text{max}} - \ln \mathcal{L}_0$. For each tested χ_{cJ} signal, the change in the number of degrees of freedom is $\Delta n_{\text{d.o.f.}} = 3$, corresponding to the signal yield and the two Gaussian smearing parameters, μ and σ . Statistical significances exceeding 5σ are obtained for the χ_{c0} , χ_{c1} , and χ_{c2} signals. Here, $n_{\text{d.o.f.}}$ is the number of degrees of freedom. The projections of the simultaneous fit in the signal as well as sideband I and II regions are shown in Fig. 4.

TABLE I. Signal yields, efficiencies, and branching-fraction results for $\chi_{cJ} \rightarrow pK^-\bar{\Lambda}\eta$ (statistical uncertainties only).

	χ_{c0}	χ_{c1}	χ_{c2}
N_{net}	130.2 ± 16.8	359.7 ± 21.8	341.2 ± 21.2
ϵ_J (%)	3.7	5.5	5.7
$\mathcal{B}(\psi(3686) \rightarrow \gamma\chi_{cJ})\mathcal{B}(\chi_{cJ} \rightarrow pK^-\bar{\Lambda}\eta) (\times 10^{-7})$	51.4 ± 6.6	95.6 ± 5.8	87.5 ± 5.4
$\mathcal{B}(\chi_{cJ} \rightarrow pK^-\bar{\Lambda}\eta) (\times 10^{-5})$	5.3 ± 0.7	9.8 ± 0.6	9.3 ± 0.6

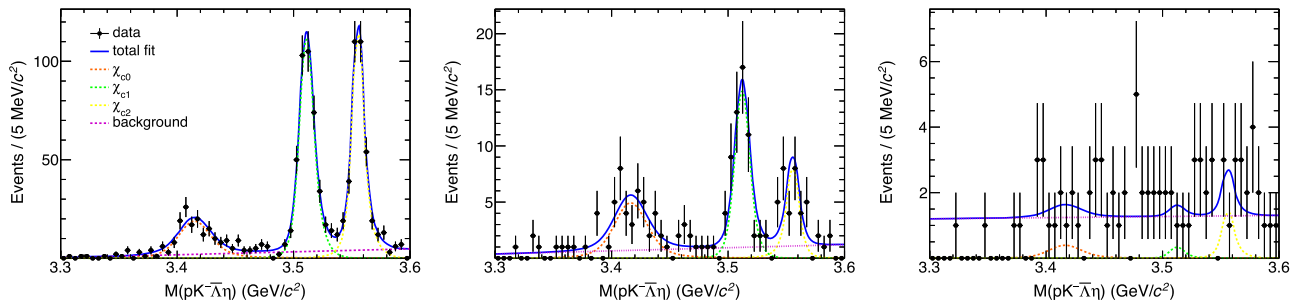


FIG. 4. Fits to the $M_{pK^-\bar{\Lambda}\eta}$ distributions. The left, middle, and right panels correspond to the signal, sideband I, and sideband II regions, respectively. Data are shown as black points with error bars. The blue solid curves represent the total fit results, the orange, green, and yellow dashed curves denote the individual χ_{c0} , χ_{c1} , and χ_{c2} signal components, respectively, and the magenta dotted curves denote the background components.

As motivated by the invariant mass distributions of two-body comparison in Figs. 5–7, enhancements in M_{pK^-} and $M_{\bar{\Lambda}\eta}$ indicate possible contributions from intermediate hyperon resonances $\Lambda(1520)$ and $\bar{\Lambda}(1690)$. To account

for their impact on the detection efficiency, a mixed signal MC sample is constructed by combining the pure PHSP process with these resonant subprocesses, weighted according to their relative fractions extracted from data. The

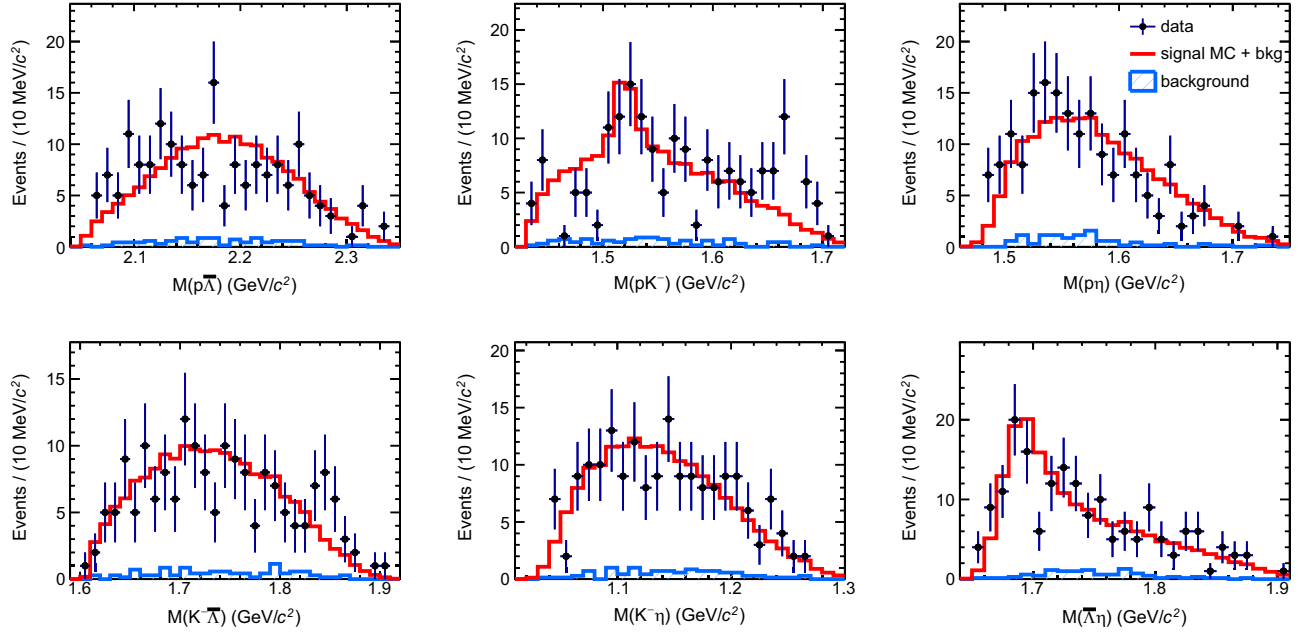


FIG. 5. Invariant mass distributions of the two-body combinations of the $\psi(3686) \rightarrow \gamma\chi_{c0}, \chi_{c0} \rightarrow pK^-\bar{\Lambda}\eta$ candidates. The events are selected within the χ_{c0} signal region of $[3.372, 3.462]$ GeV/c^2 . The data (points with error bars) are compared with the summed distribution of the signal MC including possible intermediate structures and the inclusive background (red solid histograms), and with the inclusive background (blue hatched histograms). All histograms are normalized to the data size.

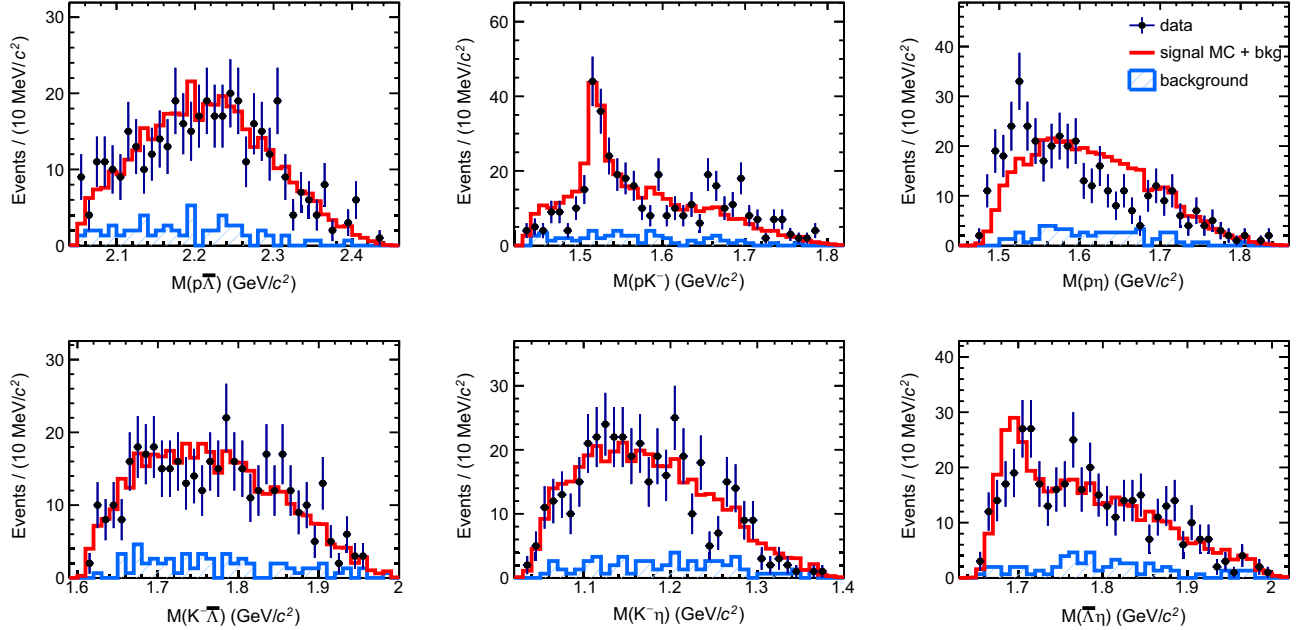


FIG. 6. Invariant mass distributions of the two-body combinations of the $\psi(3686) \rightarrow \gamma\chi_{c1}, \chi_{c1} \rightarrow pK^-\bar{\Lambda}\eta$ candidates. The events are selected within the χ_{c1} signal region of $[3.488, 3.532]$ GeV/c^2 . The data (points with error bars) are compared with the summed distribution of the signal MC including possible intermediate structures and the inclusive background (red solid histograms), and with the inclusive background (blue hatched histograms). All histograms are normalized to the data size.

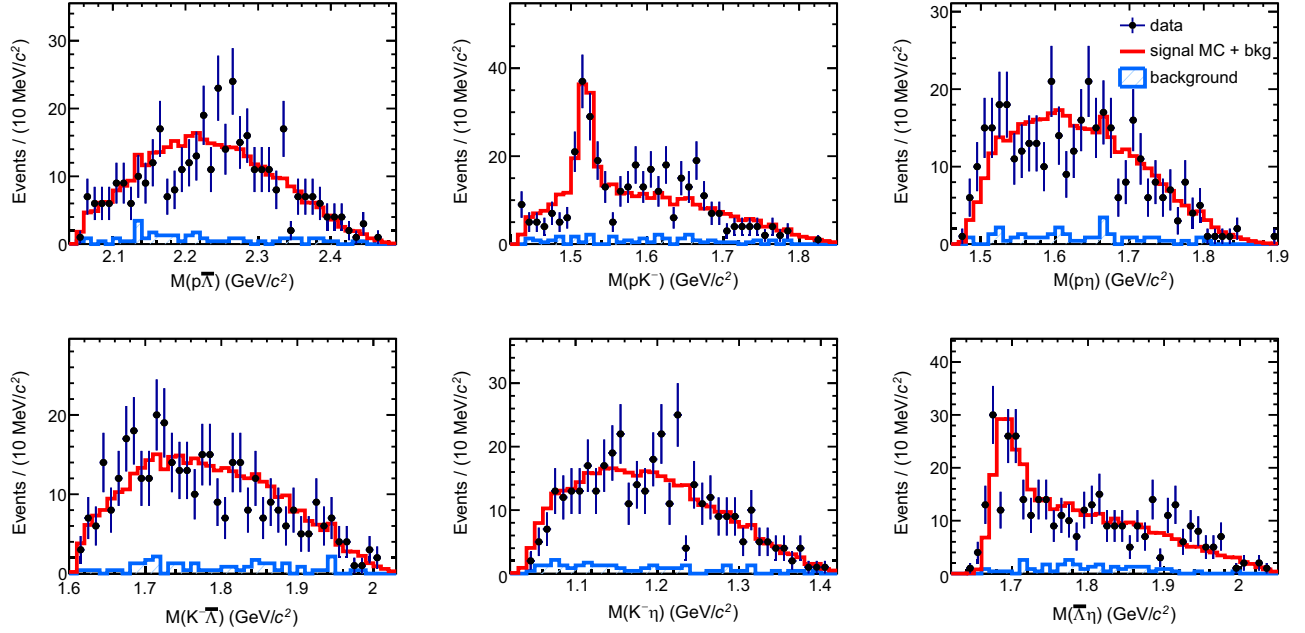


FIG. 7. Invariant mass distributions of the two-body combinations of the $\psi(3686) \rightarrow \gamma\chi_{c2}, \chi_{c2} \rightarrow pK^-\bar{\Lambda}\eta$ candidates. The events are selected within the χ_{c2} signal region of $[3.538, 3.579]$ GeV/c^2 . The data (points with error bars) are compared with the summed distribution of the signal MC including possible intermediate structures and the inclusive background (red solid histograms), and with the inclusive background (blue hatched histograms). All histograms are normalized to the data size.

resulting detection efficiencies are 3.7%, 5.5%, and 5.7% for χ_{c0} , χ_{c1} , and χ_{c2} , respectively.

Finally, the product branching fractions for the cascade decays $\psi(3686) \rightarrow \gamma\chi_{cJ}$ and $\chi_{cJ} \rightarrow pK^-\bar{\Lambda}\eta$ are determined by

$$\begin{aligned} & \mathcal{B}(\psi(3686) \rightarrow \gamma\chi_{cJ})\mathcal{B}(\chi_{cJ} \rightarrow pK^-\bar{\Lambda}\eta) \\ &= \frac{N_{\text{net}}}{N_{\psi(3686)}\varepsilon_J\mathcal{B}(\bar{\Lambda} \rightarrow \bar{p}\pi^+)\mathcal{B}(\eta \rightarrow \gamma\gamma)}, \end{aligned} \quad (1)$$

where $N_{\psi(3686)} = (2712.4 \pm 14.3) \times 10^6$, and ε_J is the mixed-signal MC efficiency for a given J . The secondary branching fractions are taken from the PDG: $\mathcal{B}(\psi(3686) \rightarrow \gamma\chi_{c0,1,2}) = (9.75 \pm 0.22)\%$, $(9.75 \pm 0.27)\%$, and $(9.38 \pm 0.23)\%$, $\mathcal{B}(\bar{\Lambda} \rightarrow \bar{p}\pi^+) = (64.1 \pm 0.5)\%$, and $\mathcal{B}(\eta \rightarrow \gamma\gamma) = (39.36 \pm 0.18)\%$. The resulting product branching fractions and the corresponding $\mathcal{B}(\chi_{cJ} \rightarrow pK^-\bar{\Lambda}\eta)$, including charge-conjugate modes, are listed in Table I.

VI. SYSTEMATIC UNCERTAINTY

The systematic uncertainties on the branching fraction measurements arise from multiple sources. These include the uncertainties associated with the total number of $\psi(3686)$ events, tracking and PID efficiencies, photon detection, η mass-window requirement, $\bar{\Lambda}$ reconstruction, the π^0 , J/ψ , and Σ^0 vetoes, the modeling of combinatorial background shapes, the choices of fit ranges and sideband regions, the 4C kinematic fit, and the limited signal-MC statistics. In addition, the uncertainties of the external

branching fractions quoted from the PDG are included. Possible contributions from the $\Lambda(1670)$ and $N(1535)$ structures are also evaluated and incorporated as additional systematic uncertainties. All these sources are treated as independent and summarized in Table II, with their individual evaluations described in the following paragraphs.

TABLE II. Relative systematic uncertainties (in %) on $\mathcal{B}(\chi_{cJ} \rightarrow pK^-\bar{\Lambda}\eta)$. Centered dots indicate that the corresponding systematic uncertainty is not applicable for that χ_{cJ} mode.

Source	χ_{c0}	χ_{c1}	χ_{c2}
$N_{\psi(3686)}$	0.5	0.5	0.5
Tracking	2.0	2.0	2.0
PID	2.0	2.0	2.0
γ selection	3.0	3.0	3.0
η mass window	1.0	1.0	1.0
$\bar{\Lambda}$ reconstruction	2.7	1.2	0.8
π^0 veto	2.2	0.9	0.6
J/ψ veto	0.1	0.5	3.1
Σ^0 veto	0.9	0.2	0.1
Background shape	5.1	0.8	0.5
Sideband regions	1.0	0.6	0.7
4C kinematic fit	1.3	1.2	1.3
MC statistics	0.2	0.2	0.2
$\mathcal{B}(\psi(3686) \rightarrow \gamma\chi_{cJ})$	2.3	2.8	2.5
$\mathcal{B}(\bar{\Lambda} \rightarrow \bar{p}\pi^+)$	0.8	0.8	0.8
$\mathcal{B}(\eta \rightarrow \gamma\gamma)$	0.5	0.5	0.5
$\Lambda(1670)$ for χ_{c0}	2.7	...	...
$N(1535)$ for χ_{c1}	...	2.8	...
Total	8.6	6.3	6.2

Here, centered dots in Table II denote that the corresponding source is not applicable to the given χ_{cJ} mode.

The total number of $\psi(3686)$ events is $N_{\psi(3686)} = (2712.4 \pm 14.3) \times 10^6$, determined with inclusive hadronic events. The associated uncertainty is 0.5% [10].

The tracking and PID efficiencies are studied with the control samples of $J/\psi \rightarrow K^*(892)K$ [27] and $J/\psi \rightarrow p\bar{p}\pi^+\pi^-$ [28]. The systematic uncertainty due to tracking or PID is assigned as 1.0% per charged track. Since the tracking effects of $\bar{p}$ and π^+ have been considered in the estimation of the systematic uncertainty in $\bar{\Lambda}$ reconstruction, only the proton and kaon are considered here. The total uncertainties are 2.0% for tracking of two charged tracks and 2.0% for PID of two charged tracks.

The systematic uncertainty due to the photon detection is estimated with the control sample of $J/\psi \rightarrow \pi^+\pi^-\pi^0$ [29] to be 1.0% per photon. Three photons in the final state lead the total uncertainty to be 3.0%.

The uncertainty due to the η mass-window requirement is evaluated with $\psi(3686) \rightarrow \eta J/\psi$, $J/\psi \rightarrow \ell^+\ell^-$ ($\ell = e, \mu$). The change of signal efficiency after smearing the η signal shape by a Gaussian function with parameters derived from the control sample, 1.0% [30] is taken as the systematic uncertainty.

The systematic uncertainties in the $\bar{\Lambda}$ reconstruction are studied with the control samples of $J/\psi \rightarrow pK^-\bar{\Lambda}$ and $J/\psi \rightarrow \Lambda\bar{\Lambda}$ [31]. The differences in $\bar{\Lambda}$ reconstruction efficiencies, including the $\bar{p}\pi^+$ tracking, decay-length, mass-window, vertex-fit, and secondary-vertex selections are taken as the systematic uncertainties due to $\bar{\Lambda}$ reconstruction, which are 2.7% for χ_{c0} , 1.2% for χ_{c1} , and 0.8% for χ_{c2} [30].

The systematic uncertainties of possible mismodeling of the veto requirements are examined by varying the π^0 , J/ψ , and Σ^0 veto windows around their nominal definitions by ± 1 MeV. The varied requirements are applied to both data and signal MC samples, and the changes in the efficiency-corrected signal yields are taken as the systematic uncertainties, which are (2.2, 0.9, 0.6)% for the π^0 veto, (0.1, 0.5, 3.1)% for the J/ψ veto, and (0.9, 0.2, 0.1)% for the Σ^0 veto, for ($\chi_{c0}, \chi_{c1}, \chi_{c2}$), respectively.

The systematic uncertainties of the combinatorial background shapes are estimated by varying the nominal first-order Chebyshev polynomial with several alternative background parametrizations in the signal, sideband I, and sideband II regions simultaneously. The alternative models include a second-order Chebyshev polynomial, a thresholdlike function $(x - x_0)^\alpha$, $(1 + ax)(x - x_0)^\alpha$, and $e^{ax}(x - x_0)^\alpha$, where x_0 is fixed to the threshold value and the other parameters are allowed to float. The largest deviations are obtained with the $(x - x_0)^\alpha$ parametrization, and are taken as the systematic uncertainties due to the background shape, corresponding to 5.1%, 0.8%, and 0.5% for χ_{c0} , χ_{c1} , and χ_{c2} , respectively.

The systematic uncertainties of the fit range are examined by several alternative fit intervals, [3.30, 3.61], [3.30, 3.59], [3.29, 3.60], and [3.31, 3.60] GeV/ c^2 . The yield variations are consistent with statistical fluctuations ($< 2\sigma$), therefore, no additional systematic uncertainty is assigned.

The systematic uncertainties of the $\bar{\Lambda}$ and η sideband windows are estimated by varying each window by $\pm 1\sigma$. The changes of the net signal yields, 1.0%, 0.6%, and 0.7% for χ_{c0} , χ_{c1} , and χ_{c2} , are taken as the systematic uncertainties.

The systematic uncertainties of the 4C kinematic fit are assigned as the differences between the detection efficiencies before and after the helix parameter corrections [32], which are 1.3%, 1.2%, and 1.3% for χ_{c0} , χ_{c1} , and χ_{c2} .

The uncertainties from limited MC statistics are calculated from $\sqrt{\frac{1-\epsilon}{N\epsilon}}$, where ϵ is the detection efficiency and N is the number of signal MC events. They are 0.2% for all channels.

The uncertainties of the branching fractions quoted from the PDG are also considered: (2.3, 2.8, 2.5)% for $\mathcal{B}(\psi(3686) \rightarrow \gamma\chi_{c0,1,2})$, 0.8% for $\mathcal{B}(\bar{\Lambda} \rightarrow \bar{p}\pi^+)$ and 0.5% for $\mathcal{B}(\eta \rightarrow \gamma\gamma)$.

As seen in Fig. 5, a mild enhancement is observed near 1.67 GeV/ c^2 in the M_{pK^-} distribution of the χ_{c0} sample, which may be due to the $\Lambda(1670)$ resonance. As seen in Fig. 6, a mild enhancement is observed near 1.535 GeV/ c^2 in the $M_{p\eta}$ distribution of the χ_{c1} sample, which may be due to the $N(1535)$ resonance. Due to the insufficient significances, their effects on the branching fraction measurements are considered as systematic uncertainties. Reweighting the χ_{c0} and χ_{c1} signal MC events to the corresponding M_{pK^-} and $M_{p\eta}$ line shapes and repeating the full selections yield efficiency shifts of 2.7% and 2.8%, which are assigned as additional uncertainties for the χ_{c0} and χ_{c1} decays, respectively.

For each signal decay, the total systematic uncertainty is calculated by adding systematic uncertainties quadratically under the assumption that all sources are independent.

VII. SUMMARY

Using a sample of $(2712.4 \pm 14.3) \times 10^6$ $\psi(3686)$ events collected with the BESIII detector, the decays $\chi_{cJ} \rightarrow pK^-\bar{\Lambda}\eta$ ($J = 0, 1, 2$) are observed for the first time. The statistical significances of the χ_{c0} , χ_{c1} , and χ_{c2} signals all exceed 5σ . The measured branching fractions are

$$\mathcal{B}(\chi_{c0} \rightarrow pK^-\bar{\Lambda}\eta) = (5.3 \pm 0.7 \pm 0.5) \times 10^{-5},$$

$$\mathcal{B}(\chi_{c1} \rightarrow pK^-\bar{\Lambda}\eta) = (9.8 \pm 0.6 \pm 0.6) \times 10^{-5},$$

$$\mathcal{B}(\chi_{c2} \rightarrow pK^-\bar{\Lambda}\eta) = (9.3 \pm 0.6 \pm 0.6) \times 10^{-5},$$

where the first and second uncertainties are statistical and systematic, respectively. To improve the determination of the detection efficiencies and account for possible hadronic substructures, a mixed signal MC sample is constructed by

combining the PHSP process with components used to describe the observed structures in the pK^- and $\bar{\Lambda}\eta$ invariant mass distributions. These structures are consistent with $\Lambda(1520)$ and $\bar{\Lambda}(1690)$, respectively. The mixed signal MC samples provide a more representative description of the selected signal events and are used to determine the detection efficiencies for the branching-fraction measurements of $\chi_{cJ} \rightarrow pK^- \bar{\Lambda}\eta + \text{c.c.}$ The results obtained in this work enrich the experimental knowledge of P -wave charmonium decays involving baryon-antibaryon-meson systems [30], and provide useful input for understanding baryon production and hadronization mechanisms in the nonperturbative QCD regime.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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