

# Observation of $\chi_{cJ} \rightarrow 3K_S^0 K^\pm \pi^\mp$

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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  $\chi_{c0,1,2} \rightarrow 3K_S^0 K^\pm \pi^\mp$  are observed for the first time with statistical significances greater than  $10\sigma$ . The branching fractions of these decays are determined to be  $\mathcal{B}(\chi_{c0} \rightarrow 3K_S^0 K^\pm \pi^\mp) = (7.95 \pm 0.50 \pm 0.65) \times 10^{-5}$ ,  $\mathcal{B}(\chi_{c1} \rightarrow 3K_S^0 K^\pm \pi^\mp) = (2.62 \pm 0.08 \pm 0.19) \times 10^{-4}$ , and  $\mathcal{B}(\chi_{c2} \rightarrow 3K_S^0 K^\pm \pi^\mp) = (1.72 \pm 0.07 \pm 0.15) \times 10^{-4}$ , where the first uncertainties are statistical and the second systematic.

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## I. INTRODUCTION

The experimental studies of hadronic decays of the charmonium states are crucial for understanding quantum chromodynamics (QCD) models and QCD-based calculations [1–3], since charmonium physics lies in the transition region between perturbative and nonperturbative QCD. At present, both experimental and theoretical studies of hadronic decays of  $\chi_{cJ}$  ( $J = 0, 1, 2$ ) states are not as extensive as for the vector charmonium states  $J/\psi$  and  $\psi(3686)$  (more than one third of the  $\chi_{cJ}$  decays are not observed based on the total width), and more measurements are needed. Since the  $\chi_{cJ}$  mesons are produced copiously in the  $\psi(3686)$  radiative decays, with branching fractions of about 9%, the world's largest  $\psi(3686)$  data sample at BESIII [4] offers good opportunities to study their different decays. Currently, there have been theoretical and experimental measurements of multibody-meson decays of  $\chi_{cJ}$  [5–7]; however, the information of five-body hadronic  $\chi_{cJ}$  decays is still very limited, and additional experimental measurements of these decays are needed.

In 2015, BESIII reported the measurement of the branching fractions of  $\chi_{cJ} \rightarrow \bar{K}^0 K^\pm \pi^\mp \phi$  and  $\chi_{cJ} \rightarrow K^+ K^- \pi^0 \phi$  decays in the final state  $\chi_{cJ} \rightarrow K K K K \pi$  [5,8], by using  $106 \times 10^6$   $\psi(3686)$  events. The obtained results are listed in Table I. In the limit of isospin symmetry, the branching fractions of the  $\chi_{cJ} \rightarrow 3K_S^0 K^\pm \pi^\mp$  decays are expected to be at  $10^{-4}$  level, which are accessible at BESIII but have not been studied to date. In this paper, we

determine the branching fractions of  $\chi_{cJ} \rightarrow 3K_S^0 K^\pm \pi^\mp$  for the first time by analyzing  $(2712.4 \pm 14.3) \times 10^6$   $\psi(3686)$  events collected with the BESIII detector.

## II. BESIII DETECTOR AND MONTE CARLO SIMULATION

The BESIII detector [9] records symmetric  $e^+e^-$  collisions provided by the BEPCII storage ring [10] 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(Tl) electromagnetic calorimeter (EMC), which are all enclosed in a superconducting solenoidal magnet providing a 1.0 T magnetic field. The magnetic field was 0.9 T in 2012, which affects 12.7% of the total  $\psi(3686)$  data. 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

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TABLE I. The world average values ( $\times 10^{-4}$ ) of the branching fractions of the decays contributing to  $\chi_{cJ} \rightarrow K K K K \pi$ .

|                                | $\chi_{c0}$    | $\chi_{c1}$    | $\chi_{c2}$ |
|--------------------------------|----------------|----------------|-------------|
| $\bar{K}^0 K^\pm \pi^\mp \phi$ | $37 \pm 6$     | $33 \pm 5$     | $48 \pm 7$  |
| $K^+ K^- \pi^0 \phi$           | $19.0 \pm 3.5$ | $16.2 \pm 3.0$ | $27 \pm 5$  |

TABLE II. The fractions (in %) of different subprocesses in  $\chi_{cJ} \rightarrow 3K_S^0 K^\pm \pi^\mp$ .

|                                         | $\chi_{c0}$ | $\chi_{c1}$ | $\chi_{c2}$ |
|-----------------------------------------|-------------|-------------|-------------|
| $3K_S^0 K^\pm \pi^\mp$ (PHSP)           | 3.1         | 10.0        | 4.7         |
| $2K_S^0 K^*(892)^\pm K^\mp$             | 33.0        | 42.1        | 40.1        |
| $3K_S^0 \bar{K}^*(892)^0 + \text{c.c.}$ | 31.3        | 27.1        | 22.1        |
| $f_X(1500)K_S^0 K^\pm \pi^\mp$          | 32.6        | 20.8        | 33.0        |

resistive plate chamber technology, providing a time resolution of 60 ps [11–13], which benefits 83.3% of the data used in this analysis.

Simulated data samples produced with a GEANT4-based [14] Monte Carlo (MC) package, which includes the geometric description of the BESIII detector and the detector response, are used to determine detection efficiencies and to estimate backgrounds. The simulation includes the beam energy spread and initial state radiation (ISR) in the  $e^+e^-$  annihilations with the generator KKMC [15].

The inclusive MC sample includes the production of the  $\psi(3686)$  resonance, the ISR production of the  $J/\psi$ , and the continuum processes incorporated in KKMC [15]. All particle decays are modeled with EVTGEN [16,17] using branching fractions either taken from the Particle Data Group (PDG) [5], when available, or otherwise estimated with LUNDCHARM [18]. Final state radiation (FSR) from charged final state particles is incorporated using the PHOTOS package [19]. An inclusive MC sample containing  $2.747 \times 10^9$  generic  $\psi(3686)$  events is used to study background. To account for effects of intermediate resonance structures on the efficiency, each of the  $\chi_{c0,1,2}$  is modeled using 200,000 mixed MC events, in which the dominant decay modes containing resonances are included. The decays  $\psi(3686) \rightarrow \gamma \chi_{cJ}$  ( $J = 0, 1, 2$ ) are generated by the P2GC0/1/2 models [16,17]. The decays  $K^*(892)^+ \rightarrow K^0 \pi^+$  and  $K^*(892)^0 \rightarrow K^+ \pi^-$  are generated by the VSS model (vector- to a pair of scalar mesons). The other decays are generated by the phase-space (PHSP) model. The mixing ratios of resonances are determined by examining the corresponding invariant mass distributions as discussed in Sec. IV, which are shown in Table II.

### III. EVENT SELECTION

Candidate events are reconstructed via the charmonium transitions  $\psi(3686) \rightarrow \gamma \chi_{cJ}$  followed by the hadronic decays  $\chi_{cJ} \rightarrow 3K_S^0 K^\pm \pi^\mp$ . They are required to contain at least eight charged tracks and at least one photon candidate.

Charged tracks (not originating from  $K_S^0$  decays) are required to be within a polar angle ( $\theta$ ) range of  $|\cos \theta| < 0.93$ , where  $\theta$  is defined with respect to the  $z$  axis, which is the symmetry axis of the MDC. The distance of closest approach to the interaction point (IP) must be less than 10 cm along the  $z$  axis,  $|V_z|$ , and less than 1 cm in the transverse plane,  $|V_{xy}|$ .

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

Particle identification (PID) for charged tracks combines measurements of the specific ionization energy loss ( $dE/dx$ ) in the MDC and the flight time in the TOF to form likelihoods  $\mathcal{L}(h)$  ( $h = K, \pi$ ) for each hadron hypothesis  $h$ . Charged kaons and pions are identified by comparing the likelihoods for the kaon and pion hypotheses and requiring  $\mathcal{L}(K) > \mathcal{L}(\pi)$  and  $\mathcal{L}(\pi) > \mathcal{L}(K)$ , respectively.

Each  $K_S^0$  candidate is reconstructed from two oppositely charged tracks satisfying  $|V_z| < 20$  cm. The two charged tracks are assigned as  $\pi^+ \pi^-$  without imposing further PID criteria. They are constrained to originate from a common vertex and are required to have an invariant mass within  $|M_{\pi^+ \pi^-} - m_{K_S^0}| < 12 \text{ MeV}/c^2$ , where  $m_{K_S^0}$  is the  $K_S^0$  nominal mass [5]. The decay length of the  $K_S^0$  candidate is required to be greater than twice the vertex resolution away from the IP. The quality of the vertex fits is required to be  $\chi^2 < 200$ . The  $K_S^0$  signal region is set to be within  $3\sigma$ ,  $|M_{\pi^+ \pi^-} - 0.498| < 0.012 \text{ GeV}/c^2$ , and the sideband regions are set to be within  $(5 - 11\sigma)$ ,  $0.020 < |M_{\pi^+ \pi^-} - 0.498| < 0.044 \text{ GeV}/c^2$ . Figure 1 shows the  $M_{\pi^+ \pi^-}$  distribution of the accepted candidates in data.

A four-constraint (4C) kinematic fit is performed under the hypothesis  $\psi(3686) \rightarrow \gamma 3K_S^0 K^\pm \pi^\mp$ , by requiring the total reconstructed four-momentum to be conserved. In each event, if more than one combination survives, the one

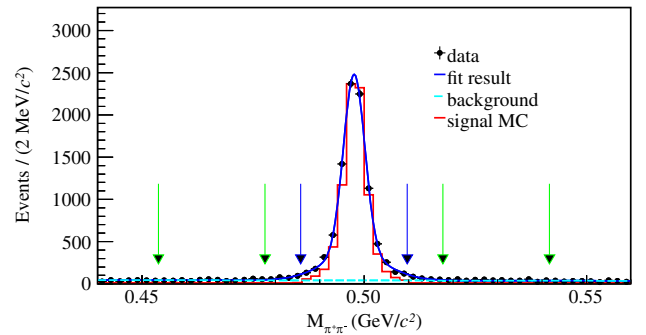


FIG. 1. The  $M_{\pi^+ \pi^-}$  distribution of the accepted candidates. The dots with error bars represent the data, the blue line is the fit result, the red line is the signal MC sample and the green line the background. The signal MC sample is normalized to have the maximum height of the data. The pair of blue arrows shows the  $K_S^0$  signal region, and the pairs of green arrows show the  $K_S^0$  sideband regions.

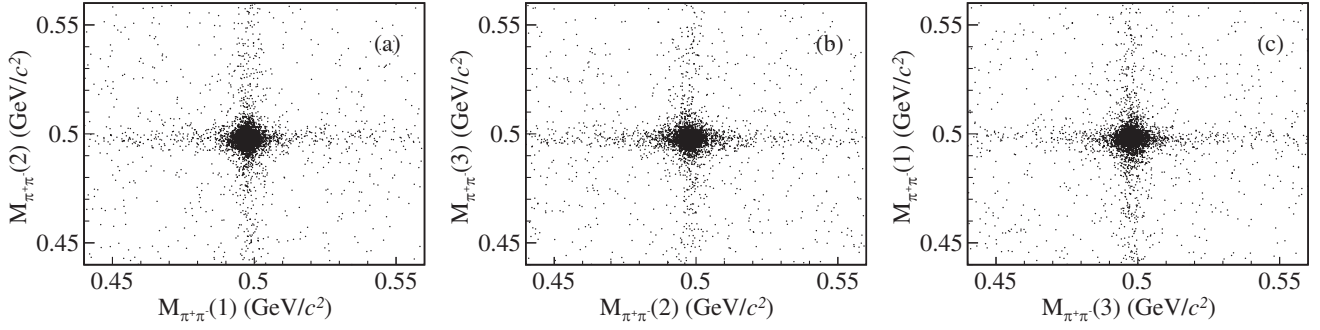


FIG. 2. Distributions of (a)  $M_{\pi^+\pi^-}(1) : M_{\pi^+\pi^-}(2)$ , (b)  $M_{\pi^+\pi^-}(2) : M_{\pi^+\pi^-}(3)$  and (c)  $M_{\pi^+\pi^-}(3) : M_{\pi^+\pi^-}(1)$  for the candidate events in data.

with the smallest  $\chi_{4C}^2$  from the 4C kinematic fit is retained. The requirement on  $\chi_{4C}^2$  is optimized with the figure-of-merit (FOM) defined as

$$\text{FOM} = \frac{S}{\sqrt{S+B}}, \quad (1)$$

where  $S$  is the number of events from the signal MC sample, normalized according to the premeasured branching fractions without the FOM optimization, and  $B$  is the number of background events from the inclusive MC sample, normalized to the data size. From the optimization, we choose  $\chi_{4C}^2 < 50$  as the nominal requirement.

The potential background components from  $\psi(3686)$  decays are studied by analyzing the inclusive MC sample with a generic event type analysis tool, TopoAna [20]. The peaking background in the inclusive MC sample can be described by the  $K_S^0$  sideband events in data, while the remaining background in the inclusive MC sample is flat. Furthermore, we examine the data sample taken at  $\sqrt{s} = 3.650$  GeV, corresponding to an integrated luminosity of  $0.4 \text{ fb}^{-1}$  [21]. The background at this energy point is found to be negligible.

#### IV. BRANCHING FRACTION

To determine the signal yields, a simultaneous unbinned maximum likelihood fit is performed on the  $M_{3K_S^0 K^\pm \pi^\mp}$  distributions of the accepted candidate events in the  $K_S^0$  signal and sideband regions. In this analysis, the combinatorial background in the  $M_{\pi^+\pi^-}$  distribution is assumed to be flat. Thus, the net numbers of the  $\chi_{cJ} \rightarrow 3K_S^0 K^\pm \pi^\mp$  decays can be calculated by

$$N_{\text{net}} = N_{\text{sig}} - \frac{1}{2}N_{\text{SB1}} + \frac{1}{4}N_{\text{SB2}} - \frac{1}{8}N_{\text{SB3}}, \quad (2)$$

where  $N_{\text{sig}}$  is the number of events with three  $\pi^+\pi^-$  pairs lying in the  $K_S^0$  signal region, called the signal region;  $N_{\text{SB1}}$  is the number of events with two  $\pi^+\pi^-$  pairs lying in the  $K_S^0$  signal region and the other one lying in the  $K_S^0$  sideband region, called the SB1 region;  $N_{\text{SB2}}$  is the number of events with one  $\pi^+\pi^-$  pair lying in the  $K_S^0$  signal region and the

other two lying in the  $K_S^0$  sideband region, called the SB2 region;  $N_{\text{SB3}}$  is the number of events with three  $\pi^+\pi^-$  pairs lying in the  $K_S^0$  sideband region, called the SB3 region. Figure 2 shows the two-dimensional distributions of the invariant mass of the three  $\pi^+\pi^-$  pairs in data.

In the fit, the signal shape of the  $\chi_{cJ}$  states is modeled by using a Breit-Wigner function convolved with a Gaussian function with free parameters, to take into account the resolution. The mass and width of each Breit-Wigner function are fixed to the respective values from the PDG. The background is described by a first-order Chebychev polynomial function in both the  $K_S^0$  signal

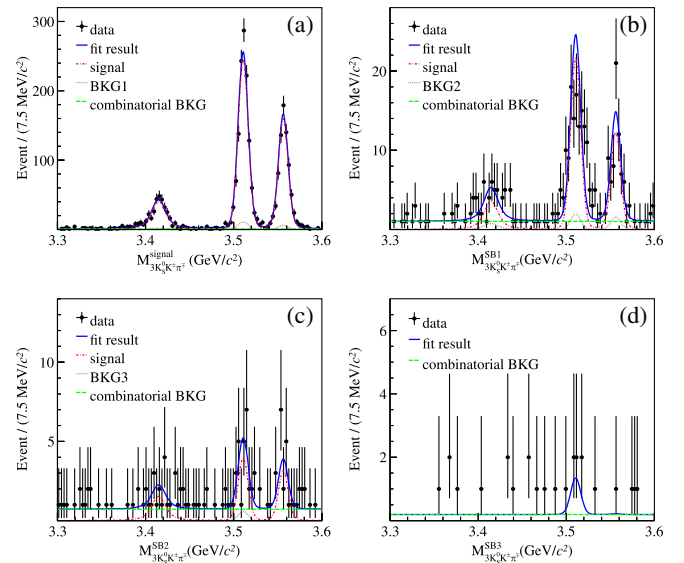


FIG. 3. Simultaneous fit to the  $M_{3K_S^0 K^\pm \pi^\mp}$  distributions of the accepted candidate events for  $\chi_{cJ} \rightarrow 3K_S^0 K^\pm \pi^\mp$  in data (dots with error bars) in the (a) signal, (b) SB1, (c) SB2, and (d) SB3 regions, where BKG1 ( $\frac{1}{2}H_{\text{SB1}} - \frac{1}{4}H_{\text{SB2}} + \frac{1}{8}H_{\text{SB3}}$ ), BKG2 ( $\frac{1}{2}H_{\text{SB2}} - \frac{1}{4}H_{\text{SB3}}$ ) and BKG3 ( $\frac{1}{2}H_{\text{SB3}}$ ) are constrained by the peaking backgrounds from the other sideband regions ( $H$  denotes the histograms of SB1, SB2 and SB3). The blue solid curves are the fit results, the red curves are the signal shapes, the brown curves are the backgrounds constrained by the  $K_S^0$  sidebands, and the green curves are the fitted backgrounds.

and sideband regions. Figure 3 shows the fit results. Significant  $\chi_{cJ}$  signals are seen for the events in the signal region, while there are also some peaking background events from the sideband regions. The number of peaking background events in the signal region is estimated to be  $\frac{1}{2}N_{\text{SB1}} - \frac{1}{4}N_{\text{SB2}} + \frac{1}{8}N_{\text{SB3}}$ , as defined before. From this fit, the signal yields of  $\chi_{c0}$ ,  $\chi_{c1}$  and  $\chi_{c2}$  decays,  $N_{\chi_{cJ}}^{\text{net}}$ , are obtained to be  $343 \pm 22$ ,  $1190 \pm 36$  and  $767 \pm 29$ , respectively. The statistical significances are larger than  $10\sigma$  for all  $\chi_{cJ}$  decays, which are estimated by comparing the likelihood values of the fits with and without each signal component and taking into account the number of degrees of freedom.

The detection efficiencies of  $\psi(3686) \rightarrow \gamma\chi_{cJ}$  with  $\chi_{cJ} \rightarrow 3K_S^0 K^\pm \pi^\mp$  are determined with the mixed MC samples with a certain fraction of  $\chi_{cJ} \rightarrow 3K_S^0 K^\pm \pi^\mp$ ,  $\chi_{cJ} \rightarrow 2K_S^0 K^*(892)^\pm K^\mp$ ,  $\chi_{cJ} \rightarrow 3K_S^0 \bar{K}^*(892)^0 + \text{c.c.}$  and  $\chi_{cJ} \rightarrow f_X(1500)K_S^0 K^\pm \pi^\mp$ . The fractions are determined from fits to the invariant mass distributions of the two-body combinations, where the signal is modeled by a signal MC shape convolved with a Gaussian function and the

background by a third-order Chebyshev polynomial, and are summarized in Table II. Figures 4–6 show the comparisons of the invariant masses of the two-body combinations of the accepted candidate events for  $\chi_{c0,1,2} \rightarrow 3K_S^0 K^\pm \pi^\mp$  in data and in mixed MC samples. Here, we mark the three different  $K_S^0$  candidates as a, b, and c, and  $K^\pm$  and  $\pi^\pm$  as 1 and 2, respectively, to identify the different combinations. The variations of these fractions will be considered as a source of systematic uncertainty.

The products of branching fractions of  $\chi_{cJ} \rightarrow 3K_S^0 K^\pm \pi^\mp$  and  $\psi(3686) \rightarrow \gamma\chi_{cJ}$  are calculated as

$$\mathcal{B}_{\psi(3686) \rightarrow \gamma\chi_{cJ}} \cdot \mathcal{B}_{\chi_{cJ} \rightarrow 3K_S^0 K^\pm \pi^\mp} = \frac{N_{\chi_{cJ}}^{\text{net}}}{N_{\psi(3686)} \cdot \varepsilon \cdot \mathcal{B}_{K_S^0 \rightarrow \pi^+ \pi^-}^3}, \quad (3)$$

where  $N_{\psi(3686)}$  is the total number of  $\psi(3686)$  events in data,  $\varepsilon$  is the detection efficiency, and  $\mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^-)$  is the branching fraction of  $K_S^0 \rightarrow \pi^+ \pi^-$  taken from the PDG [5]. The branching fractions of  $\chi_{cJ} \rightarrow 3K_S^0 K^\pm \pi^\mp$  are obtained and summarized in Table III.

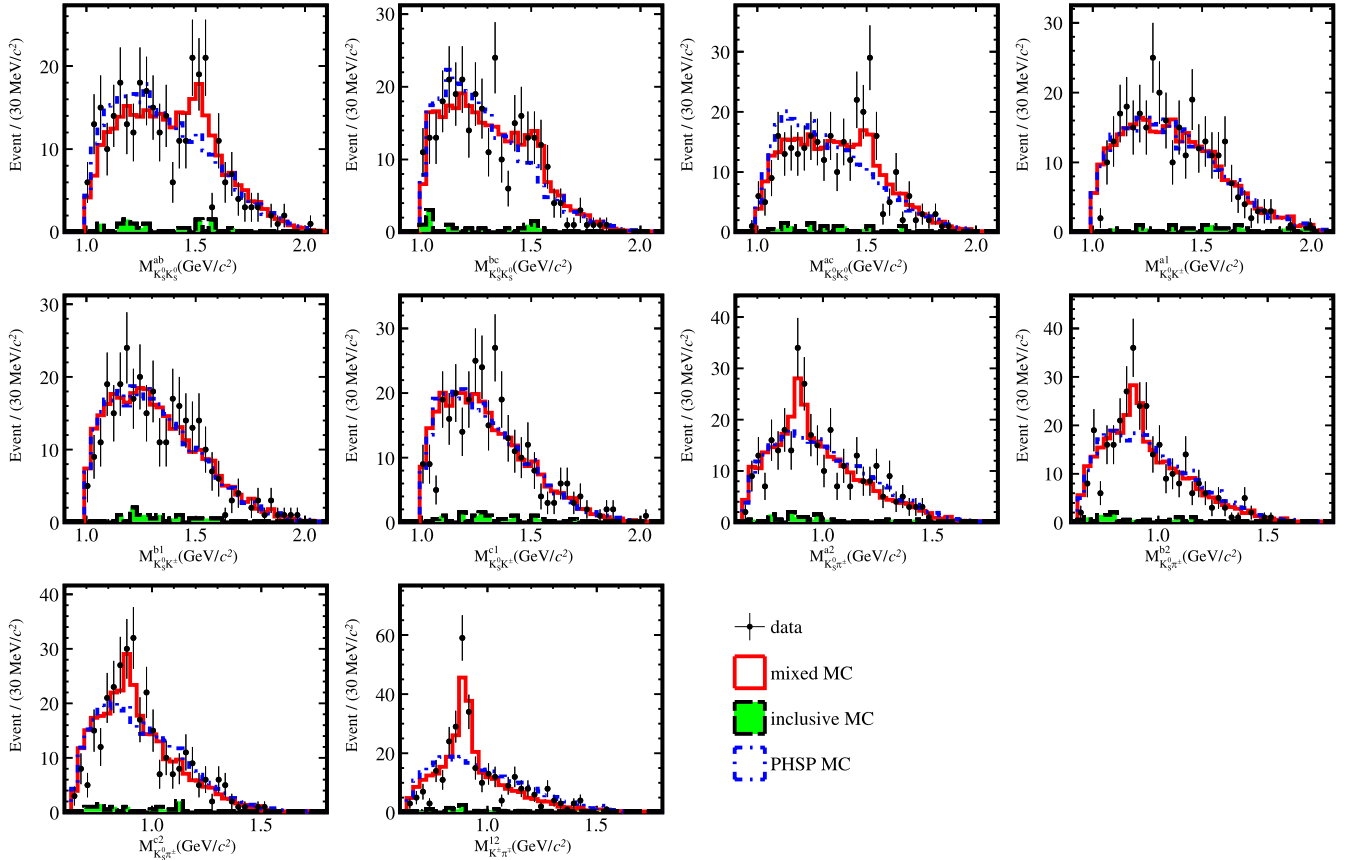


FIG. 4. Distributions of the two-body invariant masses of the accepted candidate events for  $\chi_{c0} \rightarrow 3K_S^0 K^\pm \pi^\mp$ . The black dots with error bars are data, the red histograms are the mixed MC sample, the cyan histograms are the PHSP signal MC sample, and the green histograms are the simulated background from the inclusive MC sample. Events have been required to be within  $M_{3K_S^0 K^\pm \pi^\mp} \in [3.394, 3.434] \text{ GeV}/c^2$ .

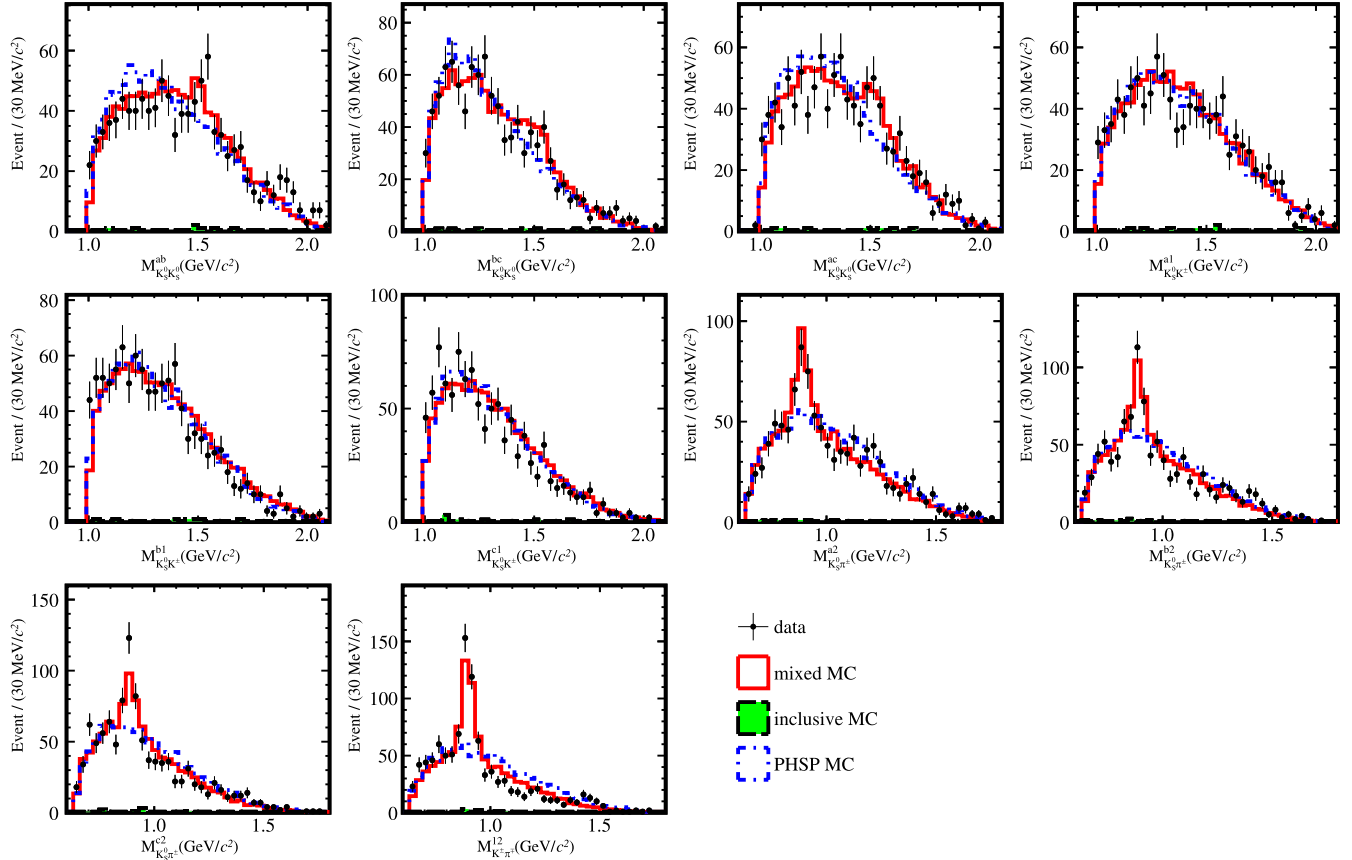


FIG. 5. Distributions of the two-body invariant masses of the accepted candidate events for  $\chi_{c1} \rightarrow 3K_S^0 K^\pm \pi^\mp$ . The black dots with error bars are data, the red histograms are the mixed MC sample, the cyan histograms are the PHSP signal MC sample, and the green histograms are the simulated background from the inclusive MC sample. Events have been required to be within  $M_{3K_S^0 K^\pm \pi^\mp} \in [3.496, 3.526]$  GeV/ $c^2$ .

## V. SYSTEMATIC UNCERTAINTIES

The different sources of systematic uncertainty in the branching fraction measurements are discussed below and summarized in Table IV.

The total number of  $\psi(3686)$  events in data has been measured to be  $N_{\psi(3686)} = (2712.4 \pm 14.3) \times 10^6$  with the inclusive hadronic data sample, as described in Ref. [4]. The uncertainty of  $N_{\psi(3686)}$  is 0.5%.

The systematic uncertainties of tracking and PID for  $K^\pm$  and  $\pi^\pm$  are estimated with the control samples  $J/\psi \rightarrow K^*(892)\bar{K}$  and  $J/\psi \rightarrow p\bar{p}\pi^+\pi^-$ , respectively. They are assigned as 1.0% for each track, excluding those from  $K_S^0$  decays [22].

The systematic uncertainty of  $K_S^0$  reconstruction, including tracking efficiency,  $K_S^0$  mass window, and vertex fitters quality, has been estimated by using the control samples  $J/\psi \rightarrow K^*(892)^\pm \bar{K}^\mp$  and  $J/\psi \rightarrow \phi K^*(892)^\pm \bar{K}^\mp$ . The systematic uncertainty of  $K_S^0$  reconstruction is assigned to be 1.5% per  $K_S^0$  [23].

The systematic uncertainty in photon detection is assigned as 1.0% per photon by studies of the control sample  $J/\psi \rightarrow \pi^+\pi^-\pi^0$  [24].

To estimate the systematic uncertainties of the MC generation of the  $\chi_{cJ} \rightarrow 3K_S^0 K^\pm \pi^\mp$  decays, we compare our nominal signal efficiencies with those determined from the mixed MC events after varying the relative fractions of the subresonant decays by  $\pm 1\sigma$ . The relative changes of the signal efficiencies, 0.2%, 0.1%, and 0.1%, are assigned as the systematic uncertainties for  $\chi_{c0}$ ,  $\chi_{c1}$ , and  $\chi_{c2}$  decays, respectively.

The systematic uncertainties of the fit to the  $M_{3K_S^0 K^\pm \pi^\mp}$  distribution are considered below. The uncertainties due to the signal shape are estimated by changing the signal shape from a Breit-Wigner function convolved with a Gaussian function to the one from the simulated signal shape convolved with a Gaussian function. The uncertainties due to the fixed widths of the  $\chi_{cJ}$  mesons are estimated by varying the fixed world average values by  $\pm 1\sigma$ . The uncertainties due to the background shape are estimated by varying the nominal ones from the first-order to second-order Chebyshev polynomial functions. The uncertainties of the simultaneous fit method are estimated by changing the nominal fit to a one-dimensional fit of the  $M_{3K_S^0 K^\pm \pi^\mp}$  distribution, with a background shape derived from data events in the three-dimensional  $K_S^0$  sidebands. The

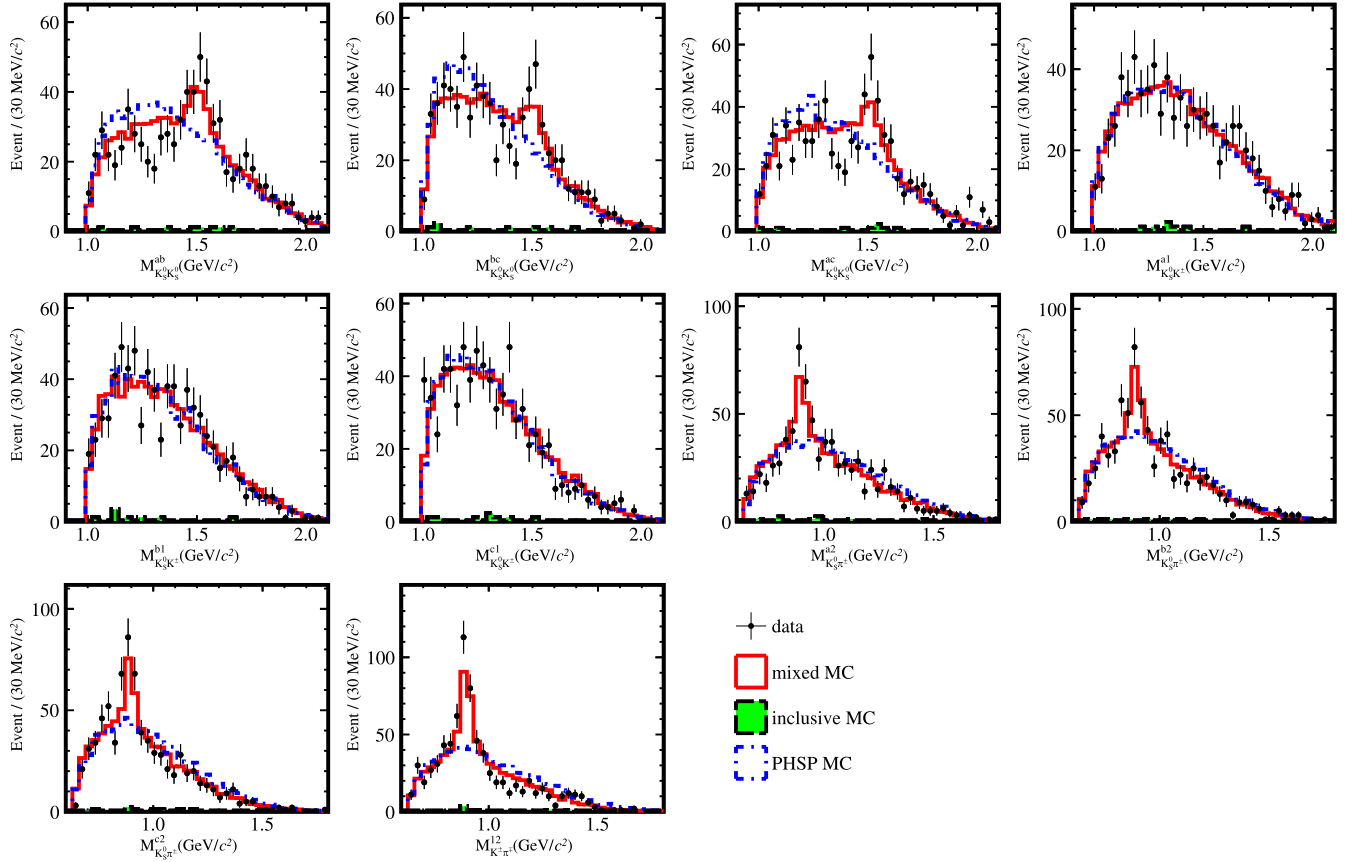


FIG. 6. Distributions of the two-body invariant masses of the accepted candidate events for  $\chi_{c2} \rightarrow 3K_S^0 K^\pm \pi^\mp$ . The black dots with error bars are data, the red histograms are the mixed MC sample, the cyan histograms are the PHSP signal MC sample, and the green histograms are the simulated background from the inclusive MC sample. Events have been required to be within  $M_{3K_S^0 K^\pm \pi^\mp} \in [3.541, 3.571] \text{ GeV}/c^2$ .

uncertainties of the fit range are estimated by changing them from  $[3.31, 3.61] \text{ GeV}/c^2$  to  $[3.28, 3.58] \text{ GeV}/c^2$  and  $[3.35, 3.65] \text{ GeV}/c^2$ . Adding these uncertainties in quadrature gives the total systematic uncertainties due to the  $M_{3K_S^0 K^\pm \pi^\mp}$  fit to be 5.2%, 3.3%, and 4.8% for  $\chi_{c0}$ ,  $\chi_{c1}$ , and  $\chi_{c2}$ , respectively.

The systematic uncertainties from the 4C kinematic fit is estimated by comparing the signal efficiencies after and before the helix parameter correction, with parameters taken from Ref. [25]. The changes of the signal efficiencies are assigned as the systematic uncertainties, which are 1.0%, 1.9%, and 1.3% for  $\chi_{c0}$ ,  $\chi_{c1}$ , and  $\chi_{c2}$ .

The systematic uncertainties due to MC statistics are 1.6%, 1.5%, and 1.4% for  $\chi_{c0}$ ,  $\chi_{c1}$ , and  $\chi_{c2}$ , respectively.

The uncertainties of the branching fractions quoted from the PDG [5] are 2.0%, 2.5%, and 2.1% for  $\psi(3686) \rightarrow \gamma \chi_{c0,1,2}$  and 0.07% for  $K_S^0 \rightarrow \pi^+ \pi^-$ .

The systematic uncertainties in the  $E_\gamma^3$  factor, which is used to take into account the electromagnetic transition rates of the lowest multipoles, are estimated by varying the signal shape from a Breit-Wigner function convolved with a Gaussian function to a Breit-Wigner function multiplied by the  $E_\gamma^3$  factor [26]. The differences in the signal yields are assigned as the systematic uncertainties, which are 1.5%, 1.3%, and 3.9% for  $\chi_{c0}$ ,  $\chi_{c1}$ , and  $\chi_{c2}$ .

TABLE III. The quantities used to calculate the branching fractions of  $\chi_{cJ} \rightarrow 3K_S^0 K^\pm \pi^\mp$ , where the first uncertainties are statistical and the second systematic.

|                                                                                                                                       | $\chi_{c0}$              | $\chi_{c1}$            | $\chi_{c2}$            |
|---------------------------------------------------------------------------------------------------------------------------------------|--------------------------|------------------------|------------------------|
| $N_{\chi_{cJ}}^{\text{net}}$                                                                                                          | $343 \pm 22$             | $1190 \pm 37$          | $767 \pm 29$           |
| $\epsilon (\%)$                                                                                                                       | $4.91 \pm 0.07$          | $5.18 \pm 0.07$        | $5.22 \pm 0.07$        |
| $\mathcal{B}(\psi(3686) \rightarrow \gamma \chi_{cJ}) \cdot \mathcal{B}(\chi_{cJ} \rightarrow 3K_S^0 K^\pm \pi^\mp) (\times 10^{-6})$ | $7.78 \pm 0.49 \pm 0.64$ | $25.6 \pm 0.8 \pm 1.9$ | $16.4 \pm 0.6 \pm 1.4$ |
| $\mathcal{B}(\chi_{cJ} \rightarrow 3K_S^0 K^\pm \pi^\mp) (\times 10^{-5})$                                                            | $7.95 \pm 0.50 \pm 0.65$ | $26.2 \pm 0.8 \pm 1.9$ | $17.2 \pm 0.7 \pm 1.5$ |

TABLE IV. Relative systematic uncertainties (in %) in the branching fraction measurements.

| Source                                                 | $\chi_{c0}$ | $\chi_{c1}$ | $\chi_{c2}$ |
|--------------------------------------------------------|-------------|-------------|-------------|
| $N_{\psi(3686)}$                                       | 0.5         | 0.5         | 0.5         |
| Tracking                                               | 2.0         | 2.0         | 2.0         |
| PID                                                    | 2.0         | 2.0         | 2.0         |
| $K_S^0$ reconstruction                                 | 4.5         | 4.5         | 4.5         |
| $\gamma$ selection                                     | 1.0         | 1.0         | 1.0         |
| 4C kinematic fit                                       | 1.0         | 1.9         | 1.3         |
| $M_{3K_S^0 K^\pm \pi^\mp}$ fit                         | 5.2         | 3.3         | 4.8         |
| $\mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^-)$           | 0.2         | 0.2         | 0.2         |
| $\mathcal{B}(\psi(3686) \rightarrow \gamma \chi_{cJ})$ | 2.0         | 2.5         | 2.1         |
| MC statistics                                          | 1.6         | 1.5         | 1.4         |
| MC generation                                          | 0.2         | 0.1         | 0.1         |
| $E_\gamma^3$ factor                                    | 1.6         | 1.5         | 3.9         |
| Total                                                  | 8.2         | 7.4         | 8.7         |

For each signal decay, the total systematic uncertainty is obtained by adding all systematic uncertainties in quadrature.

## VI. SUMMARY

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  $\chi_{c0,1,2} \rightarrow 3K_S^0 K^\pm \pi^\mp$  are observed for the first time with statistical significances greater than  $10\sigma$ . Their decay branching fractions are determined to be

$$\mathcal{B}(\chi_{c0} \rightarrow 3K_S^0 K^\pm \pi^\mp) = (7.95 \pm 0.50 \pm 0.65) \times 10^{-5},$$

$$\mathcal{B}(\chi_{c1} \rightarrow 3K_S^0 K^\pm \pi^\mp) = (2.52 \pm 0.08 \pm 0.19) \times 10^{-4},$$

$$\mathcal{B}(\chi_{c2} \rightarrow 3K_S^0 K^\pm \pi^\mp) = (1.72 \pm 0.07 \pm 0.15) \times 10^{-4}.$$

After considering the intermediate states and the effects of phase space, these results are comparable with the branching fractions in Table I. Through the measurement of the branching fractions of  $\chi_{cJ} \rightarrow 3K_S^0 K^\pm \pi^\mp$ , it is possible to derive valuable information to deepen our understanding of the mechanisms of  $\chi_{cJ}$  decays.

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## DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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