

Observation of the Decay  $X(3872) \rightarrow \pi^0 \chi_{c1}(1P)$ 

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Using a total of  $9.0 \text{ fb}^{-1}$  of  $e^+e^-$  collision data with center-of-mass energies between 4.15 and 4.30 GeV collected by the BESIII detector, we search for the processes  $e^+e^- \rightarrow \gamma X(3872)$  with  $X(3872) \rightarrow \pi^0 \chi_{cJ}$  for  $J = 0, 1, 2$ . We report the first observation of  $X(3872) \rightarrow \pi^0 \chi_{c1}$ , a new decay mode of the  $X(3872)$ , with a statistical significance of more than  $5\sigma$  for all systematic fit variations. Normalizing to the previously established process  $e^+e^- \rightarrow \gamma X(3872)$  with  $X(3872) \rightarrow \pi^+ \pi^- J/\psi$ , we find  $\mathcal{B}(X(3872) \rightarrow \pi^0 \chi_{c1}) / \mathcal{B}(X(3872) \rightarrow \pi^+ \pi^- J/\psi) = 0.88^{+0.33}_{-0.27} \pm 0.10$ , where the first error is statistical and the second is systematic. We set 90% confidence level upper limits on the corresponding ratios for the decays to  $\pi^0 \chi_{c0}$  and  $\pi^0 \chi_{c2}$  of 19 and 1.1, respectively.

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In the mass region above open-charm threshold, where charmonium states are heavy enough to decay to open-charm mesons, there are a number of states with features that are yet to be satisfactorily understood [1]. These features likely point towards the existence of non- $c\bar{c}$  configurations of charmonium. The  $X(3872)$  [also known as the  $\chi_{c1}(3872)$ ] was the first of these unexpected states to be discovered. It was first observed in 2003 by the Belle Collaboration in the process  $B \rightarrow KX(3872)$  with  $X(3872) \rightarrow \pi^+ \pi^- J/\psi$  [2]. It has since been seen by many other experiments in other processes and decay modes [3]. Its prominent features now include the following: (1) Its width is narrow ( $\Gamma < 1.2 \text{ MeV}/c^2$ ) [4]. (2) Its mass is consistent with the  $D^0 \bar{D}^{*0}$  threshold (with an error on the mass difference of  $0.18 \text{ MeV}/c^2$ ) [3]. (3) It has quantum numbers  $J^{PC} = 1^{++}$  [5]. (4) No isospin partners are currently known [4,6]. (5) It has isospin-violating decays since it decays to both  $\rho J/\psi$  [4] and  $\omega J/\psi$  [7]. (6) It also decays to  $D^0 \bar{D}^{*0}$  [8],  $\gamma J/\psi$  [9], and  $\gamma \psi(2S)$  [9]. Despite this

growing list of experimental facts, the nature of the  $X(3872)$  remains unclear [1]. Measuring pionic transitions of the  $X(3872)$  to the  $\chi_{cJ}$  has been proposed to be one way to distinguish between various interpretations. If the  $X(3872)$  were a conventional  $c\bar{c}$  state, transitions to the  $\chi_{cJ}$  should be very small [Ref. [10] predicts  $\Gamma(X(3872) \rightarrow \pi^0 \chi_{c1}) \sim 0.06 \text{ keV}$ ]; if the  $X(3872)$  were a tetraquark or molecular state, on the other hand, these rates are expected to be sizeable [10,11].

The BESIII experiment, operating at the Beijing Electron Positron Collider (BEPCII), previously observed the process  $e^+e^- \rightarrow \gamma X(3872)$  with  $X(3872) \rightarrow \pi^+ \pi^- J/\psi$  using data collected at four center-of-mass energies ( $E_{\text{c.m.}}$ ): 4.01, 4.23, 4.26, and 4.36 GeV [12]. The cross section was shown to be largest at 4.23 and 4.26 GeV. Since that time, BESIII has collected more data in this energy region, including approximately  $3 \text{ fb}^{-1}$  at 4.18 GeV and  $0.5 \text{ fb}^{-1}$  at each of seven additional points between 4.19 and 4.27 GeV. These additional datasets provide an opportunity to search for new decay modes of the  $X(3872)$  using the same production process  $e^+e^- \rightarrow \gamma X(3872)$ . Data collected at different  $E_{\text{c.m.}}$  can be combined and new  $X(3872)$  decays can be normalized to  $e^+e^- \rightarrow \gamma X(3872)$  with  $X(3872) \rightarrow \pi^+ \pi^- J/\psi$ , thereby canceling the production cross section and many systematic uncertainties.

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In this Letter, we report the first observation of the decay  $X(3872) \rightarrow \pi^0 \chi_{c1}$  with a statistical significance of  $5.2\sigma$ . Like the  $\rho J/\psi$  decay, this final state has an isospin of one. This is the first observation of a decay of the  $X(3872)$  to a  $P$ -wave charmonium state and its large branching fraction relative to  $\pi^+ \pi^- J/\psi$  supports a non- $c\bar{c}$  interpretation of the  $X(3872)$  [10,11].

We search for the processes  $e^+e^- \rightarrow \gamma_1 X(3872)$  with  $X(3872) \rightarrow \pi^0 \chi_{cJ}$  ( $J = 0, 1, 2$ ) using the decays  $\chi_{cJ} \rightarrow \gamma_2 J/\psi$  and  $J/\psi \rightarrow l^+ l^-$ , where  $l^+ l^-$  denotes both  $e^+ e^-$  and  $\mu^+ \mu^-$ , and  $\gamma_1$  and  $\gamma_2$  are the initial photon and the photon from the  $\chi_{cJ}$  decay, respectively. This is subsequently referred to as the “search” channel and it results in the final state  $\gamma_1 \gamma_2 \pi^0 l^+ l^-$  (with  $\pi^0 \rightarrow \gamma\gamma$ ). We also reconstruct the “normalization” channel  $e^+e^- \rightarrow \gamma X(3872)$  with  $X(3872) \rightarrow \pi^+ \pi^- J/\psi$  and  $J/\psi \rightarrow l^+ l^-$ , resulting in the final state  $\gamma \pi^+ \pi^- l^+ l^-$ . For the signal region, we use all available BESIII data with  $E_{\text{c.m.}}$  between 4.15 and 4.30 GeV ( $9.0 \text{ fb}^{-1}$ ), where the  $e^+e^- \rightarrow \gamma X(3872)$  cross section was measured to be largest, and for the sideband regions, we use all data with  $E_{\text{c.m.}}$  between 4.00 and 4.15 GeV ( $0.7 \text{ fb}^{-1}$ ) and between 4.30 and 4.60 GeV ( $2.8 \text{ fb}^{-1}$ ).

The Beijing Spectrometer (BESIII) experiment uses a general purpose magnetic spectrometer [13]. A superconducting solenoid magnet provides a 1.0 T magnetic field. Enclosed within the magnet are a helium-gas-based drift chamber for charged particle tracking and a CsI(Tl) electromagnetic calorimeter (EMC) to measure the energy of electromagnetic showers. Other detector components, such as the plastic scintillator time-of-flight system, are not used in this analysis.

A GEANT4-based [14] Monte Carlo (MC) simulation package is used to determine detection efficiencies and estimate background rates. The initial  $e^+e^-$  collisions, including effects due to initial state radiation (ISR), and subsequent decays are simulated using KKMC [15] and EVTGEN [16], respectively. Final state radiation is simulated with PHOTOS [17].

Optimization of the event selection criteria is performed using three categories of data samples: one to estimate signal yields ( $S$ ) and two for background yields ( $B_1$  and  $B_2$ ). For  $S$ , signal MC samples are used. The normalization channel is generated so that  $\sigma(e^+e^- \rightarrow \gamma X(3872)) \times \mathcal{B}(X(3872) \rightarrow \pi^+ \pi^- J/\psi) = 0.3 \text{ pb}$  at each  $E_{\text{c.m.}}$  [12]; the search channels are initially scaled assuming  $\mathcal{B}(X(3872) \rightarrow \pi^0 \chi_{cJ})/\mathcal{B}(X(3872) \rightarrow \pi^+ \pi^- J/\psi) = 1$ . For  $B_1$ , background MC samples for processes including a  $J/\psi$  are generated using previously measured cross sections. These include  $e^+e^- \rightarrow \pi\pi J/\psi$  [18,19],  $\pi\pi\psi(3686)$  [20,21],  $\eta J/\psi$  [22],  $\eta' J/\psi$  [23],  $\omega\chi_{cJ}$  [24,25], and  $\gamma_{\text{ISR}}\psi(3686)$  [26,27]. These also include  $e^+e^- \rightarrow \gamma X(3872)$  with  $X(3872)$  decays to  $\omega J/\psi$  [7],  $\gamma J/\psi$  [9], and  $\gamma\psi(3686)$  [9], each of which is normalized to  $X(3872) \rightarrow \pi^+ \pi^- J/\psi$  using previous measurements [3]. For  $B_2$ , background modes that do not include a  $J/\psi$  are estimated using sidebands in the reconstructed

mass spectrum of  $J/\psi$  candidates in data. Analysis of an inclusive MC sample shows no other background modes with peaks near the  $J/\psi$ ,  $\chi_{cJ}$ , or  $X(3872)$  masses.

Common charged particle and photon selection criteria are used for the normalization and search channels. Charged particles are selected using their distance of closest approach to the interaction region (within 10 cm along the beam direction and 1 cm transverse to it) and are required to be within the region  $|\cos\theta| < 0.93$ , where  $\theta$  is measured with respect to the beam axis. No particle identification is used for charged pions. Electrons and muons are distinguished using the energy they deposit in the EMC divided by their momentum ( $E/p$ ): charged tracks are labeled as electrons (muons) in the case  $E/p > 0.85$  ( $E/p < 0.25$ ), respectively. Photons must have deposited an energy greater than 25 MeV in the barrel region of the EMC ( $|\cos\theta| < 0.80$ ) and greater than 50 MeV in the end cap region ( $0.86 < |\cos\theta| < 0.92$ ) and must have a hit time within 700 ns of the event start time.

Using the selected charged particles and photons, kinematic fits are then performed for the normalization channel ( $\gamma\pi^+\pi^-l^+l^-$ ) and search channel ( $\gamma_1\gamma_2\pi^0l^+l^-$ ) hypotheses. A four-constraint (4C) kinematic fit is used for the normalization channel, where the total measured four momentum is constrained to the four momentum of the initial center-of-mass system, and the resulting  $\chi_{4C}^2/\text{d.o.f.}$  is required to be less than 10. For the search channel, an extra constraint (1C) is added to constrain a  $\gamma\gamma$  pair to the  $\pi^0$  mass and we require  $\chi_{5C}^2/\text{d.o.f.} < 5$ . These criteria are optimized by maximizing  $S/\sqrt{S+B_1+B_2}$ , where the sizes of the signal ( $S$ ) and background ( $B_1$  and  $B_2$ ) are determined from the three data samples described previously. Multiple combinations per event are allowed, but are negligible after event selection. Using signal MC samples, multiply-counted events are found to be less than 0.1% and 4% in the normalization and search channels, respectively. In data, no multiply counted events are found.

The  $J/\psi$  signal is selected by requiring  $M(l^+l^-)$  to be within 20 MeV/ $c^2$  of the nominal  $J/\psi$  mass [3]. The  $J/\psi$  sideband regions, used for background estimations, are each 40 MeV/ $c^2$  wide on either side of the  $J/\psi$  and leave a 20 MeV/ $c^2$  gap with the signal region.

Several additional criteria are used to select the normalization channel. Radiative Bhabha background events [ $e^+e^- \rightarrow e^+e^-(n\gamma)$ ], where a radiated photon converts to  $e^+e^-$  within the detector material and the resulting  $e^+e^-$  are mistaken to be  $\pi^+\pi^-$ , are removed by requiring the  $\pi^+\pi^-$  opening angle ( $\theta_{\pi\pi}$ ) to satisfy  $\cos\theta_{\pi\pi} < 0.98$ . Further suppression of this background process is obtained by requiring the opening angle of the final state photon and any charged track ( $\theta_{\gamma\text{tk}}$ ) to satisfy  $\cos\theta_{\gamma\text{tk}} < 0.98$ . Background events from  $\eta J/\psi$  and  $\eta' J/\psi$  are removed by requiring  $M(\gamma\pi^+\pi^-) > 0.6 \text{ GeV}/c^2$  and

$|M(\gamma\pi^+\pi^-) - M_0(\eta')| > 0.02 \text{ GeV}/c^2$  [ $M_0(\eta')$  is the nominal mass of the  $\eta'$  [3]], respectively.

For the search channel, the background mode  $\pi^0\pi^0 J/\psi$  is suppressed both by requiring  $M(\gamma_1\gamma_2)$  to be  $20 \text{ MeV}/c^2$  away from the  $\pi^0$  mass and by placing the same requirement on the mass of  $\gamma_1$  or  $\gamma_2$  combined with the higher energy photon from the  $\pi^0$  decay. Background events from  $\omega(782)$  decays to  $\gamma\pi^0$ , including those from  $e^+e^- \rightarrow \omega\chi_{cJ}$  and  $\gamma X(3872) \rightarrow \gamma\omega J/\psi$ , are removed by requiring  $M(\gamma_{1,2}\pi^0) < 0.732 \text{ GeV}/c^2$ . Finally, background events from  $\gamma_{\text{ISR}}\psi(3686)$  are reduced by requiring the mass recoiling against  $\gamma_1$  or  $\gamma_2$  both to be larger than  $3.7 \text{ GeV}/c^2$ .

The final distributions for the reconstructed  $\pi^+\pi^- J/\psi$  mass in the normalization channel are shown in Fig. 1. In order to improve the mass resolution,  $M(\pi^+\pi^- J/\psi)$  is calculated using  $M(\pi^+\pi^- l^+l^-) - M(l^+l^-) + M_0(J/\psi)$ , where  $M_0(J/\psi)$  is the nominal mass of the  $J/\psi$ . The mass resolution is improved from 7.4 to  $4.7 \text{ MeV}/c^2$ .

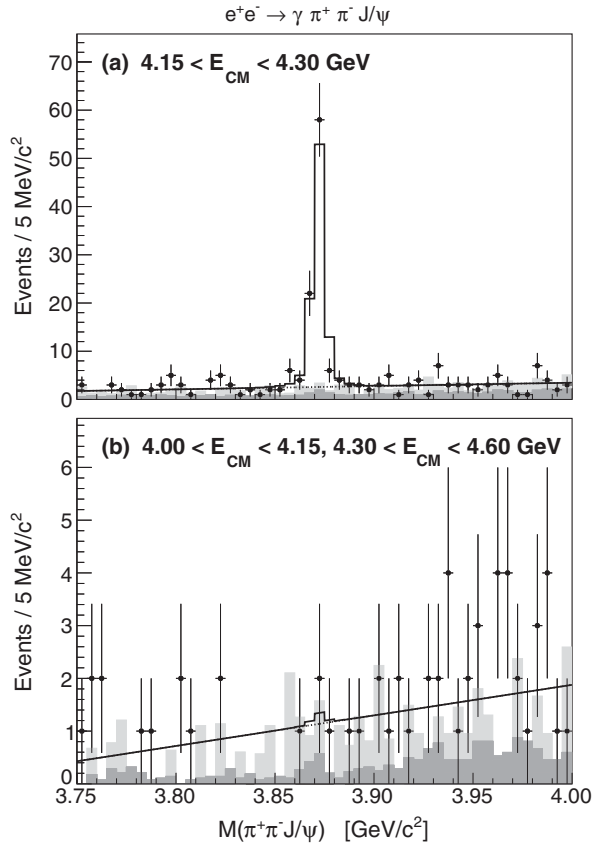


FIG. 1. Distribution of  $\pi^+\pi^- J/\psi$  mass,  $M(\pi^+\pi^- J/\psi)$ , from the normalization process  $e^+e^- \rightarrow \gamma\pi^+\pi^- J/\psi$  for (a)  $4.15 < E_{\text{c.m.}} < 4.30 \text{ GeV}$  and (b)  $4.00 < E_{\text{c.m.}} < 4.15$  or  $4.30 < E_{\text{c.m.}} < 4.60 \text{ GeV}$ . Points are data; lines (solid is the total and dotted is the polynomial background). The darker histogram is a MC estimate of peaking  $J/\psi$  backgrounds; the lighter stacked histogram is an estimate of nonpeaking backgrounds using  $J/\psi$  sidebands from data.

Figure 1(a) corresponds to data taken at  $4.15 < E_{\text{c.m.}} < 4.30 \text{ GeV}$  and shows a clear  $X(3872)$  signal. The data are fitted by a first-order polynomial representing the background and a response function of the signal process that has been obtained from the signal MC simulation. All fits are performed using a binned likelihood method; all significances are obtained by comparing the resulting likelihoods with and without the signal component included. Results are listed in Table I. Figure 1(b) shows the same for the other  $E_{\text{c.m.}}$  samples. No  $X(3872)$  signal is seen. This pattern is consistent with the previous measurement [12].

The corresponding distributions of  $M(\pi^0\chi_{cJ})$  for the search channel are shown in Fig. 2. The  $\chi_{cJ}$  region is first chosen with a loose requirement on  $M(\gamma_{1,2}J/\psi) \equiv M(\gamma_{1,2}l^+l^-) - M(l^+l^-) + M_0(J/\psi)$  between  $3.35$  and  $3.60 \text{ GeV}/c^2$ . A clear signal for the  $X(3872)$  is observed for  $4.15 < E_{\text{c.m.}} < 4.30 \text{ GeV}$  [Fig. 2(a)]; no evidence for the  $X(3872)$  is seen at other  $E_{\text{c.m.}}$  [Fig. 2(b)]. The distributions are fit with a first-order polynomial background function and a signal shape derived from the signal MC simulation, where the relative fractions of  $\pi^0\chi_{cJ}$  with  $J = 0, 1, 2$  are fixed by subsequent fits. There are two entries per event corresponding to the two combinations of  $\gamma_1$  and  $\gamma_2$ ; the signal MC includes a broad contribution from events with interchanged  $\gamma_1$  and  $\gamma_2$ . Using the background samples described earlier ( $B_1$  and  $B_2$ ), we find no other peaking background events. The fit in Fig. 2(a) yields  $16.9^{+5.2}_{-4.5}$   $X(3872)$  events with a statistical significance of  $4.8\sigma$ .

We next use the  $M(\gamma_{1,2}J/\psi)$  distribution to select the  $\chi_{c0}$ ,  $\chi_{c1}$ , and  $\chi_{c2}$  mass regions (Fig. 3). The photons  $\gamma_1$  and  $\gamma_2$  are separated by choosing  $\gamma_2$  to be the photon that minimizes  $\Delta M_J \equiv |M(\gamma_2 J/\psi) - M_0(\chi_{cJ})|$ , where  $M_0(\chi_{cJ})$  is the nominal mass of each  $\chi_{cJ}$  [3]. We require  $\Delta M_0 < 25$  and  $\Delta M_{1,2} < 20 \text{ MeV}/c^2$ . The resulting distributions for  $M(\pi^0\chi_{cJ})$  with  $J = 0, 1, 2$  are shown in Fig. 4. Each  $M(\pi^0\chi_{cJ})$  distribution is fit with a constant background function and a signal shape derived from signal MC simulation. The signal MC samples include events with interchanged  $\gamma_1$  and  $\gamma_2$  as well as cross feed among the  $\pi^0\chi_{cJ}$  channels. These effects result in an additional peak below the  $X(3872)$  signal region in the  $M(\pi^0\chi_{c0})$  distribution, but are negligible elsewhere. In the  $M(\pi^0\chi_{c1})$  distribution, we find a  $X(3872)$  signal with a  $5.2\sigma$  significance. No significant  $X(3872)$  signals are found in the  $M(\pi^0\chi_{c0,2})$  distributions. Numbers for events, efficiencies, and significances are listed in Table I. The total yield of signal events in all three channels is  $15.1^{+4.8}_{-3.8}$ , consistent with the fit in Fig. 2(a).

Also shown in Table I are the final ratios  $\mathcal{B}(X(3872) \rightarrow \pi^0\chi_{cJ})/\mathcal{B}(X(3872) \rightarrow \pi^+\pi^- J/\psi)$ . These are calculated from the ratios of yields of signal events, the ratios of efficiencies (including minor effects due to ISR), and the

TABLE I. Final results for the normalization and search channels and their ratios. Individual efficiencies are reported without considering ISR in the MC (no ISR) and are for illustration only. Efficiency ratios are for the search channels divided by the normalization channel and include effects due to ISR (with ISR), which nearly cancel in the ratio. Numbers in parentheses are 90% C.L. upper limits. The first errors are statistical and the second are systematic.

	$\pi^+\pi^-J/\psi$	$\pi^0\chi_{c0}$	$\pi^0\chi_{c1}$	$\pi^0\chi_{c2}$
Event yield	$84.1^{+10.1}_{-9.4}$	$1.9^{+1.9}_{-1.3}$	$10.8^{+3.8}_{-3.1}$	$2.5^{+2.3}_{-1.7}$
Signal significance ( $\sigma$ )	16.1	1.6	5.2	1.6
Efficiency (no ISR) (%)	32.3	8.8	14.1	12.8
Efficiency ratio (with ISR)	...	0.272	0.435	0.392
$\mathcal{B}(\chi_{cJ} \rightarrow \gamma J/\psi) \times \mathcal{B}(\pi^0 \rightarrow \gamma\gamma)$ (%)	...	1.3	33.5	19.0
Total systematic error (%)	...	17.0	11.9	9.4
$\mathcal{B}(X \rightarrow \pi^0\chi_{cJ})/\mathcal{B}(X \rightarrow \pi^+\pi^-J/\psi)$	...	$6.6^{+6.5}_{-4.5} \pm 1.1$ (19)	$0.88^{+0.33}_{-0.27} \pm 0.10$	$0.40^{+0.37}_{-0.27} \pm 0.04$ (1.1)

nominal  $\chi_{cJ}$  and  $\pi^0$  branching fractions [3]. Upper limits (at the 90% C.L.) are calculated from the likelihood curve of the fits as a function of signal yield after being convolved with a Gaussian distribution with a width the size of the systematic uncertainty. The  $J/\psi$  branching fractions,

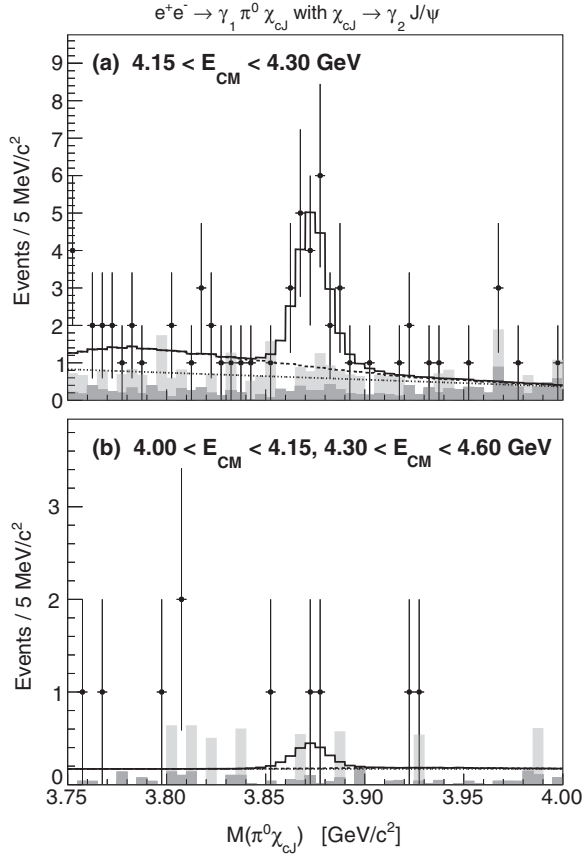


FIG. 2. Distribution of  $\pi^0\chi_{cJ}$  mass,  $M(\pi^0\chi_{cJ})$ , from the process  $e^+e^- \rightarrow \gamma\pi^0\chi_{cJ}$  for (a)  $4.15 < E_{\text{c.m.}} < 4.30 \text{ GeV}$  and (b)  $4.00 < E_{\text{c.m.}} < 4.15$  or  $4.30 < E_{\text{c.m.}} < 4.60 \text{ GeV}$ . The  $\chi_{cJ}$  are selected using a broad region of  $\gamma J/\psi$  mass. Points, lines, and histograms follow the same convention as Fig. 1. The dashed line is the total background contribution to the fit, including signal events with  $\gamma_1$  and  $\gamma_2$  interchanged.

integrated luminosities at each  $E_{\text{c.m.}}$ , and ISR correction factors, as well as a number of systematic uncertainties, cancel in the ratios.

The remaining systematic uncertainties are listed in Table II. (1),(2) For uncertainties in the photon and charged track efficiencies, we use 1% per photon [28] and track [23] that do not cancel between the search and normalization channels. (3) For input branching fractions, uncertainties from the Particle Data Group (PDG) are used [3]. (4) A systematic uncertainty due to the kinematic fit is determined using clean control samples with matching final states:  $e^+e^- \rightarrow \pi^0\pi^0 J/\psi$  for the search channel and  $e^+e^- \rightarrow \gamma_{\text{ISR}}\psi(2S) \rightarrow \gamma_{\text{ISR}}\pi^+\pi^-J/\psi$  for the normalization channel. (5) The selection criteria that distinguish between  $\gamma_1$  and  $\gamma_2$  in the search channel introduce some  $E_{\text{c.m.}}$  dependence in the efficiency ratio. To probe this uncertainty, we generate different shapes for the cross section as a function of  $E_{\text{c.m.}}$ : the nominal is constant,

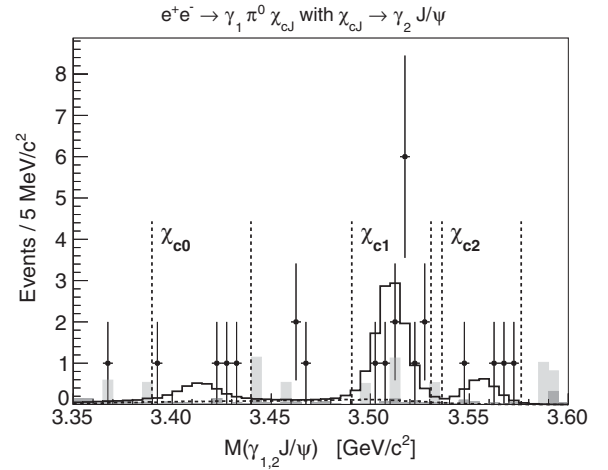


FIG. 3. Distribution of  $M(\gamma_{1,2}J/\psi)$  after selecting the  $X(3872)$  signal region from Fig. 2(a). Points and shaded histograms follow the same convention as Fig. 1. The solid line is the signal MC and is scaled using subsequent fits; the dashed line is the component of the signal MC where  $\gamma_1$  and  $\gamma_2$  are interchanged. Vertical lines show the  $\chi_{cJ}$  selection regions.

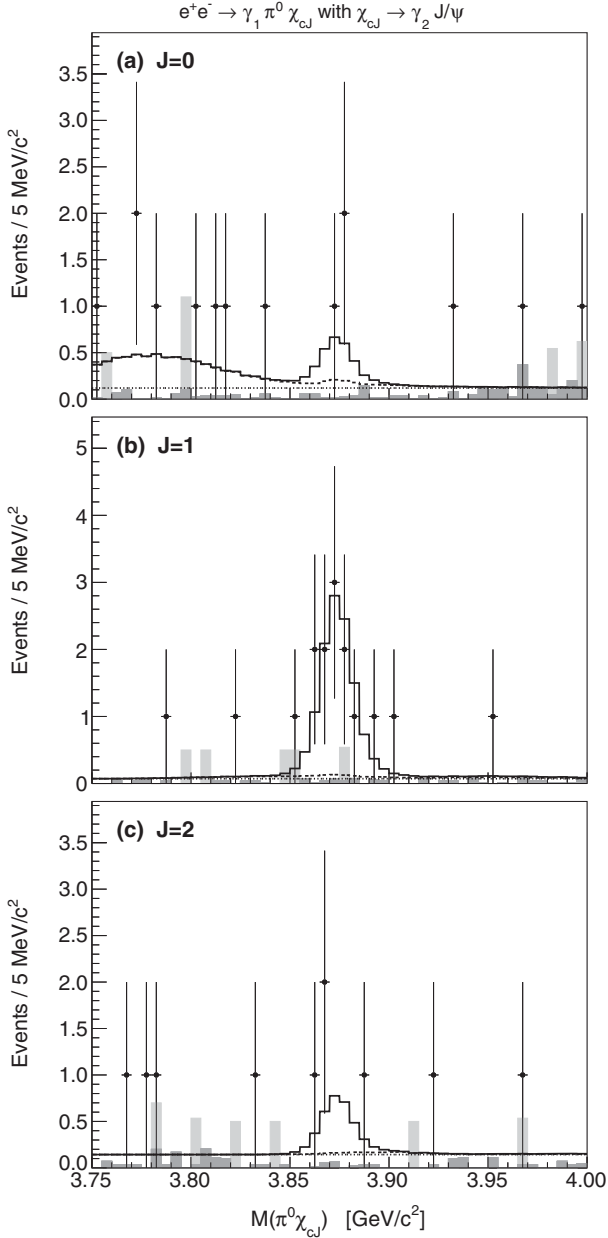


FIG. 4. Distributions of  $\pi^0\chi_{cJ}$  mass,  $M(\pi^0\chi_{cJ})$ , from the process  $e^+e^- \rightarrow \gamma\pi^0\chi_{cJ}$  for (a)  $J=0$ , (b)  $J=1$ , and (c)  $J=2$ . Points, lines, and histograms follow the same convention as Fig. 1. The dashed line is the total background in the fit and includes contributions from events with interchanged  $\gamma_1$  and  $\gamma_2$  and cross feed among the search channels.

one is based on the  $e^+e^- \rightarrow \pi^+\pi^-J/\psi$  line shape seen by BESIII [18], and one is based on the  $\psi(4160)$  line shape with parameters from the PDG [3]. We take the largest difference as a systematic uncertainty. (6) Signal MC samples are generated according to realistic spin-dependent amplitudes using EVTGEN [16]. In channels where there is ambiguity [e.g., the presence of both  $S$  and  $D$  waves in  $X(3872) \rightarrow \rho J/\psi$  [4] or both  $P$  and  $F$  waves in  $X(3872) \rightarrow \pi^0\chi_{c2}$ ], we replace our nominal models by

TABLE II. Relative systematic uncertainties on the ratio  $\mathcal{B}(X(3872) \rightarrow \pi^0\chi_{cJ})/\mathcal{B}(X(3872) \rightarrow \pi^+\pi^-J/\psi)$  for  $J=0, 1, 2$ . All entries are in percent.

	$\pi^0\chi_{c0}$	$\pi^0\chi_{c1}$	$\pi^0\chi_{c2}$
(1) Photon efficiencies	3.0	3.0	3.0
(2) Track efficiencies	2.0	2.0	2.0
(3) Input branching fractions	4.7	3.5	3.6
(4) Kinematic fit	4.6	4.6	4.6
(5) $E_{\text{c.m.}}$ dependence of efficiency ratio	3.2	5.2	5.2
(6) MC decay models	8.2	8.1	2.3
(7) Fitting to determine signal yield	12.4	1.6	3.0
Total	17.0	11.9	9.4

phase space and take the maximum difference as a systematic uncertainty. (7) Fitting uncertainties are evaluated using two fit variations: zeroth- and first-order background polynomials and a signal shape that is widened by 20% to account for possible differences in mass resolution between data and MC simulation. The significance of the signal for  $X(3872) \rightarrow \pi^0\chi_{c1}$  remains above  $5\sigma$  for all variations. The total systematic uncertainty is obtained by adding the individual uncertainties in quadrature.

In summary, we use  $9.0 \text{ fb}^{-1}$  of  $e^+e^-$  collision data with  $E_{\text{c.m.}}$  between 4.15 and 4.30 GeV to search for the processes  $e^+e^- \rightarrow \gamma X(3872)$  with  $X(3872) \rightarrow \pi^0\chi_{cJ}$ . We make the first observation of the process  $X(3872) \rightarrow \pi^0\chi_{c1}$ , where the statistical significance is greater than  $5\sigma$  for all systematic variations. Normalizing to  $e^+e^- \rightarrow \gamma X(3872)$  with  $X(3872) \rightarrow \pi^+\pi^-J/\psi$ , we determine the ratio  $\mathcal{B}(X(3872) \rightarrow \pi^0\chi_{c1})/\mathcal{B}(X(3872) \rightarrow \pi^+\pi^-J/\psi) = 0.88_{-0.27}^{+0.33} \pm 0.10$ . Upper limits (at the 90% C.L.) for the corresponding ratios for the  $\pi^0\chi_{c0}$  and  $\pi^0\chi_{c2}$  decays are 19 and 1.1, respectively. Using  $\mathcal{B}(X(3872) \rightarrow \pi^+\pi^-J/\psi) > 3.3\%$  (obtained by comparing exclusive [4] and inclusive [29]  $B^+$  decays) and  $\mathcal{B}(X(3872) \rightarrow \pi^+\pi^-J/\psi) < 6.4\%$  [obtained by assuming all measured  $X(3872)$  decays add to less than 100%], we find  $\mathcal{B}(X(3872) \rightarrow \pi^0\chi_{c1}) \sim 3\% - 6\%$ . If the  $X(3872)$  were the  $\chi_{c1}(2P)$  state of charmonium, Ref. [10] predicts  $\Gamma(X(3872) \rightarrow \pi^0\chi_{c1}) \sim 0.06 \text{ keV}$ . Combining this with our result, this would imply a total width of the  $X(3872)$  of only  $\sim 1.0 - 2.0 \text{ keV}$ , which would be orders of magnitude smaller than all other observed charmonium states. Therefore, our measurement disfavors the  $c\bar{c}$  interpretation of the  $X(3872)$ .

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