Letter

Search for the $e^+e^- \to \phi\chi_{c1}(3872)$ process at BESIII

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Based on 368.5 pb^{-1} of e^+e^- collision data collected at center-of-mass energies 4.914 and 4.946 GeV by the BESIII detector, the $e^+e^- \to \phi\chi_{c1}(3872)$ process is searched for the first time. No significant signal is observed and the upper limits at the 90% confidence level on the product of the Born cross section $\sigma(e^+e^- \to \phi\chi_{c1}(3872))$ and the branching fraction $\mathcal{B}[\chi_{c1}(3872) \to \pi^+\pi^- J/\psi]$ at 4.914 and 4.946 GeV are set to be 0.85 and 0.96 pb, respectively. These measurements provide useful information for the production of the $\chi_{c1}(3872)$ at e^+e^- colliders and deepen our understanding about the nature of this particle.

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The quark model categorizes hadrons into two types: mesons with a quark and an antiquark, and baryons with three quarks. Within the framework of the theory of strong interactions, quantum chromodynamics (QCD), it also allows the existence of more complex structures, generically called exotic hadrons. A series of exotic hadron candidates, which cannot be accommodated by the potential model [1–3], were observed experimentally in the charmonium energy region during the past decades. They are suggested as good candidates of molecule, quark-gluon hybrid, or tetraquark states [4]. The well-known $\chi_{c1}(3872)$ state was first observed by the Belle experiment in the $B^\pm \to K^\pm\pi^+\pi^- J/\psi$ decay [5], and confirmed subsequently by several other experiments [6–11]. Ten years after its discovery, its spin-parity quantum numbers were finally determined to be $J^{PC} = 1^{++}$ by the LHCb Collaboration [12]. The mass and width are determined to be $M = 3871.65 \pm 0.06$ MeV$/c^2$ and $\Gamma = 1.19 \pm 0.21$ MeV using a Breit-Wigner resonance model [13].

Since the discovery of the $\chi_{c1}(3872)$, there have been tremendous efforts to understand its inner structure. Experimentally, there are intensive studies on the $\chi_{c1}(3872)$ decays currently. The decays of $\chi_{c1}(3872) \to \pi^+\pi^- J/\psi$ [5,11,14], $\gamma J/\psi$ [15–18], $\pi^0\chi_{c1}$ [19], $\omega J/\psi$ [20,21], $D^{*0}\bar{D}^0$ [15,22,23] have been well observed. Theoretically, $\chi_{c1}(3872)$ is interpreted as a good candidate of a meson molecule [24,25] since its mass is quite near $D^{*0}\bar{D}^0$ mass threshold. On the other hand, its quantum number is 1^{++}. So far, the P-wave excited charmonium state $\chi_{c1}(2P)$ (with $J^{PC} = 1^{++}$) is still missing, and the $\chi_{c1}(3872)$ might be a good candidate for $\chi_{c1}(2P)$ since its mass is similar to the potential model prediction [1]. Other interpretations such as a tetraquark candidate [26,27] is also possible. However, there is still no solid conclusion for the nature of $\chi_{c1}(3872)$.

In complement with decay, the production of $\chi_{c1}(3872)$ offers a new window to understand its nature. In 2014, the BESIII experiment observed the $e^+e^- \to \gamma\chi_{c1}(3872)$ production [11]. What is intriguing is that the $\chi_{c1}(3872)$ might originate from the radiative transition of an excited vector state $Y(4230)$, which for the first time brings together two charmoniumlike states and hints commonality for their underlying nature [4]. Recently, the process $e^+e^- \to \omega\chi_{c1}(3872)$ was observed at BESIII [28], and the production cross section shows potential enhancement near 4.75 GeV. In analogy to γ and ω, the vector meson ϕ has the same J^{PC} and isospin quantum number. Therefore, the process of $e^+e^- \to \phi\chi_{c1}(3872)$ is expected to naturally exist. By investigating the relative production ratio $\sigma_{e^+e^-\to\phi\chi_{c1}(3872)}/\sigma_{e^+e^-\to\phi\chi_{c1}}$ [29] and also comparing to $\sigma_{e^+e^-\to\omega\chi_{c1}(3872)}/\sigma_{e^+e^-\to\omega\chi_{c1}}$ [28,30], we gain a deeper understanding of the $\chi_{c1}(3872)$ production and probe the potential $\chi_{c1}(2P)$ core component in the $\chi_{c1}(3872)$ wave function [31]. In addition, the decay $B_s^0 \to \phi\chi_{c1}(3872)$ has also been observed [32] and has a production rate $\mathcal{B}[B_s^0 \to \phi\chi_{c1}(3872)] \approx \mathcal{B}[B^0 \to K^0\chi_{c1}(3872)] \approx \frac{1}{2}\mathcal{B}[B^+ \to K^+\chi_{c1}(3872)]$ [13]. Together with the $e^+e^- \to \phi\chi_{c1}(3872)$ process, a more comprehensive understanding of $\chi_{c1}(3872)$ production will be achieved [33].

In this article, we search for the $e^+e^- \to \phi\chi_{c1}(3872)$ process using 368.5 pb^{-1} of data [34] collected with the BESIII detector [35] operated at the BEPCII storage ring [36]. The ϕ meson is reconstructed via K^+K^- decays, while the $\chi_{c1}(3872)$ is found using $\rho^0 J/\psi$ decays with $\rho^0 \to \pi^+\pi^-$ and $J/\psi \to \ell^+\ell^-$ ($\ell = e, \mu$ with close branching fraction [13]). Due to the mass threshold of the

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$\phi\chi_{c1}(3872)$ system, only the data at the e^+e^- center-of-mass (c.m.) energies $\sqrt{s} = 4.914$ and 4.946 GeV is used.

The BESIII detector [35] records symmetric e^+e^- collisions provided by the BEPCII storage ring [36] in the center-of-mass energy range from 2.0 to 4.95 GeV, with a peak luminosity of 1×10^{33} $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ achieved at $\sqrt{s} = 3.77$ GeV. BESIII has collected large data samples in this energy region [37,38]. 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. A muon chamber (MUC) based on resistive plate chambers with 2 cm position resolution provides information for muon identification. The acceptance of charged particles and photons is 93% over 4π solid angle. The charged-particle momentum resolution at 1 GeV/c is 0.5%, and the $\mathrm{d}E/\mathrm{d}x$ 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 is 60 ps [39–41].

Monte Carlo (MC) samples, simulated using GEANT4-based software, are used to optimize the selection criteria, determine the detection efficiency and study the potential backgrounds [42]. In the BESIII software framework, KKMC [43] is the generator used to generate charmonium states by including initial state radiation (ISR) effects and the spread of the beam energy. We generate 50000 signal MC events of $e^+e^- \to \phi\chi_{c1}(3872)$ at each c.m. energy with a phase space (PHSP) model describing the uniform angular distribution of the final states. The $\chi_{c1}(3872) \to \rho^0 J/\psi$ decay is described with the PHSP model. Final state radiation of charged particles are simulated with the PHOTOS package [44]. For the possible ISR effect, we model the $\sqrt{s}$-dependent $e^+e^- \to \phi\chi_{c1}(3872)$ production cross section with a two-body phase space ($\frac{\sqrt{[s-(M_\phi+M_{\chi_{c1}(3872)})^2][s-(M_\phi-M_{\chi_{c1}(3872)})^2]}}{2\sqrt{s}}$, M_ϕ, $M_{\chi_{c1}(3872)}$ is the mass of $\phi, \chi_{c1}(3872)$ [13]). Inclusive MC samples, with a luminosity which are ten times larger than the data sample, are generated at each c.m. energy to study the possible backgrounds. The inclusive MC sample includes the production of open charm processes, the ISR production of vector charmonium(like) states, and the continuum processes incorporated in KKMC. All particle decays are modeled with EVTGEN [45,46] using branching fractions taken from the Particle Data Group [13], when available, and the remaining unknown charmonium decays are modeled with LUNDCHARM [47,48].

Charged tracks detected in the MDC are required to be within a polar angle (θ) range of $|\cos\theta| < 0.93$, where θ is defined with respect to the z-axis, which is the symmetry axis of the MDC. For charged tracks, 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, $|V_{xy}|$. For each candidate event, the pions from $\chi_{c1}(3872)$ decay (kaons from ϕ decay) and the leptons from J/ψ decay are kinematically well separated. Charged tracks with momenta larger than 1.0 GeV/c in the lab frame are assumed to be leptons, and the others are assumed to be pions or kaons. The energy deposited in the EMC is used to separate electrons from muons. For both muon candidates, the deposited energy in the EMC must be less than 0.4 GeV; while for both electrons, it must be larger than 0.8 GeV. To separate pions from kaons, particle identification (PID) combines measurements of the specific ionization energy loss in the MDC ($\mathrm{d}E/\mathrm{d}x$) and the flight time in the TOF to form likelihoods $\mathcal{L}(h)(h = p, K, \pi)$ for each hadron h hypothesis. Charged kaons (pions) are identified by comparing the likelihoods for the kaon (pion) hypotheses with $\mathcal{L}(K) > \mathcal{L}(\pi)$ [$\mathcal{L}(\pi) > \mathcal{L}(K)$].

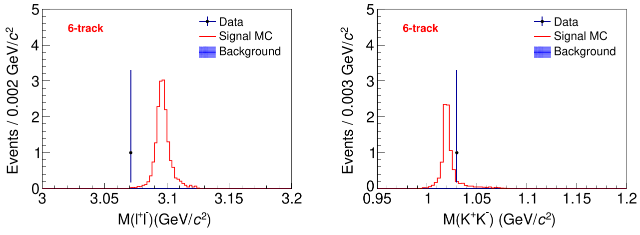
For the candidate events with $K^+K^-\pi^+\pi^-\ell^+\ell^-$ detected, referred to as 6-track events, the net charge is required to be zero. A four-constraint (4C) kinematic fit imposing energy-momentum conservation is applied on the 6-track events to improve resolution and suppress backgrounds. The kinematic fit $\chi^2_{4\mathrm{C}}$ is required to be less than 150. The selection criteria are optimized by maximizing the figure-of-merit

$$\mathrm{FOM} = \epsilon_{\mathrm{sig}}/(\alpha/2 + \sqrt{N_{\mathrm{bkg}}}), \tag{1.1}$$

where ϵ_{sig} is the detection efficiency from signal MC events, α is the assumed significance value which is set to 3 and N_{bkg} is the expected number of background events obtained from inclusive MC samples.

To select the J/ψ resonance, a mass window is defined as [3.070, 3.125] GeV/c^2 (mass resolution is 6 MeV/c^2), which roughly covers about $\pm 3\sigma$ of the J/ψ signal. The signal window of the ϕ resonance is set as [0.980, 1.080] GeV/c^2 (mass resolution is 7 MeV/c^2) with barely any efficiency loss according to signal MC events. To estimate the non-J/ψ background, the J/ψ sideband regions are defined as [3.010,3.065] and [3.130, 3.185] GeV/c^2, which are twice as wide as the J/ψ signal region. Due to the constraint of the mass threshold of double kaons, the ϕ sideband is defined as [1.080, 1.180] GeV/c^2, which is as wide as the ϕ signal region. After applying all of the selection criteria, there is no background in the 6-track events, as indicated by the inclusive MC sample. Figure 1 shows the invariant mass distributions of the lepton $M(\ell^+\ell^-)$ and kaon $M(K^+K^-)$ pairs for 6-track events from the full dataset.

In order to further improve the detection efficiency and thus the signal yield, candidate events with $K^+\pi^+\pi^-\ell^+\ell^-$ or $K^-\pi^+\pi^-\ell^+\ell^-$ detected are also reconstructed, with one of the soft kaons missing due to an inefficiency. A



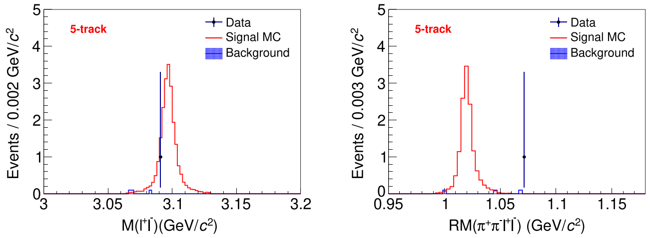
(a) (b)

FIG. 1. The distributions of $M(\ell^+\ell^-)$ (a) and $M(K^+K^-)$ (b) for 6-track events. Dots with error bars are 4.914 and 4.946 GeV data, the red histograms are the signal MC sample, and the blue filled histograms are the inclusive MC sample.

one-constraint (1C) kinematic fit is performed to these 5-track events, by constraining the mass of the missing particle to the nominal mass of the kaon [13]. The kinematic fit χ^2_{1C} is required to be less than 20, which is optimized by maximizing the FOM defined in Eq. (1.1). Due to the absence of one track in this case, the mass resolution of the event is slightly worse compared to that of the 6-track events. So the J/ψ mass window is defined as $[3.065, 3.130]$ GeV$/c^2$ (mass resolution is 10 MeV$/c^2$) and the sideband regions are [3.000,3.065] and $[3.130, 3.195]$ GeV$/c^2$ for the 5-track events, which are twice as wide as the J/ψ signal region. The signal region of the ϕ resonance is set to be $[0.980, 1.080]$ GeV$/c^2$ (mass resolution is 8 MeV$/c^2$) and the ϕ sideband is defined as $[1.080, 1.180]$ GeV$/c^2$, which is as wide as the ϕ signal region. There is a case, about 10% of the total signal events, that $K^\pm\pi^\mp\pi^+\pi^-\ell^+\ell^-$ are detected in the final state, owing to one of the soft kaon decays in the detector. This case is classified as 5-track events and reconstructed by missing a kaon.

By analyzing the inclusve MC samples, we find there are some proton backgrounds remaining in the 5-track events. To reduce the $p \to \mu$ misidentification background in the $J/\psi \to \mu^+\mu^-$ channel, the MUC is used to identify muons. At least one of the muon candidates should have a hit depth > 30 cm in the MUC. Figure 2 shows the $M(\ell^+\ell^-)$ and $RM(\pi^+\pi^-\ell^+\ell^-)$ distributions for 5-track events from the full data samples, where $RM(\pi^+\pi^-\ell^+\ell^-) = \sqrt{(P_{e^+e^-} - P_{\pi^+\pi^-\ell^+\ell^-})^2}$ is the recoil mass from the $\pi^+\pi^-\ell^+\ell^-$ system, $P_{e^+e^-}$ and $P_{\pi^+\pi^-\ell^+\ell^-}$ denoted the four-momenta of the initial colliding beams and the $\pi^+\pi^-\ell^+\ell^-$ system.

After applying all the selection criteria, Fig. 3 shows the $M(\pi^+\pi^-J/\psi)$ distribution from 6- and 5-track events at each c.m. energy. The invariant mass $M(\pi^+\pi^-J/\psi) = M(\pi^+\pi^-\ell^+\ell^-) - M(\ell^+\ell^-) + M(J/\psi)$ is defined, which partly helps to cancel the resolution effect of the lepton pairs. Here $M(J/\psi)$ is the nominal mass of J/ψ from the PDG [13]. Through studying the inclusive MC samples at each c.m. energy, no dominant background survives for both 6- and 5-tracks events. The study of the J/ψ and ϕ mass sideband events also shows the background level is low and so we neglect the background.



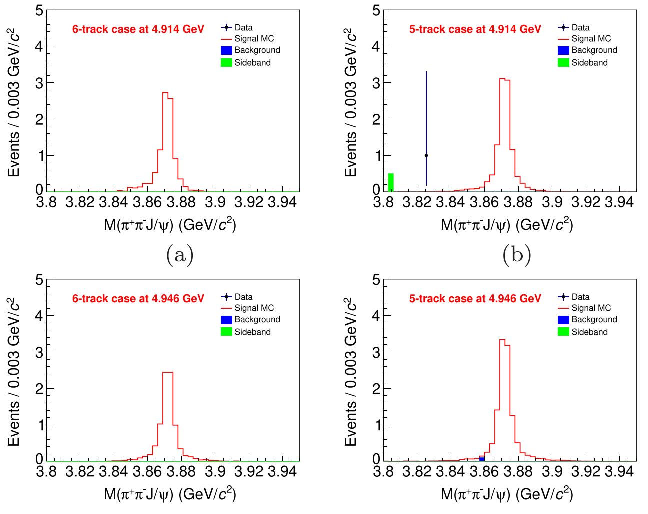
(a) (b)

FIG. 2. The distributions of $M(\ell^+\ell^-)$ (a) and $RM(\pi^+\pi^-\ell^+\ell^-)$ (b) for 5-track events. Dots with error bars are 4.914 and 4.946 GeV data, the red histograms are the signal MC sample, and the blue filled histograms are the inclusive MC sample.

The product of the Born cross section of $e^+e^- \to \phi\chi_{c1}(3872)$ and $\mathcal{B}[\chi_{c1}(3872) \to \pi^+\pi^-J/\psi]$ at c.m. energy $\sqrt{s}$ is calculated with

$$\sigma(e^+e^- \to \phi\chi_{c1}(3872)) \cdot \mathcal{B}[\chi_{c1}(3872) \to \pi^+\pi^-J/\psi] = \frac{N_{\rm sig}}{\mathcal{L}_{\rm int}(1+\delta)\frac{1}{|1-\Pi|^2}\epsilon\mathcal{B}_{\rm sub}}, \tag{1.2}$$

where $N_{\rm sig}$ is the number of signal events, $\mathcal{L}_{\rm int}$ is the integrated luminosity, ϵ is the selection efficiency, $\frac{1}{|1-\Pi|^2} = 1.056$ is the vacuum polarization factor taken from QED calculation with an accuracy of 0.05% [49], $\mathcal{B}_{\rm sub}$ is a



(a) (b) (c) (d)

FIG. 3. The distributions of $M(\pi^+\pi^-J/\psi)$ from (a) 6-track events at $\sqrt{s} = 4.914$ GeV, (b) 5-track events at $\sqrt{s} = 4.914$ GeV, (c) 6-track events at $\sqrt{s} = 4.946$ GeV and (d) 5-track events at $\sqrt{s} = 4.946$ GeV, respectively. Dots with error bars are data, the red histograms are the signal MC sample, the blue filled histograms are the inclusive MC sample and the green filled histograms are the $\phi - J/\psi$ 2-dimensional sideband.

TABLE I. The upper limit on the product of the Born cross section of $e^+e^- \to \phi\chi_{c1}(3872)$ and the branching fraction of $\chi_{c1}(3872) \to \pi^+\pi^- J/\psi$ [denoted as $\sigma_B^{\rm up}$ (pb)] at 90% CL at each c.m. energy. $\sqrt{s}$ (GeV) is the c.m. energy, $\mathcal{L}_{\rm int}$ (pb^{-1}) is the integrated luminosity, $N_{\rm obs}$ is the number of observed events in signal region, $N_{\rm sdb}$ is the number of observed events in the sideband region, $N_{\rm signal}^{\rm up}$ is the upper limit on the number of observed signal at the 90% CL, $\epsilon^5(\%)$ and $\epsilon^6(\%)$ are detection efficiencies for the 5- and 6-track events, respectively, $(1+\delta)$ is the radiative correction factor.

$\sqrt{s}$	$\mathcal{L}_{\rm int}$	$N_{\rm obs}$	$N_{\rm sdb}$	$N_{\rm signal}^{\rm up}$	$(1+\delta)$	ϵ^5	ϵ^6	$\sigma_B^{\rm up}$
4.914	208.11	0	1	1.70	0.690	19.7	2.8	0.85
4.946	160.37	0	0	2.00	0.755	20.8	7.0	0.96

product of the branching fractions $\mathcal{B}(J/\psi \to \ell^+\ell^-)$ and $\mathcal{B}(\phi \to K^+K^-)$, and $(1+\delta)$ is the radiative correction factor calculated by KKMC [43].

Due to no events observed in the $\chi_{c1}(3872)$ signal region, we report an upper limit on the Born cross section at the 90% confidence level (CL) using a frequentist method with an unbounded profile likelihood treatment [50]. The number of signal events is determined by the $\chi_{c1}(3872)$ signal region for 6- and 5-track events, which is defined as $[3.86, 3.88]$ GeV/c^2. The possible background estimated by the $\chi_{c1}(3872)$ sideband regions [3.80, 3.85] and $[3.90, 3.95]$ GeV/c^2 from 6- and 5-track events is subtracted (at $\sqrt{s} = 4.914$ GeV the sideband region is defined as $[3.80, 3.85]$ GeV/c^2 due to the limitation of kinematics). Assuming the background follows a Poisson distribution and the efficiency (sum of 6- and 5-track events) follows a Gaussian distribution with a standard deviation equal to the systematic uncertainty, the upper limit on the product of the Born cross section of $e^+e^- \to \phi\chi_{c1}(3872)$ and the branching fraction of $\chi_{c1}(3872) \to \pi^+\pi^- J/\psi$ at the 90% CL at each c.m. energy are measured and listed in Table I.

In the cross section measurement, the systematic uncertainties are mainly from the luminosity measurement, branching fractions, tracking efficiency, PID efficiency, MUC hit depth requirement, kinematic fit, radiative correction factor $(1+\delta)$, MC decay model and J/ψ mass window.

The uncertainty from the luminosity measurement is estimated to be less than 0.66% using large angle Bhabha scattering events [34]. The uncertainties of the decay branching fractions are quoted from the PDG [13]. The uncertainty of the tracking efficiency for high momentum leptons is assigned to be 1% per track according to the study of $e^+e^- \to \pi^+\pi^- J/\psi$ at BESIII [51]. In this measurement, both one- and two kaon events are reconstructed. The total uncertainty of the kaon tracking efficiency is 1.0% (2.0%) for 5-track(6-track) events. Considering the uncertainty of PID efficiency is 1% per kaon track at BESIII, the kaon PID uncertainty is 1.0%(2.0%) for 5-track(6-track) events, too. The systematic uncertainty from pion tracking and PID efficiencies are both 1.0% per pion track [52].

The uncertainty of the MUC hit depth is studied using the control sample of $e^+e^- \to \mu^+\mu^-$ [29]. The difference in efficiency between data and MC simulation due to the requirement of the μ hit depth in the MUC is taken as the systematic uncertainty. A helix parameters correction method is used to estimate the difference between data and signal MC events caused by the kinematic fit. The difference in efficiency with and without correction is taken as the systematic uncertainty. The systematic uncertainty of the radiative correction factor is studied by comparing the difference between factors obtained with the two-body phase space model and with a flat cross section line shape. The difference in $(1+\delta)\epsilon$ is taken as the uncertainty. To estimate the uncertainty due to the MC model, the angular distribution of $e^+e^- \to \phi\chi_{c1}(3872)$ is modeled by a $1 \pm \cos^2(\theta)$ distribution, where the efficiency difference with respect to PHSP is taken as the systematic uncertainty. The control sample $e^+e^- \to \pi^+\pi^-\psi(3686)$ with $\psi(3686) \to \pi^+\pi^- J/\psi$ [53] is selected to study the system uncertainty caused by the J/ψ mass window. The difference in efficiency between data and signal MC events due to the mass window is taken as the systematic uncertainty.

In the measurement, two subdata samples, i.e. the 6- and 5-track events are reconstructed. The same source of systematic uncertainties contribute to the two subdata samples, namely the 5- and 6-track events. These are combined by taking the weighted average of their systematic uncertainties: Eq. (1.3) etc.

$$\Delta_{\rm tot}^2 = \sum_{i=1}^{2} \omega_i^2 \Delta_i^2 + 2\sum_{i<j}^{2} {\rm cov}(i,j), \tag{1.3}$$

$${\rm cov}(i,j) = \omega_i \omega_j \Delta_i \Delta_j, \tag{1.4}$$

$$\omega_i = \frac{\epsilon_i}{\sum_{i=1}^{2} \epsilon_i}, \tag{1.5}$$

TABLE II. Systematic uncertainties (%) in the measurement of the Born cross section at 4.914 GeV.

Uncertainty	5-track	6-track	Weighted average
Luminosity	0.7		0.7
Tracking	5.0	6.0	5.2
PID	3.0	4.0	3.2
$\mathcal{B}(J/\psi \to \ell^+\ell^-)$	0.6		0.6
$\mathcal{B}(\phi \to K^+K^-)$	1.0		1.0
Radiative correction	0.7		0.7
J/ψ mass window	0.1	0.1	0.1
MUC hit depth	2.1	0	1.8
Kinematic fit	0.7	0.4	0.7
MC model	5.2	5.9	5.4
Total	...	...	8.5

TABLE III. Systematic uncertainties (%) in the measurement of the Born cross section at 4.946 GeV.

Uncertainty	5-track	6-track	Weighted average
Luminosity	0.7		0.7
Tracking	5.0	6.0	5.3
PID	3.0	4.0	3.3
$\mathcal{B}(J/\psi \to \ell^+\ell^-)$	0.6		0.6
$\mathcal{B}(\phi \to K^+K^-)$	1.0		1.0
Radiative correction	1.9		1.9
J/ψ mass window	0.1	0.1	0.1
MUC hit depth	2.9	0	2.2
Kinematic fit	0.6	0.3	0.5
MC model	2.1	14.0	6.2
Total	…	…	9.4

where $\Delta_{\rm tot}$ is the average systematic uncertainty on the cross section, while ω_i, ϵ_i and Δ_i are the weight, efficiency and systematic uncertainty for the ith subdata sample, respectively. For the soft kaon decay events ($K^\pm\pi^\mp\pi^+\pi^-\ell^+\ell^-$), its weight contributes to the 5-track subdata sample for the J/ψ mass window, the MUC hit depth requirement and the kinematic fit; otherwise its weight contributes to the 6-track subdata sample.

Assuming all these sources are independent, the total systematic uncertainty in the cross section measurement is obtained by adding them in quadrature. Tables II and III summarize all of the systematic sources and their contributions at 4.914 GeV and 4.946 GeV, respectively.

In summary, with a data sample corresponding to an integrated luminosity of 368.5 pb^{-1} collected by the BESIII detector, the process of $e^+e^- \to \phi\chi_{c1}(3872)$ is searched for the first time. No significant signal is observed and the upper limits at the 90% CL on the product of the Born cross section $\sigma(e^+e^- \to \phi\chi_{c1}(3872))$ and the branching fraction $\mathcal{B}[\chi_{c1}(3872) \to \pi^+\pi^- J/\psi]$ at 4.914 and 4.946 GeV are set to be 0.85 and 0.96 pb, respectively. Considering the cross section $\sigma(e^+e^- \to \phi\chi_{c1}) \sim 2.6$ pb near the production threshold [29], we obtain a rough estimation for the production ratio $\sigma_{\phi\chi_{c1}(3872)}/\sigma_{\phi\chi_{c1}} < 9$. It is in the same order as the relative production ratio $\sigma_{\omega\chi_{c1}(3872)}/\sigma_{\omega\chi_{c1}} \sim 5$ [28,30]. These measurements provide important inputs to the production of $\chi_{c1}(3872)$ at e^+e^- colliders, and help constrain the possible $\chi_{c1}(2P)$ component in the $\chi_{c1}(3872)$ wave function. With the upgrade of the BEPCII [37] project, more data in this energy region is expected and a more comprehensive study of the $\chi_{c1}(3872)$ production will be achieved, which will hopefully reveal the nature of $\chi_{c1}(3872)$ state.

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