Search for a strangeonium-like structure $Z_s$ decaying into $\phi\pi$ and a measurement of the cross section $e^+e^-\rightarrow\phi\pi$
Using a data sample of $e^+e^−$ collision data corresponding to an integrated luminosity of 108 pb$^{-1}$ collected with the BESIII detector at a center-of-mass energy of 2.125 GeV, we study the process $e^+e^− \rightarrow φπ^+$ and search for a strangeonium-like structure $Z_4$ decaying into $φπ^+$. No signal is observed in the $φπ^+$ mass spectrum at 2.125 GeV are measured.
A charged charmonium-like structure, \( Z_c(3900) \), was observed in the \( \pi^+\pi^-/\psi \) final states by the BESIII and Belle experiments.\(^1,2\) Subsequently, several analogous structures were reported and confirmed by different experiments.\(^3\)–\(^7\) These observations inspired extensive discussions of their nature, and one of the reasonable interpretations is the tetraquark state due to these structures carrying charge and prominently decaying into a pion and a conventional charmonium state.\(^8\) More recently, the neutral partners of these charmonium-like structures were observed\(^8,11\), which indicate the isotriplet property of these structures and hint of a new hadron spectroscopy.

By replacing the \( c\bar{c} \) pair in the \( Z_c \) structure with a \( s\bar{s} \), it is possible to consider an analogous \( Z_s \) structure. Similar to \( Y(4260) \rightarrow J/\psi \pi^+\pi^- \) in which the \( Z_c(3900) \) was observed\(^1,2\), the process \( \phi(2170) \rightarrow \pi^+\pi^- \) is considered as a unique place to search for the \( Z_s \) structure, as the \( \phi(2170) \) is regarded as the strangeonium-like states analogy to \( Y(4260) \) in charmonium sector.\(^12\) Furthermore, the conventional isosinglet \( s\bar{s} \) state decaying into \( \phi \pi \) is suppressed by the conservation of isospin symmetry, while for a conventional meson composed of \( u, d \) quarks, the \( \phi \pi \) decay mode is strongly suppressed by the Okubo-Zweig-Iizuka (OZI) rule.\(^13\) Therefore, it is of interest to perform an experimental search for the strangeonium-like structure \( Z_s \) since its observation may imply the existence of an exotic state.

In this Letter, we present a search for the \( Z_s \) structure in the process \( e^+e^- \rightarrow \phi\pi\pi \) using a data sample corresponding to an integrated luminosity of \( (108.49 \pm 0.75) \) pb\(^{-1}\)\(^14\), taken at a center-of-mass energy of 2.125 GeV with the BESIII detector. Since the observed \( Z_c(3900) \) and \( Z_c(3885) \) are close to the \( D\bar{D} \) mass threshold and have a narrow width, we will focus on the search for a narrow width \( Z_s \) structure around the \( K\bar{K} \) mass threshold \((1.4 \text{ GeV}/c^2)\) in the \( \phi\pi \) mass spectrum. This also allows us to test the novel scenario of the initial single pion emission mechanism (ISPE)\(^15\).

The BESIII detector\(^16\) is a magnetic spectrometer located at the Beijing Electron Position Collider (BEPCII), which is a double-ring \( e^+e^- \) collider with a peak luminosity of \( 10^{33} \text{ cm}^{-2}\text{s}^{-1} \) at a center-of-mass energy of 3.773 GeV. The cylindrical core of the BESIII detector consists of a helium-based multi-layer drift chamber (MDC), a plastic scintillator time-of-flight system (TOF), and a CsI(Tl) electromagnetic calorimeter (EMC), which are all immersed in a superconducting solenoidal magnet providing a 1.0 T magnetic field. The solenoid is supported by an octagonal flux-return yoke with resistive plate counter muon identifier modules interleaved with steel. The acceptance of charged particles is 93% over \( 4\pi \) solid angle. The charged-particle momen-
tum resolution at 1 GeV/c is 0.5%, and the specific energy loss (\( dE/dx \)) resolution is 6%. The EMC measures photon energies with a resolution of 2.5% (5%) at 1 GeV in the barrel (end caps) region. The time resolution of TOF is 80 ps in the barrel and 110 ps in the end caps.

The GEANT4\(^17\) based Monte Carlo (MC) simulation software, which includes the geometric description of the BESIII detector and the detector response, is used to determine the detection efficiencies and estimate backgrounds. To simulate the \( e^+e^- \rightarrow \phi\pi\pi \) process, the lineshape reported by BaBar\(^18\) is adopted. Intermediate states in the simulation of \( e^+e^- \rightarrow \phi\pi\pi \) process are modeled according to the BESIII data as described later.

Candidate events of \( e^+e^- \rightarrow \phi\pi^+\pi^- \) \((\phi \rightarrow K^+K^-)\) are required to have three or four charged tracks. Charged tracks are reconstructed from hits in the MDC within the polar angle \(|\cos\theta| < 0.93\). The tracks are required to pass the interaction point within 10 cm along the beam direction and within 1 cm in the plane perpendicular to the beam. For each charged track, the TOF and the \( dE/dx \) information are combined to form particle identification (PID) confidence levels for the \( \pi, K, \) and \( p \) hypotheses, and the particle type with the highest confidence level is assigned to each track. Two pions with opposite charges and at least one kaon are required to be identified. A one-constraint (1C) kinematic fit is performed under the hypothesis that the \( K\pi^+\pi^- \) missing mass corresponds to the kaon mass, and the corresponding \( \chi^2 \), denoted as \( \chi^2_{1C}(\pi^+\pi^-KK_{\text{miss}}) \), is required to be less than 10. For events with two reconstructed and identified kaons, the combination with the smaller \( \chi^2_{1C}(\pi^+\pi^-KK_{\text{miss}}) \) is retained.

Candidate events of \( e^+e^- \rightarrow \phi\pi^0\pi^0 \) \((\phi \rightarrow K^+K^-, \pi^0 \rightarrow \gamma\gamma)\) are required to have one or two charged tracks and at least four photon candidates. Photon candidates are reconstructed from isolated showers in the EMC, and the corresponding energies are required to be at least 25 MeV in the barrel \((|\cos\theta| < 0.80)\) or 50 MeV in the end caps \((0.86 < |\cos\theta| < 0.92)\). To eliminate showers associated with charged particles, the angle between the cluster and the nearest charged track must be larger than 10 degrees. An EMC cluster timing requirement of \( 0 \leq t \leq 700 \) ns is also applied to suppress electronic noise and energy deposits unrelated to the event. At least one kaon is required to be identified. A 1C kinematic fit is then performed under the hypothesis that the \( K4\gamma \) missing mass is the kaon mass. For events with two identified kaons or more than four photons, the combination with the smallest \( \chi^2_{1C}(4\gamma KK_{\text{miss}}) \) is retained and required to be less than 20. The four selected photons are grouped into pairs to form \( \pi^0 \) mesons. Two \( \pi^0 \) candidates are then selected by minimizing the quantity \( M(\gamma\gamma_1-m_{\pi^0})^2 + M(\gamma\gamma_2-m_{\pi^0})^2 \), where \( m_{\pi^0} \) is the nomi-
nal $\pi^0$ mass from Particle Data Group (PDG) \cite{PDG}. In order to select a clean sample, both $M(\gamma\gamma_1)$ and $M(\gamma\gamma_2)$ are required to be within $\pm 20 \text{ MeV}/c^2$ of $m_{\phi}$.

After applying the above selection criteria, the $K^+K^-$ invariant mass, $M(K^+K^-)$, is computed using the four-momenta of the reconstructed $K$ and $K_{\text{miss}}$ from the kinematic fit. The $M(K^+K^-)$ spectra for the selected candidate events are shown in Figs. 1 (a) and (b), where $\phi$ signals are clearly seen. The Dalitz plots of the $\phi\pi^+\pi^-$ and $\phi\pi^0\pi^0$ events are shown in Figs. 2(a) and (b), respectively, where the $M(K^+K^-)$ is required to be in the $\phi$ mass range, $|M(K^+K^-) - m_{\phi}| < 0.01 \text{ GeV}/c^2$, and $m_{\phi}$ is the nominal $\phi$ mass from PDG \cite{PDG}. The apparent structures are from the decay processes $e^+e^- \rightarrow \phi f_0(980)$ with $f_0(980)$ decaying to $\pi^+\pi^-$ or $\pi^0\pi^0$ final states, which are also clearly indicated in the $\pi\pi$ invariant mass spectra, $M(\pi\pi)$, displayed in Figs. 2(c) and (d).

![Figure 1](data-url)  
Figure 1. Invariant mass distributions of $K^+K^-$ for (a) $e^+e^- \rightarrow K^+K^-\pi^+\pi^-$ and (b) $e^+e^- \rightarrow K^+K^-\pi^0\pi^0$ events. The dots with error bars are data, the solid lines are the fit results and the shaded parts are the combinatorial backgrounds obtained from fits.

The mass spectrum of a $\phi$ candidate paired with a low-momentum $\pi$ (denoted as $\pi_l$) is expected to be sensitive in searching for a $Z_s$ structure around 1.4 GeV/$c^2$. The invariant mass distributions for $\phi\pi_l^+$ and $\phi\pi_l^0$, $M(\phi\pi_l^0)$ and $M(\phi\pi_l^0)$, are shown in Fig. 3. There is no evidence of a structure around 1.4 GeV/$c^2$. In the determination of the yields of $Z_s$ production in $e^+e^- \rightarrow \phi\pi\pi$, the contributions from non-$\phi$ backgrounds are described by the events in the $\phi$ sideband regions, $0.995 < M(K^+K^-) < 1.005$ and $1.035 < M(K^+K^-) < 1.045 \text{ GeV}/c^2$, and are normalized according to the fitted intensities in Fig. 1. The $M(\pi\pi)$ distributions of $\phi$ sideband events are represented by the dotted lines in Figs. 2(c) and (d). Contributions from $pK^+K^-$ and $\omega K^+K^-$ are clearly seen in the $K^+K^+\pi^-\pi^-$ channel, while no obvious contribution is observed in the neutral process. In addition, $K^+(892)K^+\pi^\pm$ events also contaminate the charged process. The candidate events of $e^+e^- \rightarrow \phi\pi\pi$ dominantly come from the processes with intermediate states $f_0(980)$ and $\sigma$, as shown in Figs. 2(c) and (d).

To obtain the production yields of $Z_s$, a good description of data without the $Z_s$ signal is essential. Therefore, a partial wave analysis (PWA) of the $e^+e^- \rightarrow \phi\pi\pi$ candidate events is performed, since no obvious $Z_s$ structure is observed. A detailed description of the PWA procedure can be found in Ref. \cite{PWA}. In the fit, the $e^+e^- \rightarrow \phi\pi\pi$ process is described by four subprocesses: $e^+e^- \rightarrow \phi f_0(980)$, $\phi\sigma$, $\phi f_0(1370)$, and $\phi f_2(1270)$. The resonance parameters are fixed on the values determined in previous BES results \cite{BES1,BES2}. Non-

![Figure 2](data-url)  
Figure 2. Dalitz plots for (a) $e^+e^- \rightarrow \phi\pi^+\pi^-$ and (b) $e^+e^- \rightarrow \phi\pi^0\pi^0$ candidate events and invariant mass distributions of (c) $\pi^+\pi^-$ and (d) $\pi^0\pi^0$. The dots with error bars are data, the dotted histograms are non-$\phi$ backgrounds estimated from $\phi$ sidebands, and the solid histograms are the sum of the projections of the PWA results and non-$\phi$ backgrounds. Each $e^+e^- \rightarrow \phi\pi^0\pi^0$ event contributes two entries for (b).

![Figure 3](data-url)  
Figure 3. Invariant mass distributions of (a) $M(\phi\pi_l^0)$ and (b) $M(\phi\pi_l^0)$ for $\phi\pi\pi$ candidate events. The dots with error bars are data, the solid lines are the fit results with the numbers of $Z_s$ fixed to the upper limits at the 90$\%$ C.L., the histograms are the projections of the PWA results and non-$\phi$ backgrounds, the dotted lines are the MC simulated shapes, the dash-dotted lines are non-$\phi$ backgrounds (estimated from $\phi$ sidebands), and the shaded histograms are the $Z_s$ signal with the production rates fixed to the upper limits (three times for $\phi\pi^0$ to show the $Z_s$ peak clearly).
φ backgrounds estimated from the φ sidebands are represented by a non-interfering term. The projections of nominal PWA results on the $M(ππ)$ distributions are shown as the solid lines in Figs. 2 (c) and (d). Based on the nominal PWA results, a dedicated MC sample is generated, which is used to explore the $Z_s$ signal yields and estimate the detection efficiency.

Since no obvious $Z_s$ signal is observed, the upper limit on its production is determined. A series of unbinned maximum likelihood fits to the $M(φπ)$ distribution is performed by varying the number of $Z_s$ signal events. In each fit, the corresponding probability density function (PDF) is a linear combination of the $φπ$ component described by MC simulation based on the nominal PWA results, non-$φ$ backgrounds estimated from $φ$ sidebands, and a MC simulated $Z_s$ signal assuming $M(Z_s) = 1.4$ GeV/$c^2$ and $Γ(Z_s) = 0$. The resultant normalized likelihood values as a function of the number of $Z_s$ events are shown in Fig. 4. The upper limits $N^{UL}_s$ are the number of $Z_s$ events, $N(Z_s)$, corresponding to 90% of the area under the likelihood curves, and are determined to be 16.6 for $Z_s^0$ and 25.2 for $Z_s^1$ at the 90% confidence level (C.L.). The corresponding fit curves with the number of $Z_s$ signal fixed to $N^{UL}_s$ are displayed as the solid lines in Fig. 3. Additionally, we also determine the upper limits with the scenario of different width and mass of $Z_s$, i.e., $Γ(Z_s) = 5$ or 10 MeV and $M(Z_s) = 1.38$ or 1.42 GeV/$c^2$. The corresponding upper limits on the yields of $Z_s$ signal and the detection efficiencies obtained with the phase space distributed MC sample are summarized for the alternative cases in Table I. The correlated systematic uncertainties on the upper limit of $Z_s$ signal yields associated with the fit range, signal shape, $φ$ and $π^0$ mass window requirements, $φ$ sideband range, and the $φπ$ PWA model are considered by performing alternative fits and taking the maximum value of $N^{UL}_s$ as the upper limit, while the uncorrelated systematic uncertainties described in detail later are taken into account by smearing the likelihood curves.

The $e^+e^- → φπφ$ signal yields are obtained from extended unbinned maximum likelihood fits to the $M(K^+K^-)$ distributions. In the fit, the $φ$ peak is modeled as the signal MC simulated shape convoluted with a Gaussian function to account for the mass resolution difference between data and MC simulation, while the background is described by a second-order polynomial function. The fits to $M(K^+K^-)$ spectra, shown in Figs. 1 (a) and (b), yield $(9421 ± 138)$ $φπ^+π^−$ and $(1649 ± 60)$ $φπ^0π^0$ events. The detection efficiencies are $(52.7 ± 0.1)%$ and $(16.0 ± 0.1)%$, respectively, obtained from the signal MC samples generated according to the nominal PWA results. The cross sections for $e^+e^- → φπ^+π^−$ and $e^+e^- → φπ^0π^0$ are determined to be $(343.0 ± 5.1)$ pb and $(208.3 ± 7.6)$ pb, respectively.

Sources of systematic uncertainties and their corresponding contributions to the measurements of the cross sections are summarized in Table III. The uncertainties of the MDC tracking efficiency for each charged kaon and pion and the photon selection efficiency are studied with a control sample $e^+e^- → φπ^+π^−$ taken at the energy of 2.125 GeV and a control sample of $J/ψ → π^+π^−π^0$, respectively, and the differences between data and MC simulation are less than 1.5% per charged track and 1.0% per photon. Similarly, the uncertainties related to the pion and kaon PID efficiencies are also studied with the sample $e^+e^- → φπ^+π^−$ taken at the energy of 2.125 GeV, and the average differences of the

\[
s_{0,s}^{UL}(e^+e^- → Z_sπ, Z_s → φπ) = \frac{N_{UL}^{s0}}{L(1 + δ)ε},
\]
PIT efficiencies between data and MC simulation are determined to be 3% and 1% for each charged kaon and pion, respectively, which are taken as the systematic uncertainties.

Uncertainties associated with kinematic fits come from the inconsistency of the track helix parameters between data and MC simulation. The helix parameters for the charged tracks of MC samples are corrected to eliminate the inconsistency, as described in Ref. [24], and the agreement of $\chi^2$ distributions between data and MC simulation is much improved. We take half of the differences on the selection efficiencies with and without the correction as the systematic uncertainties, which are 2.1% for $\phi \pi^+\pi^-$ and 0.1% for $\phi \pi^0\pi^0$ channels, respectively. The difference of the selection efficiencies associated with the $\pi^0$ mass window requirement between data and MC simulation is estimated to be about 0.1%, which is taken as the systematic uncertainty for the mode $e^+e^- \rightarrow \phi \pi^0\pi^0$.

In the measurement of the cross section for $e^+e^- \rightarrow \phi \pi\pi$, the nominal fit range for $M(K^+K^-)$ is (0.99, 1.09) GeV/c$^2$. Alternative fits are performed by varying the fitting range. The maximum changes on the calculated cross sections are determined around the K$^*$ mass threshold (around 1.4 GeV/c$^2$) with different width hypotheses, as summarized in Table II. The results indicate the ISPE mechanism at K$^*$ threshold is not as significant as predicted in Ref. [15]. Further study with larger statistics is essential to examine the existence of $Z_\pi$ structure and test the ISPE mechanism.

In addition, the cross sections for $e^+e^- \rightarrow \phi \pi^+\pi^-$ and $e^+e^- \rightarrow \phi \pi^0\pi^0$ are determined to be $(343.0 \pm 5.1 \pm 25.1)$ pb and $(203.3 \pm 7.6 \pm 13.5)$ pb, respectively. The measured cross section for $e^+e^- \rightarrow \phi \pi^+\pi^-$ slightly differs from previous measurements from the BaBar [18] (510.50 \pm 21 pb at 2.1125 GeV) and Belle [25] (480 \pm 60 \pm 42 pb at 2.1125 GeV) experiments, but the measurements are still compatible within 3 standard deviations. The cross section for $e^+e^- \rightarrow \phi \pi^0\pi^0$ is consistent with BaBar’s measurement [18] (195 \pm 10 \pm 14 pb at 2.100 GeV) within uncertainties. For both measurements, the statistical uncertainties are reduced significantly.

The BESIII collaboration thanks the staff of BEPCII and the IHEP computing center for their strong support. This work is supported in part by National Key Basic Research Program of China under Contract No. 2015CB856700; National Natural Science Foundation of China (NSFC) under Contracts Nos. 11235011, 11425524, 11625523, 11635010, 11675184, 11735014; the Chinese Academy of Sciences (CAS) Large-Scale Scientific Facility Program; Shanghai Education Committee; the Chinese Academy of Sciences (CAS) Large-Scale Scientific Facility Program; Youth Science Foundation of China under Contract No. Y511BT005C; the CAS Center for Excellence in Particle Physics (CCEPP); Joint Large-Scale Scientific Facility Centers of the NSFC and CAS under Contracts Nos. U1332201, U1532257, U1532258; CAS under Contracts Nos. KJCX2-YW-N29, KJCX2-YW-N45, QYZDJ-SSW-SLH003; 100 Talents Program of CAS; National Talents Program of China; INPAC and Shanghai Key Laboratory for Particle Physics and Cosmology; German Research Foundation DFG under Contracts Nos. Collaborative Research

| Source                  | $Z_\pi^+$ | $Z_\pi^-$ | $Z_\pi^0$ | $Z_\pi^\pi^0$ |
|-------------------------|----------|----------|----------|----------------|
| MDC tracking            | 4.5      | 4.5      | 1.5      | 1.5            |
| Photon detection        | ...      | ...      | 4        | 4              |
| K PID                   | 3        | 3        | 3        | 3              |
| $\pi$ PID               | 2        | 2        | ...      | ...            |
| Kinematic fit           | 2.1      | 2.1      | 0.1      | 0.1            |
| $\pi^0$ mass window     | ...      | ...      | 0.1      | 0.1            |
| Fitting range           | 0.1      | 0.1      | ...      | ...            |
| Signal shape            | 1.3      | ...      | 2.2      |                |
| Background shape        | 1.3      | ...      | 2.0      |                |
| Model uncertainty       | 0.8      | ...      | 1.3      |                |
| Branching fractions     | 1.1      | 1.1      | 1.1      | 1.1            |
| Integrated luminosity   | 0.7      | 0.7      | 0.7      | 0.7            |
| ISR                     | 3.1      | 3.1      | 1.2      | 1.2            |
| Total                   | 7.0      | 7.3      | 5.5      | 6.5            |
Center CRC 1044, FOR 2359; Istituto Nazionale di Fisica Nucleare, Italy; Koninklijke Nederlandse Akademie van Wetenschappen (KNAW) under Contract No. 530-4CDP03; Ministry of Development of Turkey under Contract No. DPT2006K-120470; National Natural Science Foundation of China (NSFC) under Contracts Nos. 11505034, 11575077; National Science and Technology fund; The Swedish Research Council; U. S. Department of Energy under Contracts Nos. DE-FG02-05ER41374, DE-SC-0010118, DE-SC-0010504, DE-SC-0012069; University of Groningen (RuG) and the Helmholtzzentrum fuer Schwerionenforschung GmbH (GSI), Darmstadt; WCU Program of National Research Foundation of Korea under Contract No. R32-2008-000-10155-0.

[1] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. 110, 252001 (2013).
[2] Z. Q. Liu et al. (Belle Collaboration), Phys. Rev. Lett. 110, 252002 (2013).
[3] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. 111, 242001 (2013).
[4] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. 112, 132001 (2014).
[5] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. 112, 022001 (2014).
[6] K. Chilikin et al. (Belle Collaboration), Phys. Rev. D 90, 112009 (2014).
[7] A. Roel et al. (LHCb Collaboration), Phys. Rev. Lett. 112, 222002 (2014).
[8] L. Maiani, V. Riquer, R. Faccini, F. Piccinini, A. Pilloni, and A. D. Polosa, Phys. Rev. D 87, 111102 (2013).
[9] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. 115, 112003 (2015).
[10] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. 113, 212002 (2014).
[11] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. 115, 182002 (2015).
[12] G. J. Ding and M. L. Yan, Phys. Lett. B 650, 390 (2007).
[13] S. Okubo, Phys. Lett. 5, 165 (1963); G. Zweig, CERN Report No. 8419/TH412, 1964; J. Iizuka, Prog. Theor. Phys. Suppl. 37, 21 (1966).
[14] M. Ablikim et al. (BESIII Collaboration), Chin. Phys. C 41, 113001 (2017).
[15] D. Y. Chen, X. Liu, and T. Matsuki, Eur. Phys. J. C 72, 2008 (2012).
[16] M. Ablikim et al. (BESIII Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 614, 345 (2010).
[17] S. Agostinelli et al., Nucl. Instrum. Methods Phys. Res., Sect. A 506, 250 (2003).
[18] J. P. Lees et al. (BaBar Collaboration), Phys. Rev. D 86, 012008 (2012).
[19] C. Patrignani et al. (Particle Data Group), Chin. Phys. C 40, 100001 (2016).
[20] B. S. Zou and D. V. Bugg, Eur. Phys. J. A 16, 537 (2003).
[21] M. Ablikim et al. (BES Collaboration), Phys. Lett. B 607, 243 (2005).
[22] M. Ablikim et al. (BES Collaboration), Phys. Lett. B 598, 149 (2004).
[23] E. A. Kuraev and V. S. Fadin, Yad. Fiz. 41, 733 (1985) [Sov. J. Nucl. Phys. 41, 466 (1985)]; R. G. Ping, Chin. Phys. C 38, 083001 (2014).
[24] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. D 87, 012002 (2013).
[25] C. P. Shen et al. (Belle Collaboration), Phys. Rev. D 80, 031101 (2009).