


## Search for a strangeonium-like structure $Z_s$ decaying into $\phi\pi$ and a measurement of the cross section $e^+e^- \rightarrow \phi\pi\pi$

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Using a data sample of  $e^+e^-$  collision data corresponding to an integrated luminosity of  $108 \text{ pb}^{-1}$  collected with the BESIII detector at a center-of-mass energy of 2.125 GeV, we study the process  $e^+e^- \rightarrow \phi\pi\pi$  and search for a strangeoniumlike structure  $Z_s$  decaying into  $\phi\pi$ . No signal is observed in the  $\phi\pi$  mass spectrum. Upper limits on the cross sections for  $Z_s$  production at the 90% confidence level are determined. In addition, the cross sections of  $e^+e^- \rightarrow \phi\pi^+\pi^-$  and  $e^+e^- \rightarrow \phi\pi^0\pi^0$  at 2.125 GeV are measured to be  $(436.2 \pm 6.4 \pm 30.1) \text{ pb}$  and  $(237.0 \pm 8.6 \pm 15.4) \text{ pb}$ , respectively, where the first uncertainties are statistical and the second systematic.

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A charged charmoniumlike structure,  $Z_c(3900)$ , was observed in the  $\pi^\pm J/\psi$  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 the reasonable interpretations are tetraquark states, molecular or hadroquarkonium

states [8–14], due to these structures carrying charge and prominently decaying into a pion and a conventional charmonium state. More recently, the neutral partners of these charmoniumlike structures were observed [15–18], 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 an  $s\bar{s}$ , 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  $\phi(2170) \rightarrow \phi\pi^+\pi^-$  is considered as a unique place to search for the  $Z_s$  structure, as the  $\phi(2170)$  is regarded as the strangeoniumlike states analogy to  $Y(4260)$  in charmonium sector [19]. 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 [20]. Therefore, it is of interest to perform an experimental search for the strangeoniumlike structure  $Z_s$  since its observation may imply the existence of an exotic state.

In this article, 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  $(108.49 \pm 0.75) \text{ pb}^{-1}$  [21], taken at a center-of-mass energy of 2.125 GeV with the BESIII detector. Since the observed  $Z_c(3900)$  [1,2] and  $Z_c(3885)$  [5] are close to the  $D^*\bar{D}$  mass threshold and have a narrow width, 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 allows us to test the novel scenario of the initial single pion emission mechanism (ISPE) [22].

The BESIII detector [23] is a magnetic spectrometer located at the Beijing Electron Position Collider (BEPCII), which is a double-ring  $e^+e^-$  collider with a peak luminosity

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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 multilayer drift chamber (MDC), a plastic scintillator time-of-flight system (TOF), and a CsI (TI) 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 (MUC) modules interleaved with steel. The acceptance of charged particles is 93% over  $4\pi$  solid angle. The charged-particle momentum 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 position resolution in the MUC is better than 2 cm.

The GEANT4-based [24] 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 line-shape reported by *BABAR* [25] 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 range  $|\cos\theta| < 0.93$ . 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 (C.L.) for the  $\pi$ ,  $K$ , and  $p$  hypotheses, and the particle type with the highest C.L. 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

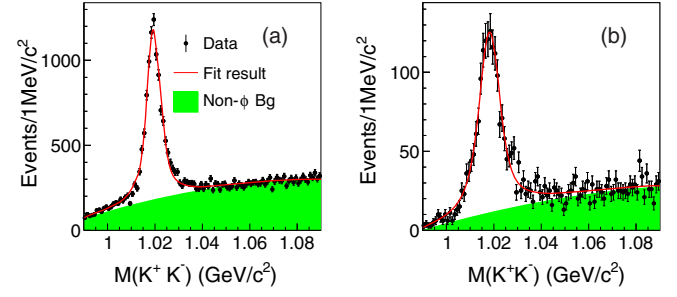


FIG. 1. Invariant mass distributions of  $K^+K^-$  for (a)  $e^+e^- \rightarrow K^+K^-\pi^+\pi^-$  and (b)  $e^+e^- \rightarrow K^+K^-\pi^0\pi^0$  events. The dots with error bars are data, the solid lines are the fit results and the shaded parts are the combinatorial backgrounds obtained from fits.

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 nominal  $\pi^0$  mass from Particle Data Group (PDG) [26]. In order to select a clean sample, both  $M(\gamma\gamma)_1$  and  $M(\gamma\gamma)_2$  are required to be within  $\pm 20$  MeV/c<sup>2</sup> of  $m_{\pi^0}$ .

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 1(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 2(b), respectively, where the  $M(K^+K^-)$  is required to be in the  $\phi$  mass range,  $|M(K^+K^-) - m_\phi| < 0.01$  GeV/c<sup>2</sup>, and  $m_\phi$  is the nominal  $\phi$  mass from PDG [26]. 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 2(d). There is a clear structure around  $\rho$  mass region in the  $\pi\pi$  mass spectrum in the  $K^+K^-\pi^+\pi^-$  channel. In addition,  $K^*(892)K^\mp\pi^\pm$  events also contaminate the charged process. The contributions from those non- $\phi$  backgrounds are described by the events in the  $\phi$  sideband regions,  $0.995 < M(K^+K^-) < 1.005$  and  $1.035 < M(K^+K^-) < 1.045$  GeV/c<sup>2</sup>, 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 2(d).

The mass spectra of the  $\phi$  candidate paired with  $\pi$  are shown in Fig. 3. There is no evidence of structures in the entire  $\phi\pi$  region. To describe the  $M(\pi\pi)$  spectrum, an amplitude analysis on  $e^+e^- \rightarrow \phi\pi\pi$  is performed using the relativistic covariant tensor amplitude method [27].

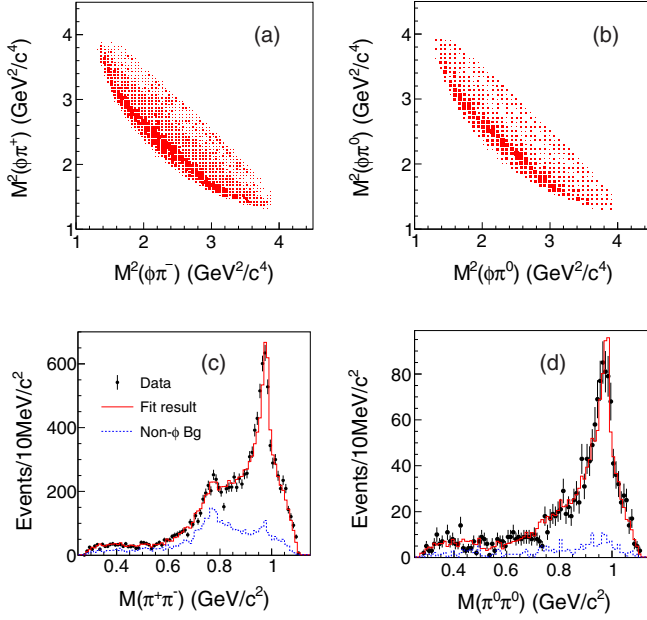


FIG. 2. Dalitz plots for (a)  $e^+e^- \rightarrow \phi\pi^+\pi^-$  and (b)  $e^+e^- \rightarrow \phi\pi^0\pi^0$  candidate events and invariant mass distributions of (c)  $\pi^+\pi^-$  and (d)  $\pi^0\pi^0$ . The dots with error bars are data, the dotted histograms are non- $\phi$  backgrounds estimated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

The  $e^+e^- \rightarrow \phi\pi\pi$  process can be described by four subprocesses:  $e^+e^- \rightarrow \phi\sigma$ ,  $\phi f_0(980)$ ,  $\phi f_0(1370)$ , and  $\phi f_2(1270)$ .  $\sigma$  is described with the form used fitting  $\pi\pi$  elastic scattering data [28],  $f_0(980)$  is described with a Flatté formula [29], and others are described with relativistic Breit-Winger (BW) function. The resonance parameters are fixed on the values determined in previous BES results [30,31]. Non- $\phi$  backgrounds estimated from the  $\phi$

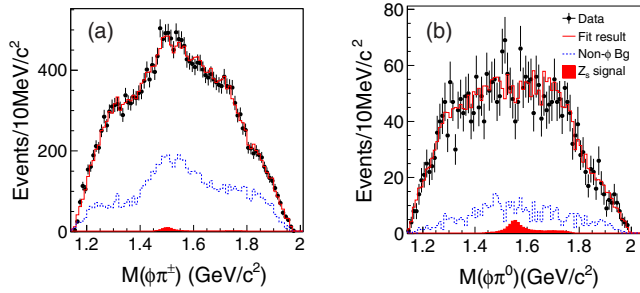


FIG. 3. Invariant mass distributions of (a)  $M(\phi\pi^\pm)$  and (b)  $M(\phi\pi^0)$  for  $\phi\pi\pi$  candidate events. The dots with error bars are data, the solid histograms are the projections of the amplitude analysis results including the contributions from  $Z_s \rightarrow \phi\pi$  process with the mass and width of  $Z_s^\pm$  ( $Z_s^0$ ) assumed to be 1.5 (1.55)  $\text{GeV}/c^2$  and 50 MeV for the case of  $J^P = 1^+$ , the dashed histograms are non- $\phi$  backgrounds, and the shaded histograms are the  $Z_s$  signal.

sidebands are represented by a non-interfering term. The projections of nominal amplitude analysis results on the  $M(\pi\pi)$  distributions are shown as the solid lines in Figs. 2(c) and 2(d). The comparisons of angular distributions between data and the amplitude analysis projections for these two interested processes are also displayed in Fig. 4. To illustrate the fit quality, we present a  $\chi^2$  test for each distribution ( $\chi^2/\text{nbin}$ ), where nbin is the number of bins. In general the values of  $\chi^2/\text{nbin}$  are around 1, which indicates that the amplitude analysis results provide a reasonable description of data.

To estimate the statistical significance for each component, alternative fits by excluding the corresponding amplitude are performed. The statistical significance is then determined by the changes of the log likelihood values and the number of degrees of freedom. The statistical significances of all these states are found to be larger than  $5\sigma$ . A full partial wave analysis of  $e^+e^- \rightarrow K^+K^-\pi^+\pi^-$  is in progress with more statistics taken at different energy points around  $Y(2175)$  at BESIII, in which detailed results will be presented.

With a hypothesis of  $J^P = 1^+$ , the contribution of  $Z_s$  is examined by introducing an additional component in the amplitude analysis. To simplify the analysis, we neglect the D-wave and assume that the contribution is only from the S-wave amplitude. The  $Z_s$  is parameterized as a relativistic BW function in the  $\phi\pi$  system. As the mass and width of the state are unknown, we have tested signals with masses of 1.2–1.95  $\text{GeV}/c^2$  in steps of 0.05  $\text{GeV}/c^2$ . For the width, values of 10, 20, and 50 MeV are combined with each mass. With these different signal hypotheses, we performed the fit to data and found, in general, that the observed statistical significances are less than  $3\sigma$  in the explored region. For  $e^+e^- \rightarrow \phi\pi^+\pi^-$ , the maximum local significance is  $2.7\sigma$  in the case of  $M(Z_s^\pm) = 1.5 \text{ GeV}/c^2$  and  $\Gamma(Z_s^\pm) = 50 \text{ MeV}$ , which becomes to be  $2.1\sigma$  after taking the systematic uncertainty into account, and the signal yields are determined to be  $46.9 \pm 21.6$ . While for  $e^+e^- \rightarrow \phi\pi^0\pi^0$ , the maximum local significance is  $3.3\sigma$  in the case of  $M(Z_s^0) = 1.55 \text{ GeV}/c^2$  and  $\Gamma(Z_s^0) = 50 \text{ MeV}$ , which becomes to be  $2.8\sigma$  after taking the systematic uncertainty into account, and the signal yields are determined to be  $25.2 \pm 8.9$ . The corresponding projections of the amplitude analysis results on  $M(\phi\pi^\pm)$  and  $M(\phi\pi^0)$  are shown in Figs. 3(a) and 3(b), respectively.

In the determination of the upper limits on the number of  $Z_s$  ( $N_s^{\text{UL}}$ ) for different scenarios, the same approach as that in Ref. [32] is used. For each case, the statistical uncertainty is used to determine the 90% C.L. deviation, and added to the nominal yields to obtain the corresponding upper limit on the number of  $Z_s$  signals.

The systematic uncertainties on the upper limit of  $Z_s$  signal yields associated with  $\phi$  sideband range and the nominal  $\phi\pi\pi$  model, estimated by varying the resonance parameters or replacing the  $f_0(1370)$  component with a

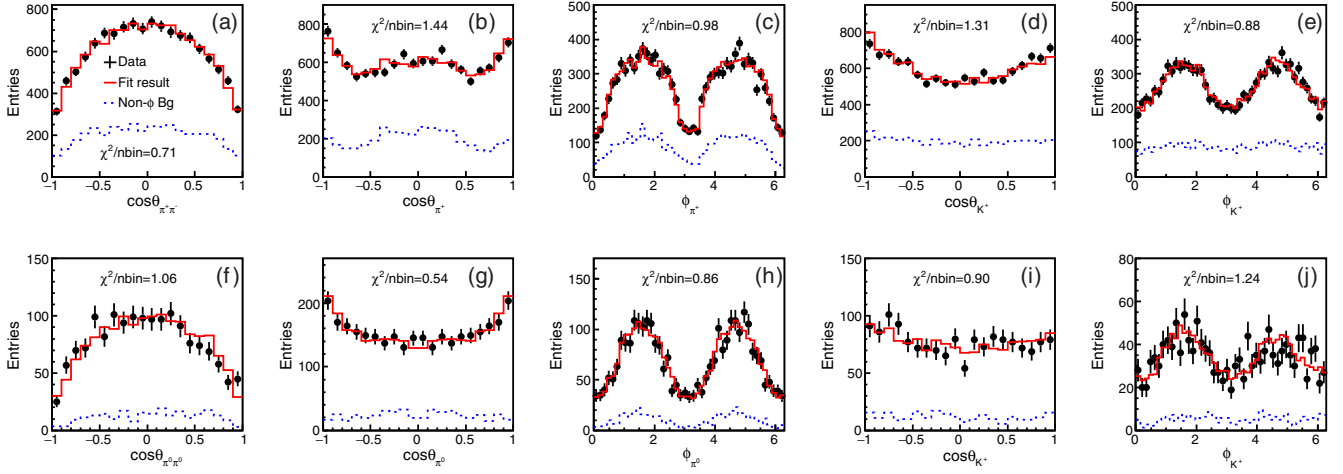


FIG. 4. Angular distributions for  $e^+e^- \rightarrow \phi\pi^+\pi^-$  (a–e) and  $e^+e^- \rightarrow \phi\pi^0\pi^0$  (f–j). For (g) and (h), there are two entries for each event due to the two identical  $\pi^0$ s in  $e^+e^- \rightarrow \phi\pi^0\pi^0$  process. The dots with error bars are data, the dotted histograms are non- $\phi$  backgrounds estimated from  $\phi$  sidebands, and the solid histograms are the sum of the backgrounds and the fit projections.  $\cos\theta_{\pi\pi}$  is the polar angle of  $\pi\pi$  in the rest frame of  $e^+e^-$  annihilation,  $\cos\theta_\pi$  ( $\cos\theta_K$ ) and  $\phi_\pi$  ( $\phi_K$ ) are the polar angle and azimuthal angle of  $\pi$  ( $K^+$ ) in the  $\pi\pi$  ( $K^+K^-$ ) system.

phase space process, are considered by performing alternative fits and taking the maximum value of  $N^{\text{UL}}$  as the upper limit, while the other systematic uncertainties are taken into account by dividing the factor  $(1 - \delta_{\text{sys}})$ , where  $\delta_{\text{sys}}$  is total systematic uncertainties, described in detail later. With the detection efficiency obtained from the dedicated MC simulation for each  $Z_s$  hypothesis, the upper limit on the cross section is calculated with

$$\sigma_{Z_s}^{\text{UL}}(e^+e^- \rightarrow Z_s\pi, Z_s \rightarrow \phi\pi) = \frac{N^{\text{UL}}}{\mathcal{L}(1 + \delta)(1 - \delta_{\text{sys}})\epsilon\mathcal{B}}, \quad (1)$$

where  $\mathcal{L}$  is the integrated luminosity of the data taken at 2.125 GeV, and determined to be  $(108.49 \pm 0.75) \text{ pb}^{-1}$  [21] from large-angle Bhabha scattering events;  $(1 + \delta)$  is a radiative correction factor calculated to the second-order in QED [33] by assuming that the line shape follows the measured cross section of the BABAR experiment [25], determined as 0.982 and 0.986 for the  $e^+e^- \rightarrow \phi\pi^+\pi^-$  and  $\phi\pi^0\pi^0$  channels, respectively;  $\epsilon$  is the detection efficiency; and  $\mathcal{B}$  is either  $\mathcal{B}(\phi \rightarrow K^+K^-)$  for  $\phi\pi^+\pi^-$  or  $\mathcal{B}(\phi \rightarrow K^+K^-) \times \mathcal{B}^2(\pi^0 \rightarrow \gamma\gamma)$  for  $\phi\pi^0\pi^0$  [26]. The corresponding upper limits on the differential cross sections of  $Z_s$  production as a function of the assumed mass of  $Z_s$  with different width scenario are shown in Figs. 5(a) and 5(b).

In addition, we performed the alternative amplitude analysis by assuming  $J^P = 1^-$  to explore the  $Z_s$  contribution to the data. With the same approach as described above, the upper limits on the differential cross sections of  $Z_s$  production as a function of the assumed mass of  $Z_s$  with different width scenario are also estimated at 90% C.L., which are displayed in Figs. 5(c) and 5(d).

The  $e^+e^- \rightarrow \phi\pi\pi$  signal yields are obtained from extended unbinned maximum likelihood fits to the  $M(K^+K^-)$  distributions. In the fit, the  $\phi$  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 1(b), yield  $(9421 \pm 138) \phi\pi^+\pi^-$  and  $(1649 \pm 60)$

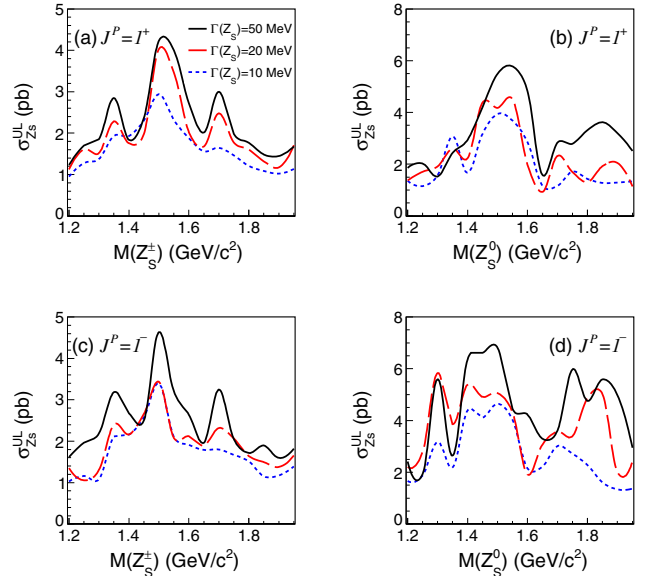


FIG. 5. The upper limits at 90% C.L. on the differential cross sections of  $Z_s$  as a function of assumed signal peak mass for the cases (a)  $J^P = 1^+$  of  $Z_s^\pm$ , (b)  $J^P = 1^+$  of  $Z_s^0$ , (c)  $J^P = 1^-$  of  $Z_s^\pm$ , and (d)  $J^P = 1^-$  of  $Z_s^0$ . The dotted, dashed and solid lines are the results of  $\Gamma = 10, 20,$  and  $50$  MeV, respectively.



TABLE I. Systematic uncertainties (in %) for the measurements of the upper limits (uncorrelated ones) and cross sections. Assuming the uncertainties are uncorrelated, the total uncertainty is the quadratic sum of the individual values.

Source	$Z_s^\pm$	$\phi\pi^+\pi^-$	$Z_s^0$	$\phi\pi^0\pi^0$
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
$K^+K^-$ mass window	1.5	...	1.5	...
Fitting range	...	0.1	...	1.4
Signal shape	...	1.5	...	2.3
Background shape	...	1.3	...	2.0
Model uncertainty	...	0.8	...	1.3
Branching fractions	1.0	1.0	1.0	1.0
Integrated luminosity	0.7	0.7	0.7	0.7
ISR	1.0	1.0	0.7	0.7
Total	6.5	6.9	5.6	6.5

$\phi\pi^0\pi^0$  events. The detection efficiencies are  $(41.2 \pm 0.1)\%$  and  $(13.7 \pm 0.1)\%$ , respectively, obtained from the signal MC samples generated according to the nominal amplitude analysis results. The cross sections for  $e^+e^- \rightarrow \phi\pi^+\pi^-$  and  $e^+e^- \rightarrow \phi\pi^0\pi^0$  are determined to be  $(436.2 \pm 6.4)$  pb and  $(237.0 \pm 8.6)$  pb, respectively.

Sources of systematic uncertainties and their corresponding contributions to the measurements of the cross sections are summarized in Table I. The uncertainties of the MDC tracking efficiency for each charged kaon and pion and the photon selection efficiency are studied with a control sample  $e^+e^- \rightarrow K^+K^-\pi^+\pi^-$  taken at the energy of 2.125 GeV and a control sample of  $e^+e^- \rightarrow \pi^+\pi^-\pi^0$  taken at the energy of 3.097 GeV, 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  $e^+e^- \rightarrow K^+K^-\pi^+\pi^-$ , and the average differences of the PID 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. [34], 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  $e^+e^- \rightarrow \phi\pi^0\pi^0$ . The systematic uncertainty on the  $Z_s$  production associated with the  $M(K^+K^-)$  mass window is estimated by alternative fits varying the cut by  $1\sigma$  and found to be 1.5%.

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 assigned as the uncertainties from the fitting range. The uncertainties associated with the background shape in the fits to  $M(K^+K^-)$  are estimated with alternative fits by changing the second-order polynomial function to a third-order Chebychev polynomial function. Alternative fits to  $M(K^+K^-)$  are performed by removing the smeared resolution function to estimate the uncertainties associated with the  $\phi$  signal shape. The resultant differences are assigned as the systematic uncertainties. In the amplitude analysis, alternative fits are performed by varying the parameters of resonances according to the previous BES results [30,31] or replacing the component of  $f_0(1370)$  intermediate state with a phase space process with  $J^{PC} = 0^{++}$ . The model with the maximum changes on the log-likelihood values are used to estimate the systematic uncertainties associated with the model.

The branching fractions of the intermediate processes  $\phi \rightarrow K^+K^-$  [ $(49.2 \pm 0.5)\%$ ] and  $\pi^0 \rightarrow \gamma\gamma$  [ $(98.823 \pm 0.034)\%$ ] are taken from the PDG [26], where the overall uncertainty, 1.0%, is taken as the systematic uncertainty. The luminosity is determined to be  $(108.49 \pm 0.75)$  pb $^{-1}$  in Ref. [21] with an uncertainty of 0.7%. Uncertainties in the  $Y(2125)$  resonance parameters and possible distortions of the  $Y(2125)$  line shape introduce small systematic uncertainties in the radiative correction factor and the efficiency. This is estimated using the different line shapes measured by *BABAR* and *Belle*, and the difference in  $(1 + \delta) \cdot \epsilon$  are taken as a systematic error, 1.0% for  $e^+e^- \rightarrow \phi\pi^+\pi^-$  and 0.7% for  $e^+e^- \rightarrow \phi\pi^0\pi^0$ , respectively.

In summary, a search for a strangeoniumlike structure,  $Z_s$ , in the process  $e^+e^- \rightarrow \phi\pi\pi$  is performed using 108 pb $^{-1}$  of data collected with the BESIII detector at 2.125 GeV. No  $Z_s$  signal is observed in the  $\phi\pi$  invariant mass spectrum, and corresponding upper limits on the cross sections of  $Z_s$  production at the 90% C.L. are determined for different mass and width hypotheses, as displayed in Fig. 5. The results around 1.4 GeV/ $c^2$  indicate the ISPE mechanism at  $K^*\bar{K}$  threshold is not as significant as predicted in Ref. [22]. Further study with larger statistics is essential to examine the existence of the  $Z_s$  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  $(436.2 \pm 6.4 \pm 30.1)$  pb and  $(237.0 \pm 8.6 \pm 15.4)$  pb, respectively. The measured cross sections are consistent with previous

measurements from the *BABAR* ( $510 \pm 50 \pm 21$  pb at 2.1125 GeV for  $e^+e^- \rightarrow \phi\pi^+\pi^-$  and  $195 \pm 50 \pm 14$  pb at 2.100 GeV for  $e^+e^- \rightarrow \phi\pi^0\pi^0$ ) [25] and Belle experiments ( $480 \pm 60 \pm 42$  pb at 2.1125 GeV for  $e^+e^- \rightarrow \phi\pi^+\pi^-$ ) [35] within uncertainties. For both measurements, the statistical uncertainties are reduced significantly.

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