Evidence for a neutral near-threshold structure in the $K^0_S D^+_s D^-$ and $e^+e^- \rightarrow K^0_S D^+_s D^-$ capture processes in the $K^0_S D^+_s D^-$ decay.
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Extensive evidence exists for several non-strange hidden-charm tetraquark \( Z_c \) candidates, with quark constituent of \( c\bar{c}q\bar{q} \) \((q^{(*)} = u \text{ or } d)\) [1–4]. In electron-positron annihilation, both charged and neutral \( Z_c(3900) \) and \( Z_c(4020) \) states have been observed by the BESIII, Belle and CLEO collaborations [5–15]. Under SU(3) flavor symmetry, one expects the existence of corresponding strange partners with \( c\bar{s}q\bar{q} \) configurations, denoted as \( Z_{cs} \) states [16]. These \( Z_{cs} \) states are predicted to have masses close to the \( D_s^0D^* \) and \( D_s^*D \) thresholds in a variety models explaining their
nature, including the tetraquark scenario \[17, 18\], the molecular model \[19\], the hadron-quarkonium model \[18\], and the initial-single-chiral-particle-emission mechanism \[20\].

The charged-tetraquark candidate \(Z_{cs}(3985)\) \[1\] was observed at BESIII in the \(D_s^+ \bar{D}^0\) and \(D_s^+ \bar{D}^0\) final states \[22–26\]. The mass of the \(Z_{cs}(3985)\) is close to the \(D_s^+ \bar{D}^0\) and \(D_s^+ \bar{D}^0\) thresholds, which is consistent with theoretical predictions \[17–20\]. Meanwhile, another charged-tetraquark candidate, \(Z_{cs}(4000)\) \[27\], was observed in the \(J/\psi K^+\) final states in an amplitude analysis of the decay \(B^+ \to J/\psi \phi K^+\) at LHCb. However, the widths of these two \(Z_{cs}\) states are inconsistent with each other. The observation of these charged \(Z_{cs}\) states motivates a search for a neutral isospin partner \(Z_{cs}^0\). The mass of the \(Z_{cs}^0\) is expected to be heavier than that of the \(Z_{cs}^+\) by \((0.05 \pm 0.21)\) GeV/\(c^2\) under the molecular hypothesis, or by \((0.06 \pm 0.12)\) GeV/\(c^2\) under the tetraquark hypothesis \[23\]. A promising approach to this challenge at BESIII is to search for the process \(e^+e^- \to K^0 Z_{cs}(3985)^0 + \text{c.c.}\) and then compare its cross section to that of \(e^+e^- \to K^- Z_{cs}(3985)^+ + \text{c.c.}\), which tests the isospin symmetry in the production and decay dynamics. A similar strategy was pursued in the analysis of the \(Z_{cs}\) charged and neutral states \[10, 11\]. Observation and study of the \(Z_{cs}^0\) is crucial for understanding the nature of the \(Z_{cs}\) states.

In this letter, we study the processes \(e^+e^- \to K_S^0 D_s^+ D^*-\) and \(e^+e^- \to K_S^0 D_{s}^{*+} D^-\), which is denoted as \(e^+e^- \to K_S^0 (D_s^+ D^*^- + D_{s}^{*+} D^-)\) in the context, as well as their charge conjugated modes, using \(e^+e^-\) collision data sets corresponding to an integrated luminosity of 3.8 fb\(^{-1}\) \[28\] at center-of-mass energies \(\sqrt{s} = 4.628\), 4.641, 4.661, 4.682 and 4.699 GeV \[28\]. These samples were collected by the BESIII detector at the Beijing Electron Positron Collider (BEPCII). Detailed information about BEPCII and BESIII can be found in Refs. \[29–31\]. We use a partial reconstruction technique to maximize the detection efficiency; only the \(K_S^0\) produced in association with the \(D_s^+ D^*^-\) or \(D_{s}^{*+} D^-\) (the bachelor \(K_S^0\)) and one of the ground-state D mesons (here D subsequently denotes \(D_s^+\) or \(D^-\)) are detected, while the other final-state particles are not reconstructed. The \(Z_{cs}^0\) candidate is then searched for in the invariant mass distribution recoiling against the bachelor \(K_S^0\) candidate. Charge conjugation is implied throughout the discussion.

Simulated samples produced with a GEANT4-based \[32\] Monte Carlo (MC) package, which includes the geometric description of the BESIII detector and the detector response, are used to determine the detection efficiency and to understand the backgrounds. The \(e^+e^-\) annihilations are simulated with the KKMC \[33\] generator, which includes the effects of the beam-energy spread and initial-state radiation (ISR). The inclusive MC sample consists of the production of open-charm hadronic systems, ISR production of vector charmonium-(like) states, and continuum processes incorporated in KKMC \[33\]. The known decay modes are modelled with EVTGEN \[34\] using branching fractions reported by the Particle Data Group (PDG) \[2\], and the remaining unknown decays from charmonium states are modelled with LUNDCHARM \[36\]. The final-state radiation (FSR) from charged final-state particles is simulated with the PHOTOS package \[37\]. For the non-resonant three-body signal processes \(e^+e^- \to K_S^0 (D_s^+ D^*^- + D_{s}^{*+} D^-)\), the momenta distributions of final-state particles are generated following phase space. For the resonant signal process \(e^+e^- \to K_S^0 Z_{cs}^0 \to K_S^0 (D_s^+ D^*^- + D_{s}^{*+} D^-)\), we assume that the \(Z_{cs}^0\) state has a spin-parity of \(1^+\), which corresponds to S-waves in both of the decays \(e^+e^- \to K_S^0 Z_{cs}^0\) and \(Z_{cs}^0 \to D_s^+ D^*^- + D_{s}^{*+} D^-\), which we denote as \((S, S)\). The corresponding angular distribution is taken into account in simulating the cascade decays. Other possibilities for the \(Z_{cs}^0\) spin-parity are tested to evaluate the systematic uncertainty related to this assumption.

We carry out two types of partial reconstruction, which are referred as the \(D_s^+\)-tag and \(D^-\)-tag methods, respectively. For \(D_s^+(D^-)-\)tag method, only the bachelor \(K_S^0\) and \(D_s^+(D^-)\) candidates are reconstructed. We use the decay modes \(D_s^+ \to K_s^+ K^-\pi^+\), \(K_S^0 K^+ K^-\pi^0\), \(K_S^0 K^+\pi^+\pi^-\) and \(K_S^0 \pi^0\) to form the \(D_s^+\) candidates; and the decay modes \(D^- \to K^+\pi^-\pi^+\), \(K_S^0 \pi^-\pi^+\) and \(K_S^0 \pi^0\) to form the \(D^-\) candidates.

To ensure that each charged track, which is not associated to \(K_S^0\) detection, originates from the \(e^+e^-\) interaction point (IP), \(|V_e| < 1\) cm and \(|V_\pi| < 10\) cm are required. Here, \(|V_e|\) is the distance between the charged track and the beam axis in the transverse plane, and \(|V_\pi|\) is the closest distance of the charged track to the IP along the axis of beam. The polar angles of charged tracks are required to satisfy \(|\cos\theta| < 0.93\). The flight time in the time-of-flight system and the energy deposited in the multilayer drift chamber for each charged track are used to identify particles by calculating the probabilities \(P(i)\), where \(i\) denotes \(K\) or \(\pi\). We require \(P(K) (P(\pi))\) to be greater than \(P(\pi) (P(K))\) to classify a particle as a kaon (pion) candidate.

The \(K_S^0\) candidates are reconstructed through the \(\pi^+\pi^-\) decay mode without particle identification requirements. Both pions must satisfy \(|V_\pi| < 20\) cm, and \(|\cos\theta| < 0.93\) and their trajectories are constrained to originate from a common vertex by applying a vertex fit, the \(\chi^2\) of which is required to be less than 100. The \(K_S^0\) candidate is then formed and the opposite direction of its momentum is constrained to point at the IP, with the corresponding \(\chi^2\) required to be less than 40. The decay length of \(K_S^0\) candidate must be greater than two standard deviations of the vertex resolution away from the IP. The invariant mass of \(\pi^+\pi^-\) pair, \(M(\pi^+\pi^-)\), is required to be within \((0.492, 0.503)\) GeV/\(c^2\).

The \(\pi^0\) and \(\eta\) candidates are reconstructed through \(\pi^0/\eta \to \gamma\gamma\). The photon showers in the electromagnetic
FIG. 1. Invariant-mass distributions of the singly tagged $D_+^*$ (a) and $D^-$ (b), together with the fits to the recoil-mass distributions $RQ(K_S^0 D_+^*)$ (c) and $RQ(K_S^0 D^-)$ (d) at 4.682 GeV. The points with error bars are data. The blue-dashed lines show the fit results of the sideband regions, which are denoted by the red arrows. The histograms show the distributions from the non-resonant signal MC samples, which are scaled according to the yields of $D^{*-}$ and $D_+^{*+}$. The orange arrows indicate the signal regions of the $D^{*-}$ in (c) and $D_+^{*+}$ in (d).

TABLE I. Summary of the cuts applied to the $D_+^*$ and $D^-$ decay modes for the combinatorial background suppression. Here $M$ denotes the reconstructed invariant mass and $m$ the known mass.

| Final state | Requirement |
|-------------|-------------|
| $D_+^* \rightarrow K^+ K^- \pi^+$ | $M(K^+ K^-) < 1.05$ GeV/$c^2$ |
| $D_+^* \rightarrow K^+ K^- \pi^+ \pi^0$ | $M(K^+ K^-) < 1.05$ GeV/$c^2$ |
| $D_+^* \rightarrow K_S^0 K^+\pi^- \pi^-$ | $|M(K^+ K^-) - m(K^{*+}(892))| < 1.5$ GeV/$c^2$ |
| $D^* \rightarrow K_S^0 K^+\pi^- \pi^-$ | $|M(K^+ K^-) - m(K^{*+}(892))| < 1.5$ GeV/$c^2$ |
| $D^- \rightarrow K_S^0 \pi^- \pi^- \pi^0$ | $|M(K^+ K^-) - m(K^{*+}(892))| < 1.5$ GeV/$c^2$ |

Incorporating

The recoil mass $RM(K_S^0 D)$ of the $K_S^0 D$ system is obtained according to $RM(X) = |p_{e^+ e^-} - p_X|$, where $p_{e^+ e^-}$ is the four-momentum of the initial $e^+ e^-$ system and $p_X$ is the four-momentum of the $X$ system. The $RM(K_S^0 D)$ resolution is then improved through use of the quantity $RQ(K_S^0 D) = RM(K_S^0 D) + M(D) - m(D)$ [38], where $M(D)$ is the invariant mass of the signal $D$ candidate, and $m(D)$ is the known mass quoted in PDG [2]. The $RQ(K_S^0 D)$ spectra are shown in Fig. 1. These spectra are used to identify the three body processes $K_S^0 D_+^* D^+$ and $K_S^0 D_+^* D^-$, which contribute to peaking structures in the regions of the $D^{*-}$ and $D_+^{*+}$ mass, respectively. We require $|RQ(K_S^0 D^{*-}) - m(D^{*-})| < 20$ MeV/$c^2$ and $|RQ(K_S^0 D_+^{*+}) - m(D_+^{*+})| < 10$ MeV/$c^2$. Studies of the inclusive MC simulations show...
We adopt two signal probability density functions (PDFs) constructed as follows:

where \( E \) is the efficiency function and \( \Gamma_1(M) = \Gamma_0 \cdot \frac{p_1}{p_1'} \cdot \frac{m_0}{M} \), \( \Gamma_2(M) = \Gamma_0 \cdot \frac{p_2}{p_2'} \cdot \frac{m_0}{M} \), where \( R_1 \) describes the decay \( Z_{cs}^0 \to D_s^+ D_s^- \), and \( R_2 \) describes \( Z_{cs}^0 \to D_s^+ D^- \), \( M \) equals \( RM(K_S^0) \), \( m_0 \) is the mass of the \( Z_{cs}^0 \), and \( \Gamma_0 \) is the total width of the \( Z_{cs}^0 \). The momentum of the \( K_S^0 \) in the initial \( e^+ e^- \) system is \( q \), the momentum of the \( D_s^+ (D^-) \) in the rest frame of the \( D_s^+ D_s^- (D_s^+ D^-) \) system is \( p_{1(2)} \), and the corresponding momentum at \( M = m_0 \) is \( p_{1(2)}' \). In the fit, under the assumption of the isospin symmetry, a Gaussian constraint is imposed to restrict the width of the \( Z_{cs}^0 \) within the uncertainty of the \( Z_{cs}(3985)^+ \) width, which is \( (13.8^{+8.1}_{-5.2} \pm 4.9) \) MeV\(^1\). The factor \( f \) denotes the ratio of the two signal channels

\[
f = \frac{B(Z_{cs}^0 \to D_s^+ D_s^-)}{B(Z_{cs}^0 \to D_s^+ D^-) + B(Z_{cs}^0 \to D_s^+ D^-)}.
\]

The default value of \( f \) is chosen to be 0.5, with other possibilities considered as a systematic uncertainty.

The fit depends on the detector resolution and mass-dependent efficiency, which are derived from simulated samples. The detector resolution is determined using the \( Z_{cs}^0 \) signal MC samples, in which the width of the \( Z_{cs}^0 \) is set to be 0.

The signal probability density function (PDF) is constructed as follows:

\[
\mathcal{F} \propto (f \cdot \mathcal{E}_1 \cdot R_1 + (1-f) \cdot \mathcal{E}_2 \cdot R_2) \otimes G(\mu, \sigma),
\]

where \( \mathcal{E}_1(2) \) is the efficiency function and \( G \) is the Gaussian resolution function.
The backgrounds in the fit include three components: the non-resonant process $e^+e^- \rightarrow K_S^0(D_s^+D_s^- + D_s^{*+}D_s^-)$, the excited $D_s^{*+}D_s$ backgrounds, and the combinatorial backgrounds. The first and second components are described using histogram PDFs extracted from MC samples, and the third component is described using the distribution from the $D_s^+$ ($D^-$) sideband. In the fit, the yields of the excited $D_s^{*+}D_s$ backgrounds are estimated from isospin relations according to those calculated for the $e^+e^- \rightarrow K^-Z_{cs}(3985)^+$ process, and the numbers are fixed in the fit [1], while the yields of the non-resonant process are free. The sizes of the combinatorial background are fixed to the values in Table II.

The fitted mass and width of the $Z_{cs}^0$ are given in Table III, where the $Z_{cs}(3985)^+$ resonance parameters are included for comparison. The results are consistent with the theoretical predictions [17–20, 23]. We sum up the $RM(K_S^0)$ distributions from all data sets, and superimpose the simultaneous fit curves in the last plot of Fig. 2. Comparing the fits with or without considering the contribution from the $Z_{cs}^0$, the number of degrees of freedom is changed by 7 (the mass and width of the $Z_{cs}^0$, together with the cross section of the $Z_{cs}^0$ at the five center-of-mass energies). The value of $2\ln L$, where $L$ is the likelihood value, is changed by 42.0. This corresponds to a statistical significance of 5.0σ according to Wilks’ theorem [40]. When also considering systematic uncertainties, which are described in the supplemental material [39], the significance of the $Z_{cs}^0$ signal becomes 4.6σ. The reduced chi-squared of the fit in Fig. 2 is 0.9, indicating good compatibility between the model and the data.

**TABLE III.** The measured masses and widths of the $Z_{cs}(3985)^0$ and $Z_{cs}(3985)^+$ [1].

|          | Mass (MeV/c^2) | Width (MeV) |
|----------|----------------|-------------|
| $Z_{cs}(3985)^0$ | 3992.2 ± 1.7 ± 1.6 | 7.7^{+1.8}_{-3.8} ± 4.3 |
| $Z_{cs}(3985)^+$ | 3985.2^{+2.1}_{-2.0} ± 1.7 | 13.8^{+6.1}_{-5.2} ± 4.9 |

According to the fitted signal yields in Table IV, the Born cross section of $e^+e^- \rightarrow \bar{K}^0Z_{cs}^0$ multiplied by the branching fraction of $Z_{cs}^0$ decays, $\sigma^{\text{Born}}(e^+e^- \rightarrow \bar{K}^0Z_{cs}^0 + \text{c.c.}) \times \mathcal{B}(Z_{cs}^0 \rightarrow D_s^+D_s^- + D_s^{*+}D_s^-)$, can be obtained by the
TABLE IV. Summary of the integrated luminosity ($\mathcal{L}$), the number of signal events ($N_{\text{obs}}$), reconstruction efficiency ($\hat{\epsilon}$), radiative-correction factor $(1 + \delta)$, and vacuum polarization factor ($\delta_{\text{vac}}$).

| $\sqrt{s}$ (MeV) | $\mathcal{L}$ (pb$^{-1}$) | $N_{\text{obs}}$ | $\hat{\epsilon}$ (%) | $(1 + \delta)\delta_{\text{vac}}$ |
|-----------------|--------------------------|----------------|---------------------|-------------------------------|
| 4628            | 511.1                    | 1.88           | 0.69                |
| 4641            | 541.4                    | 1.88           | 0.74                |
| 4661            | 523.6                    | 1.83           | 0.77                |
| 4682            | 1643.4                   | 1.80           | 0.79                |
| 4699            | 526.2                    | 1.78           | 0.80                |

TABLE V. Born cross sections multiplied by branching fraction of $K^0 Z_{cs}(3985)^0$ and $K^- Z_{cs}(3985)^+$ at the 5 energy points. The $\chi^2$/ndf quantifies the compatibility of the five measurements.

| $\sqrt{s}$ (MeV) | $\sigma_{\text{Born}} \times B$ (pb) | $\chi^2$ | $\chi^2_{\text{total}}$/ndf |
|-----------------|-----------------------------------|--------|-----------------------------|
| 4628            | $4.4^{+2.6}_{-2.2} \pm 2.0$ $0.8^{+1.3}_{-0.8} \pm 0.6$ $1.2$ | ...    | ...                         |
| 4641            | $0.0^{+1.6}_{-0.0} \pm 0.2$ $1.6^{+1.2}_{-1.1} \pm 1.3$ $0.5$ | ...    | ...                         |
| 4661            | $2.8^{+1.8}_{-1.0} \pm 0.6$ $1.6^{+1.3}_{-1.1} \pm 0.8$ $0.3$ | ...    | $5.1/5$                     |
| 4682            | $2.2^{+1.2}_{-1.2} \pm 0.8$ $4.4^{+0.9}_{-0.9} \pm 1.4$ $1.0$ | ...    | ...                         |
| 4699            | $7.0^{+2.2}_{-2.0} \pm 1.8$ $2.4^{+1.1}_{-1.0} \pm 1.2$ $2.1$ | ...    | ...                         |

The following equation

$$\sigma_{\text{Born}} \times B = \frac{N_{\text{obs}}}{2\mathcal{L} \times \hat{\epsilon} \times (1 + \delta) \times \delta_{\text{vac}}}.$$

where $N_{\text{obs}}$ are the signal yields, $\hat{\epsilon}$ are the combined MC-determined reconstruction efficiencies in the two $D$-tag methods, $\mathcal{L}$ is the integrated luminosity, $(1 + \delta)$ is the radiative correction factor, and $\delta_{\text{vac}}$ is the vacuum-polarization correction factor [41]; their values are given in Table IV. We assume $B(Z_{cs}^0 \rightarrow D^+_s D^-) = B(Z_{cs}^0 \rightarrow D^+_s D^-)$. The factor of 2 in the denominator in Eq. (3) is necessary because of the equal transition rate of $K^0$ and $\bar{K}^0$ to $K^0_{cs}$. The cross section results at the five center-of-mass energies are listed in Table V. The $\chi^2$ of each energy point is defined as the square of difference of the cross sections of two channels divided by the sum-of-squares of these uncertainties. The $\chi^2_{\text{total}}$/ndf is the sum of the $\chi^2$ divided by the number of energy points. The cross section results for the neutral channel are consistent with those for the charged one [1], which agree with the prediction based on isospin symmetry.

Systematic uncertainties on the measurement of the $Z_{cs}^0$ resonance parameters and production cross sections are extensively investigated as detailed in Ref. [39]. An important contribution is associated with the background modelling in the fit and the $Z_{cs}^0$ signal model. For the background modelling, we vary the size and shape of the combinatorial backgrounds according to the $M(D)$ sideband control samples, as well as explore the additional contributions from the highly excited $D_{cs}^{(*)}$ states. For the signal modelling, we test different $J^P$ assignments of the $Z_{cs}^0$ by changing the matrix elements in the signal simulations. The total systematic uncertainties are, overall, similar to the statistical uncertainties on each measurement.

In summary, based on data sets with center-of-mass energies from 4.628 GeV to 4.699 GeV at BESIII, evidence of a neutral open-strange hidden-charm state, $Z_{cs}(3985)^0$, is found in the $K^0_{cs}$ recoil-mass spectrum of the $e^+e^- \rightarrow K^0_{cs}(D^+_s D^- + D^+_s D^-) + \text{c.c.}$ processes, with a resonance mass and width determined as $(3992.2 \pm 1.7 \pm 1.6)$ MeV/c$^2$ and $(7.7^{+4.1}_{-3.8} \pm 4.3)$ MeV, respectively. The significance of the state is determined to be 4.6$\sigma$. Since this state decays through $D^+_s D^- + D^- + D^+ D^-$, it should contain at least four quarks, $c\bar{c}d\bar{d}$. The measured mass of the $Z_{cs}(3985)^0$ is larger than that of the $Z_{cs}(3985)^+$, which is consistent with theoretical prediction [23]. In addition, the Born cross sections of $e^+e^- \rightarrow K^0_{cs}(3985)^0 + \text{c.c.}$ multiplied by the branching fraction of $Z_{cs}(3985)^0 \rightarrow D^+_s D^- + D^+_s D^-$ at the five energy points are measured and found to be consistent with those of $e^+e^- \rightarrow K^- Z_{cs}(3985)^+ + \text{c.c.}$ [1], as expected under isospin symmetry. Hence, we conclude that the $Z_{cs}(3985)^0$ is the isospin partner of the $Z_{cs}(3985)^+$. 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 R&D Program of China under Contracts Nos. 2020YFA0406400, 2020YFA0406300; National Natural Science Foundation of China (NSFC) under Contracts Nos. 11521505, 11635010, 11735014, 11805086, 11822506, 11835012, 11935015, 11935016, 11935018, 11961141012, 12022510, 12025502, 12035009, 12035013; National 1000 Talents Program of China; the Academy of Sciences (CAS) Large-Scale Scientific Facility Program; Joint Large-Scale Scientific Facility Funds of the NSFC and CAS under Contract No. U1832207;
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Supplemental Material for “Evidence for a neutral near-threshold structure in the $K_S^0$ recoil-mass spectra in $e^+e^- \rightarrow K_S^0 D^+ D^{*-}$ and $e^+e^- \rightarrow K_S^0 D^*+ D^-$”

Appendix A: Fit results of $D_s$-tag and $D$-tag methods

Figure 3 and Fig. 4 show the fits to the recoil mass distributions $RM(K_S^0)$ using only the $D_s^+$-tag or $D^-$-tag method, respectively. Table VI lists the yields of the two methods.

| $\sqrt{s}$ (MeV) | $D_s^+$-tag | $D^-$-tag |
|------------------|-------------|-----------|
| 4628             | 6.5$^{+4.1}_{-3.4}$ | 7.8$^{+4.9}_{-4.1}$ |
| 4641             | 0.0$^{+2.7}_{-0.3}$ | 0.0$^{+3.1}_{-0.2}$ |
| 4661             | 4.6$^{+3.2}_{-2.7}$ | 5.3$^{+3.7}_{-3.1}$ |
| 4682             | 12.0$^{+5.4}_{-5.3}$ | 13.6$^{+7.2}_{-6.1}$ |
| 4699             | 12.2$^{+3.9}_{-3.5}$ | 14.0$^{+4.5}_{-4.0}$ |

FIG. 3. Fits to the recoil mass distributions $RM(K_S^0)$ using $D_s^+$-tag method.
FIG. 4. Fits to the recoil mass distributions $RM(K_S^0)$ using $D^-$-tag method.

Appendix B: Fit results based on two subsets of data sample at $\sqrt{s} = 4.682$ GeV

To avoid potential bias, the analysis strategy is firstly implemented using 1/3 of the data set at $\sqrt{s} = 4.682$ GeV. The remaining 2/3 of data set at $\sqrt{s} = 4.682$ GeV is then used for a consistency check.

The distributions of $RQ(K_S^0D^*_+)$ and $RQ(K_S^0D^-)$ are shown in Fig. 5 and Fig. 6, respectively, for the two subsets. Using the method described in the paper, we determine the number of combinatorial background events in the $D^{*-}$ and $D^*_+^-$ signal regions that are listed in Table VII. The ratios between the numbers from two data subsets are all consistent with two, as expected.

The $RM(K_S^0)$ distributions from two data subsets are shown in Fig. 7. The yields of $Z_{cs}(3985)^0$ are obtained from the fits to the distributions, which are listed in Table VIII. The ratio between the number of $Z_{cs}(3985)^0$ signal events from two data subsets is also consistent with two.

| TABLE VII. Number of combinatorial backgrounds events in the signal regions of $K_S^0D^*_+^D^{*-}$ and $K_S^0D^*_+^D^-$ three-body processes. |
|-----------------|-----------------|-----------------|
|                 | Tag $D^*_+$     | Tag $D^{*-}$    |
| 1/3 of 4682 data| $66.6 \pm 4.2$  | $227.4 \pm 7.6$ |
| 2/3 of 4682 data| $132.4 \pm 5.9$ | $441.5 \pm 10.5$|
| Ratio           | $2.0 \pm 0.2$   | $1.9 \pm 0.1$   |
FIG. 5. Fits to the recoil mass distributions $RQ(K^0_S D^0)$ from two data subsets at 4.682 GeV.

FIG. 6. Fits to the recoil mass distributions $RQ(K^0_S D^-)$ from two data subsets at 4.682 GeV.

TABLE VIII. Yields of the $Z_{cs}(3985)^0$ from two data subsets at 4.682 GeV.

|          | Yield of $Z_{cs}(3985)^0$ |
|----------|-----------------------------|
| 1/3 of 4682 data | $12.5^{+8.4}_{-6.9}$ |
| 2/3 of 4682 data | $12.7^{+8.8}_{-8.3}$ |
| Ratio     | $1.0 \pm 1.0$               |

FIG. 7. Fit to the recoil mass distribution $RM(K^0_S)$ from two data subsets at 4.682 GeV.
Appendix C: Two-dimensional distributions

Figures 8 and 9 show the two-dimensional distributions of \( M(K^0_S D^-) \) vs \( RM(K^0_S) \), and \( M(K^0_S D^+_s) \) vs \( RM(K^0_S) \) in data.

FIG. 8. Two-dimensional distributions of \( M(K^0_S D^+_s) \) vs \( RM(K^0_S) \) in data.
FIG. 9. Two-dimensional distributions of $M(K^0_S D^-)$ vs $RM(K^0_S)$ in data.
Appendix D: Systematic studies

The total systematic uncertainties on the $Z_{cs}(3985)^0$ resonance parameters and cross sections are the quadrature sums of the assigned uncertainties arising from the sources discussed below. A summary of these contributions is listed in Table IX. When including all these sources of systematic uncertainty, the significance of the $Z_{cs}(3985)^0$ signal becomes 4.6σ.

In the nominal fit to the $RM(K_S^0)$ spectra, we choose to constrain the width of the $Z_{cs}^0$ with the uncertainty of the $Z_{cs}^0$ width, to improve the precision of our measurement, according to the isospin symmetry of the $Z_{cs}^0$ and $Z_{cs}^+$. If the constraint is removed, the fit width of the $Z_{cs}$ becomes 4.1–3.9 (stat. only), which is consistent with the nominal result.

| Source | Mass(MeV/c²) | Width(Mev) | $\sigma_{4.695}$ · B(pb) | $\sigma_{4.695}$ · B(pb) | $\sigma_{4.695}$ · B(pb) | $\sigma_{4.695}$ · B(pb) | $\sigma_{4.695}$ · B(pb) | $Z_{cs}$ Significance |
|--------|--------------|------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|------------------------|
| Tracking | 2.8% | 2.8% | 2.8% | 2.8% | 2.8% | 2.8% |
| Particle ID | 2.8% | 2.8% | 2.8% | 2.8% | 2.8% | 2.8% |
| $K_0^0$ | 2.4% | 2.4% | 2.4% | 2.4% | 2.4% | 2.4% |
| $\pi^0,\eta$ | 0.1% | 0.1% | 0.1% | 0.1% | 0.1% | 0.1% |
| $D^-/D_s^+$ signal window | 0.5% | 0.5% | 0.5% | 0.5% | 0.5% | 0.5% |
| Mass scale | 0.8 |
| Resolution | 0.1 | 0.1 | 1.2% | 1.2% | 1.2% | 0.9% | 0.8% | 5.0σ |
| $f$ factor | 0.8 | 0.4 | 4.9% | 7.2% | 9.5% | 6.7% | 14.4% | 4.8σ |
| Signal model | 0.5 | 3.1 | 9.8% | 8.6% | 7.3% | 6.1% | 15.2% | 5.3σ |
| Backgrounds | 0.4 | 2.2 | 35.9% | 27.2% | 18.5% | 12.7% | 6.8% | 4.9σ |
| Efficiency | 0.1 | 0.1 | 0.7% | 0.5% | 0.2% | 1.0% | 0.6% | 5.0σ |
| $D_s^+$ states | 0.6 | 1.6 | 19.8% | 14.5% | 9.2% | 26.6% | 9.4% | 4.6σ |
| $\sigma_{4.695}$($K_S^0Z_{cs}$) | 0.6 | 1.1 | 12.1% | 6.8% | 15.0% | 7.0% | 1.8% | 4.7σ |
| Luminosity | 1.0% | 1.0% | 1.0% | 1.0% | 1.0% | 1.0% |
| Input BFs | 2.8% | 2.8% | 2.8% | 2.8% | 2.8% |
| total | 1.6 | 4.3 | 44.5% | 34.0% | 24.6% | 32.1% | 24.7% |

Tracking, PID and reconstruction of intermediate states: The uncertainties on both the tracking and PID efficiencies for each charged track are assigned to be 1%. The uncertainties associated with $K_S^0$, $\pi^0$ and $\eta$ reconstruction are assigned to be 2%. The uncertainties from tracking, PID and intermediate states reconstruction in different tag channels are weighted by the factor $B_{\ell\ell}$. Here, “$\ell$” indicates each $D^+$ or $D_s^-$ decay channel.

$D^-/D_s^+$ signal window: The uncertainty associated with the definition of the $D^-/D_s^+$ signal window is estimated by comparing the $D^-/D_s^+$ signal from data and MC. The widths of the $D^-/D_s^+$ peaks in data and MC are slightly different. We estimate that these differences in resolution lead to a relative 0.5% difference in efficiency, which is assigned as a systematic uncertainty.

Mass scale: A control sample of $e^+e^- \rightarrow K_S^0D^-D_s^+$ events with $\sqrt{s}$ larger than 4.62 GeV is selected, in which the $K_S^0$ and $D_s^+$ are reconstructed. We fit the $D^-$ peak in the corrected recoil mass spectrum $RM(K_S^0D_s^+)+M(D_s^+)-m(D_s^+)$. The $D^-$ signal is modelled with a MC-determined signal shape convolved with a Gaussian function. The Gaussian parameters are determined to be $\mu=(0.07 \pm 0.68)$ MeV/c² and $\sigma=(0.60 \pm 2.62)$ MeV. Since the corrected recoil mass $RM(K_S^0D_s^+)+M(D_s^+)-m(D_s^+)$ is largely insensitive to the resolution of the $D_s^+$ mass, we attribute any mass shift to the bachelor $K_S^0$. Hence, considering the central value and uncertainty of this study, we take a maximum mass shift of 0.8 MeV/c² as the systematic uncertainty.

Detector resolution: To understand the potential difference of detector resolution in data and MC simulations, the same control sample of $e^+e^- \rightarrow K_S^0D^-D_s^+$ events is used. From the “Mass scale” study, the width of the smearing function is at most 3.2 MeV. We therefore smear the resolution function in the $Z_{cs}$ fit by this amount and reperform the mass fit. The resultant differences on the final results are taken as systematic uncertainties.

$f$ factor: In the default fit, the two signal processes $Z_{cs}^0 \rightarrow D_s^+D_s^-$ and $Z_{cs}^0 \rightarrow D_s^+D_s^-$ are combined and we assume their fraction factor is 0.5 in nominal calculation. To estimate the possible systematic bias arising from this source, we assume the probability distribution of $f$ is uniform between 0 and 1 with no prior knowledge, we take the RMS value of $1/\sqrt{2}$ (0.3) as the uncertainty on $f$. Hence, we vary $f$ to 0.2 and 0.8 and take the largest difference with respect to the nominal result as the systematic uncertainty from this source.
**Signal model:** In the default fit, we assume the $J^P$ of the $Z_{cs}^0$ is $1^+$ and that the $K_S^0$ and $Z_{cs}^0$ in the rest frame of the $e^+e^-$ system and the $D_s^+(D_s^{*+})$ and $D_s^0(D_s^{*-})$ in the $Z_{cs}^0$ system are both in an $S$-wave state, denoted as $(S, S)$. As a systematic check, we also consider $0^-(P, P)$, $1^-(P, P)$, $1^+(D, S)$ and $2^-(P, P)$ configurations. To minimize the effect of systematic uncertainties in the study, 1000 toy MC samples are generated with the PDF determined from the default fit of $RM(K_S^0)$. The number of events in each sample is the same as the data sample. The whole analysis procedure is repeated under different $J^P$ assumptions and the mean fit result from the ensemble of toys is measured. We take the largest difference with respect to the $1^+(S, S)$ configuration as being the systematic uncertainty associated with the signal model.

**Backgrounds:** The signal description is sensitive to the contribution from background. We vary the number of combinatorial background within 1σ. We also use the inclusive MC samples instead of the $D^- (D_s^+)_{sideband}$ samples to extract the shape of combinatorial backgrounds. We take the largest difference with respect to the default result as the systematic uncertainty.

**Efficiency functions:** We vary the parameters of the efficiency functions used in the fitting to estimate the impact of the modelling of the acceptance. The parameters of the efficiency functions are varied within 1σ, and the new functions are used to re-fit. The relative differences with the nominal results are taken into account as systematic uncertainties.

**Highly excited $D_s^{*\ast}(s)$ states:** In the default analysis, we include the contributions of three highly excited $D_s^{*\ast}(s)$ processes, $D_s^{\ast 1}(2536)^-(\rightarrow D_s^{*\ast}K_S^0)D_s^{*+}$, $D_s^{\ast 2}(2573)^-(\rightarrow D_s^{*\ast}K_S^0)D_s^{*+}$ and $D_s^{\ast 3}(2700)^-(\rightarrow D_s^{*\ast}K_S^0)D_s^{*+}$, based on the results of the control samples studied in the charged $Z_{cs}(3985)^+$ analysis [1]. Another potential $D_s^{*\ast}$ background is $D_1^0(2600)^+\rightarrow D_s^{\ast \ast}(K_S^0)D_s^{*-}$. According to the study of the charged $Z_{cs}(3985)^+$ [1], the ratio $B(D_1^0(2600)^0 \rightarrow D_s^{\ast \ast}K_S^0)/B(D_1^0(2600)^0 \rightarrow D_s^{*-}\pi^0) = 0.00 \pm 0.02$. Assuming the cross section of $D_1^0(2600)^0D_s^{*-}$ is the same as $D_1^0(2600)^0D_s^{*\ast}$, we fix the ratio $B(D_1^0(2600)^0 \rightarrow D_s^{\ast \ast}K_S^0)/B(D_1^0(2600)^0 \rightarrow D_s^{*-}\pi^0)$ to 0.02 in the fit. We also replace the PHSP component with other possible processes with $D_s^{*\ast}(s)$ states, such as $D_s^{\ast 1}(2750)^+(\rightarrow D_s^{*\ast}K_S^0)D_s^{*-}$, $D_s^{\ast 2}(2460)^+(\rightarrow D_s^{*\ast}K_S^0)D_s^{*-}$, $D_s^{\ast 3}(2550)^+(\rightarrow D_s^{*\ast}K_S^0)D_s^{*-}$, $D_s^{\ast 4}(2600)^+(\rightarrow D_s^{*\ast}K_S^0)D_s^{*-}$ and $D_s^{\ast 5}(2740)^+(\rightarrow D_s^{*\ast}K_S^0)D_s^{*-}$. The resultant changes are assigned as the systematic uncertainty associated with this source.

**$\sigma(K_S^0Z_{cs}^0)$ line shape:** In the default fit, the lineshape of the $K_S^0Z_{cs}^0$ cross section is extracted with a 4th order polynomial function, and then inserted into the KKMC generator to evaluate the ISR effect in MC generation, which affects the radiative correction factor, detection efficiency and detection-resolution function of the default result. For the systematic uncertainty study, we vary the cross sections within 1σ and refit the lineshape. Then the signal MC samples are generated based on the new lineshape. The resultant maximum changes are taken as the systematic uncertainty from this source.

**Luminosity:** The uncertainty of the luminosity measurement at each energy point is assigned to be 1%.

**Branching fractions:** In this analysis, the branching fractions of $K_S^0 \rightarrow \pi^+\pi^-$, $D^{*-} \rightarrow D^-X$ and all the decay channels used in the $D_s^+$ and $D_s^0$ reconstruction are taken from the PDG [2]. We use the quoted uncertainties on these quantities to determine the corresponding systematic uncertainties for our measurements.

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