

## Study of $\phi \rightarrow K\bar{K}$ and $K_S^0 - K_L^0$ Asymmetry in the Amplitude Analysis of $D_s^+ \rightarrow K_S^0 K_L^0 \pi^+$ Decays

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Using  $e^+e^-$  annihilation data corresponding to a total integrated luminosity of  $7.33 \text{ fb}^{-1}$  collected at center-of-mass energies between 4.128 and 4.226 GeV with the BESIII detector, we provide the first amplitude analysis and absolute branching fraction measurement of the hadronic decay  $D_s^+ \rightarrow K_S^0 K_L^0 \pi^+$ . The branching fraction of  $D_s^+ \rightarrow K_S^0 K_L^0 \pi^+$  is determined to be  $(1.86 \pm 0.06_{\text{stat}} \pm 0.03_{\text{syst}})\%$ . Combining the  $\mathcal{B}[D_s^+ \rightarrow \phi(\rightarrow K_S^0 K_L^0)\pi^+]$  obtained in this Letter and the world average of  $\mathcal{B}[D_s^+ \rightarrow \phi(\rightarrow K^+ K^-)\pi^+]$ , we measure the relative branching fraction  $\mathcal{B}(\phi \rightarrow K_S^0 K_L^0)/\mathcal{B}(\phi \rightarrow K^+ K^-) = (0.593 \pm 0.023_{\text{stat}} \pm 0.014_{\text{syst}} \pm 0.016_{\phi\pi})$ , where the third error is due to the uncertainty of the  $\mathcal{B}(D_s^+ \rightarrow \phi\pi^+, \phi \rightarrow K^+ K^-)$ . Our result deviates from the Particle Data Group value by more than  $3\sigma$ . Furthermore, the asymmetry of the branching fractions of  $D_s^+ \rightarrow K_S^0 K^*(892)^+$  and  $D_s^+ \rightarrow K_L^0 K^*(892)^+$ ,  $(\{\mathcal{B}[D_s^+ \rightarrow K_S^0 K^*(892)^+]-\mathcal{B}[D_s^+ \rightarrow K_L^0 K^*(892)^+]\}/\{\mathcal{B}[D_s^+ \rightarrow K_S^0 K^*(892)^+] + \mathcal{B}[D_s^+ \rightarrow K_L^0 K^*(892)^+]\})$ , is determined to be  $(-14.5 \pm 5.1_{\text{stat}} \pm 1.8_{\text{syst}})\%$ .

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The  $\phi$  meson, with a large proportion of  $s\bar{s}$  and a mass in the nonperturbative QCD region, is considered a potential carrier of the interaction between hadrons, as proposed in Hideki Yukawa's meson exchange theory [1]. It is also a valuable probe for studying QCD matter formed in relativistic heavy-ion collisions [2]. Consequently, the precise measurement of its decay characteristics holds significant theoretical and experimental value for investigating the nonperturbative behavior of the strong interaction and the properties of the nuclear force between baryons [3], thus deepening understanding of the structure of hadronic matter.

About 80% of  $\phi$  mesons decay into  $\phi \rightarrow K\bar{K}$ , and the relative branching fraction (BF),  $R_\phi \equiv \mathcal{B}(\phi \rightarrow K_S^0 K_L^0)/\mathcal{B}(\phi \rightarrow K^+ K^-)$ , is naively expected to equal 1.0 due to isospin symmetry. Different theoretical predictions of  $R_\phi$ , however, fall within a relatively large range of 0.62–0.71 [4–7], taking into account phase-space difference, radiative corrections, isospin breaking, etc. The experimental measurements of  $R_\phi$  currently range from 0.64 to 0.89 [8–12]. It is evident that although there is overlap between theoretical predictions and experimental measurements, further studies are required.

The Particle Data Group (PDG) average value of  $R_\phi = 0.740 \pm 0.031$  [8] has not been updated for many years (while updated measurements of  $R_\phi$  were reported by the CMD2 [13] and CMD3 [14] experiments in 1995 and 2018, respectively, they have not been taken into account for the averages by PDG). In addition, the measurements were primarily through  $e^+e^-$  annihilation and  $K-p$  scattering experiments [8,9,15–17], which usually suffer challenges from complex backgrounds and various interferences. Recently, Ref. [18] used total cross-section measurements of the processes  $e^+e^- \rightarrow K^+ K^-/K_S^0 K_L^0$ , yielding an  $R_\phi$  value of  $0.644 \pm 0.017$  with the unitary and analytic model, suggesting the possibility that the experimental average may not be a reliable estimate of  $R_\phi$  anymore. Therefore, exploring the reasons behind these differences and understanding the underlying mechanisms affecting  $\phi$  meson decays requires a new and more accurate method to determine the BF of  $\phi$  decays. The measurement of the BF of  $D_s^+ \rightarrow \phi(\rightarrow K_S^0 K_L^0)\pi^+$ , along with  $D_s^+ \rightarrow \phi(\rightarrow K^+ K^-)\pi^+$  [19], serves as a new approach to determine  $R_\phi$  in a more controlled environment. In addition, the BESIII Collaboration found that the measured BF ratio  $\mathcal{B}(\phi \rightarrow \pi^+ \pi^- \pi^0)/\mathcal{B}(\phi \rightarrow K^+ K^-)$  deviates from the world average value by more than  $4\sigma$  [20]. This further stimulates the urgent study of  $\phi$  decays in the amplitude analysis of  $D_s^+ \rightarrow K_S^0 K_L^0 \pi^+$  to explore the source of this tension.

Moreover, the symmetry  $\Gamma(\bar{K}^0) = 2\Gamma(K_S^0) = 2\Gamma(K_L^0)$  is usually used for the decay modes containing a neutral kaon  $K_S^0$  or  $K_L^0$ . However, it is expected that the interference between Cabibbo-Favored and Doubly-Cabibbo-Suppressed

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transitions could lead to a significant asymmetry, called  $K_S^0 - K_L^0$  asymmetry [21–26]. The  $K_S^0 - K_L^0$  asymmetry has not been observed in the  $D \rightarrow K_{S,L}^0 + \text{Vector}$  [27–29]. Phenomenological models, such as the factorization-assisted topological amplitude [24] and topological diagram approaches [26], predict non-zero  $K_S^0 - K_L^0$  asymmetry in the decay process of  $D_s^+ \rightarrow K_{S,L}^0 + \text{Vector}$ . Measurements for the  $K_S^0 - K_L^0$  asymmetries serve as critical constraints on the dynamic models of charmed meson decays. In the amplitude analysis of  $D_s^+ \rightarrow K_S^0 K_L^0 \pi^+$ , the asymmetry of  $D_s^+ \rightarrow K_S^0 K^*(892)^+$  and  $D_s^+ \rightarrow K_L^0 K^*(892)^+$  can be measured with most systematic uncertainties canceled. The obtained result will be crucial to better understand the dynamics of Cabibbo-Favored and Doubly-Cabibbo-Suppressed transitions.

In this Letter, we present the first amplitude analysis and absolute BF measurement of the  $D_s^+ \rightarrow K_S^0 K_L^0 \pi^+$  decay using  $7.33 \text{ fb}^{-1}$  data samples collected at center-of-mass (c.m.) energies between 4.128 and 4.226 GeV with the BESIII detector. Charge conjugation is implied throughout this Letter.

The BESIII detector [30,31] records symmetric  $e^+e^-$  collisions provided by the BEPCII storage ring [32]. The cylindrical core of the BESIII detector covers 93% of the full solid angle and consists of a helium-based multilayer drift chamber, a plastic scintillator time-of-flight system, and a CsI(Tl) electromagnetic calorimeter, which are all enclosed in a superconducting solenoidal magnet providing a 1.0 T magnetic field. The end cap time-of-flight system was upgraded in 2015 using multigap resistive plate chamber technology, providing a time resolution of 60 ps, which benefits 83% of the data used in this analysis [33].

Simulated data samples produced with Geant4-based [34] Monte Carlo (MC) software, which includes the geometric description of the BESIII detector and the detector response, are used to determine detection efficiencies and to estimate backgrounds. The simulation models the beam energy spread and initial state radiation in the  $e^+e^-$  annihilations with the generator KKMC [35]. The inclusive MC sample includes the production of open charm processes, the initial state radiation production of vector charmonium(like) states, and the continuum processes. All particle decays are modeled with EvtGen [36] using BFs either taken from the PDG [8], when available, or otherwise estimated with Lundcharm [37]. Final-state radiation from charged final-state particles is incorporated using the PHOTOS package [38].

The process  $e^+e^- \rightarrow D_s^{*\pm} D_s^\mp \rightarrow \gamma D_s^+ D_s^-$  allows studies of  $D_s^+$  decays using a tag technique [39,40]. Two types of samples are used: single tag (ST) and double tag (DT). An ST candidate is an event where only the  $D_s^-$  meson is reconstructed through particular hadronic decays, designated as “tag,” is reconstructed through one of ten hadronic decay modes:  $K_S^0 K^-$ ,  $K^+ K^- \pi^-$ ,  $K_S^0 K^- \pi^0$ ,  $K^+ K^- \pi^- \pi^0$ ,

$K_S^0 K^- \pi^- \pi^+$ ,  $K_S^0 K^+ \pi^- \pi^-$ ,  $\pi^- \pi^- \pi^+$ ,  $\pi^- \eta$ ,  $\pi^- \eta'$ , and  $K^- \pi^- \pi^+$ . A DT candidate is an event where the  $D_s^+$  is reconstructed through  $D_s^+ \rightarrow K_S^0 K_L^0 \pi^+$  in addition to the  $D_s^-$  being reconstructed through the tag modes. A detailed description of selection conditions concerning charged and neutral particle candidates, the mass recoiling against  $D_s^\pm$  candidates, and the mass of the tag candidates is provided in Refs. [41–45].

After a  $D_s^-$  tag candidate is identified, we reconstruct the signal  $D_s^+ \rightarrow K_S^0 K_L^0 \pi^+$  candidate recoiling against the tag by requiring two positively charged particles identified as  $\pi^+$ , one negatively charged  $\pi^-$ , and at least one more photon to reconstruct the transition photon of  $D_s^{*\pm} \rightarrow \gamma D_s^\pm$ . The four-momentum of the  $K_L^0$  needs to be determined, which is calculated with the momentum of the initial  $e^+e^-$  system and other detected particles. If there are multiple signal candidates for  $K_S^0$ , the best candidate with the minimum  $\chi^2$  of a four-constraint (4C) kinematic fit is chosen. The total four-momentum is constrained to the four-momentum of the initial  $e^+e^-$  beams. The invariant masses of the tag  $D_s^-$ , the signal  $D_s^+$ , the  $D_s^*$ , and  $K_S^0$  are constrained to their PDG values [8]. The two cases  $D_s^{*+} \rightarrow D_s^+ \gamma$  and  $D_s^{*-} \rightarrow D_s^- \gamma$  are considered. The combination with the minimum  $\chi^2$  is chosen. Furthermore, the square of the recoil mass against the transition photon and the tag  $D_s^- (M_{\text{rec}}^2)$  is expected to peak at the known  $D_s^\pm$  meson mass squared before the kinematic fit for signal  $D_s^{*\pm} D_s^\mp$  events, and must satisfy  $3.80 < M_{\text{rec}}^2 < 4.0 \text{ GeV}^2/c^4$ . The requirement that the number of additional  $\pi^0 (N_{\pi^0})$  composed of unused photons in the ST candidate selection and  $D_s^{*\pm} \rightarrow \gamma D_s^\pm$  is equal to zero is applied to suppress backgrounds. Here, since  $K_L^0$  may cause fake photons in the electromagnetic calorimeter, the angles of any photons that form  $\pi^0$ s and the shower produced by  $K_L^0$  are required to be greater than  $10^\circ$ .

The purity is determined by fitting the missing mass squared ( $M_{\text{miss}}^2$ ) of the  $K_L^0$  candidates after the 4C kinematic fit, which is defined as

$$M_{\text{miss}}^2 = \frac{1}{c^2} (p_{\text{c.m.}} - p_{\text{tag}} - p_{K_S^0} - p_{\pi^+} - p_\gamma)^2, \quad (1)$$

where  $p_{\text{c.m.}}$  is the four-momentum of the  $e^+e^-$  c.m. system,  $p_{\text{tag}}$  and  $p_i$  ( $i = K_S^0, \pi^+, \gamma$ ) are the four-momenta of the tag candidate and the final-state particle  $i$  on the signal side. The  $M_{\text{miss}}^2$  mass window,  $[0.21, 0.29] \text{ GeV}^2/c^4$ , is applied on the signal candidates for the amplitude analysis. Signal candidates from all center-of-mass energy points are combined into a single sample, resulting in 2310 events with a purity of  $f_s = (78.2 \pm 1.0)\%$ . Here, the peaking background from  $D_s^+ \rightarrow K_S^0 K_S^0 \pi^+$  is 4.3%, and simulated based on the amplitude analysis by BESIII [45].

Based on the 4C kinematic fit, an additional constraint on the mass of  $K_L^0$  is added (five-constraint) and the

four-momenta of the final-state particles of the five-constraint kinematic fit are used for the amplitude analysis to ensure that all candidates fall within the phase-space boundary. The isobar formulation is used in the covariant tensor formalism [46]. The total signal amplitude  $\mathcal{M} = \sum \rho_n e^{i\varphi_n} A_n$ , is described by a coherent sum of the amplitudes from all intermediate processes, where  $n$  represents the  $n$ th intermediate state with magnitude  $\rho_n$  and phase  $\varphi_n$ . The decay amplitude  $A_n$  depends on the phase space and intermediate resonance spin, and is given by  $A_n = P_n S_n F_n^r F_n^D$ , where  $S_n$  and  $F_n^{r(D)}$  are the spin factor [46] and the Blatt-Weisskopf barrier factor of the intermediate state (the  $D_s^\pm$  meson) [47], respectively, and  $P_n$  is the propagator of the intermediate resonance, which is the relativistic Breit-Wigner amplitude [48].

The unbinned maximum likelihood method is adopted in the amplitude analysis. A combined probability density function (PDF) for the signal and background hypotheses is constructed, with the four-momenta of the final-state particles. The signal PDF is constructed from the total amplitude  $\mathcal{M}$ . The background PDF,  $B$ , is constructed from a background shape derived from the inclusive MC samples using the XGBoost package [49,50]. This background PDF is then added to the signal PDF incoherently. The likelihood function is written as

$$\mathcal{L} = \prod_j \left[ \frac{\epsilon f_s |\mathcal{M}|^2 R_3}{\int \epsilon |\mathcal{M}|^2 R_3 dp_j} + \frac{(1-f_s) BR_3}{\int BR_3 dp_j} \right], \quad (2)$$

where  $j$  runs over the selected events,  $p_j^\mu$  represents the four-momenta of the final-state particles, and  $\epsilon$  is the detection efficiency determined with a MC sample of  $D_s^+ \rightarrow K_S^0 K_L^0 \pi^+$  uniformly distributed over the Dalitz plot. Finally,  $f_s$  and  $R_3 dp_j$  denote the purity and three-body phase-space element, respectively. Among them,  $\mathcal{M}$ ,  $B$ ,  $\epsilon$ , and  $R_3$  are all functions of the variable  $p_j^\mu$ . The normalization integral in the denominator is determined by an MC technique as described in Refs. [42–45,51].

The Dalitz plot of  $M_{K_L^0 \pi^+}^2$  versus  $M_{K_S^0 \pi^+}^2$  from all data samples is shown in Fig. 1(a). The diagonal band in the upper right corner is caused by the process  $D_s^+ \rightarrow \phi \pi^+$ , the vertical and horizontal bands around  $0.8 \text{ GeV}^2/c^4$  are  $D_s^+ \rightarrow K_L^0 K^*(892)^+$  and  $D_s^+ \rightarrow K_S^0 K^*(892)^+$ , respectively. The  $D_s^+ \rightarrow \phi \pi^+$  process is used as a reference so that the magnitudes and phases of other amplitudes can be fitted as relative values to this reference amplitude. The purity is fixed in the fit. Other possible contributing resonances such as  $K^*(1410)^+$ ,  $K_0^*(1430)^+$ ,  $K_2^*(1430)^+$ ,  $(K_S^0 \pi^+)_{S\text{-wave}}$ ,  $(K_L^0 \pi^+)_{S\text{-wave}}$ ,  $\phi(1680)$ ,  $\rho(980)$ ,  $\rho(1450)$ ,  $\rho(1700)$ ,  $\omega(1650)$ ,  $\omega_3(1670)$ , and  $\rho_3(1690)$  are added to the fit one at a time. The masses and widths of all resonances are fixed to their PDG values [8]. The statistical significance of each new amplitude is calculated from the change of the log-likelihood

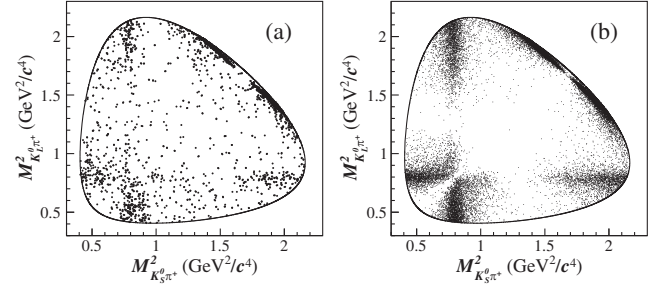


FIG. 1. Dalitz plots of  $M_{K_L^0 \pi^+}^2$  versus  $M_{K_S^0 \pi^+}^2$  for  $D_s^+ \rightarrow K_S^0 K_L^0 \pi^+$ , of (a) the sum of all data samples and (b) the signal MC samples generated based on the amplitude analysis. The black curve indicates the kinematic boundary.

taking the change in the number of degrees of freedom into account. Various combinations of these resonances are also tested. Only the amplitudes  $D_s^+ \rightarrow \phi \pi^+$ ,  $D_s^+ \rightarrow K_L^0 K^*(892)^+$ ,  $D_s^+ \rightarrow K_S^0 K^*(892)^+$ , and  $D_s^+ \rightarrow \phi(1680) \pi^+$  are found, and no other contribution has a significance greater than  $3\sigma$ . The Dalitz plot of the signal MC sample generated based on the result of the amplitude analysis is shown in Fig. 1(b). The mass projections of the fit are shown in Fig. 2.

The contribution of the  $n$ th amplitude relative to the total BF is quantified by the fit fraction (FF) defined as  $\text{FF}_n = \int |\rho_n A_n|^2 R_3 dp_j / \int |\mathcal{M}|^2 R_3 dp_j$ . The FFs of both amplitudes and the phase differences relative to the reference

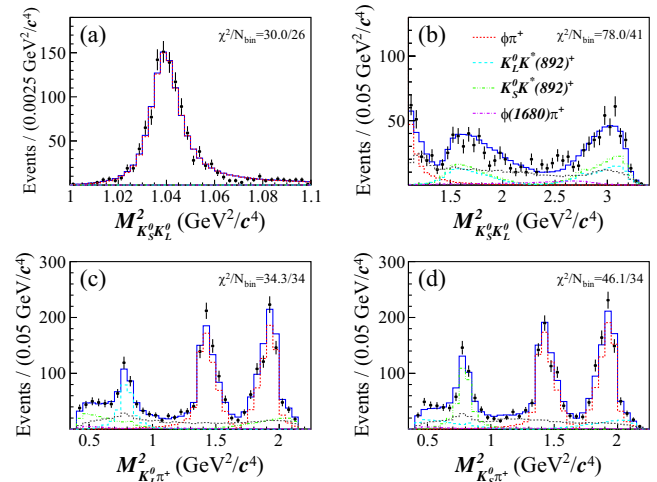


FIG. 2. Distributions of (a)  $M_{K_S^0 K_L^0}^2$  less than  $1.1 \text{ GeV}^2/c^4$ , (b)  $M_{K_S^0 K_L^0}^2$  greater than  $1.1 \text{ GeV}^2/c^4$ , (c)  $M_{K_L^0 \pi^+}^2$  and (d)  $M_{K_S^0 \pi^+}^2$  from the nominal fit. The data samples are represented by points with error bars, the fit results by blue lines, and the backgrounds by gray dashed lines. Colored dashed lines show the individual components of the fit model. The numbers in the upper right corner represent the goodness of fit,  $\chi^2/N_{\text{bin}}$ , where  $N_{\text{bin}}$  denotes the number of bins for each projection. In the calculation, adjacent bins are merged to ensure that each bin has no fewer than 10 entries.

TABLE I. Phases, FFs, BF, and statistical significances ( $\sigma$ ) of intermediate processes in  $D_s^+ \rightarrow K_S^0 K_L^0 \pi^+$ . The first and second uncertainties are statistical and systematic, respectively.

| Amplitude                            | Phase (rad)               | FF (%)                 | BF (%)                   | $\sigma$ |
|--------------------------------------|---------------------------|------------------------|--------------------------|----------|
| $D_s^+ \rightarrow \phi \pi^+$       | 0.0 (fixed)               | $70.2 \pm 1.4 \pm 1.2$ | $1.31 \pm 0.05 \pm 0.03$ | $> 10$   |
| $D_s^+ \rightarrow K_L^0 K^*(892)^+$ | $1.10 \pm 0.20 \pm 0.20$  | $19.3 \pm 1.2 \pm 1.0$ | $0.36 \pm 0.03 \pm 0.02$ | $> 10$   |
| $D_s^+ \rightarrow K_S^0 K^*(892)^+$ | $-1.93 \pm 0.20 \pm 0.25$ | $14.4 \pm 1.2 \pm 1.2$ | $0.27 \pm 0.02 \pm 0.02$ | $> 10$   |
| $D_s^+ \rightarrow \phi(1680) \pi^+$ | $-1.26 \pm 0.22 \pm 0.14$ | $3.3 \pm 0.9 \pm 0.7$  | $0.06 \pm 0.02 \pm 0.02$ | 4.3      |

process are listed in Table I. The phase difference of nearly  $\pi$  radians between  $D_s^+ \rightarrow K_L^0 K^*(892)^+$  and  $D_s^+ \rightarrow K_S^0 K^*(892)^+$  decays leads to destructive interference between them. The sum of the three FFs is 107.2%. The interference fit fraction between amplitudes and the correlation matrix of amplitude parameters are given in Supplemental Material [52]. The asymmetry of the branching fractions of  $D_s^+ \rightarrow K_S^0 K^*(892)^+$  and  $D_s^+ \rightarrow K_L^0 K^*(892)^+$  is determined to be  $(\{\mathcal{B}[D_s^+ \rightarrow K_S^0 K^*(892)^+] - \mathcal{B}[D_s^+ \rightarrow K_L^0 K^*(892)^+]\} / \{\mathcal{B}[D_s^+ \rightarrow K_S^0 K^*(892)^+] + \mathcal{B}[D_s^+ \rightarrow K_L^0 K^*(892)^+]\}) = (-14.5 \pm 5.1_{\text{stat}} \pm 1.8_{\text{syst}})\%$ , where the correlation of uncertainties between  $D_s^+ \rightarrow K_S^0 K^*(892)^+$  and  $D_s^+ \rightarrow K_L^0 K^*(892)^+$  is considered.

The systematic uncertainties related to the amplitude analysis, including the phase difference, FFs, and  $K_S^0 - K_L^0$  asymmetry, are determined by the differences between the results of the nominal fit and the alternative fits. The masses and widths of the  $\phi$ ,  $K^*(892)^+$ , and  $\phi(1680)$  are shifted by their uncertainties [8]. The radii of the Blatt-Weisskopf barrier factors are varied from their nominal values of 5 and 3  $\text{GeV}^{-1}$  (for the  $D_s^+$  meson and the intermediate resonances, respectively) by  $\pm 1 \text{ GeV}^{-1}$ . The uncertainties associated with the size of the background sample are studied by varying the purity within its statistical uncertainty. An alternative background sample is used to determine the background PDF, where the relative fractions of background processes from direct  $q\bar{q}$  and non- $D_s^{\pm} D_s^{\mp}$  open-charm processes are varied by the statistical uncertainties of the known cross sections. The uncertainty from the peaking background is also considered based on the uncertainty from the measurement of  $D_s^+ \rightarrow K_S^0 K_S^0 \pi^+$  [8] with one  $K_S^0 \rightarrow \pi^0 \pi^0$ . In addition, potential intermediate resonances that were excluded from the baseline fit model due to low significance are introduced individually as systematic variations of the model. The following resonances are considered:  $K^*(1410)^+$ ,  $K_0^*(1430)^+$ ,  $K_2^*(1430)^+$ ,  $(K_S^0 \pi^+)_{S\text{-wave}}$ ,  $(K_L^0 \pi^+)_{S\text{-wave}}$ ,  $\rho(980)$ ,  $\rho(1450)$ ,  $\rho(1700)$ ,  $\omega(1650)$ ,  $\omega_3(1670)$ , and  $\rho_3(1690)$ . The total uncertainties are obtained by adding these contributions in quadrature. A breakdown of the systematic uncertainty by source can be found in Supplemental Material [52]. Correlations between the systematic uncertainties on the  $D_s^+ \rightarrow K_{S/L}^0 K^*(892)^+$  branching fractions are accounted for when calculating the asymmetry.

The selection criteria for the BF measurement are the same as for the amplitude analysis with the exception that the requirements of  $N_{\pi^0} = 0$  and  $0.21 < M_{\text{miss}}^2 < 0.29 \text{ GeV}^2/c^4$  are removed. This is done to maximize the statistical significance of the signal and minimize the systematic uncertainties as much as possible. The BF is given by [42,43]

$$\mathcal{B}_{\text{sig}} = \frac{N_{\text{total, sig}}^{\text{DT}}}{\mathcal{B}_{\text{sub}} \sum_{\alpha, i} N_{\alpha, i}^{\text{ST}} \epsilon_{\alpha, \text{sig}, i}^{\text{DT}} / \epsilon_{\alpha, i}^{\text{ST}}}, \quad (3)$$

where  $\alpha$  runs over the various tag modes, and  $i$  denotes the different c.m. energies, and  $\mathcal{B}_{\text{sub}}$  represent the product of the BF of  $D_s^+ \rightarrow \gamma D_s$  and  $K_S^0 \rightarrow \pi^+ \pi^-$ . The ST yields in data  $N_{\alpha, i}^{\text{ST}}$  and the DT yield  $N_{\text{total, sig}}^{\text{DT}}$  are determined by fitting the mass of  $D_s^-$  and  $M_{\text{miss}}^2$  distributions, respectively. The fit to the  $M_{\text{miss}}^2$  distribution is shown in Fig. 3. The signal shape is modeled with the MC-simulated shape convolved with a Gaussian function. The dominant peaking background is  $D_s^+ \rightarrow K_S^0 K_S^0 \pi^+$  with one  $K_S^0 \rightarrow \pi^0 \pi^0$ . This peaking background is modeled by the MC-simulated shape based on the amplitude analysis [45], with a size Gaussian-constrained to the expected yield  $584 \pm 33$  according to its measured BF [8]. The shape of combinatorial background is derived from the inclusive MC samples and its size is floated in the fit. The corresponding efficiencies  $\epsilon$  are obtained by

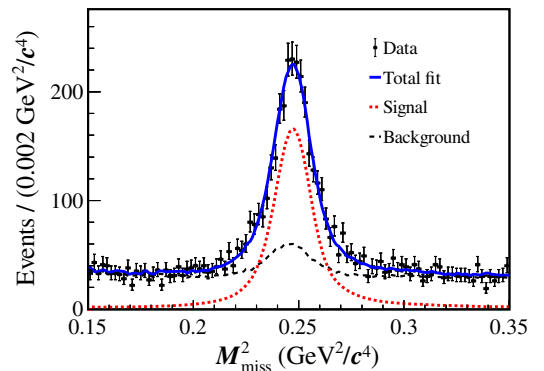


FIG. 3. Fit to the  $M_{\text{miss}}^2$  distribution of the DT signal candidates. The data samples are represented by points with error bars, the signal contributions by the red dashed line, the total fit results by the solid blue line, and the background contributions by the dashed black line.

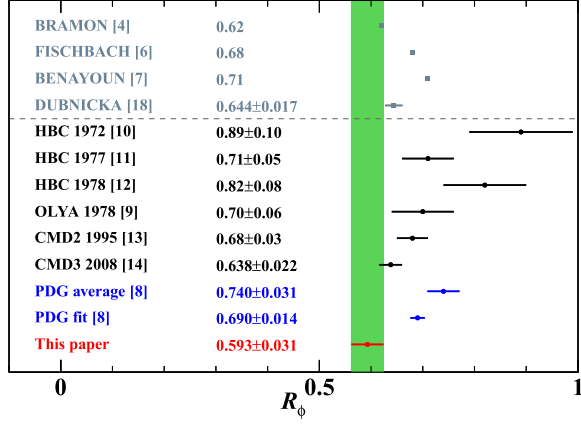


FIG. 4. Comparison of the results for  $R_\phi$  measured in this analysis and the HBC, OLYA, CMD2, and CMD3 experiments. Above the dotted line are the theoretical calculations, below are the experimental results. The green band present the total uncertainty obtained in this Letter.

analyzing the inclusive MC samples, with the signal MC events of  $D_s^+ \rightarrow K_S^0 K_L^0 \pi^+$  generated based on the results of the amplitude analysis. The details of ST yields, ST efficiencies, and DT efficiencies can be found in Supplemental Material [52]. The total ST yields of all tag modes and the DT yields are  $665265 \pm 2750$  and  $2349 \pm 76$ , respectively. The BF of  $D_s^+ \rightarrow K_S^0 K_L^0 \pi^+$  is determined to be  $(1.86 \pm 0.06_{\text{stat}} \pm 0.03_{\text{syst}})\%$ .

The following systematic uncertainties are considered in the BF measurement. The relative uncertainty in the total number of ST  $D_s^-$  mesons is assigned to be 0.4%. The uncertainty related to a nonpeaking background shape in the fit to a  $M_{\text{miss}}^2$  distribution is assigned by repeating the fit with the MC background components varied by  $\pm 30\%$ . The  $\pi^+$  particle identification and tracking efficiencies are studied with  $e^+e^- \rightarrow K^+K^-\pi^+\pi^-$  and the corresponding uncertainties are assigned to be 0.5% and 0.2%, respectively. The uncertainty for the  $K_S^0$  reconstruction is 1.0% using control samples of  $J/\psi \rightarrow K_S^0 K^\pm \pi^\mp$  and  $J/\psi \rightarrow \phi K_S^0 K^\pm \pi^\mp$ . The systematic uncertainty of photon reconstruction is assigned as 1.0% with the control sample of  $D_s^{*+} \rightarrow \gamma D_s^+(\rightarrow K_S^0 K^+)$ . The uncertainty from the signal MC model based on the results of the amplitude analysis is studied by varying the fit parameters according to the covariance matrix. The change of signal efficiency, 0.1%, is assigned as the uncertainty. The uncertainties from the

quoted BFs of  $K_S^0 \rightarrow \pi^+\pi^-$  and  $D_s^{*\pm} \rightarrow \gamma D_s^\pm$  are 0.1% and 0.4% [8], respectively. The uncertainty due to the limited signal MC sample size is 0.3%. The total uncertainty is determined by adding all the contributions in quadrature and is 1.6%.

In summary, we have presented the first amplitude analysis and BF measurement of the hadronic decay  $D_s^+ \rightarrow K_S^0 K_L^0 \pi^+$  using  $7.33 \text{ fb}^{-1}$  of  $e^+e^-$  annihilation data taken at c.m. energies between 4.128 and 4.226 GeV. The amplitude analysis results are listed in Table I. With a detection efficiency obtained based on the amplitude analysis model, we obtain  $\mathcal{B}(D_s^+ \rightarrow K_S^0 K_L^0 \pi^+) = (1.86 \pm 0.06_{\text{stat}} \pm 0.03_{\text{syst}})\%$ . The BFs of intermediate processes are calculated via  $\mathcal{B}_i = \text{FF}_i \times \mathcal{B}(D_s^+ \rightarrow K_S^0 K_L^0 \pi^+)$  and  $\mathcal{B}(D_s^+ \rightarrow \phi \pi^+, \phi \rightarrow K_S^0 K_L^0)$  is determined to be  $(1.31 \pm 0.05_{\text{stat}} \pm 0.03_{\text{syst}})\%$ . With the PDG value of  $\mathcal{B}(D_s^+ \rightarrow \phi \pi^+, \phi \rightarrow K^+K^-) = (2.21 \pm 0.06)\%$  [8], we determine a relative BF between  $\phi \rightarrow K_S^0 K_L^0$  and  $\phi \rightarrow K^+K^-$  to be  $R_\phi = (0.593 \pm 0.023_{\text{stat}} \pm 0.014_{\text{syst}} \pm 0.016_{\phi\pi})$ , where the third error is due to the uncertainty of the PDG value of  $\mathcal{B}(D_s^+ \rightarrow \phi \pi^+, \phi \rightarrow K^+K^-)$  [8]. The obtained  $R_\phi$  is consistent with theoretical expectations as reported in Ref. [4]. However, it is  $(1.0\text{--}2.8)\sigma$  below all previous measurements (see Fig. 4) and deviates from the PDG average (PDG fit) by  $3.2\sigma$  ( $2.6\sigma$ ). Note that the earlier measurement of  $\mathcal{B}(\phi \rightarrow \pi^+\pi^-\pi^0)/\mathcal{B}(\phi \rightarrow K^+K^-)$  by BESIII [20] also significantly deviates from the PDG values that were obtained in  $e^+e^-$  annihilation and  $K-p$  scattering experiments. To further explore the reasons behind these differences and to understand the underlying mechanisms that influence the BFs of  $\phi$  meson decays, more precise measurements are needed in the future.

In addition, the  $K_S^0 - K_L^0$  asymmetry in  $D_s^+ \rightarrow \bar{K}^0 K^*(892)^+$  is determined to be  $(\{\mathcal{B}[D_s^+ \rightarrow K_S^0 K^*(892)^+] - \mathcal{B}[D_s^+ \rightarrow K_L^0 K^*(892)^+]\} / \{\mathcal{B}[D_s^+ \rightarrow K_S^0 K^*(892)^+] + \mathcal{B}[D_s^+ \rightarrow K_L^0 K^*(892)^+]\}) = (-14.5 \pm 5.1_{\text{stat}} \pm 1.8_{\text{syst}})\%$ . The predicted  $K_S^0 - K_L^0$  asymmetries from different approaches, as well as the measured value, are summarized in Table II. This is the first observation of the  $K_S^0 - K_L^0$  asymmetry in the  $D \rightarrow K_{S,L}^0 + \text{Vector}$  system of charmed meson decays.

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TABLE II. Predictions for  $K_S^0 - K_L^0$  asymmetries in  $D_s^+ \rightarrow \bar{K}^0 K^{*+}$  decays from different phenomenological models and our measurement result (FAT, factorization-assisted topological amplitude model; TDA, topological diagram approach). The unit is %.

| Model                                | DAT(F4)         | DAT(F1')        | FAT            | This Letter             |
|--------------------------------------|-----------------|-----------------|----------------|-------------------------|
| $D_s^+ \rightarrow \bar{K}^0 K^{*+}$ | $-16.4 \pm 3.2$ | $-15.9 \pm 2.8$ | $-7.0 \pm 3.2$ | $-14.5 \pm 5.1 \pm 1.8$ |

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*Data availability*—The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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