Amplitude Analysis of $D_s^+ \to \pi^+\pi^0\eta$ and First Observation of the W-Annihilation Dominant Decays $D_s^+ \to a_0(980)^+\pi^0$ and $D_s^+ \to a_0(980)^0\pi^+$

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We present the first amplitude analysis of the decay $D_s^+ \to \pi^+\pi^0\eta$. We use an e^+e^- collision data sample corresponding to an integrated luminosity of 3.19 fb^{-1} collected with the BESIII detector at a center-of-mass energy of 4.178 GeV. We observe for the first time the W-annihilation dominant decays $D_s^+ \to a_0(980)^+\pi^0$ and $D_s^+ \to a_0(980)^0\pi^+$. We measure the absolute branching fraction $\mathcal{B}(D_s^+ \to a_0(980)^{+(0)}\pi^{0(+)}, a_0(980)^{+(0)} \to \pi^{+(0)}\eta) = (1.46 \pm 0.15_{\mathrm{stat}} \pm 0.23_{\mathrm{sys}})\%$, which is larger than the branching fractions of other measured pure W-annihilation decays by at least one order of magnitude. In addition, we measure the branching fraction of $D_s^+ \to \pi^+\pi^0\eta$ with significantly improved precision.

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The theoretical understanding of the weak decay of charm mesons is challenging because the charm quark mass is not heavy enough to describe exclusive processes with a heavy-quark expansion. The W-annihilation (WA) process may occur as a result of final-state-interactions (FSIs) and the WA amplitude may be comparable with the tree-external-emission amplitude [1–4]. However, the theoretical calculation of the WA amplitude is currently difficult. Hence measurements of decays involving a WA contribution provide the best method to investigate this mechanism.

Among the measured decays involving WA contributions, two decays with VP final states, $D_s^+ \to \omega\pi^+$ and $D_s^+ \to \rho^0\pi^+$, occur only through WA amplitude, and we refer to these as "pure WA decays." Here V and P denote vector and pseudoscalar mesons, respectively. The branching fractions (BFs) of these pure WA decays are at the $\mathcal{O}(0.1\%)$ [5]. These BF measurements allow the determination of two distinct WA amplitudes for VP final states. However, for SP final states, where S denotes a scalar meson, there are neither experimental measurements nor theoretical calculations of the BFs.

Two decays with SP final states $D_s^+ \to a_0(980)^+\pi^0$ and $D_s^+ \to a_0(980)^0\pi^+$ can proceed via the WA transition. If $a_0(980)$ is a $q\bar{q}$ or a tetraquark state, $D_s^+ \to a_0(980)^+\pi^0$ is pure WA decay while $D_s^+ \to a_0(980)^0\pi^+$ further receive contributions from $a_0(980)^0 - f_0(980)$ mixing. Their decay diagrams for the WA process are shown in Fig. 1. In this Letter, we search for them with an amplitude analysis of $D_s^+ \to \pi^+\pi^0\eta$. We also present improved measurements of the BFs of $D_s^+ \to \pi^+\pi^0\eta$ and $D_s^+ \to \rho^+\eta$ decays. Throughout this Letter, charge conjugation and $a_0(980) \to \pi\eta$ are implied unless explicitly stated.

We use a data sample corresponding to an integrated luminosity of 3.19 fb^{-1}, taken at a center-of-mass energy of 4.178 GeV with the BESIII detector located at the Beijing Electron Position Collider [6]. The BESIII detector and the upgraded multigap resistive plate chambers used in the

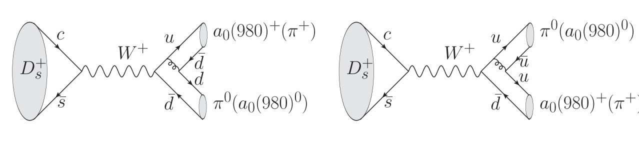

FIG. 1. $D_s^+ \to a_0(980)^{+(0)}\pi^{0(+)}$ WA-topology diagrams, where the gluon lines can be connected with the quark lines in all possible cases and the contributions from FSI are included.

time-of-flight systems are described in Refs. [7] and [8], respectively. We study the background and determine tagging efficiencies with a generic Monte Carlo (GMC) sample that is simulated with GEANT4 [9]. The GMC sample includes all known open-charm decay processes, which are generated with CONEXC [10] and EVTGEN [11], initial-state radiative decays to the J/ψ or $\psi(3686)$, and continuum processes. We determine signal efficiencies from Monte Carlo (MC) samples of $D_s^+ \to \pi^+\pi^0\eta$ decays that are generated according to the amplitude fit results to the data described in this Letter.

In the data sample, the D_s mesons are mainly produced via the process of $e^+e^- \to D_s^{*-}D_s^+$, $D_s^{*-} \to \gamma D_s^-$; we refer to the γ directly produced from the D_s^{*-} decay as $\gamma_{\rm direct}$. To exploit the dominance of the $e^+e^- \to D_s^{*-}D_s^+$ process, we use the double-tag (DT) method [12]. The single-tag (ST) D_s^- mesons are reconstructed using seven hadronic decays: $D_s^- \to K_S^0K^-$, $D_s^- \to K^+K^-\pi^-$, $D_s^- \to K_S^0K^-\pi^0$, $D_s^- \to K^+K^-\pi^-\pi^0$, $D_s^- \to K_S^0K^+\pi^-\pi^-$, $D_s^- \to \pi^-\eta$, and $D_s^- \to \pi^-\eta'$. A DT is formed by selecting a $D_s^+ \to \pi\pi^0\eta$ decay in the side of the event recoiling against the D_s^- tag. Here, K_S^0, π^0, η, and η' are reconstructed using $\pi^+\pi^-$, $\gamma\gamma$, $\gamma\gamma$, and $\pi^+\pi^-\eta$ channels, respectively. The selection criteria for charged tracks, photons, K_S^0, and π^0 are the same as those reported in Ref. [13]. The $\eta^{(\prime)}$ candidate is required to have an invariant mass of the $\gamma\gamma(\pi^+\pi^-\eta)$ combination in the interval $[0.490, 0.580]([0.938, 0.978])$ GeV$/c^2$.

The invariant masses of the tagged (signal) $D_s^{-(+)}$ candidates $M_{\rm tag}(M_{\rm sig})$ without any constraint are required to be in the interval $[1.90, 2.03]$ GeV$/c^2$ ($[1.87, 2.06]$ GeV$/c^2$). For the ST D_s^- mesons, the recoil mass $M_{\rm rec} = [E_{\rm tot} - (|\mathbf{p}_{D_s}|^2 + m_{D_s}^2)^{1/2}]^2 - |\mathbf{p}_{\rm tot} - \mathbf{p}_{D_s}|^2 1/2$ is required to be within the range $[2.05, 2.18]$ GeV$/c^2$ to suppress events from non-$D_s^{*-}D_s^+$ processes. Here, $(E_{\rm tot}, \mathbf{p}_{\rm tot})$ is the four-momentum of the colliding e^+e^- system, $\mathbf{p}_{D_s}$ is the three-momentum of the D_s candidate, and m_{D_s} is the D_s mass [5]. For events with multiple tag candidates for a single tag mode, the one with a value of $M_{\rm rec}$ closest to m_{D_s} is chosen. If there are multiple signal candidates present against a selected tag candidate, the one with a value of $(M_{\rm tag} + M_{\rm sig})/2$ closest to m_{D_s} is accepted.

To successfully perform an amplitude analysis with all events falling within the Dalitz plot and to allow the selection of the $\gamma_{\rm direct}$ candidate, we perform a seven-constraint (7C) kinematic fit, where aside from constraints arising from four-momentum conservation, the invariant masses of the $(\gamma\gamma)_{\pi^0}$, $(\gamma\gamma)_\eta$, and $\pi^+\pi^0\eta$ combinations used to reconstruct the signal D_s^+ candidate are constrained to the nominal π^0, η and D_s^+ masses [5], respectively. The $\gamma_{\rm direct}$ candidate used in the 7C fit that produces the smallest $\chi^2_{\rm 7C}$ is selected. We only require the kinematic fit to be successful to avoid introducing a broad peak in the background distribution of $M_{\rm sig}$ arising from events that are inconsistent with the signal hypothesis. Then, we perform another 7C kinematic fit, referred to as the "7CA fit," by replacing the signal D_s^+ mass constraint with a D_s^* mass constraint in which the invariant mass of either the D_s^+ or D_s^- candidate and the selected $\gamma_{\rm direct}$ is constrained to the nominal D_s^* mass [5]. To ensure reasonable consistency with the signal hypothesis, the hypothesis with smaller 7CA χ^2 is selected. To suppress the background associated with the fake $\gamma_{\rm direct}$ candidates in the signal events, we veto events with $\cos\theta_\eta < 0.998$, where θ_η is the angle between the η momentum vector from a η mass constraint fit and that from the 7CA kinematic fit. After applying these criteria, we further reduce the background, by using a multivariable analysis method [14] in which a boosted decision tree (BDT) classifier is developed using the GMC sample. The BDT takes three discriminating variables as inputs: the invariant mass of the photon pair used to reconstruct the η candidate, the momentum of the lower-energy photon from the η candidate, and the momentum of the $\gamma_{\rm direct}$ candidate. Studies of the GMC sample show that a requirement on the output of the BDT retains 77.8% signal and rejects 73.4% background. Events in which the signal candidate lies within the interval $1.93 < M_{\rm sig} < 1.99$ GeV$/c^2$ are retained for the amplitude analysis. The background events in the signal region from the GMC sample are used to model the corresponding background in the data. To check the validity of the GMC background modeling, we compare the $M_{\pi^-\pi^0}$, $M_{\pi^+\eta}$, and $M_{\pi^0\eta}$ distributions of events outside the selected $M_{\rm sig}$ interval between the data and the GMC sample; the distributions are found to be compatible within the statistical uncertainties. We retain a sample of 1239 $D_s^+ \to \pi^+\pi^-\eta$ candidates that has a purity of $(97.7 \pm 0.5)\%$.

The amplitude analysis is performed using an unbinned maximum-likelihood fit to the accepted candidate events in the data. The background contribution is subtracted in the likelihood calculation by assigning negative weights to the background events. The total amplitude $\mathcal{M}(p_j)$ is modeled as the coherent sum of the amplitudes of all intermediate processes, $\mathcal{M}(p_j) = \sum c_n e^{i\phi_n} A_n(p_j)$, where c_n and ϕ_n are the magnitude and phase of the nth amplitude, respectively. The nth amplitude $A_n(p_j)$ is given by $A_n(p_j) = P_n S_n F_n^r F_n^D$. Here P_n is a function that describes the propagator of the intermediate resonance. The resonance ρ^+ is parametrized by a relativistic Breit-Wigner function, while the resonance $a_0(980)$ is parametrized as a two-channel-coupled Flatté formula ($\pi\eta$ and $K\bar{K}$), $P_{a_0(980)} = 1/[(m_0^2 - s_a) - i(g_{\eta\pi}^2\rho_{\eta\pi} + g_{K\bar{K}}^2\rho_{K\bar{K}})]$. Here, $\rho_{\eta\pi}$ and $\rho_{K\bar{K}}$ are the phase space factors: $2q/\sqrt{s_a}$, where q is denoted as the magnitude of the momentum of the daughter particle in the rest system and s_a is the invariant mass squared of $a_0(980)$. We use the coupling constants $g_{\eta\pi}^2 = 0.341 \pm 0.004$ GeV$^2/c^4$ and $g_{K\bar{K}}^2 = (0.892 \pm 0.022)g_{\eta\pi}^2$, reported in Ref. [15]. The function S_n describes angular-momentum conservation in the decay and is constructed using the covariant tensor formalism [16]. The function $F_n^{r(D)}$ is the Blatt-Weisskopf barrier factor of the intermediate state (D_s meson). To quantify the relative contribution of the nth intermediate process, the fit fraction (FF) is calculated with $\mathrm{FF}_n = \int |A_n|^2 d\Phi_3 / \int |\mathcal{M}|^2 d\Phi_3$, where $d\Phi_3$ is the standard element of the three-body phase space. Furthermore, according to the topology diagrams shown in Fig. 1, the W-annihilation amplitudes of the decays $D_s^+ \to a_0(980)^+\pi^0$ and $D_s^+ \to a_0(980)^0\pi^+$ imply the relationship $A(D_s^+ \to a_0(980)^+\pi^0) = -A(D_s^+ \to a_0(980)^0\pi^+)$.

For each amplitude, the statistical significance is determined from the change in log-likelihood and the number of degrees of freedom (NDOF) when the fit is performed with and without the amplitude included. In the nominal fit, only amplitudes that have a significance greater than 5σ are considered, where σ is the standard deviation. In addition to the $D_s^+ \to \rho^+\eta$ amplitude, both $D_s^+ \to a_0(980)^+\pi^0$ and $D_s^+ \to a_0(980)^0\pi^+$ amplitudes are found to be significant. In the fit, however, we notice that the latter two amplitudes have highly correlated phases; their c_n's are consistent with each other and the difference in ϕ_n is found to be close to π. The given FF of $D_s^+ \to a_0(980)^0\pi^+$ is greater than the expected $a_0(980)^0 - f_0(980)$ mixing effect [17] by 2 orders of magnitude. Consequently, in the nominal fit, we neglect the $a_0(980)^0 - f_0(980)$ mixing effect and set the values of c_n of these two amplitudes to be equal with a phase difference of π. We refer to the coherent sum of these two amplitudes as "$D_s^+ \to a_0(980)\pi$." The nonresonant process $D_s^+ \to (\pi^+\pi^0)_V\eta$ is also considered, where the subscript V denotes a vector nonresonant state of the $\pi^+\pi^0$ combination. We consider other possible amplitudes that involve $\rho(1450)$, $a_0(1450)$, $\pi_1(1400)$, $a_2(1320)$, or $a_2(1700)$, as well as the nonresonant partners; none of these amplitudes has a statistical significance greater than 2σ, so they are not included in the nominal model. In the fit, the values of c_n and ϕ_n for the $D_s^+ \to \rho^+\eta$ amplitude are fixed to be one and zero, respectively, so that all other amplitudes are measured relative to this amplitude. The masses and widths of the intermediate resonances used in the fit, except for those of the $a_0(980)$, are taken from Ref. [5].

For $D_s^+ \to \rho^+\eta$, $D_s^+ \to (\pi^+\pi^0)_V\eta$, and $D_s^+ \to a_0(980)\pi$, the resulting statistical significances are greater than 20σ, 5.7σ, and 16.2σ, respectively. Their phases and FFs are listed in Table I. The Dalitz plot of $M^2_{\pi^+\eta}$ vs $M^2_{\pi^0\eta}$ for the data is shown in Fig. 2(a). The projections of the fit on $M_{\pi^-\pi^0}$, $M_{\pi^+\eta}$, and $M_{\pi^0\eta}$ are shown in Figs. 2(b)–2(d). The projections on $M_{\pi^+\eta}$ and $M_{\pi^0\eta}$ for events with $M_{\pi^+\pi^0} > 1.0$ GeV$/c^2$ are shown in Figs. 2(e) and 2(f), in which $a_0(980)$ peaks are observed. The fit quality is determined by calculating the χ^2 of the fit using an adaptive binning of the $M^2_{\pi^+\eta}$ vs $M^2_{\pi^0\eta}$ Dalitz plot that requires each bin contains at least 10 events. The goodness of fit is $\chi^2/\mathrm{NDOF} = 82.8/77$.

TABLE I. Significance, ϕ_n, and FF_n for the intermediate processes in the nominal fit. The first and second uncertainties are statistical and systematic, respectively.

Amplitude	ϕ_n (rad)	FF_n
$D_s^+ \to \rho^+\eta$	0.0 (fixed)	$0.783 \pm 0.050 \pm 0.021$
$D_s^+ \to (\pi^+\pi^0)_V\eta$	$0.612 \pm 0.172 \pm 0.342$	$0.054 \pm 0.021 \pm 0.025$
$D_s^+ \to a_0(980)\pi$	$2.794 \pm 0.087 \pm 0.044$	$0.232 \pm 0.023 \pm 0.033$

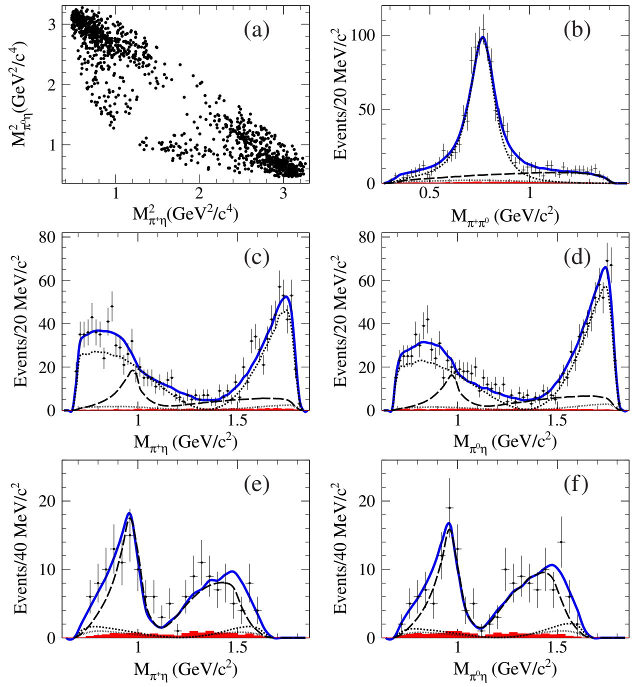

FIG. 2. (a) Dalitz plot of $M^2_{\pi^+\eta}$ vs $M^2_{\pi^0\eta}$ for data, the projections of the fit on (b) $M_{\pi^-\pi^0}$, (c) $M_{\pi^+\eta}$, and (d) $M_{\pi^0\eta}$, and the projections on (e) $M_{\pi^+\eta}$ and (f) $M_{\pi^0\eta}$ after requiring $M_{\pi^+\pi^0} > 1.0$ GeV$/c^2$. In (b)–(f), the dots with error bars and the solid line are data and the total fit, respectively; the dashed, dotted, and long-dashed lines are the contributions from $D_s^+ \to \rho^+\eta$, $D_s^+ \to (\pi^+\pi^0)_V\eta$, and $D_s^+ \to a_0(980)\pi$, respectively. The (red) hatched histograms are the simulated background.

Systematic uncertainties for the amplitude analysis are considered from five sources: (I) line shape parameterizations of the resonances, (II) fixed parameters in the amplitudes, (III) the background level and distribution in the Dalitz plot, (IV) experimental effects, and (V) the fitter performance. We determine these systematic uncertainties separately by taking the difference between the values of ϕ_n, and FF_n found by the altered and nominal fits. The uncertainties related to the assumed resonance line shape are estimated by using the following alternatives: a Gounaris-Sakurai function [21] for the ρ^+ propagator and a three-channel-coupled Flatté formula, which adds the $\pi\eta'$ channel [15], for the $a_0(980)$ propagator. Since varying the propagators results in different normalization factors, the effect on all FFs is considered. The uncertainties related to the fixed parameters in the amplitudes are considered by varying the mass and width of ρ^+ by $\pm 1\sigma$ [5], the mass and coupling constants of $a_0(980)$ by the uncertainties reported in Ref. [15], and the effect of varying the radii of the nonresonant state and D_s meson within ± 2 GeV^{-1}. In addition, for the ρ^+ resonance, the effective radius reported in Ref. [5] is used as an alternative. The uncertainty related to the assumed background level is determined by changing the background fraction within its statistical uncertainty. The uncertainty related to the assumed background shape is estimated by using an alternative distribution simulated with $D_s^+ \to \pi^+ f_0(980)$, $f_0(980) \to \pi^0\pi^0$. To estimate the uncertainty from the experimental effect related to the kinematic fits and BDT classifier, we alter the χ^2 requirements for the result of the two kinematic fits, the $\cos\theta_\eta$ requirement, and the BDT requirement such that the purity is approximately equal to the sample used in the nominal fit. The fitter performance is investigated with the same method as reported in Ref. [22]. The biases are small and taken as the systematic uncertainties. The contributions of individual systematic uncertainties are summarized in Table II, and are added in quadrature to obtain the total systematic uncertainty.

Further, we measure the total BF of $D_s^+ \to \pi^+\pi^0\eta$ without reconstructing $\gamma_{\rm direct}$ to improve the statistical precision. The ST yields ($Y_{\rm tag}$) and DT yield ($Y_{\rm sig}$) of data are determined by the fits to the resulting $M_{\rm tag}$ and $M_{\rm sig}$ distributions, as shown in Figs. 3(a)–3(g) and Fig. 3(h), respectively. In each fit, the signal shape is modeled with the MC-simulated shape convoluted with a Gaussian function, which accounts for any difference in resolution between data and MC calculations, and the background is described with a second-order Chebychev polynomial. These fits give a total ST yield of $Y_{\rm tag} = 255895 \pm 1358$ and a signal yield of $Y_{\rm sig} = 2626 \pm 77$. Based on the signal MC sample, generated according to the amplitude analysis results reported in this Letter, the DT efficiencies ($\epsilon_{\rm tag,sig}$) are determined. With $Y_{\rm tag}$, $Y_{\rm sig}$, $\epsilon_{\rm tag,sig}$, and the ST efficiencies ($\epsilon_{\rm tag}$), the relationship $\mathcal{B}(D_s^+ \to \pi^+\pi^0\eta) = (Y_{\rm sig}/\sum_i Y^i_{\rm tag}\epsilon^i_{\rm tag,sig}/\epsilon^i_{\rm tag})$, where the index i denotes the ith tag mode, is used to obtain $\mathcal{B}(D_s^+ \to \pi^+\pi^0\eta) = (9.50 \pm 0.28_{\rm stat})\%$.

TABLE II. Systematic uncertainties on the ϕ and FFs for different amplitudes, in units of the corresponding statistical uncertainties.

Amplitude		Source I	II	III	IV	V	Total
$D_s^+ \to \rho^+\eta$	FF	0.06	0.34	0.13	0.12	0.15	0.41
$D_s^+ \to (\pi^+\pi^0)_V\eta$	ϕ	$\cdots$	1.97	0.18	0.03	0.17	1.99
	FF	0.61	1.03	0.12	0.06	0.08	1.21
$D_s^+ \to a_0(980)\pi$	ϕ	$\cdots$	0.41	0.07	0.28	0.09	0.51
	FF	0.58	1.31	0.02	0.06	0.11	1.45

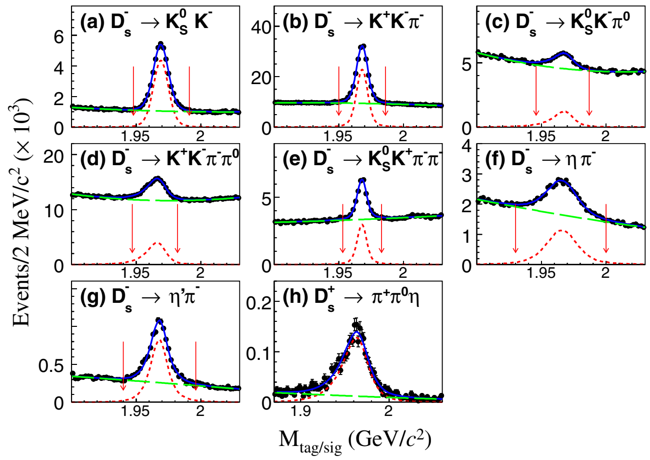

FIG. 3. Fits to (a)–(g) the $M_{\rm tag}$ distributions of seven tag modes (indicated in each sub-figure) and (h) the $M_{\rm sig}$ distribution of signal candidates. The dots with error bars are data. The (blue) solid lines are the total fit. The (red) dashed and the (green) long-dashed lines are signal and background, respectively. In (a)–(g), the D_s^- signal regions are between the arrows.

For the total BF measurement, the systematic uncertainty related to the signal shape is studied by performing an alternative fit without convolving the Gaussian resolution function. The BF shift of 0.5% is taken as the uncertainty. The systematic uncertainty arising from the assumed background shape and the fit range is studied by replacing our nominal ones with a first-order Chebychev polynomial and a fit range of $[1.88, 2.04]$ GeV$/c^2$, respectively. The largest BF shift of 0.6% is taken as the related uncertainty. The possible bias due to the measurement method is estimated to be 0.2% by comparing the measured BF in the GMC sample, using the same method as in data analysis, to the value assumed in the generation. The uncertainties from particle identification and tracking efficiencies are assigned to be 0.5% and 1.0% [13], respectively. The relative uncertainty in the π^0 reconstruction efficiency is 2.0% [13], and the uncertainty in η reconstruction is assumed to be comparable to that on π^0 reconstruction and correlated with it. The uncertainty from the Dalitz model of 0.6% is estimated as the change of efficiency when the model parameters are varied by their systematic uncertainties (this term is not considered when calculating the BFs of the intermediate processes). The uncertainties due to MC statistics (0.2%) and the value of $\mathcal{B}(\pi^0/\eta \to \gamma\gamma)$ used [5] (0.5%) are also considered. Adding these uncertainties in quadrature gives a total systematic uncertainty of 4.3%.

We obtain $\mathcal{B}(D_s^+ \to \pi^+\pi^0\eta)$ to be $(9.50 \pm 0.28_{\rm stat} \pm 0.41_{\rm sys})\%$. Using the FFs listed in Table I, the BFs for the intermediate processes $D_s^+ \to \rho^+\eta$ and $D_s^+ \to (\pi^+\pi^0)_V\eta$ are calculated to be $(7.44 \pm 0.52_{\rm stat} \pm 0.38_{\rm sys})\%$ and $(0.51 \pm 0.20_{\rm stat} \pm 0.25_{\rm sys})\%$, respectively. With the definition of the fit fraction, the fraction of $D_s^+ \to a_0(980)^{+(0)}\pi^{0(+)}$,

$a_0(980)^{+(0)} \to \pi^{+(0)}\eta$ with respect to the total fraction of $D_s^+ \to a_0(980)\pi, a_0(980) \to \pi\eta$ is evaluated to be 0.66. Multiplying by the FF of $D_s^+ \to a_0(980)\pi$ determined from the nominal fit and $\mathcal{B}(D_s^+ \to \pi^+\pi^0\eta)$, the BF of $D_s^+ \to a_0(980)^{+(0)}\pi^{0(+)}, a_0(980)^{+(0)} \to \pi^{+(0)}\eta$ is determined to be $(1.46 \pm 0.15_{\rm stat} \pm 0.23_{\rm sys})\%$.

In summary, we present the first amplitude analysis of the decay $D_s^+ \to \pi^+\pi^0\eta$. The absolute BF of $D_s^+ \to \pi^+\pi^0\eta$ is measured with a precision improved by a factor of 2.5 compared with the world average value [5]. We observe the pure WA decays $D_s^+ \to a_0(980)\pi$ for the first time with a statistical significance of 16.2σ. The measured $\mathcal{B}(D_s^+ \to a_0(980)^{+(0)}\pi^{0(+)})$ is larger than other measured BFs of pure WA decays $D_s^+ \to \omega\pi^+$ and $D_s^+ \to \rho^0\pi^+$ by at least one order of magnitude. Furthermore, when the measured $a_0(980)^0$-$f_0(980)$ mixing rate [18] is considered, the expected effect of $a_0(980)^0$-$f_0(980)$ mixing is lower than the WA contribution in $D_s^+ \to a_0(980)^0\pi^+$ decay by 2 orders of magnitude, make it negligible in this measurement.

With the measured $\mathcal{B}(D_s^+ \to a_0(980)^{+(0)}\pi^{0(+)})$, the WA contribution with respect to the tree-external-emission contribution in SP mode is estimated to be 0.84 ± 0.23 [23], which is significantly greater than that (0.1–0.2) in VP and PP modes [3,4]. This measurement sheds light on the FSI effect and nonperturbative effects of the strong interaction [1,4], and provides a theoretical challenge to understanding such a large WA contribution. In addition, the result of this analysis is an essential input to determine the effect from $a_0(980)^0$ on the K^+K^- S-wave contribution to the model-dependent amplitude analysis of $D_s^+ \to K^+K^-\pi^+$ [24,25].

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