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Observation of the Singly Cabibbo-Suppressed Decay $D^+ \to \omega\pi^+$ and Evidence for $D^0 \to \omega\pi^0$

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Based on 2.93 fb^{-1} e^+e^- collision data taken at center-of-mass energy of 3.773 GeV by the BESIII detector, we report searches for the singly Cabibbo-suppressed decays $D^+ \to \omega\pi^+$ and $D^0 \to \omega\pi^0$. A double tag technique is used to measure the absolute branching fractions $\mathcal{B}(D^+ \to \omega\pi^+) = (2.79 \pm 0.57 \pm 0.16) \times 10^{-4}$ and $\mathcal{B}(D^0 \to \omega\pi^0) = (1.17 \pm 0.34 \pm 0.07) \times 10^{-4}$, with statistical significances of 5.5σ and 4.1σ, where the first and second uncertainties are statistical and systematic, respectively.

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Hadronic decays of charm mesons provide important input for beauty physics and also open a window into the study of strong final state interactions. For Cabibbo-suppressed charm decays, precise measurements are challenging due to low statistics and high backgrounds. Among them, the singly Cabibbo-suppressed (SCS) decays $D^{+,0} \to \omega\pi^{+,0}$ have not yet been observed, and only upper limits on the branching fractions were set to be 3.4×10^{-4} and 2.6×10^{-4} at the 90% confidence level (C.L.) for $D^+ \to \omega\pi^+$ and $D^0 \to \omega\pi^0$, respectively, by the CLEO-c Collaboration [1] . Following the diagrammatic approach, the small decay rates may be caused by the destructive interference between the color-suppressed quark diagrams C_V and C_P [2]. Numerically, if W-annihilation contributions are neglected, the branching fractions of the $D \to \omega\pi$ decays should be at about 1.0×10^{-4} level [2, 3].

Besides searching for $D^{+,0} \to \omega\pi^{+,0}$, we also report measurements of the branching fractions for the decays $D^{+,0} \to \eta\pi^{+,0}$. Precise measurements of these decay rates can improve understanding of U-spin and $SU(3)$-flavor symmetry breaking effects in D decays, benefiting theoretical predictions of CP violation in D decays [4].

The data used has an integrated luminosity of 2.93 fb^{-1} [5] and was collected with the BESIII detector at the $\psi(3770)$ resonance ($\sqrt{s} \approx 3.773$ GeV). Details on the features and capabilities of the BESIII detector can be found in Ref. [6]. The response of the experimental apparatus is studied with a detailed GEANT-based [7] Monte Carlo (MC) simulation of the BESIII detector for particle trajectories generated by the generator KKMC [8] using EVTGEN [9], with initial state radiation (ISR) effects [10] and final state radiation effects [11] included. Simulated events are processed in a fashion similar to data. At the $\psi(3770)$ resonance, $D\bar{D}$ pairs are produced in a coherent 1^{--} final state with no additional particles. To suppress huge non-$D\bar{D}$ backgrounds [1], we employ the "double tag" (DT) technique first developed by the MARK-III Collaboration [12, 13] to perform absolute measurements of the branching fractions. We select "single tag" (ST) events in which either a D or $\bar{D}$ is fully reconstructed. We then look for the D decays of interest in the remainder of each event, namely, in DT events where both the D and $\bar{D}$ are fully reconstructed. The absolute branching fractions for D meson decays are calculated by the general formula

$$\mathcal{B}_{\rm sig} = \frac{\sum_\alpha N^{{\rm obs},\alpha}_{\rm sig}}{\sum_\alpha N^{{\rm obs},\alpha}_{\rm tag}\epsilon^\alpha_{\rm tag,sig}/\epsilon^\alpha_{\rm tag}}, \quad (1)$$

where α denotes different ST modes, $N^{{\rm obs},\alpha}_{\rm tag}$ is the yield of ST events for the tag mode α, $N^{{\rm obs},\alpha}_{\rm sig}$ is the corresponding yield of DT events, and $\epsilon^\alpha_{\rm tag}$ and $\epsilon^\alpha_{\rm tag,sig}$ are the ST and DT efficiencies for the tag mode α . Correlation between the reconstructions of D and $\bar{D}$ in an event has been considered in the efficiency determination.

The ST candidate events are selected by reconstructing a D^- or $\bar{D}^0$ in the following hadronic final states: $D^- \to K^+\pi^-\pi^-$, $K^+\pi^-\pi^-\pi^0$, $K^0_S\pi^-$, $K^0_S\pi^-\pi^0$, $K^0_S\pi^+\pi^-\pi^-$, $K^+K^-\pi^-$, and $\bar{D}^0 \to K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$, $K^+\pi^-\pi^0\pi^0$, $K^+\pi^-\pi^+\pi^-\pi^0$, comprising approximately 28.0% and 38.0% [14] of all D^- and $\bar{D}^0$ decays, respectively. For the signal side, we reconstruct $D^+ \to \omega\pi^+(\eta\pi^+)$ and $D^0 \to \omega\pi^0(\eta\pi^0)$, with $\omega(\eta) \to \pi^+\pi^-\pi^0$. Throughout the paper, charge-conjugate modes are implicitly implied, unless otherwise noted.

The reconstruction of D mesons uses charged particles, π^0s and K^0_Ss reconstructed with standard selection requirements [15]. To identify the reconstructed D candidates, we use two variables, the beam-constrained mass, $M_{\rm BC}$, and the energy difference, ΔE, which are defined as $M_{\rm BC} \equiv \sqrt{E^2_{\rm beam}/c^4 - |\vec{p}_D|^2/c^2}$, $\Delta E \equiv E_D - E_{\rm beam}$. Here, $\vec{p}_D$ and E_D are the reconstructed momentum and energy of the D candidate in the e^+e^- center-of-mass system, and $E_{\rm beam}$ is the beam energy. We accept D candidates with $M_{\rm BC}$ greater than 1.83 GeV/c^2 and with mode-dependent ΔE requirements of approximately three standard deviations. For the ST modes, we accept at most one candidate per mode per event; the candidate with the smallest $|\Delta E|$ is chosen [16].

To obtain ST yields, we fit the $M_{\rm BC}$ distributions of the accepted D candidates, as shown in Fig. 1. The signal shape which is modeled by MC shape convoluted with a Gaussian function includes the effects of beam energy spread, ISR, the $\psi(3770)$ line shape, and resolution. Combinatorial background is modeled by an ARGUS function [17]. With requirement of $1.866 < M^{\rm tag}_{\rm BC} < 1.874$ GeV/c^2 for D^+ case or $1.859 < M^{\rm tag}_{\rm BC} < 1.871$ GeV/c^2 for D^0 case, ST yields are calculated by subtracting the integrated ARGUS background yields within the signal region from the total event counts in this region. The tag efficiency is studied using MC samples following the same procedure. The ST yields in data and corresponding tag efficiencies are listed in Table I.

On the signal side we search for $D^+ \to \pi^+\pi^-\pi^0\pi^+$ and $D^0 \to \pi^+\pi^-\pi^0\pi^0$ modes containing an $\omega(\eta) \to \pi^+\pi^-\pi^0$ decay. For both D^+ and D^0 decays, two possible ω (η) combinations exist. Combinations with 3π mass in the interval $(0.4, 1.0)$ GeV/c^2 are considered. The chance that both ω (η) candidates combinations lie in this region is only about 0.3%, rendering this source of multiple candidates negligible.

With the DT technique, the continuum background $e^+e^- \to q\bar{q}$ is highly suppressed. The remaining background dominantly comes from $D\bar{D}$ events broadly populating the 3π mass window. To suppress the non-ω background, we require that the helicity, $H_\omega \equiv \cos\theta_{\rm H}$, of the ω have an absolute value larger than 0.54 (0.51) for D^+ (D^0). The angle θ_H is the opening angle between the direction of the normal to the $\omega \to 3\pi$ decay plane and direction of the D meson in the ω rest frame. True ω signal from D decays is longitudinally polarized so we expect a $\cos^2\theta_{\rm H} \equiv H^2_\omega$ distribution. To further suppress background from $D^{+,0} \to K^0_S\pi^+\pi^{0,-}$ with $K^0_S \to \pi^+\pi^-$, we apply a K^0_S veto by requiring $|M_{\pi^+\pi^-} - m^{\rm PDG}_{K^0_S}| > 12\ (9)$ MeV/c^2 for the D^+ (D^0) analysis. Here, $m^{\rm PDG}_{K^0_S}$ is the known K^0_S mass and $M_{\pi^+\pi^-}$ is calculated at the interaction point for simplicity.

After the above selection criteria, the signal region **S** for the DT candidates is defined as $1.866 < M_{\rm BC} < 1.874$ GeV/c^2 for the D^+ ($1.859 < M_{\rm BC} < 1.871$ GeV/c^2 for the D^0) in the two-dimensional (2D) $M^{\rm sig}_{\rm BC}$ versus $M^{\rm tag}_{\rm BC}$ plane,

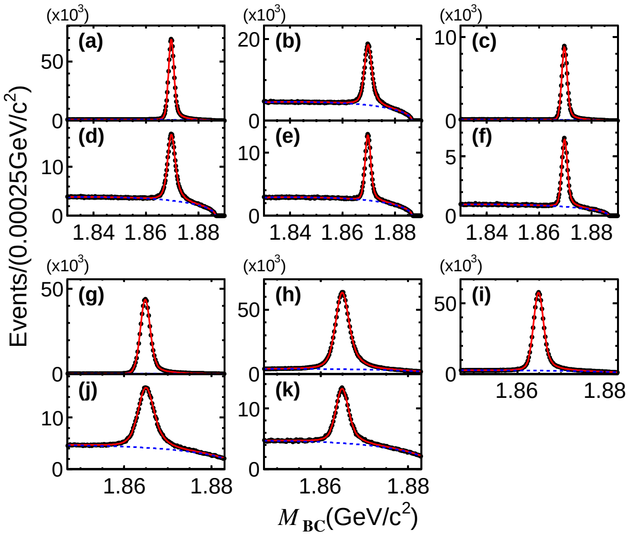

FIG. 1. $M_{\rm BC}$ distributions of ST samples for different tag modes. The first two rows show charged D decays: (a) $K^+\pi^-\pi^-$, (b) $K^+\pi^-\pi^-\pi^0$, (c) $K^0_S\pi^-$, (d) $K^0_S\pi^-\pi^0$, (e) $K^0_S\pi^+\pi^-\pi^-$, (f) $K^+K^-\pi^-$, the latter two rows show neutral D decays: (g) $K^+\pi^-$, (h) $K^+\pi^-\pi^0$, (i) $K^+\pi^-\pi^+\pi^-$, (j) $K^+\pi^-\pi^0\pi^0$, (k) $K^+\pi^-\pi^+\pi^-\pi^0$. Data are shown as points, the (red) solid lines are the total fits and the (blue) dashed lines are the background shapes. D and $\bar{D}$ candidates are combined.

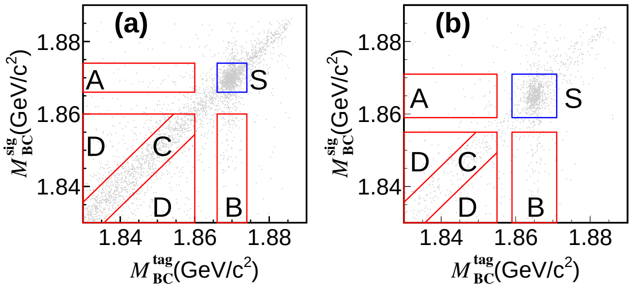

FIG. 2. 2D $M_{\rm BC}$ distributions for (a) $D^+ \to \omega\pi^+$ and (b) $D^0 \to \omega\pi^0$ with the signal (**S**) and sideband (**A, B, C, D**) regions used for background estimation indicated.

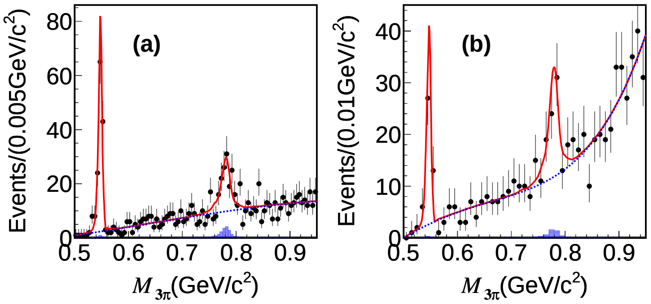

FIG. 3. Fits to the 3π mass spectra for (a) $D^+ \to \pi^+\pi^-\pi^0\pi^+$ and (b) $D^0 \to \pi^+\pi^-\pi^0\pi^0$ in the signal region **S** as defined in Fig. 2. Points are data; the (red) solid lines are the total fits; the (blue) dashed lines are the background shapes, and the hatched histograms are peaking background estimated from 2D $M_{\rm BC}$ sidebands.

as illustrated in Fig. 2. We also define sideband box regions to estimate potential background [18]. Sidebands **A** and **B** contain candidates where either the D or the $\bar{D}$ is misreconstructed. Sidebands **C** and **D** contain candidates where both D and $\bar{D}$ are misreconstructed, either in a correlated way (**C**), by assigning daughter particles to the wrong parent, or in an uncorrelated way (**D**).

TABLE I. ST data yields ($N^{\rm obs}_{\rm tag}$), ST ($\epsilon_{\rm tag}$) and DT ($\epsilon^{\omega}_{\rm tag,sig}$ and $\epsilon^{\eta}_{\rm tag,sig}$) efficiencies, and their statistical uncertainties. Branching fractions of the K^0_S and π^0 are not included in the efficiencies, but are included in the branching fraction calculations. The first six rows are for D^- and the last five are for $\bar{D}^0$.

Mode	ST Yields	$\epsilon_{\rm tag}$ (%)	$\epsilon^{\omega}_{\rm tag,sig}$(%)	$\epsilon^{\eta}_{\rm tag,sig}$(%)
$K^+\pi^-\pi^-$	772711 ± 895	48.76 ± 0.02	11.01 ± 0.15	12.64 ± 0.17
$K^+\pi^-\pi^-\pi^0$	226969 ± 608	23.19 ± 0.02	4.47 ± 0.10	5.26 ± 0.11
$K^0_S\pi^-$	95974 ± 315	52.35 ± 0.07	11.69 ± 0.18	13.99 ± 0.21
$K^0_S\pi^-\pi^0$	211872 ± 572	26.68 ± 0.03	5.35 ± 0.13	6.44 ± 0.14
$K^0_S\pi^-\pi^+\pi^-$	121801 ± 459	30.53 ± 0.04	6.16 ± 0.13	7.17 ± 0.15
$K^+K^-\pi^-$	65955 ± 306	38.72 ± 0.07	8.50 ± 0.13	9.76 ± 0.14
$K^+\pi^-$	529558 ± 745	64.79 ± 0.03	12.44 ± 0.16	14.17 ± 0.17
$K^+\pi^-\pi^0$	1044963 ± 1164	34.13 ± 0.01	5.73 ± 0.11	6.87 ± 0.12
$K^+\pi^-\pi^+\pi^-$	708523 ± 946	38.33 ± 0.02	6.04 ± 0.11	7.00 ± 0.13
$K^+\pi^-\pi^0\pi^0$	236719 ± 747	13.87 ± 0.02	1.78 ± 0.06	2.10 ± 0.07
$K^+\pi^-\pi^+\pi^-\pi^0$	152025 ± 684	15.55 ± 0.03	1.93 ± 0.06	2.08 ± 0.07

To obtain the $\omega(\eta)$ yield, we perform a fit to the $\pi^+\pi^-\pi^0$ invariant mass ($M_{3\pi}$) distribution with events in the signal region **S**. The $\omega(\eta)$ shape is modeled by the signal MC shape convoluted with a Gaussian function to describe the difference in the $M_{3\pi}$ resolution between MC and data. Due to high statistics, the width σ_η of the Gaussian for the η case is determined by the fit, while the width σ_ω for the ω case is constrained by the MC-determined ratio $R = \sigma^{\rm MC}_\omega/\sigma^{\rm MC}_\eta$ giving the relative $M_{3\pi}$ resolution for η and ω final states. For D^+, the background shape is described by a third-order Chebychev polynomial, while for D^0 we use a shape of $a_0M^{1/2}_{3\pi} + a_1M^{3/2}_{3\pi} + a_2M^{5/2}_{3\pi} + a_3M^{7/2}_{3\pi} + a_4M^{9/2}_{3\pi}$, where a_i ($i = 0, \ldots, 4$) are free parameters. The fit results are shown in Fig. 3, and the total ω yields N_ω for D^+ and D^0 cases are listed in Table II.

To estimate the $\omega(\eta)$ yield in the signal region **S** from background processes, event counts in sidebands **A**, **B**, and **C** are projected into the signal region **S** using scale factors determined from integrating the background shape in the ST $M_{\rm BC}$ fits. Contributions to sideband **D** are assumed to be uniformly distributed across the other regions [18]. For these events from the sideband regions, we perform similar fits to the 3π mass spectra, and find the peaking background yields $N^{\rm bkg}_{\omega(\eta)}$ for D^+

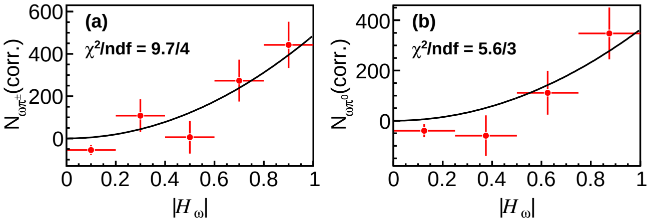

FIG. 4. Efficiency corrected yields versus $|H_\omega|$ for (a) $D^+ \to \omega\pi^+$ and (b) $D^0 \to \omega\pi^0$. Both are consistent with a distribution like $\cos^2\theta_H$ (black line).

and D^0 respectively, as listed in Table II. By subtracting the ω peaking background extending underneath the signal region, the DT signal yields, $N^{\rm obs}_{\rm sig}$, are obtained. The statistical significances for $D^+ \to \omega\pi^+$ and $D^0 \to \omega\pi^0$ are found to be 5.5σ and 4.1σ, respectively.

TABLE II. Summary for the total ω (η) yields ($N_{\omega(\eta)}$), $\omega(\eta)$ peaking background yields ($N^{\rm bkg}_{\omega(\eta)}$) and net DT yields ($N^{\rm obs}_{\rm sig}$) in the signal region **S** as defined in Fig. 2. $N^{\rm obs}_{\rm sig}$ is estimated from the defined sidebands. The errors are statistical.

Mode	$N_{\omega(\eta)}$	$N^{\rm bkg}_{\omega(\eta)}$	$N^{\rm obs}_{\rm sig}$
$D^+ \to \omega\pi^+$	100 ± 16	21 ± 4	79 ± 16
$D^0 \to \omega\pi^0$	50 ± 12	5 ± 5	45 ± 13
$D^+ \to \eta\pi^+$	264 ± 17	6 ± 2	258 ± 18
$D^0 \to \eta\pi^0$	78 ± 10	3 ± 2	75 ± 10

We now remove the ω helicity requirement, and investigate the helicity dependence of our signal yields. By following procedures similar to those described above, we obtain the signal yield in each $|H_\omega|$ bin. The efficiency corrected yields are shown in Fig. 4, demonstrating agreement with expected $\cos^2\theta_H$ behavior, further validating this analysis.

As shown in Fig. 3, the background level in the η signal region of the 3π invariant mass distribution is small compared to that near the ω mass. Therefore, to improve statistics, we remove the K^0_S veto requirements and also make no helicity requirement since $H_\eta \equiv \cos\theta_{\rm H}$ for signal is flat. Following a similar fit procedure, with results shown in Fig. 5, we determine $\eta\pi^+$ and $\eta\pi^0$ DT yields as listed in Table II.

With the DT technique, the branching fraction measurements are insensitive to systematics coming from the ST side since they mostly cancel. For the signal side, systematic uncertainties mainly come from imperfect knowledge of the efficiencies for tracking finding, PID criteria, the K^0_S veto, and the H_ω requirement; additional uncertainties are related to the fit procedures.

Possible differences in tracking, PID and π^0 reconstruction efficiencies between data and the MC simulations are investigated using a partial-reconstruction technique based on the control samples $D^0 \to K^-\pi^+\pi^0$ and $D^0 \to K^-\pi^+$. We assign uncertainties of 1.0% and 0.5% per track for track finding and PID, respectively, and 1.0% per reconstructed π^0.

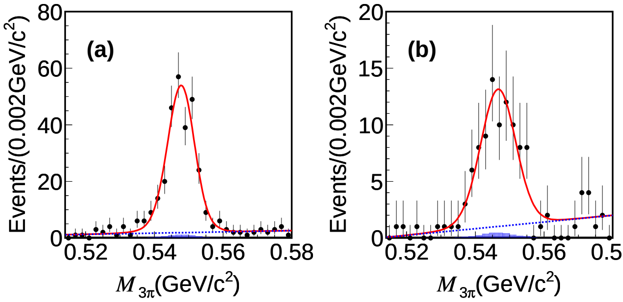

FIG. 5. Fits to the 3π mass spectra for (a) $D^+ \to \pi^+\pi^-\pi^0\pi^+$ and (b) $D^0 \to \pi^+\pi^-\pi^0\pi^0$ in the η mass region for the signal region **S** as defined in Fig. 2. Points are data; the (red) solid lines are the total fits; the (blue) dashed lines are the background shapes, and the hatched histograms are peaking background estimated from 2D $M_{\rm BC}$ sidebands.

Uncertainty due to the 2D signal region definition is investigated via the relative change in signal yields for different signal region definitions based on the control samples $D^+ \to K^0_S\pi^+\pi^0$ and $D^0 \to K^0_S\pi^0\pi^0$ which have the same pions in the final state as our signal modes. With the same control samples, uncertainties due to the ΔE requirements are also studied. The relative data-MC efficiency differences are taken as systematic uncertainties, as listed in Table III.

Uncertainty due to the $|H_\omega|$ requirement is studied using the control sample $D^0 \to K^0_S\omega$. The data-MC efficiency difference with or without this requirement is taken as our systematic. Uncertainty due to the K^0_S veto is similarly obtained with this control sample.

The ω peaking background is estimated from 2D $M_{\rm BC}$ sidebands. We change the sideband ranges by 2 MeV/c^2 for both sides and investigate the fluctuation on the signal yields, which is taken as a systematic uncertainty.

In the nominal fit to the $M_{3\pi}$ distribution, the ratio R, which is the relative difference on the $M_{3\pi}$ resolution between η and ω positions, is determined by MC simulations. With control samples $D^0 \to K^0_S\eta$ and $K^0_S\omega$, the difference between data and MC defined as $\delta R = R_{\rm data}/R_{\rm MC} - 1$ is obtained. We vary the nominal R value by $\pm1\sigma$ and take the relative change of signal yields as a systematic uncertainty.

Uncertainties due to the background shapes are investigated by changing the orders of the polynomials employed. Uncertainties due to the $M_{3\pi}$ fitting range are investigated by changing the range from $(0.50, 0.95)$ GeV/c^2 to $(0.48, 0.97)$ GeV/c^2 in the fits, yielding relative differences which are taken as systematic uncertainties.

We summarize the systematic uncertainties in Table III. The total effect is calculated by combining the uncertainties from all sources in quadrature.

Finally, the measured branching fractions of $D \to \omega\pi$ and

$\eta\pi$ are summarized in Table IV, where the first errors are statistical and the second ones are systematic.

In summary, we present the first observation of the SCS decay $D^+ \to \omega\pi^+$ with statistical significance of 5.5σ. We find the first evidence for the SCS decay $D^0 \to \omega\pi^0$ with statistical significance of 4.1σ. The results are consistent with the theoretical prediction [2], and can improve understanding of U-spin and $SU(3)$-flavor symmetry breaking effects in D decays [4]. We also present measurements of the branching fractions for $D^+ \to \eta\pi^+$ and $D^0 \to \eta\pi^0$ which are consistent with the previous measurements [19].

TABLE III. Summary of systematic uncertainties in %. Uncertainties which are not involved are denoted by "–".

Source	$\omega\pi^+$	$\omega\pi^0$	$\eta\pi^+$	$\eta\pi^0$
$\pi^\pm$ tracking	3.0	2.0	3.0	2.0
$\pi^\pm$ PID	1.5	1.0	1.5	1.0
π^0 reconstruction	1.0	2.0	1.0	2.0
2D $M_{\rm BC}$ window	0.1	0.2	0.1	0.2
ΔE requirement	0.5	1.6	0.5	1.6
$\lvert H_\omega \rvert$ requirement	3.4	3.4	–	–
K^0_S veto	0.8	0.8	–	–
Sideband regions	1.3	2.2	0.0	0.5
Signal resolution	0.9	0.9	–	–
Background shape	2.3	1.3	1.9	3.5
Fit range	0.3	1.9	0.8	1.5
$\mathcal{B}(\omega(\eta) \to \pi^+\pi^-\pi^0)$ [14]	0.8	0.8	1.2	1.2
Overall	5.8	6.0	4.3	5.3

TABLE IV. Summary of branching fraction measurements, and comparison with the previous measurements [1, 19].

Mode	This work	Previous measurements
$D^+ \to \omega\pi^+$	$(2.79 \pm 0.57 \pm 0.16) \times 10^{-4}$	$< 3.4 \times 10^{-4}$ at 90% C.L.
$D^0 \to \omega\pi^0$	$(1.17 \pm 0.34 \pm 0.07) \times 10^{-4}$	$< 2.6 \times 10^{-4}$ at 90% C.L.
$D^+ \to \eta\pi^+$	$(3.07 \pm 0.22 \pm 0.13) \times 10^{-3}$	$(3.53 \pm 0.21) \times 10^{-3}$
$D^0 \to \eta\pi^0$	$(0.65 \pm 0.09 \pm 0.04) \times 10^{-3}$	$(0.68 \pm 0.07) \times 10^{-3}$

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