Suplemento de la Revista Mexicana de Física **3** 0308048 (2022) 1–6

Doubly cabibbo-suppressed D decays at BESIII

Xiang Pan (For BESIII Collaboration)
Fudan University, Shanghai, China.
e-mail: xpan19@fudan.edu.cn

Received 11 December 2021; accepted 18 February 2022

BESIII reports the first observation of the doubly Cabibbo-Suppressed decay $D^+ \to K^+\pi^+\pi^-\pi^0$ and the first evidence for $D^+ \to K^+\omega$ using an e^+e^- collision data sample corresponding to an integrated luminosity of 2.93 fb^{-1} taken at a center-of-mass energy of 3.773 GeV. The ratio of the branching fractions of $D^+ \to K^+\pi^+\pi^-\pi^0$ over $D^+ \to K^-\pi^+\pi^+\pi^0$ is significantly larger than other doubly Cabibbo-Suppressed decays in the charm sector. The CP asymmetry in the separated charge-conjugate branching fractions for $D^+ \to K^+\pi^+\pi^-\pi^0$ is determined and no evidence of CP violation is found. An independent measurement of $D^+ \to K^+\pi^+\pi^-\pi^0$ with semileptonic tags is also reported.

Keywords: Charm physics; Hadronic decays; CP violation; Branching fractions; BESIII.

DOI: https://doi.org/10.31349/SuplRevMexFis.3.0308048

1. Introduction

Doubly Cabibbo-suppressed (DCS) decays in charm sector play an important role in the understanding of the weak decay mechanisms of charmed hadrons. Compared with the Cabibbo-favored (CF) and singly Cabibbo-suppressed (SCS) decays, the branching fraction (BF) of the DCS decay is expected to be much smaller and only fewer DCS decays have been observed to date [1]. The ratio of DCS to its relative CF counterpart BFs is simply expected to be of the order $\tan^4\theta_C \sim 0.29\%$ [2,3], where θ_C is the Cabibbo mixing angle [1]. This expectation is roughly supported by the known rates of DCS and CF decays [1]. Precise measurement of the BF of $D^+ \to K^+\pi^+\pi^-\pi^0$ and the rate with its CF counterpart can offer a crucial check of this expectation.

Measurements of the BFs of $D \to VP$ decays (V and P refer to vector and pseudoscalar mesons, respectively) provide insight into quark SU(3)-flavor symmetry and charge-parity (CP) violation [3–8]. Study of the DCS decay $D^+ \to K^+\pi^+\pi^-\pi^0$ offers an ideal opportunity to determine the BF of $D^+ \to K^+\omega$. The result is important to improve the understanding of quark SU(3)-flavor symmetry and symmetry breaking, and also benefits theoretical calculations of CP violation [3–8].

In the Standard Model (SM), the direct CP violation is predicted in D decays, *e.g.*, due to a single irreducible phase in the Cabibbo-Kobayashi-Maskawa matrix [9]. In the charm sector, CP violation for SCS processes is expected to be small ($\sim 10^{-3}$), and much smaller for CF and DCS processes [7,10]. Searching for CP violation in DCS decays allows for more comprehensive understanding of CP violation in the D sector.

BESIII has collected 2.93 fb^{-1} of e^+e^- collision data at the center-of-mass energy of 3.773 GeV. This data sample provides the world largest threshold $D\bar{D}$ sample and an ideal experimental platform to study the DCS decays. Simulated samples produced with the GEANT4-based [11] Monte Carlo (MC) package which includes the geometric description of the BESIII detector and the detector response. The MC samples are generally used in the charm physics of BESIII [12,13].

2. Measurements of $D^+ \to K^+\pi^+\pi^-\pi^0$

Taking the advantage of the pair production of $D\bar{D}$ from the data sample, the DCS decay can be studied with the double-tag (DT) technique. Events where one D^- meson is fully reconstructed are referred to as "single-tag" (ST) candidates. A correct tag guarantees the presence of the other D^+ meson, and we search for the signal decays recoiling against a tagged D^- meson. Events with both a tag and such a signal-mode candidate are referred to as "double-tag" (DT) events. In this article, we report two methods to measure the BF of $D^+ \to K^+\pi^+\pi^-\pi^0$. Charge-conjugated decays are always implied except when discussing CP violation.

2.1. Hadronic tags

Hadronic decays are the dominant decay channels of D^- meson [1] and widely used as the tagged channels in D physics [12, 13]. In the first method, the ST D^- meson is reconstructed in one of the three hadronic decay modes $D^- \to K^+\pi^-\pi^-$, $D^- \to K^0_S\pi^-$, and $D^- \to K^+\pi^-\pi^-\pi^0$. The BF of the signal decay is determined according to

$$\mathcal{B}_{\rm sig} = \frac{N_{\rm DT}}{N_{\rm ST}\epsilon_{\rm sig}\mathcal{B}_{\rm sub}}, \tag{1}$$

where $N_{\rm ST}$, $N_{\rm DT}$, $\epsilon_{\rm sig}$, and $\mathcal{B}_{\rm sub}$ are the ST yield, DT yield, average efficiency of reconstructing the signal decay, and the BF of $\pi^0 \to \gamma\gamma$ [1], respectively. $\epsilon_{\rm sig}$ is weighted by the measured yields of tag modes i in data which is given by

$$\epsilon_{\rm sig} = \frac{\left(\sum_{i=1}^{3} N^i_{\rm ST}\epsilon^i_{\rm DT}/\epsilon^i_{\rm ST}\right)}{\left(\sum_{i=1}^{3} N^i_{\rm ST}\right)}. \tag{2}$$

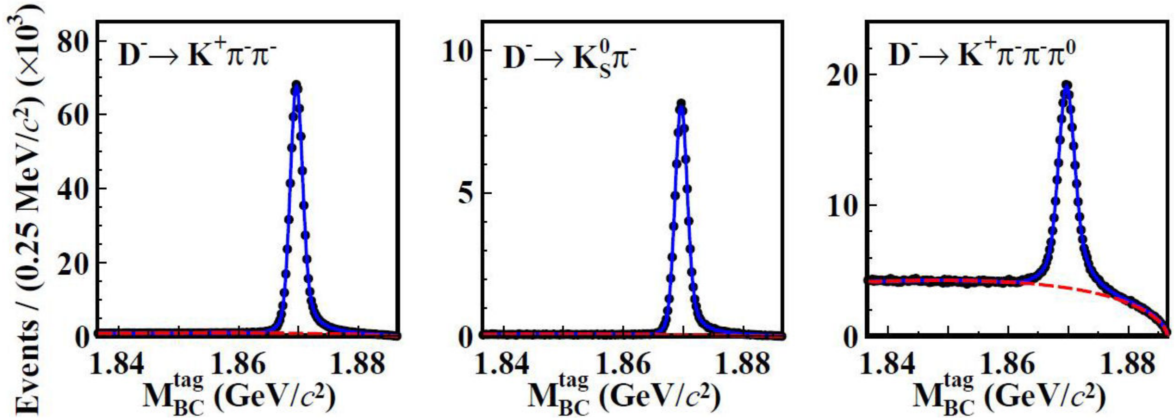

FIGURE 1. Fits to the $M_{\rm BC}$ distributions of the D^- tagging decay modes. Data are shown as dots with error bars. The blue solid and red dashed curves are the fit results and the fitted backgrounds, respectively.

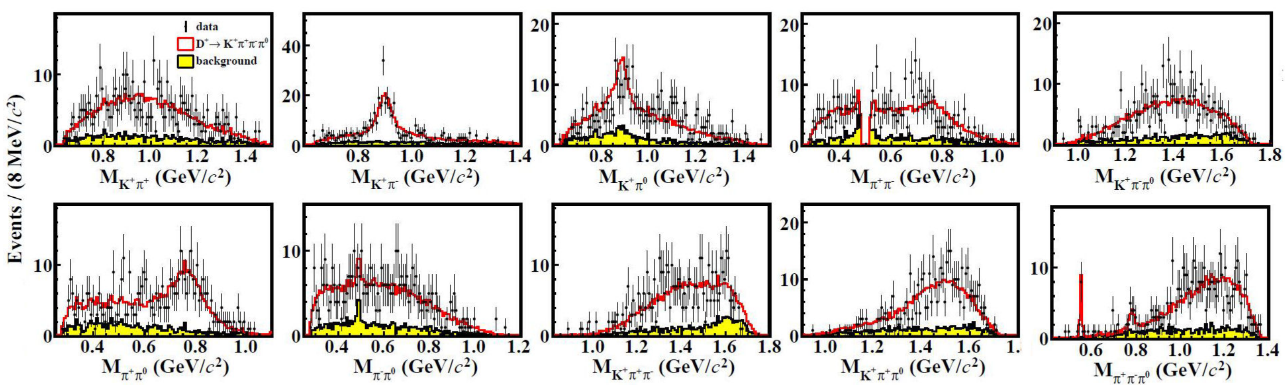

FIGURE 2. Comparison of two-body and three-body mass distributions of the $D^+ \to K^+\pi^+\pi^-\pi^0$ candidate events between data (dots with error bars) and inclusive MC sample (red histograms). The yellow hatched histograms denote the MC-simulated backgrounds.

The ST yields are obtained from maximum likelihood fits to the $M_{\rm BC}^{\rm tag}$ distributions of the accepted ST candidates [12,13], where the $M_{\rm BC}^{\rm tag}$ is defined by $M_{\rm BC}^{\rm tag} \equiv \sqrt{E_b^2 - |\vec{p}_{D^-}|^2}$, E_b and $\vec{p}_{D^-}$ are the beam energy and the momentum of D^- candidate in the e^+e^- rest frame. The fit results are shown in Fig. 1. The total ST D^- yield is $N_{\rm ST} = (1150.3 \pm 1.5) \times 10^3$.

The signal D^+ candidates are identified using the $M_{\rm BC}$ distribution of the signal side. The dominant peaking background from the singly Cabibbo-Suppressed decay $D^+ \to K_S^0 K^+\pi^0$ has been rejected by requiring $|M_{\pi^+\pi^-} - M_{K_S^0}| > 20$ MeV/c^2. Figure 2 shows the comparison of two-body and three-body invariant mass distributions for the $D^+ \to K^+\pi^+\pi^-\pi^0$ candidate events.

Figure 3 shows the comparison of the $M_{\pi^+\pi^-\pi^0}$ distributions between data and MC simulation. The signal peak of $D^+ \to K^+\eta$ is clearly seen in Fig. 3. Since the $D^+ \to K^+\eta$ has been well measured by BESIII and 439 ± 72 signal events are observed, where η is reconstructed by $\gamma\gamma$ and ST method is used [14], we do not report $D^+ \to K^+\eta$ in this article. The definitions of the ω signal and sideband regions are shown in Fig. 3.

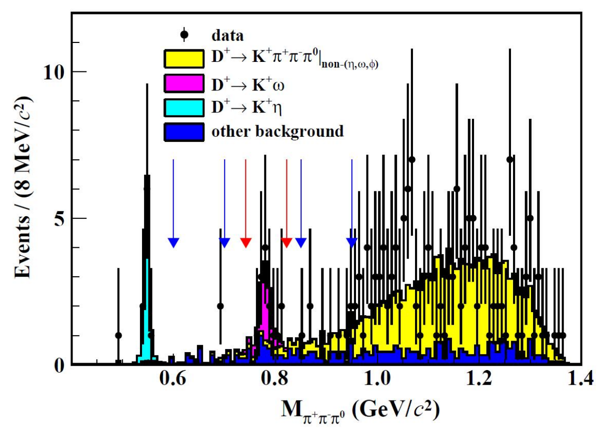

FIGURE 3. Distribution of $M_{\pi^+\pi^-\pi^0}$ for $D^+ \to K^+\pi^+\pi^-\pi^0$ candidates in data. The red arrows denote the ω signal region. The blue arrows denote the ω sideband regions.

The left column of Fig. 4 shows the distributions of $M_{\rm BC}^{\rm tag}$ vs. $M_{\rm BC}^{\rm sig}$ for DT candidate events in data. Signal events and three categories of backgrounds are discussed below:

- Signal events concentrate around $M_{\rm BC}^{\rm tag} = M_{\rm BC}^{\rm sig} = M_{D^+}$, where M_{D^+} is the nominal mass of the D^+ meson [1].

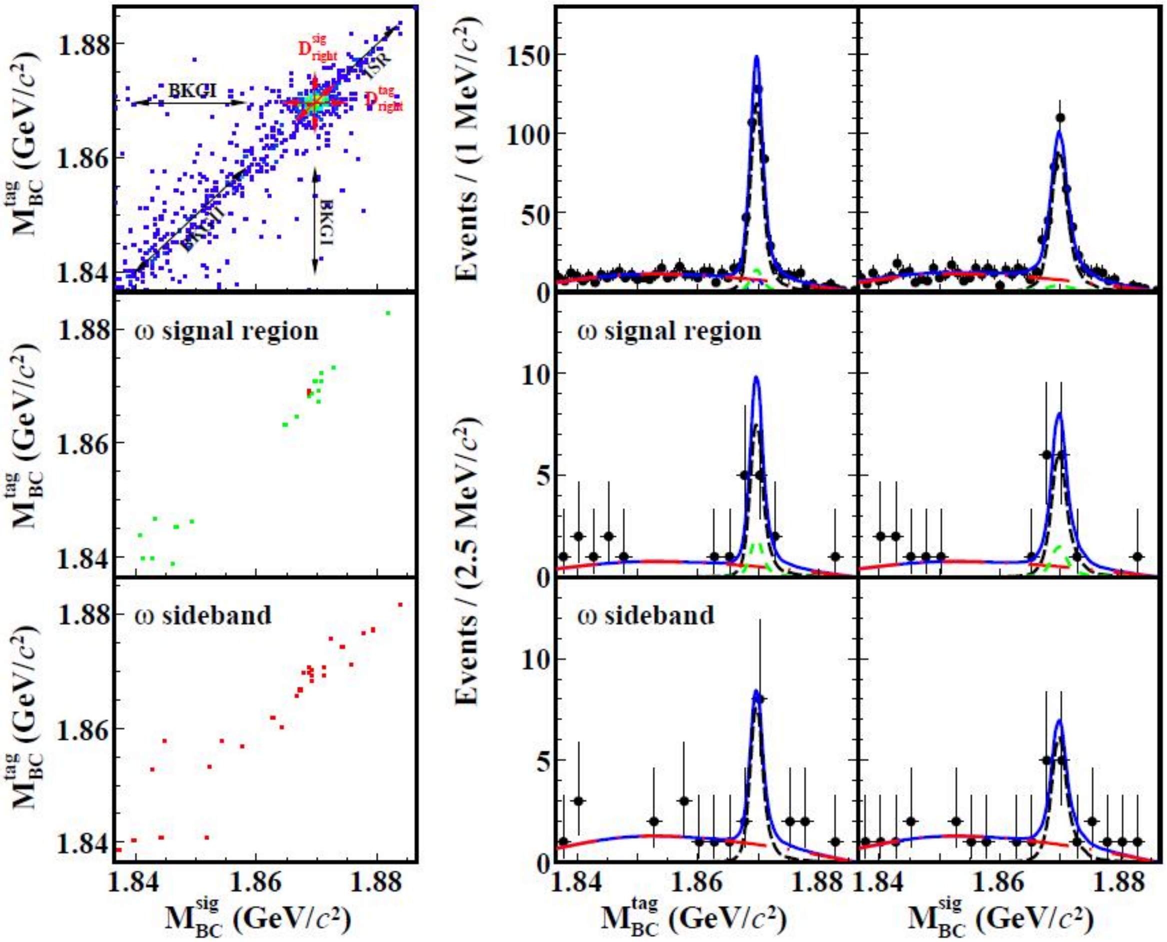

FIGURE 4. Distributions of (left column) $M_{\rm BC}^{\rm tag}$ vs. $M_{\rm BC}^{\rm sig}$, and the projections of the corresponding 2D fits on (middle column) $M_{\rm BC}^{\rm tag}$ and (right column) $M_{\rm BC}^{\rm sig}$, for the DT candidate events of $D^-\to$ all tags vs. $D^+\to K^+\pi^+\pi^-\pi^0$. The top, middle, and bottom rows correspond to all events, events lying in ω signal region, and those falling in ω sideband region, respectively. In the figures of the middle and right columns, data are shown as dots with error bars; the blue solid, black dashed, blue dot-dashed, red dot-long-dashed, and green dashed curves denote the overall fit results, signal, BKGI, BKGII, and peaking background components, respectively.

- BKGI is from the events with one $D^{+/-}$ meson reconstructed correctly and another $D^{-/+}$ meson reconstructed incorrectly, which distributed along the horizontal and vertical bands.

- BKGII is mainly from the $e^+e^-\to q\bar{q}$ processes and the events found along the diagonal.

- BKGIII is the events in which both the two D mesons are reconstructed incorrectly.

Peaking backgrounds in the decay $D^+\to K^+\pi^+\pi^-\pi^0$ is from $D^+\to K^+K^-(\to\pi^-\pi^0)\pi^+$ decays and from the residual $D^+\to K_S^0(\to\pi^+\pi^-)K^+\pi^0$ events, which are evaluated using the MC simulations. For the decay $D^+\to K^+\omega$, the peaking background contributions are dominated by the non-ω decays $D^+\to K^+\pi^+\pi^-\pi^0$.

The DT yields are determined by performing a two-dimensional (2D) unbinned maximum likelihood fit on the corresponding $M_{\rm BC}^{\rm tag}$ vs. $M_{\rm BC}^{\rm sig}$ distribution. For the decay $D^+\to K^+\omega$, simultaneous 2D fits are performed on the events in the ω signal and sideband regions.

The fit results as well as the BFs are summarized in Table I, and the projections on $M_{\rm BC}^{\rm tag}$ and $M_{\rm BC}^{\rm sig}$ of the 2D fits to data are shown in the middle and right columns in Fig. 4. The statistical significance of $D^+\to K^+\pi^+\pi^-\pi^0$ and $D^+\to K^+\omega$ are found to be 23.3σ and 3.3σ, respectively.

Using the world averaged BF for $D^+\to K^-\pi^+\pi^+\pi^0$ [1], we determine the ratio of $\mathcal{B}^*_{D^+\to K^+\pi^+\pi^-\pi^0}$ over $\mathcal{B}_{D^+\to K^-\pi^+\pi^+\pi^0}$ to be $(1.81\pm0.15)\%$, corresponding to $(6.28\pm0.52)\tan^4\theta_C$, which is significantly larger than the values (0.21-0.58)% for the other DCS decays [1]. This unexpected ratio implies that there may be a massive isospin symmetry violation in the decays $D^+\to K^+\pi^+\pi^-\pi^0$ and $D^0\to K^+\pi^-\pi^-\pi^+$, which may be caused by final state interactions and very different resonance structures in these two decays.

The BF for the decay $D^+\to K^+\omega$ is consistent with theoretical predictions that incorporate quark SU(3)-flavor sym-

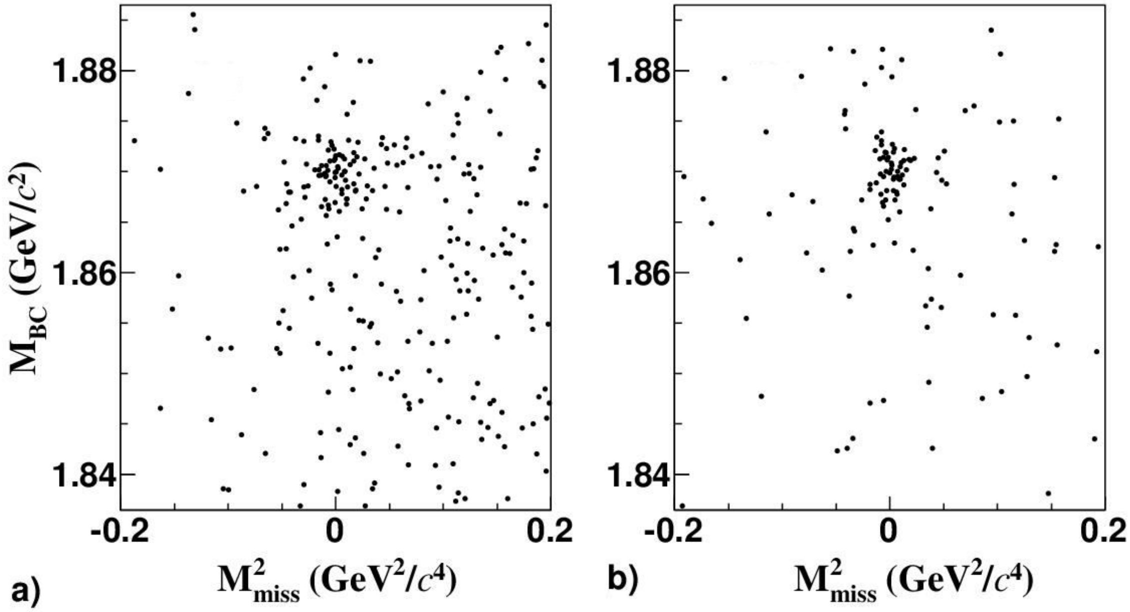

FIGURE 5. Distributions of $M_{\rm BC}$ vs. $M^2_{\rm miss}$ of the accepted DT candidate events tagged by (a) $D^- \to K^0 e^- \bar{\nu}_e$ and (b) $D^- \to K^+\pi^- e^- \bar{\nu}_e$ in data.

TABLE I. The ST yields ($N_{\rm ST}$), the DT yields ($N_{\rm DT}$), the averaged signal efficiencies ($\epsilon_{\rm sig}$), and the obtained BFs before ($\mathcal{B}_{\rm sig}$) and after ($\mathcal{B}^*_{\rm sig}$) removing the contribution from $D^+ \to K^+\eta$, $K^+\omega$, and $K^+\phi$ [15].

Decay channel	$N_{\rm ST}$ $(\times 10^3)$	$N_{\rm DT}$	$\epsilon_{\rm sig}$ (%)	$\mathcal{B}_{\rm sig}$ $(\times 10^{-3})$	$\mathcal{B}^*_{\rm sig}$ $(\times 10^{-3})$
$D^\pm \to K^\pm\pi^\pm\pi^\mp\pi^0$	1150.3 ± 1.5	350 ± 22	25.03 ± 0.13	$1.21 \pm 0.08 \pm 0.03$	$1.13 \pm 0.08 \pm 0.03$
$D^\pm \to K^\pm\omega$	1150.3 ± 1.5	$9.2^{+4.0}_{-3.4}$	14.14 ± 0.09	$(5.7^{+2.5}_{-2.1} \pm 0.2)\ \times 10^{-2}$	-
$D^+ \to K^+\pi^+\pi^-\pi^0$	573.5 ± 1.0	181 ± 15	25.20 ± 0.18	$1.25 \pm 0.11 \pm 0.03$	$1.17 \pm 0.11 \pm 0.03$
$D^- \to K^-\pi^-\pi^+\pi^0$	572.7 ± 1.0	165 ± 15	24.95 ± 0.18	$1.16 \pm 0.11 \pm 0.03$	$1.08 \pm 0.11 \pm 0.03$

metry and symmetry breaking [4], but disfavors predictions based on quark SU(3)-flavor symmetry without symmetry breaking [5] and predictions based on the pole model [16] by 1.8–2.8σ. This result will benefit future calculations of CP violation in the charm sector [3–9].

The CP asymmetry of $D^+ \to K^+\pi^+\pi^-\pi^0$ is determined by

$$\mathcal{A}_{CP}{}^{D^\pm \to K^\pm\pi^\pm\pi^\mp\pi^0} = \frac{\mathcal{B}_{D^+\to K^+\pi^+\pi^-\pi^0} - \mathcal{B}_{D^-\to K^-\pi^-\pi^+\pi^0}}{\mathcal{B}_{D^+\to K^+\pi^+\pi^-\pi^0} + \mathcal{B}_{D^-\to K^-\pi^-\pi^+\pi^0}}, \tag{3}$$

where $\mathcal{B}_{D^+\to K^+\pi^+\pi^-\pi^0}$ and $\mathcal{B}_{D^-\to K^-\pi^-\pi^+\pi^0}$ are the BFs of the charge-conjugated decays $D^+ \to K^+\pi^+\pi^-\pi^0$ and $D^- \to K^-\pi^-\pi^+\pi^0$, which are measured separately. The last two rows of Table I summarize the corresponding ST yields, DT yields, signal efficiencies, and the obtained BFs. The $\mathcal{A}_{CP}^{D^\pm \to K^\pm\pi^\pm\pi^\mp\pi^0}$ is determined to be $(-0.04 \pm 0.06_{\rm stat} \pm 0.01_{\rm syst})$ after considering the correlated systematic uncertainties of tracking and PID of the $\pi^+\pi^-$ pair, π^0 reconstruction, quoted BFs, and MC modeling. No evidence for CP violation is found.

2.2. Semileptonic tags

In the measurements of DCS D^0 decays using e^+e^- collision data taken at the $\psi(3770)$ resonance peak, hadronic tagged method suffers from complicated cross feeds between the events of CF $\bar{D}^0 \to {\rm tag}$ vs. DCS $D^0 \to {\rm signal}$ and those from DCS $D^0 \to {\rm tag}$ vs. CF $\bar{D}^0 \to {\rm signal}$. This is mainly due to there is possible interference between the DCS and CF amplitudes for hadronic neutral D decays. We introduce and utilize a method using semileptonic $D^- \to K^0 e^- \nu_e$ and $D^- \to K^+\pi^- e^- \nu_e$ decays to tag the DCS D decays. This new technique helps to avoid the aforementioned troubles because the semileptonic D^0 decays have no DCS component and the $D^0 - \bar{D}^0$ mixing [17, 18] effect is small.

For each of the two semileptonic tags, the BF for $D^+ \to K^+\pi^+\pi^-\pi^0$ can be determined by

$$\mathcal{B}_{\rm sig} = \frac{N_{\rm SL,sig}}{2 \cdot N_{D^+D^-} \cdot \mathcal{B}_{\rm SL} \cdot \epsilon_{\rm SL,sig} \cdot \mathcal{B}_{\rm sub}}, \tag{4}$$

where $N_{\rm SL,sig}$ is the yield of the signal DT events in the data sample, $N_{D^+D^-} = (8296 \pm 31 \pm 65) \times 10^3$ is the total number of D^+D^- pairs [19], $B_{\rm SL}$ is the BF for the semileptonic decay [1], $\epsilon_{\rm SL,sig}$ is the efficiency of reconstructing the DT

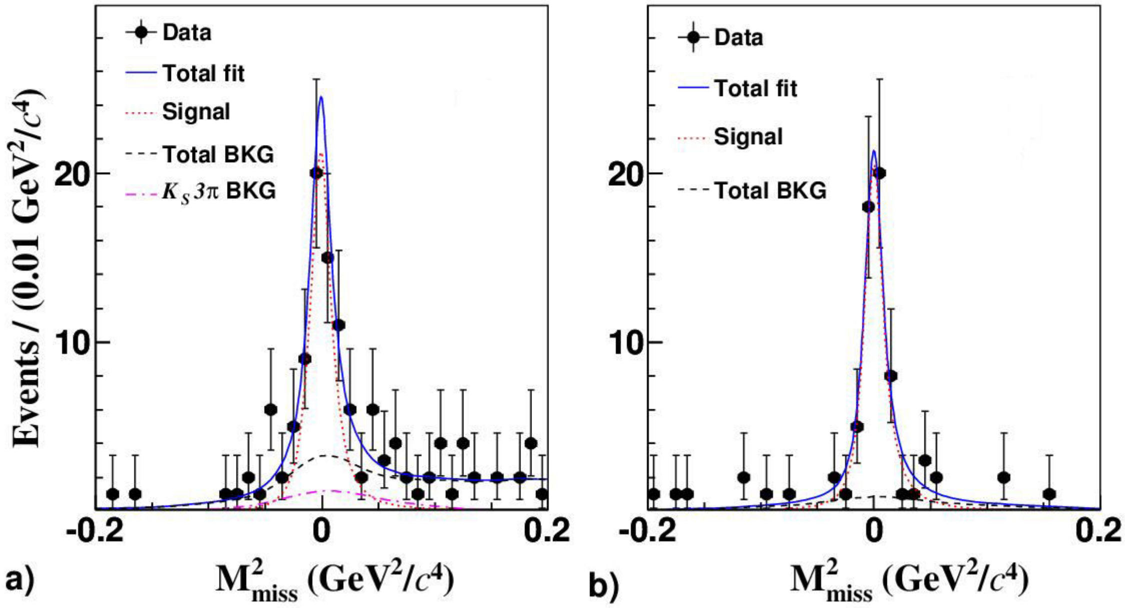

FIGURE 6. Simultaneous fits to the $M^2_{\rm miss}$ distributions of the accepted DT candidate events tagged by (a) $D^- \to K^0 e^- \bar{\nu}_e$ and (b) $D^- \to K^+\pi^- e^- \bar{\nu}_e$.

events, $B_{\rm sub}$ is the BFs $\mathcal{B}_{\pi^0\to\gamma\gamma}$ and $\mathcal{B}_{K^0\to\pi^+\pi^-}$. Throughout this section, charge conjugate modes are implied. Information concerning the undetectable neutrino is inferred by the kinematic quantity defined as

$$M^2_{\rm miss} \equiv E^2_{\rm miss} - |\vec{p}_{\rm miss}|^2, \qquad (5)$$

where $E_{\rm miss}$ and $\vec{p}_{\rm miss}$ are the missing energy and momentum of the DT event in the e^+e^- center-of-mass system.

The distributions of $M_{\rm BC}$ vs. $M^2_{\rm miss}$ for the DT candidates in data are shown in Fig. 5. The signal DT candidate events concentrate around the D^+ known mass and zero.

The signal yield is extracted by the unbinned maximum likelihood simultaneous fits on the $M^2_{\rm miss}$ distributions for the two semileptonic tags. In the fit, the two semileptonic tags are constrained to have the same BF for $D^+ \to K^+\pi^+\pi^-\pi^0$. The fit results are shown in Fig. 6. The fits give a total yield of 112 ± 12 for signal DT events. Using the signal MC events, the efficiencies of reconstructing the DT events $D^- \to K^0 e^- \nu_e$ and $D^- \to K^+\pi^- e^- \nu_e$ are obtained to be 0.103 ± 0.001 and 0.076 ± 0.001, respectively, where the efficiencies do not include the BFs for $K^0 \to \pi^+\pi^-$ and $\pi^0 \to \gamma\gamma$. The BF is determined to be $\mathcal{B}(D^+ \to K^+\pi^+\pi^-\pi^0) = (1.03 \pm 0.12 \pm 0.06) \times 10^{-3}$ after subtracting the sum of the product BFs for decays containing narrow intermediate resonances, $D^+ \to K^+ X$ ($X = \eta, \omega, \phi$) with $X \to \pi^+\pi^-\pi^0$. This result is consistent with the one tagged by hadronic tags.

2.3. Combined results

After considering the correlated uncertainties of $K^\pm$, $\pi^+\pi^-$ tracking and PID, π^0 reconstruction, and MC model, the averaged BFs of $D^+ \to K^+\pi^+\pi^-\pi^0$ measured by two tagged methods are determined to be $\bar{\mathcal{B}}_{D^+\to K^+\pi^+\pi^-\pi^0} = (1.10 \pm 0.07 \pm 0.03)\%$. The ratio of $\mathcal{B}_{D^+\to K^+\pi^+\pi^-\pi^0}/\mathcal{B}_{D^+\to K^-\pi^+\pi^+\pi^0}$ is determined to be $(1.76 \pm 0.13)\%$, corresponding to $(6.11 \pm 0.52)\tan^4\theta_C$.

3. Summary and Outlook

BESIII reports the first observation of the DCS decay $D^+ \to K^+\pi^+\pi^-\pi^0$ and the first evidence for $D^+ \to K^+\omega$. The BF of $D^+ \to K^+\pi^+\pi^-\pi^0$ is the largest among the known DCS D decays. The ratio of $\mathcal{B}_{D^+\to K^+\pi^+\pi^-\pi^0}/\mathcal{B}_{D^+\to K^-\pi^+\pi^+\pi^0}$ is determined to be $(6.11 \pm 0.52)\tan^4\theta_C$, which is significantly larger than the values (0.21-0.58)% for the other DCS decays in charm sector. No evidence for CP violation is found in $D^\pm \to K^\pm\pi^\pm\pi^\mp\pi^0$.

In the near future, BESIII plan to collect another 17 fb^{-1} e^+e^- collision data sample at $\sqrt{s} = 3.773$ GeV [20]. With larger data samples, amplitude analyses of this decay will provide crucial information for understanding the origin of the anomalously large ratio. Meanwhile, more other DCS decays, $D^+ \to K^+\eta$, $D^0 \to K^+\pi^-\eta$, $D^+ \to K^+\eta\eta$, etc., will also be studied and help to check the theoretical prediction [3,5].

1. P. A. Zyla *et al.* (Particle Data Group), *Prog. Theor. Exp. Phys.* **2020** (2020) 083C01. https://academic.oup.com/ptep/article/2020/8/083C01/5891211
2. H. J. Lipkin, *Nucl. Phys. Suppl.* **115** (2003) 117. https://www.sciencedirect.com/science/article/pii/S0920563202019655?via%3Dihub
3. H. Y. Cheng and C. W. Chiang, *Phys. Rev. D* **81** (2010) 074021. https://journals.aps.org/prd/abstract/10.1103/PhysRevD.81.074021
4. Q. Qin, H. N. Li, C. D. Lü, and F. S. Yu, *Phys. Rev. D* **89** (2014) 054006. https://journals.aps.org/prd/abstract/10.1103/PhysRevD.89.054006.
5. H. Y. Cheng, C. W. Chiang, and A. L. Kuo, *Phys. Rev. D* **93** (2016) 114010. https://journals.aps.org/prd/abstract/10.1103/PhysRevD.93.114010.
6. Y. Grossman and D. J. Robinson, *J. High Energy Phys.* **1304** (2013) 067. https://doi.org/10.1007/JHEP04(2013)067.
7. H. N. Li, C. D. Lü, and F. S. Yu, *Phys. Rev. D* **86** (2012) 036012. https://journals.aps.org/prd/abstract/10.1103/PhysRevD.86.036012
8. M. Saur and F. S. Yu, arXiv:2002.12088. https://arxiv.org/abs/2002.12088
9. M. Kobayashi and T. Maskawa, *Prog. Theor. Phys.* **49** (1973) 652. https://academic.oup.com/ptp/article/49/2/652/1858101
10. H. Y. Cheng and C. W. Chiang, *Phys. Rev. D* **86** (2012) 014014. https://journals.aps.org/prd/abstract/10.1103/PhysRevD.86.014014
11. S. Agostinelli *et al.* (GEANT4 Collaboration), *Nucl. Instrum. Meth. A* **506** (2003) 250. https://doi.org/10.1016/S0168-9002(03)01368-8
12. M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. Lett.* **121** (2018) 171803. https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.121.171803
13. M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. Lett.* **123** (2019) 231801. https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.123.231801
14. M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. D* **97** (2018) 072004. https://journals.aps.org/prd/abstract/10.1103/PhysRevD.97.072004
15. This contribution is calculated by $\sum_{\mathcal{R}=1}^{3}\left[\mathcal{B}(D^+\to K^+\mathcal{R})\cdot\mathcal{B}(\mathcal{R}\to\pi^+\pi^-\pi^0)\right]$, where $\mathcal{R}$ sums over η, ω, and ϕ, $\mathcal{B}(D^+\to K^+\omega)$ is obtained in this work, and the other BFs are quoted from the PDG [1].
16. F. S. Yu, X. X. Wang, and C. D. Lü, *Phys. Rev. D* **84** (2011) 074019. https://journals.aps.org/prd/abstract/10.1103/PhysRevD.84.074019
17. Z. Z. Xing, *Phys. Rev. D* **55** (1997) 196. https://journals.aps.org/prd/abstract/10.1103/PhysRevD.55.196
18. J. Libby *et al. Phys. Lett. B* **731** (2014) 197. https://www.sciencedirect.com/science/article/pii/S0370269314001233?via%3Dihub
19. M. Ablikim *et al.* (BESIII Collaboration), **Chin. Phys. C 42** (2018) 083001. https://iopscience.iop.org/article/10.1088/1674-1137/42/8/083001
20. M. Ablikim *et al.* (BESIII Collaboration), *Chin. Phys. C* **44** (2020) 040001. https://doi.org/10.1088/1674-1137/44/4/040001.