

Measurements of the absolute branching fractions of the doubly Cabibbo-suppressed decays $D^+ \rightarrow K^+\pi^0$, $D^+ \rightarrow K^+\eta$ and $D^+ \rightarrow K^+\eta'$



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ABSTRACT: Using 20.3 fb^{-1} of e^+e^- collision data collected at a center-of-mass energy of 3.773 GeV with the BESIII detector, we present the measurements of the absolute branching fractions of the doubly Cabibbo-suppressed decays $D^+ \rightarrow K^+\pi^0$, $D^+ \rightarrow K^+\eta$ and $D^+ \rightarrow K^+\eta'$ with the double-tag method, with significantly improved precision compared to the previous measurements. The statistical significance of each signal decay exceeds 10σ . The branching fractions are determined to be $\mathcal{B}(D^+ \rightarrow K^+\pi^0) = (1.45 \pm 0.06 \pm 0.08) \times 10^{-4}$, $\mathcal{B}(D^+ \rightarrow K^+\eta) = (1.17 \pm 0.10 \pm 0.03) \times 10^{-4}$ and $\mathcal{B}(D^+ \rightarrow K^+\eta') = (1.88 \pm 0.15 \pm 0.11) \times 10^{-4}$, where the first uncertainties are statistical and the second systematic. The branching fractions of $D^+ \rightarrow K^+\eta$ and $D^+ \rightarrow K^+\eta'$ are consistent with the world average values. The reported branching fraction of $D^+ \rightarrow K^+\pi^0$ deviates with the world average value by 3σ .

KEYWORDS: Branching fraction, Charm Physics, e^+e^- Experiments

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1 Introduction

Studies of doubly Cabibbo-suppressed (DCS) decays of charmed mesons are important for the understanding of charmed hadron dynamics. In theory, the branching fractions (BFs) of the two-body decays $D \rightarrow PP$ and $D \rightarrow VP$, where V and P denote vector and pseudoscalar mesons, respectively, can be calculated by incorporating quark SU(3)-flavor symmetry and symmetry breaking as well as charge-parity (CP) violation [1–6]. These decay amplitudes are typically decomposed using topology amplitudes [7]. Compared to Cabibbo-favored and singly Cabibbo-suppressed D decays, experimental information on DCS decays $D \rightarrow PP$ remains limited. Improved measurements of the BFs of these decays are able to provide valuable insights into charmed meson decays [1–7].

Previous measurements by CLEO, Belle, BaBar, and BESIII [8–12] have determined the BFs of the DCS decays $D^+ \rightarrow K^+\pi^0$, $D^+ \rightarrow K^+\eta$ and $D^+ \rightarrow K^+\eta'$. Both CLEO and BESIII measurements are based on $\psi(3770)$ data with single-tag (ST) method which suffers from high backgrounds, while Belle and BaBar employed relative methods with data on and near the $\Upsilon(4S)$ resonance [9, 10].

This paper reports the measurements of the absolute BFs of the DCS decays $D^+ \rightarrow K^+\pi^0$, $D^+ \rightarrow K^+\eta$ and $D^+ \rightarrow K^+\eta'$ using the double-tag (DT) method [13, 14], with significantly improved precision compared to the previous measurements. Charge-conjugated decays are implied. The obtained BFs of $D^+ \rightarrow K^+\eta$ and $D^+ \rightarrow K^+\eta'$ are consistent with the world average values, while the BF of $D^+ \rightarrow K^+\pi^0$ deviates with the world average value by 3σ . This work is performed by using 20.3 fb^{-1} of e^+e^- collision data [15] collected with the BESIII detector at a center-of-mass energy of $\sqrt{s} = 3.773 \text{ GeV}$. This energy corresponds to the $\psi(3770)$ resonance, which predominantly decays into $D\bar{D}$ (D denotes D^0 or D^+) pairs. The D and \bar{D} mesons are produced without accompanying hadron(s), thereby offering an ideal environment to study D meson decays with the DT technique.

2 BESIII detector and Monte Carlo simulation

The BESIII detector [16] records symmetric e^+e^- collisions provided by the BEPCII storage ring [17] in the center-of-mass energy range from 1.84 to 4.95 GeV, with a peak luminosity of $1.1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ achieved at $\sqrt{s} = 3.773 \text{ GeV}$. The cylindrical core of the BESIII detector covers 93% of the full solid angle and consists of a helium-based multilayer drift chamber (MDC), a plastic scintillator time-of-flight system (TOF), and a CsI(Tl) electromagnetic calorimeter (EMC), which are all enclosed in a superconducting solenoidal magnet providing a 1.0 T magnetic field. The solenoid is supported by an octagonal flux-return yoke with resistive plate counter muon identification modules interleaved with steel. The charged-particle momentum resolution at 1 GeV/c is 0.5%, and the dE/dx resolution is 6% for electrons from Bhabha scattering. The EMC measures photon energies with a resolution of 2.5% (5%) at 1 GeV in the barrel (end cap) region. The time resolution in the TOF barrel region is 68 ps, while that in the end cap region was 110 ps. The end-cap TOF system was upgraded in 2015 using multi-gap resistive plate chamber technology, providing a time resolution of 60 ps [18], which benefits about 85% of the data used in this analysis. Details about the design and performance of the BESIII detector are given in ref. [16].

Simulated samples produced with a GEANT4-based [19] Monte Carlo (MC) package, which includes the geometric description of the BESIII detector and the detector response, are used to determine the detection efficiency and to estimate backgrounds. The simulation includes the beam energy spread and initial state radiation (ISR) in the e^+e^- annihilations modeled with the generator KKMC [20]. The signal decays $D^+ \rightarrow K^+\pi^0$, $D^+ \rightarrow K^+\eta$ and $D^+ \rightarrow K^+\eta'$ are simulated to distribute uniformly in the available phase space. The decays $\eta' \rightarrow \pi^+\pi^-\eta$ and $\eta' \rightarrow \pi^+\pi^-\gamma$ are simulated by using a specific generator developed with the amplitude analysis result [21–23]. The background is studied using an inclusive MC sample that consists of the production of $D\bar{D}$ pairs with consideration of quantum coherence for all neutral D modes, the non- $D\bar{D}$ decays of the $\psi(3770)$, the ISR production of the J/ψ and $\psi(3686)$ states, and the continuum processes incorporated in KKMC. The known decay modes are modeled with EVTGEN [21–23] using the known BFs taken from the Particle Data Group (PDG) [12], while the remaining unknown decays from the charmonium states are modeled with LUNDCHARM [24]. Final state radiation from charged final state particles is incorporated with the PHOTOS package [25].

3 Measurement method and single tag yields

Signal D^+ decays are reconstructed in events where D^- decays are also reconstructed through three hadronic decay modes: $D^- \rightarrow K^+\pi^-\pi^-$, $D^- \rightarrow K_S^0\pi^-$, and $D^- \rightarrow K^+\pi^-\pi^-\pi^0$. The K_S^0 and π^0 candidates are reconstructed via $K_S^0 \rightarrow \pi^+\pi^-$ and $\pi^0 \rightarrow \gamma\gamma$, respectively. Selection criteria for K^\pm , π^\pm , K_S^0 and π^0 follow ref. [26]. If a D^- meson is found, it is referred to as an ST candidate. An event in which a signal D^+ decay and an ST D^- are simultaneously reconstructed is referred to as a DT event. The BF of the signal decay is determined as

$$\mathcal{B}(\text{sig}) = \frac{N_{\text{DT}}}{\sum_{i=1}^3 N_{\text{ST}}^i (\epsilon_{\text{DT}}^i / \epsilon_{\text{ST}}^i)}, \quad (3.1)$$

Tag mode	ΔE (MeV)	$N_{ST} (\times 10^3)$	$\epsilon_{ST}(\%)$
$K^+\pi^-\pi^-$	$[-25, 24]$	5526.6 ± 2.5	51.07 ± 0.01
$K_S^0\pi^-$	$[-25, 26]$	656.5 ± 0.8	51.42 ± 0.01
$K^+\pi^-\pi^-\pi^0$	$[-57, 46]$	1740.2 ± 1.8	24.53 ± 0.01

Table 1. Requirement on ΔE , ST D^- yields in data and ST efficiencies (ϵ_{ST}) [26].

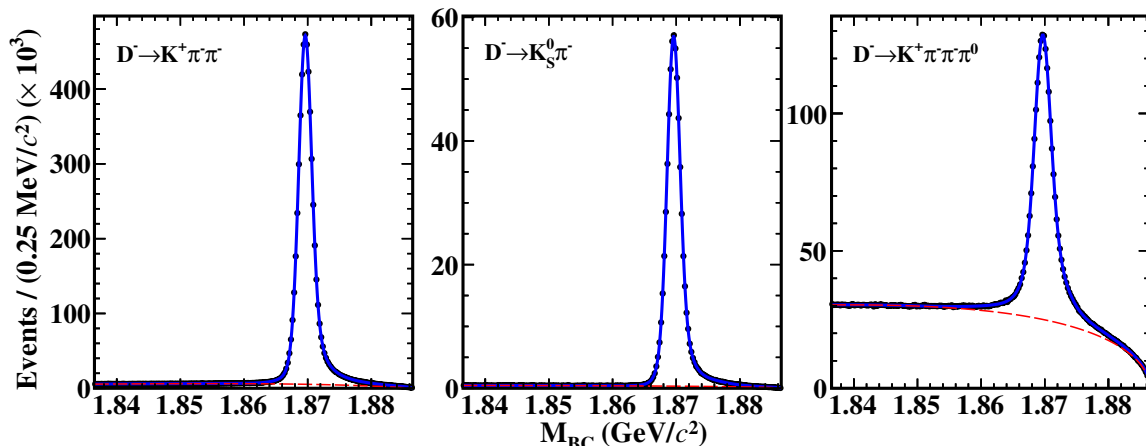


Figure 1. Fits to the M_{BC} distributions of the ST D^- candidates. The dots with error bars are data, and the blue solid and red dashed curves are the fit results and the fitted backgrounds, respectively.

where N_{DT} is the number of DT events, ϵ_{DT}^i is the efficiency of detecting DT events including the sub-BFs, N_{ST}^i is the number of ST D^- mesons, ϵ_{ST}^i is the corresponding ST efficiency for the i -th tag mode.

The tagged D^- mesons are selected using two variables: the energy difference

$$\Delta E_{\text{tag}} \equiv E_{D^-} - E_b, \quad (3.2)$$

and the beam-constrained mass

$$M_{BC}^{\text{tag}} \equiv \sqrt{E_b^2 - |\vec{p}_{D^-}|^2}, \quad (3.3)$$

where E_b is the beam energy, and \vec{p}_{D^-} and E_{D^-} candidates are the momentum and the energy of the D^- candidate in the e^+e^- rest frame. For each tag mode, if there are multiple combinations, the one with the minimum $|\Delta E_{\text{tag}}|$ is retained for further analysis. For the tag modes $D^- \rightarrow K^+\pi^-\pi^-$, $D^- \rightarrow K_S^0\pi^-$ and $D^- \rightarrow K^+\pi^-\pi^-\pi^0$, the tagged D^- candidates are required to satisfy $\Delta E_{\text{tag}} \in (-25, 24)$, $(-25, 25)$ and $(-57, 46)$ MeV, respectively. The yields of ST D^- mesons are obtained from maximum likelihood fits to the M_{BC}^{tag} distributions of the accepted ST candidates, as shown in table 1. The fit results are shown in figure 1. The long tails of high side in each figure are mainly due to the ISR and final state radiation effects; while that in low side for figure 1(c) is mainly due to energy loss of photons. The total ST D^- yield is $N_{ST} = (8131.7 \pm 3.3) \times 10^3$.

The signal D^+ candidates are reconstructed from the particles not used in the tagged D^- reconstruction. The K_S^0 , π^0 and η candidates are reconstructed via the decays $K_S^0 \rightarrow \pi^+\pi^-$,

$\pi^0 \rightarrow \gamma\gamma$ and $\eta \rightarrow \gamma\gamma$, respectively. The selection criteria for K^\pm , π^\pm , K_S^0 , π^0 and η are the same as those in ref. [26]. The η' signal regions are defined as $|M_{\pi^+\pi^-\eta} - 0.958| < 0.012 \text{ GeV}/c^2$ and $|M_{\pi^+\pi^-\gamma} - 0.958| < 0.020 \text{ GeV}/c^2$. The corresponding sideband regions are $0.020 < |M_{\pi^+\pi^-\eta} - 0.958| < 0.044 \text{ GeV}/c^2$ and $0.030 < |M_{\pi^+\pi^-\gamma} - 0.958| < 0.070 \text{ GeV}/c^2$.

The energy difference (ΔE_{sig}) and beam-constrained mass ($M_{\text{BC}}^{\text{sig}}$) are used to select signal D^+ candidates. These quantities are calculated similarly to eqs. (3.2) and (3.3), respectively, with D^- replaced by D^+ . If there are multiple combinations, primarily due to incorrect π^0 reconstruction, the combination with the minimum $|\Delta E_{\text{sig}}|$ is retained for further analysis. The signal side is required to satisfy $\Delta E_{\text{sig}} \in (-72, 49), (-43, 41), (-32, 31)$ and $(-43, 40) \text{ MeV}$ for $D^+ \rightarrow K^+\pi^0$, $D^+ \rightarrow K^+\eta$, $D^+ \rightarrow K^+\eta'_{\pi^+\pi^-\eta}$ and $D^+ \rightarrow K^+\eta'_{\pi^+\pi^-\gamma}$.

The $D^+ \rightarrow K^+\pi^0$ candidates are required to have no additional π^0 meson to suppress the peaking background from $D^+ \rightarrow \pi^+\pi^0\pi^0$. To further reject possible K_S^0 background, a veto window $|M_{\pi^+\pi^-} - 0.498| > 0.012 \text{ GeV}/c^2$ is applied for $D^+ \rightarrow K^+\eta'(\pi^+\pi^-\gamma)$ candidates.

To suppress non- D^+D^- events, such as $\psi(3770) \rightarrow D^0\bar{D}^0 \rightarrow K^+\pi^-K_S^0\eta$ for $D^+ \rightarrow K^+\pi^0$ and $D^+ \rightarrow K^+\eta$ channels, $\psi(3770) \rightarrow D^0\bar{D}^0 \rightarrow K^+\pi^-K_S^0\eta'$ and $\psi(3770) \rightarrow D^0\bar{D}^0 \rightarrow K^+K^+\pi^+\pi^-\pi^-\pi^-$ for $D^+ \rightarrow K^+\eta'_{\pi^+\pi^-\eta}$ and $D^+ \rightarrow K^+\eta'_{\pi^+\pi^-\gamma}$ channels, respectively, The opening angle between the D^+ and D^- candidates is required to be greater than 160° . The left panels of figures 2 and 3 show the $M_{\text{BC}}^{\text{tag}}$ versus $M_{\text{BC}}^{\text{sig}}$ distributions of the accepted candidates for $D^+ \rightarrow K^+\pi^0$, $D^+ \rightarrow K^+\eta$, $D^+ \rightarrow K^+\eta'_{\pi^+\pi^-\eta}$ and $D^+ \rightarrow K^+\eta'_{\pi^+\pi^-\gamma}$ in data.

4 Signal yields and branching fractions

The yields of DT events are extracted from a two-dimensional (2D) extended unbinned maximum likelihood fit to the corresponding distribution of $M_{\text{BC}}^{\text{tag}}$ versus $M_{\text{BC}}^{\text{sig}}$ [27–29]. The signal shape is described by a 2D probability density function (PDF) from the MC simulation after convolved with a Gaussian resolution function with parameters derived from data. For various background components, the individual PDFs are constructed as follows: [27–29]

- BKGI: $b(x) \cdot c_y(y; E_b, \xi_y) + b(y) \cdot c_x(x; E_b, \xi_x)$,
- BKGII: $c_z(z; \sqrt{2}E_b, \xi_z) \cdot g(k; 0, \sigma_k)$,
- BKGIII: $c_x(x; E_b, \xi_x) \cdot c_y(y; E_b, \xi_y)$.

Here, $x = M_{\text{BC}}^{\text{tag}}$, $y = M_{\text{BC}}^{\text{sig}}$, $z = (x + y)/\sqrt{2}$, and $k = (x - y)/\sqrt{2}$. The functions $b(x)$ and $b(y)$ are the one-dimensional signal shapes taken from the MC simulation. The function c_f is an ARGUS function [30] defined as

$$c_f(f; E_b, \xi_f) = A_f f \left(1 - \frac{f^2}{E_b^2}\right)^{\frac{1}{2}} e^{-\xi_f \left(1 - \frac{f^2}{E_b^2}\right)}, \quad (4.1)$$

where f denotes x , y , or z , E_b is fixed at 1.8865 GeV , A_f is a normalization factor, and ξ_f is a fit parameter. The function $g(k; \sigma_k)$ is a Gaussian distribution with a mean of zero and a standard deviation $\sigma_k = \sigma_0 \cdot (\sqrt{2}E_b - z)^p$, where σ_0 and p are free parameters in the fit. All other parameters are left free to vary. The three types of background are illustrated as one curve in figures 2 and 3. For $D^+ \rightarrow K^+\pi^0$, the peaking background yield, including $\pi^+\pi^0$

Signal decay	$D^+ \rightarrow K^+\pi^0$	$D^+ \rightarrow K^+\eta$	$D^+ \rightarrow K^+\eta'$
N_{DT}	629 ± 28	182 ± 15	214 ± 17
$\epsilon_{\text{DT}}/\epsilon_{\text{ST}}$ (%)	53.29 ± 0.36	19.20 ± 0.13	14.02 ± 0.11
\mathcal{B}_{sig} ($\times 10^{-4}$)	1.45 ± 0.06	1.17 ± 0.10	1.88 ± 0.15

Table 2. The numbers used in the BF calculations. N_{DT} is the fitted number of the DT events in data, $\epsilon_{\text{DT}}/\epsilon_{\text{ST}}$ is the efficiency of detecting the signal decay in the presence of the ST D^- , which includes BFs of the intermediate states. \mathcal{B}_{sig} is the BF of signal decay, where the uncertainties are statistical only.

and $K_S^0\pi^+$, is fixed at the value estimated from the inclusive MC samples. Furthermore, for $D^+ \rightarrow K^+\eta'(\pi^+\pi^-\eta)$ and $D^+ \rightarrow K^+\eta'(\pi^+\pi^-\gamma)$, a simultaneous fit is performed to extract the BF as a shared parameter. The contribution from the $D^+ \rightarrow K^+\eta'(\pi^+\pi^-\gamma)$ sideband regions is used to estimate the numbers of non $\eta'(\pi^+\pi^-\gamma)$ background events and is re-normalized to the signal region in the fit procedure. The contribution from the $D^+ \rightarrow K^+\eta'(\pi^+\pi^-\eta)$ sideband regions is neglected since only one event survives after event selection.

The spectra in the middle and right columns in figures 2 and 3 show the projections on $M_{\text{BC}}^{\text{tag}}$ and $M_{\text{BC}}^{\text{sig}}$ of the 2D fits to data. For each signal decay, the statistical significance is evaluated as $\sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{\text{max}})}$, where \mathcal{L}_{max} is the maximum likelihood of the nominal fit and \mathcal{L}_0 is the likelihood of the fit without including the signal. The change of the number of degrees of freedom is assumed to be 5 for $K^+\pi^0$ and $K^+\eta$ decay mode, representing the signal yield. The change of the number of degrees of freedom is assumed to be 7 for $K^+\eta'$, representing the signal yield of $K^+\eta'(\pi^+\pi^-\eta)$, the signal yield of $K^+\eta'(\pi^+\pi^-\gamma)$ and the shared parameter for the BF of $D^+ \rightarrow K^+\eta'$. The statistical significance of each signal decay exceeds 10σ . The detailed ST, DT and DT/ST efficiencies are shown in table 3. The signal yields in data, the detection efficiencies, and the obtained BFs of each signal decay are summarized in table 2.

5 Systematic uncertainty

With the DT method, most of the uncertainties related to the ST selection cancel out. The systematic uncertainties arise from the following sources and are estimated relative to the measured BFs.

The uncertainty of the total ST D^- yield is due to the fit to the $M_{\text{BC}}^{\text{tag}}$ distributions and is assigned as 0.3% [26].

The tracking or particle identification (PID) efficiencies of K^+ and π^\pm are estimated by analyzing DT $D^+ \rightarrow K^-\pi^+\pi^+$ versus $D^- \rightarrow K^+\pi^-\pi^-$ hadronic events. The systematic uncertainties in the tracking or PID are assigned as 1.0% per track [31].

The systematic uncertainty of the γ selection is estimated by studying the control sample of $J/\psi \rightarrow \pi^0\pi^+\pi^-$ [32]. The systematic uncertainty in the γ selection is assigned as 1.0% per photon.

The systematic uncertainty of the π^0 reconstruction has been studied by using the DT $\bar{D}^0 \rightarrow K^+\pi^-$ versus $D^0 \rightarrow K^-\pi^+\pi^0$ events. We assign the systematic uncertainty in the π^0 reconstruction to be 2.0% per π^0 [31]. Due to limited η sample, the systematic uncertainty of the η reconstruction is assigned as 2.0% per η by referring to that of π^0 .

Tag mode	ϵ_{DT}^i for $D^+ \rightarrow K^+\pi^0$ (%)	$\epsilon_{\text{DT}}^i/\epsilon_{\text{ST}}^i$ for $D^+ \rightarrow K^+\pi^0$ (%)
$D^- \rightarrow K^+\pi^-\pi^-$	27.23 ± 0.17	53.31 ± 0.33
$D^- \rightarrow K_S^0\pi^-$	27.75 ± 0.17	53.97 ± 0.33
$D^- \rightarrow K^+\pi^-\pi^-\pi^0$	12.84 ± 0.12	52.36 ± 0.49
Weight		53.29 ± 0.36
Tag mode	ϵ_{DT}^i for $D^+ \rightarrow K^+\eta$ (%)	$\epsilon_{\text{DT}}^i/\epsilon_{\text{ST}}^i$ for $D^+ \rightarrow K^+\eta$ (%)
$D^- \rightarrow K^+\pi^-\pi^-$	9.83 ± 0.06	19.24 ± 0.12
$D^- \rightarrow K_S^0\pi^-$	9.95 ± 0.06	19.36 ± 0.12
$D^- \rightarrow K^+\pi^-\pi^-\pi^0$	4.59 ± 0.04	18.72 ± 0.18
Weight		19.20 ± 0.13
Tag mode	ϵ_{DT}^i for $D^+ \rightarrow K^+\eta'$ (%)	$\epsilon_{\text{DT}}^i/\epsilon_{\text{ST}}^i$ for $D^+ \rightarrow K^+\eta'$ (%)
$D^- \rightarrow K^+\pi^-\pi^-$	7.28 ± 0.05	14.26 ± 0.10
$D^- \rightarrow K_S^0\pi^-$	7.53 ± 0.05	14.64 ± 0.11
$D^- \rightarrow K^+\pi^-\pi^-\pi^0$	2.99 ± 0.03	12.21 ± 0.14
Weight		14.02 ± 0.11

Table 3. The efficiencies ϵ_{DT}^i and $\epsilon_{\text{DT}}^i/\epsilon_{\text{ST}}^i$ which includes BFs of the intermediate states. The efficiencies are weighted by the corresponding ST yields in data. The uncertainties are statistical only.

The systematic uncertainty of the η' mass window selection has been studied in $D^+ \rightarrow \eta'\ell^+v_\ell$ [33], and computed as 0.7.

The uncertainties of the quoted BFs of $\pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$, $\eta' \rightarrow \pi^+\pi^-\eta$ and $\eta' \rightarrow \pi^+\pi^-\gamma$ are 0.03%, 0.5%, 1.2% and 1.4%, respectively [12].

The systematic uncertainty of the ΔE^{sig} requirement is estimated with the control samples of $D^+ \rightarrow \pi^+\pi^0$, $D^+ \rightarrow \pi^+\eta$, $D^+ \rightarrow \pi^+\eta'_{\pi^+\pi^-\eta}$ and $D^+ \rightarrow \pi^+\eta'_{\pi^+\pi^-\gamma}$. The differences in efficiencies between data and inclusive MC sample are taken as the systematic uncertainties. They are 1.1%, 0.4%, 0.1% and 0.1% for $D^+ \rightarrow K^+\pi^0$, $D^+ \rightarrow K^+\eta$, $D^+ \rightarrow K^+\eta'_{\pi^+\pi^-\eta}$ and $D^+ \rightarrow K^+\eta'_{\pi^+\pi^-\gamma}$, respectively.

The systematic uncertainties of the 2D fit are mainly due to signal shapes, background shapes, and peaking background. The uncertainties due to signal shapes are estimated by using Crystal-ball function. The uncertainties due to the background shapes are estimated by varying the endpoint by 0.2 MeV/ c^2 for the ARGUS function. The systematic uncertainties due to peaking background are estimated by varying the BFs of the peaking background channels by $\pm 1\sigma$ and the data-MC difference of the peaking background channels including PID, tracking, π^0 reconstruction, K_S^0 reconstruction, ΔE^{sig} cut and opening angle requirement [12, 15, 31]. After adding these three uncertainties in quadrature, the systematic uncertainties of the 2D fit are assigned to be 3.9%, 1.2%, 4.8% and 4.8% for $D^+ \rightarrow K^+\pi^0$, $D^+ \rightarrow K^+\eta$, $D^+ \rightarrow K^+\eta'_{\pi^+\pi^-\eta}$ and $D^+ \rightarrow K^+\eta'_{\pi^+\pi^-\gamma}$, respectively.

The systematic uncertainty of K_S^0 veto is estimated by examining the BFs after enlarging the veto window by ± 10 and ± 20 MeV/ c^2 . The change of the re-measured BF, 1.8%, is assigned for $D^+ \rightarrow K^+\eta'$.

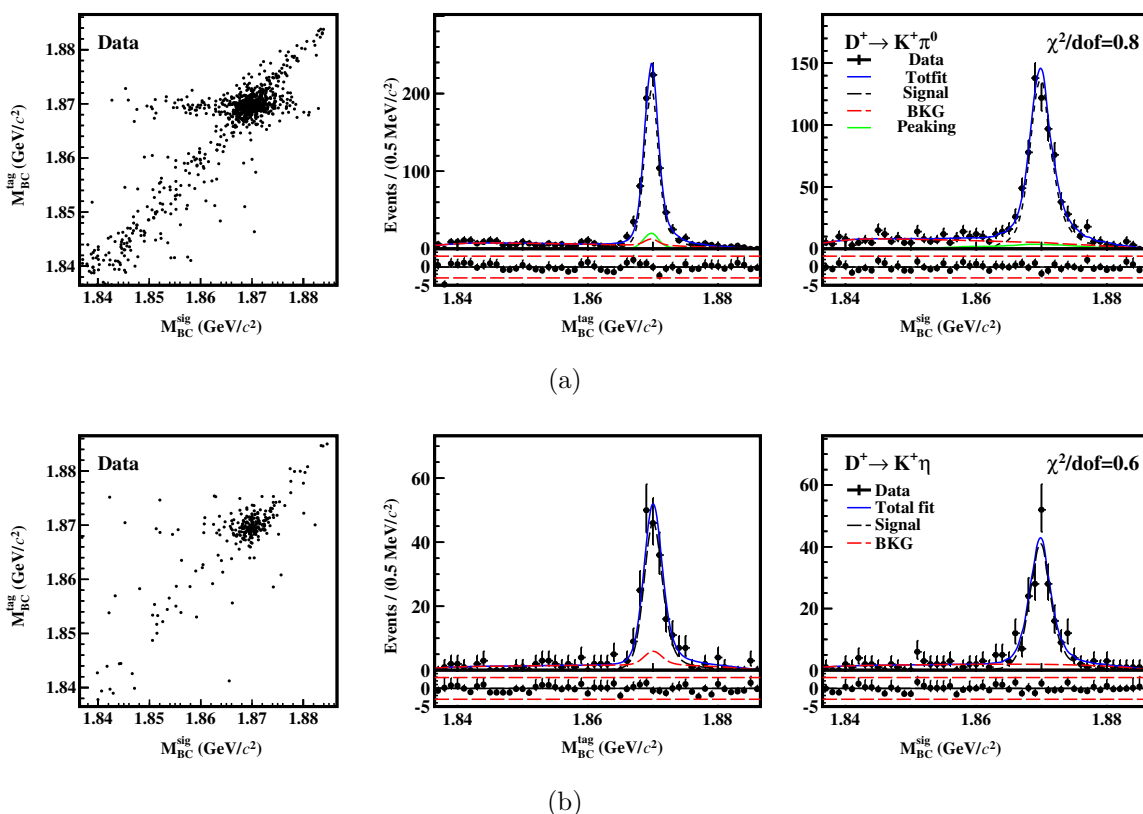


Figure 2. The distributions of M_{BC}^{tag} versus M_{BC}^{sig} and the projections on M_{BC}^{sig} and M_{BC}^{tag} of the 2D fits to the DT candidate events of (a) $D^+ \rightarrow K^+\pi^0$ and (b) $D^+ \rightarrow K^+\eta$ in data sample with three tags. For both sub-figures (a) and (b), in the right two columns, the dots with error bars are data, the blue solid curves are the fit results, the black dashed lines are the signals, and the red dashed lines are the BKG I, II and III. For sub-figure (a), the green dashed line is fixed peaking background.

The systematic uncertainty of fit bias is estimated with 40 times fake data which include signal MC with input BFs and background derived from inclusive MC, each with an equivalent size to the data. The difference between the fit mean value of the 40 times fake data and the input value, 3.0%, is taken as systematic uncertainty for $D^+ \rightarrow K^+\pi^0$. The systematic uncertainty is negligible for other signal decays.

The systematic uncertainties due to the D^+D^- opening angle requirement are estimated by using the control samples of $D^+ \rightarrow \pi^+\pi^0$, $D^+ \rightarrow \pi^+\eta$, $D^+ \rightarrow \pi^+\eta'_{\pi^+\pi^-\eta}$ and $D^+ \rightarrow \pi^+\eta'_{\pi^+\pi^-\gamma}$. The differences in the acceptance efficiencies between data and MC simulation are assigned as individual systematic uncertainties, which are 1.3%, 0.2%, 2.8% and 1.9% for $D^+ \rightarrow K^+\pi^0$, $D^+ \rightarrow K^+\eta$, $D^+ \rightarrow K^+\eta'_{\pi^+\pi^-\eta}$ and $D^+ \rightarrow K^+\eta'_{\pi^+\pi^-\gamma}$, respectively.

By adding each of the systematic uncertainties in quadrature, we obtain the total systematic uncertainties for $D^+ \rightarrow K^+\pi^0$, $D^+ \rightarrow K^+\eta$, $D^+ \rightarrow K^+\eta'_{\pi^+\pi^-\eta}$ and $D^+ \rightarrow K^+\eta'_{\pi^+\pi^-\gamma}$, respectively. All these systematic uncertainties are summarized in table 4. Since the $D^+ \rightarrow K^+\eta'_{\pi^+\pi^-\eta}$ and $D^+ \rightarrow K^+\eta'_{\pi^+\pi^-\gamma}$ are fitted simultaneously, we consider the systematic uncertainties correlation of $D^+ \rightarrow K^+\eta'_{\pi^+\pi^-\eta}$ and $D^+ \rightarrow K^+\eta'_{\pi^+\pi^-\gamma}$. The correlated systematic uncertainties include the total ST D^- yield, $K^+(\pi^\pm)$ PID or tracking,

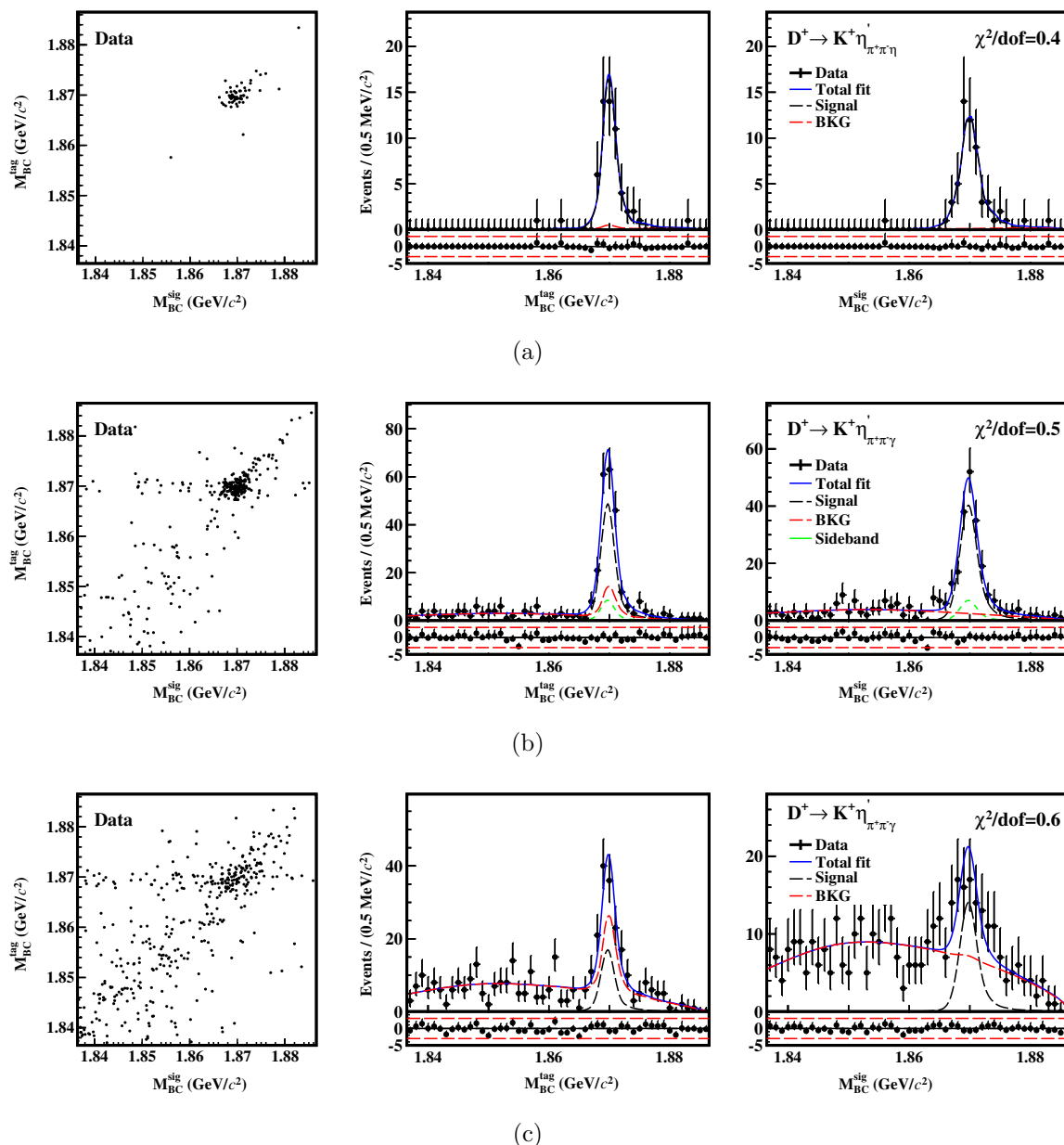


Figure 3. The distributions of M_{BC}^{tag} versus M_{BC}^{sig} and the projections on M_{BC}^{sig} and M_{BC}^{tag} of the 2D fits to the DT candidate events of (a) $D^+ \rightarrow K^+ \eta'(\pi^+ \pi^- \eta)$, (b) $D^+ \rightarrow K^+ \eta'(\pi^+ \pi^- \gamma)$ in the η' signal region and (c) $D^+ \rightarrow K^+ \eta'(\pi^+ \pi^- \gamma)$ in the η' sideband region in data sample with three tags. In the fit of (c), the parameters of the smeared Gaussian function have been fixed to those in the η' signal region. For all three sub-figures (a), (b) and (c), in the right two columns, the dots with error bars are data, the blue solid curves are the fit results, the black dashed lines are the signals, and the red dashed lines are the BKG I, II and III. For sub-figure (b), the green dashed line is the normalized sideband events. For sub-figure (a), due to the low backgrounds, the black curves overlap with blue curves.

Uncertainty	$D^+ \rightarrow K^+\pi^0$	$D^+ \rightarrow K^+\eta$	$D^+ \rightarrow K^+\eta'_{\pi^+\pi^-\eta}$	$D^+ \rightarrow K^+\eta'_{\pi^+\pi^-\gamma}$
N_{tag}	0.3	0.3	0.3	0.3
$K^+(\pi^\pm)$ tracking or PID	1.0	1.0	3.0	3.0
η' mass window	...	...	0.7	0.7
2D fit	3.9	1.2	4.8	4.8
γ selection	...	...	...	1.0
$\pi^0(\eta)$ reconstruction	2.0	2.0	2.0	...
Quoted \mathcal{B}	0.03	0.4	1.3	1.4
ΔE^{sig} cut	1.1	0.4	0.1	0.1
MC statistics	0.2	0.2	0.3	0.2
K_S^0 veto	...	...	...	1.8
Fit bias	3.0	...	...	...
Opening angle requirement	0.3	0.2	1.3	0.3
Total	5.5	2.5	6.0	5.9

Table 4. Relative systematic uncertainties (%) in the BF measurements. The top and bottom parts are correlated and uncorrelated systematic uncertainties for $D^+ \rightarrow K^+\eta'_{\pi^+\pi^-\eta}$ and $D^+ \rightarrow K^+\eta'_{\pi^+\pi^-\gamma}$, respectively. The ... means that the uncertainty is negligible.

η' mass window and 2D fit; the total effect of these sources is 5.7%. The un-correlated systematic uncertainties are from γ selection, $\pi^0(\eta)$ reconstruction, quoted BFs, ΔE^{sig} , MC statistics, K_S^0 veto, fit bias and opening angle requirement; they are 2.7% and 2.5% for $D^+ \rightarrow K^+\eta'_{\pi^+\pi^-\eta}$ and $D^+ \rightarrow K^+\eta'_{\pi^+\pi^-\gamma}$, respectively. The total systematic uncertainty is obtained to be 5.8% by combining the systematic uncertainties of $D^+ \rightarrow K^+\eta'_{\pi^+\pi^-\eta}$ and $D^+ \rightarrow K^+\eta'_{\pi^+\pi^-\gamma}$ [34].

6 Summary

In summary, using 20.3 fb^{-1} of e^+e^- collision data taken at $\sqrt{s} = 3.773 \text{ GeV}$ with the BESIII detector, we measure the BFs of the DCS decays $D^+ \rightarrow K^+\pi^0$, $D^+ \rightarrow K^+\eta$ and $D^+ \rightarrow K^+\eta'$ to be $\mathcal{B}(D^+ \rightarrow K^+\pi^0) = (1.45 \pm 0.06 \pm 0.08) \times 10^{-4}$, $\mathcal{B}(D^+ \rightarrow K^+\eta) = (1.17 \pm 0.10 \pm 0.03) \times 10^{-4}$ and $\mathcal{B}(D^+ \rightarrow K^+\eta') = (1.88 \pm 0.15 \pm 0.11) \times 10^{-4}$, where the first uncertainties are statistical and the second are systematic. The precision of the BF of $D^+ \rightarrow K^+\pi^0$ is improved by a factor of two compared to the world average, while the latter two are comparable with the world averages. We notice that there are about four standard deviations between $\mathcal{B}(D^+ \rightarrow K^+\pi^0)$ measured in this work and that in ref. [11]. This difference is likely attributable to that the measurement in ref. [11] used the single-tag method, which suffers from much higher background, and the systematic uncertainty due to background shape could be substantially underestimated. The BF of $D^+ \rightarrow K^+\pi^0$ is consistent with the DASU(3)L and GFRE calculations within 3σ [1, 3], but disfavors with the TASU(3)B and FDWC calculations [2, 4]. The BF of $D^+ \rightarrow K^+\eta$ is consistent with the DASU(3)L, TASU(3)B and GFRE calculations within 3σ [1–3], but disfavors with the FDWC calculation [4]. The BF of $D^+ \rightarrow K^+\eta'$ is consistent with the LSU(3)F calculation within 3σ [35], but disfavors with the DASU(3)L,

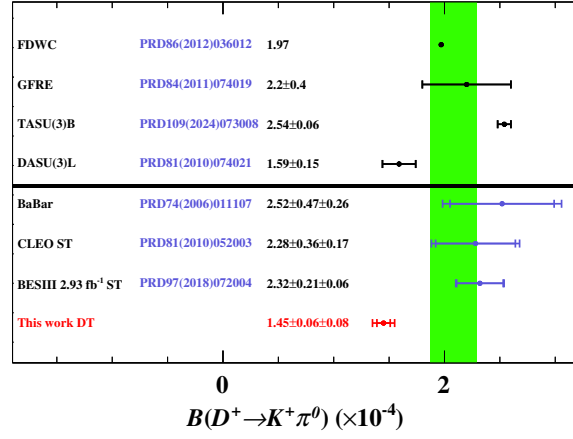
Signal decay	$D^+ \rightarrow K^+\pi^0$	$D^+ \rightarrow K^+\eta$	$D^+ \rightarrow K^+\eta'$
CLEO [8]	$2.28 \pm 0.36 \pm 0.17$	...	...
Belle [9]	...	$1.15 \pm 0.16 \pm 0.05$	$1.87 \pm 0.19 \pm 0.05$
BaBar [10]	$2.52 \pm 0.47 \pm 0.26$	...	...
BESIII [11]	$2.32 \pm 0.21 \pm 0.06$	$1.51 \pm 0.25 \pm 0.14$	$1.64 \pm 0.51 \pm 0.24$
PDG [12]	2.08 ± 0.21	1.25 ± 0.16	1.85 ± 0.20
DASU(3)L [1]	1.59 ± 0.15	0.98 ± 0.04	0.91 ± 0.17
TASU(3)B [2]	2.54 ± 0.06	1.04 ± 0.01	1.07 ± 0.01
GFRE [3]	2.2 ± 0.4	1.2 ± 0.2	1.0 ± 0.1
FDWC [4]	1.97	0.66	1.14
LSU(3)F [35]	...	...	2.11 ± 0.17
This work	$1.45 \pm 0.06 \pm 0.08$	$1.17 \pm 0.10 \pm 0.03$	$1.88 \pm 0.15 \pm 0.11$

Table 5. The BFs ($\times 10^{-4}$) of $D^+ \rightarrow K^+\pi^0$, $D^+ \rightarrow K^+\eta$ and $D^+ \rightarrow K^+\eta'$ from experimental measurements and theoretical calculations. For the experimental results, the first uncertainties are statistical and the second ones are systematic. For the theoretical predictions, the uncertainties are systematic only. The ... means not measured

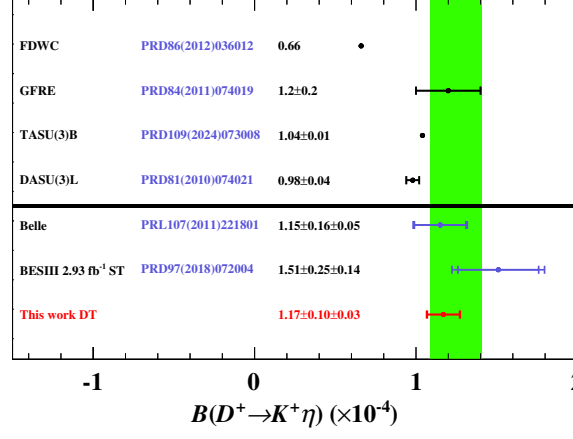
TASU(3)B, GFRE, and FDWC calculations [1–4]. These new BFs are helpful to improve theoretical calculations. The comparisons of our results with other experimental measurements and theoretical calculations are shown in table 5 and figure 4.

Acknowledgments

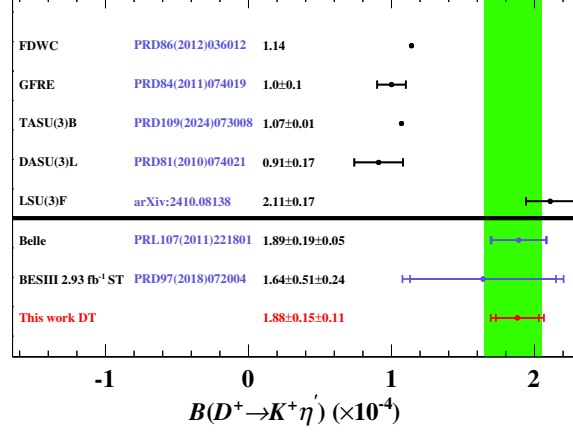
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(a)



(b)



(c)

Figure 4. Comparisons of experimental measurements and theoretical calculations for (a) $D^+ \rightarrow K^+\pi^0$, (b) $D^+ \rightarrow K^+\eta$ and (c) $D^+ \rightarrow K^+\eta'$. The green bands represent the 1σ PDG values. Results before and after the horizontal black line are theoretical and experimental results, respectively. For experimental results, the first uncertainties are statistical and the second ones are systematic. For theoretical calculations, the uncertainties are systematic only.

Data Availability Statement. This article has no associated data or the data will not be deposited.

Code Availability Statement. This article has no associated code or the code will not be deposited.

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