

Measurements of the absolute branching fractions of $D^0 \rightarrow \gamma \bar{K}^{*0}$ and $D^0 \rightarrow \gamma \phi$

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By analyzing a sample of 20.3 fb^{-1} of e^+e^- annihilation data collected at the center-of-mass energy of 3.773 GeV with the BESIII detector, we have made a first measurement of the absolute branching fractions of the radiative decays $D^0 \rightarrow \gamma \bar{K}^{*0}$ and $D^0 \rightarrow \gamma \phi$ to be $(3.81 \pm 0.18_{\text{stat}} \pm 0.20_{\text{syst}}) \times 10^{-4}$ and $(2.51 \pm 0.44_{\text{stat}} \pm 0.11_{\text{syst}}) \times 10^{-5}$, respectively. The statistical significances of $D^0 \rightarrow \gamma \bar{K}^{*0}$ and $D^0 \rightarrow \gamma \phi$ are 26.8σ and 7.9σ , respectively. The obtained branching fractions are consistent with the corresponding world average values. In addition, the measured CP asymmetry $\mathcal{A}_{CP}(D^0 \rightarrow \gamma \bar{K}^{*0}) = (-0.7 \pm 5.0_{\text{stat}} \pm 4.1_{\text{syst}})\%$ is consistent with CP conservation.

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I. INTRODUCTION

Charmed meson decays provide a sensitive laboratory for probing nonperturbative quantum chromodynamics (QCD). The radiative decays $D^0 \rightarrow \gamma V$ (V denotes light vector mesons) receive contributions from both short-distance and long-distance interactions. Although the short-distance amplitude is enhanced by QCD corrections, it remains smaller than the long-distance contribution [1]. The latter, dominated by nonperturbative mechanisms such as those described by the vector meson dominance (VMD) model, can enhance branching fractions (BFs) up to 10^{-4} .

Predictions from various theoretical approaches for the $D^0 \rightarrow \gamma \bar{K}^{*0}$ [$\bar{K}^{*0}$ denotes $\bar{K}^*(892)^0$] and $D^0 \rightarrow \gamma \phi$ [ϕ denotes $\phi(1020)$] BFs are summarized in Table I. The decay $D^0 \rightarrow \gamma \phi$ was first observed by the Belle collaboration [14] and subsequently confirmed by BABAR with improved precision [12]. The decay $D^0 \rightarrow \gamma \bar{K}^{*0}$ was first observed by BABAR [12] and later confirmed by Belle [13], both of which were relative measurements. In contrast, this work presents the first absolute measurement of this decay. The corresponding measurements are listed in Table I.

Notably, the latest Belle [13] measurement of $D^0 \rightarrow \gamma \bar{K}^{*0}$ differs from the BABAR result by above 3σ . Improved measurements of radiative D^0 decays are therefore essential to clarify this tension and to further constrain the underlying decay dynamics. Throughout this

paper, charge-conjugated decays are implied unless otherwise stated.

Measurements of charge-conjugation and parity (CP) asymmetries in radiative charm decays provide complementary information on weak decay mechanisms in the charm sector. Within the Standard Model, direct CP violation in charm decays is expected to be at most of order 10^{-3} . Evidence for CP violation at the 10^{-4} level has been reported by LHCb in $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ decays [15]. The Belle Collaboration [13] reported the first

TABLE I. Theoretical calculations and experimental measurements for the BFs (in unit of $\times 10^{-5}$) of $D^0 \rightarrow \gamma \bar{K}^{*0}$ and $D^0 \rightarrow \gamma \phi$. The theoretical calculations include: Vector meson dominance (VMD), heavy quark effective theory (HQET), effective Lagrangian approach (ELA), nonperturbative QCD (NPQCD), effective field theory (EFT), and left-right symmetric model (LRSB).

Theoretical calculation	$D^0 \rightarrow \gamma \bar{K}^{*0}$	$D^0 \rightarrow \gamma \phi$
VMD 1 [1]	7–12	0.1–3.4
VMD 2 [2]	16–34	...
HQET 1 [3]	21–43	...
HQET 2 [4]	20–40	...
HQET 3 [5]	2.6–46	0.24–2.8
HQET 4 [6]	≤ 3.0	2.0
HQET 5 [7]	7–20	0.4–3
ELA [8]	11	...
NPQCD [9]	$3.59^{+0.20}_{-0.22}$	$2.76^{+0.36}_{-0.35}$
EFT [10]	6–36	0.1–1.9
LRSB [11]	4.6–18	0.48–0.64
Experimental measurement	$D^0 \rightarrow \gamma \bar{K}^{*0}$	$D^0 \rightarrow \gamma \phi$
BABAR [12]	$33.3 \pm 2.0 \pm 2.8$	$2.82 \pm 0.31 \pm 0.27$
Belle [13]	$46.9 \pm 2.0 \pm 2.0$	$2.71 \pm 0.19 \pm 0.09$

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measurement of the CP asymmetry in radiative charm decays, with results consistent with CP conservation.

In this paper, we present measurements of the absolute BFs of the decays $D^0 \rightarrow \gamma \bar{K}^{*0}$ and $D^0 \rightarrow \gamma \phi$, as well as the CP asymmetry ($\mathcal{A}_{CP}$) for $D^0 \rightarrow \gamma \bar{K}^{*0}$, using 20.3 fb^{-1} of e^+e^- collision data [16,17] collected with the BESIII detector at a center-of-mass energy of $\sqrt{s} = 3.773 \text{ GeV}$. This energy is near the $\psi(3770)$ resonance, which predominantly decays into $D\bar{D}$ (D denotes D^0 or D^+) pairs. Operating close to the $D\bar{D}$ production threshold, the D mesons are produced nearly at rest, providing a clean kinematic environment for studying their decays.

II. BESIII DETECTOR AND MONTE CARLO

The BESIII detector [18] records symmetric e^+e^- collisions provided by the BEPCII storage ring [19] in the center-of-mass energy range from $\sqrt{s} = 1.84$ to 4.95 GeV , with a peak luminosity of $1.1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ achieved at $\sqrt{s} = 3.773 \text{ GeV}$. BESIII has collected large data samples in this energy region [20–22]. 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), 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 identifier modules interleaved with steel. The charged-particle momentum resolution at $1 \text{ GeV}/c$ is 0.5%, and the specific ionization energy loss 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 of the TOF barrel section is 68 ps, while that of the end cap section was 110 ps. The end cap TOF system was upgraded in 2015 using multigap resistive plate chamber technology, providing a time resolution of 60 ps, which benefits 85.5% of the data used in this analysis [23].

Simulated samples produced with the Geant4-based [24] Monte Carlo (MC) package, which includes the geometric description of the BESIII detector and its response, are used to determine the detection efficiency and estimate backgrounds. The simulation includes the beam-energy spread and initial-state radiation (ISR) in e^+e^- annihilation modeled with the generator KKMC [25]. The inclusive MC samples consist of quantum-coherent neutral $D\bar{D}$ production, non- $D\bar{D}$ decays of the $\psi(3770)$, ISR production of the J/ψ and $\psi(3686)$ states, and continuum processes. Known decay modes are modeled with EvtGen [26,27] using BFs taken from the Particle Data Group (PDG) [28], while the remaining unknown charmonium decays are modeled with LUNDCHARM [29,30]. Final-state

radiation from charged particles is simulated with the PHOTOS package [31].

III. MEASUREMENT METHOD

This analysis is performed using the double-tag (DT) method, which was first developed at the Mark III experiment [32]. If a $\bar{D}^0$ meson is fully reconstructed in one of the following six tag modes: $\bar{D}^0 \rightarrow K^+\pi^-$, $\bar{D}^0 \rightarrow K^+\pi^-\pi^0$, $\bar{D}^0 \rightarrow K^+\pi^-\pi^-\pi^+$, $\bar{D}^0 \rightarrow K^+\pi^-\pi^-\pi^+\pi^0$, $\bar{D}^0 \rightarrow K^+\pi^-\pi^0\pi^0$, and $\bar{D}^0 \rightarrow K_S^0\pi^+\pi^-$, it is referred to as a single-tag (ST) candidate. A DT event [33] is defined as an event containing either a signal decay of $D^0 \rightarrow \gamma \bar{K}^{*0}$ or $D^0 \rightarrow \gamma \phi$, in conjunction with an ST $\bar{D}^0$. Consequently, the BF of the signal decay is determined by

$$\mathcal{B}_{\text{sig}} = \frac{N_{\text{DT}}}{N_{\text{ST}}^{\text{tot}} \cdot \epsilon_{\text{sig}} \cdot \mathcal{B}_{\text{sub}}}, \quad (1)$$

where N_{DT} is the number of events with any $\bar{D}^0$ tag and a signal candidate. $N_{\text{ST}}^{\text{tot}} = \sum_{i=1}^6 N_{\text{ST}}^i$ is the total ST yield, N_{ST}^i is the number of ST $\bar{D}^0$ candidates in tag mode i , $\epsilon_{\text{sig}} = \sum_{i=1}^6 [(N_{\text{ST}}^i \cdot \epsilon_{\text{DT}}^i) / (N_{\text{ST}}^{\text{tot}} \cdot \epsilon_{\text{ST}}^i)]$ is the signal efficiency in the presence of the ST candidate, where ϵ_{ST}^i and ϵ_{DT}^i are the efficiencies for selecting ST and DT candidates, respectively, i denotes the tag modes. $\mathcal{B}_{\text{sub}}$ is the BF of $\bar{K}^{*0} \rightarrow K^-\pi^+$ or $\phi \rightarrow K^+K^-$.

A. Single-tag selection

Candidates for K_S^0 and π^0 are reconstructed via $K_S^0 \rightarrow \pi^+\pi^-$ and $\pi^0 \rightarrow \gamma\gamma$, respectively. Candidates for $K^\pm$, $\pi^\pm$, K_S^0 , γ , and π^0 are reconstructed and identified using the same criteria as those in Refs. [34–37]. The tagged $\bar{D}^0$ mesons are selected using two variables: the energy difference

$$\Delta E_{\text{tag}} \equiv E_{\bar{D}^0} - E_b, \quad (2)$$

and the beam-energy-constrained mass

$$M_{\text{BC}}^{\text{tag}} \equiv \sqrt{E_b^2/c^4 - |\vec{p}_{\bar{D}^0}|^2/c^2}, \quad (3)$$

where E_b is the beam energy, $\vec{p}_{\bar{D}^0}$ and $E_{\bar{D}^0}$ are the momentum and energy of the $\bar{D}^0$ candidate in the e^+e^- rest frame, respectively. If multiple combinations are found in an event, only the combination with the minimum $|\Delta E_{\text{tag}}|$ is retained for further analysis. To suppress combinatorial backgrounds in the M_{BC} distribution, tag dependent ΔE requirements are imposed on the ST candidates. The ΔE requirements are obtained by fitting the signal MC samples of each tag. The ΔE selection windows are defined as $\pm 3.5\sigma$ around the peak. The detailed ΔE requirements are summarized in Table II. The yields of ST $\bar{D}^0$ mesons are obtained from unbinned maximum-likelihood fits to the

TABLE II. The ΔE requirements, ST yields in data, and the ST efficiencies for different tag modes, where the uncertainties are statistical, and the efficiencies do not include the BF of $K_S^0 \rightarrow \pi^+\pi^-$ and $\pi^0 \rightarrow \gamma\gamma$.

$\bar{D}^0$ mode	$\Delta E(\text{GeV})$	$N_{\text{ST}}^i (\times 10^3)$	$\epsilon_{\text{ST}}^i (\%)$
$K^+\pi^-$	$(-0.027, 0.027)$	3725.7 ± 2.0	65.10 ± 0.01
$K^+\pi^-\pi^0$	$(-0.062, 0.049)$	7422.3 ± 3.2	35.60 ± 0.01
$K^+\pi^-\pi^-\pi^+$	$(-0.026, 0.024)$	4987.5 ± 2.5	40.94 ± 0.01
$K^+\pi^-\pi^-\pi^+\pi^0$	$(-0.057, 0.051)$	1154.9 ± 1.8	16.27 ± 0.01
$K^+\pi^-\pi^0\pi^0$	$(-0.068, 0.053)$	1770.9 ± 2.2	15.11 ± 0.01
$K_S^0\pi^+\pi^-$	$(-0.024, 0.024)$	1168.6 ± 1.2	37.90 ± 0.01
$N_{\text{ST}}^{\text{tot}}$	...	20229.9 ± 5.5	...

$M_{\text{BC}}^{\text{tag}}$ distributions of the accepted ST candidates. In the fit, the signal shape is described by an MC-simulated shape convolved with a double Gaussian plus an additional single Gaussian. The shape is constructed using RooHistPdf in ROOT [38], based on inclusive MC samples after performing a truth match, which requires the opening angle between the generated and reconstructed three-momenta of all ST daughter particles to be less than 15° . The parameters of those functions are free. The combinatorial background is described by an ARGUS function [39]. The parameters of the ARGUS function are floated, except for the end point, which is fixed at $1.8865 \text{ GeV}/c^2$. The fit results are shown in Fig. 1. Candidates with $M_{\text{BC}}^{\text{tag}} \in (1.859, 1.873) \text{ GeV}/c^2$ are retained for further analysis. The ST yields in data and the ST efficiencies estimated by analyzing the inclusive MC sample for different tag modes are summarized in Table II. For ST

candidates of $\bar{D}^0 \rightarrow K^+\pi^-$, backgrounds from cosmic rays and Bhabha events are further suppressed using the requirement described in Ref. [40].

B. Signal selection

To form candidates for $D^0 \rightarrow \gamma \bar{K}^{*0}$ and $D^0 \rightarrow \gamma \phi$, the $\bar{K}^{*0}$ and ϕ are reconstructed via their decays $\bar{K}^{*0} \rightarrow K^-\pi^+$ and $\phi \rightarrow K^+K^-$. The γ , $K^\pm$, and $\pi^\pm$ are selected using the same criteria as on the tag side. It is required that no extra charged tracks are present to suppress background from hadronic D decays. The most energetic γ is retained as the radiative photon.

The invariant masses $M_{K^-\pi^+}$ and $M_{K^+K^-}$ of the $\bar{K}^{*0}$ and ϕ candidates are required to satisfy $M_{K^-\pi^+} \in (0.855, 0.945)$ and $M_{K^+K^-} \in (1.010, 1.030) \text{ GeV}/c^2$. The former requirement is determined by optimizing the figure of merit $S/\sqrt{S+B}$, where S and B are the signal and background

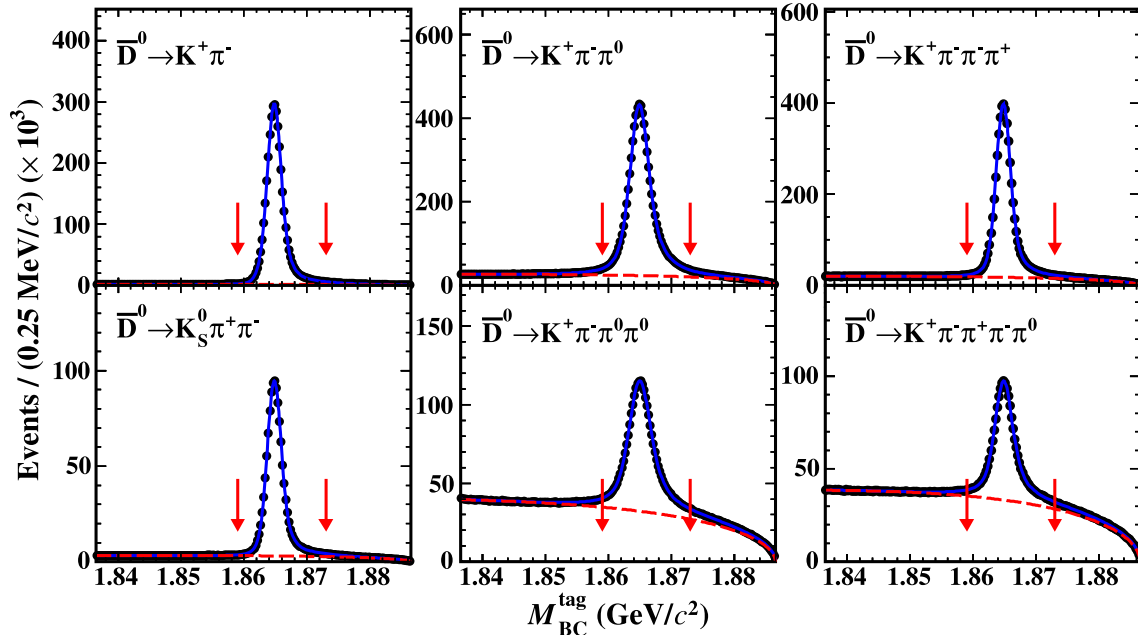


FIG. 1. Fits to the $M_{\text{BC}}^{\text{tag}}$ distributions of the ST $\bar{D}^0$ candidates. Points with error bars represent the data; the solid curve shows the total fit, and the dashed curve shows the background component. The pairs of arrows denote the chosen signal windows.

yields in the inclusive MC sample, respectively. The latter corresponds to approximately twice the ϕ width around the mass given by the PDG [28]. To further suppress backgrounds associated with extra π^0 mesons, events containing any additional two-photon combination that satisfies the π^0 selection criteria are rejected.

On the signal side, the energy difference and the beam-energy-constrained mass, ΔE_{sig} and $M_{\text{BC}}^{\text{sig}}$, are defined analogously to those on the tag side. To suppress combinatorial backgrounds, we require $M_{\text{BC}}^{\text{sig}} \in (1.859, 1.873) \text{ GeV}/c^2$.

IV. BRANCHING FRACTION

To extract the DT yields, a two-dimensional (2D) extended unbinned maximum-likelihood fit is performed to the ΔE_{sig} versus $\cos \theta_H$ distribution. The helicity angle θ_H of the K^- , defined in the rest frame of the $\bar{K}^{*0}$ or ϕ , is used to further discriminate signal from background, as shown in Fig. 2. Due to angular-momentum conservation, the signal is expected to follow a $1 - \cos^2 \theta_H$ distribution. For the $D^0 \rightarrow \phi \pi^0$ categories, the shape is close to $\cos^2 \theta_H$, while the $\cos \theta_H$ distribution of $D^0 \rightarrow K^- \pi^+ \pi^0$ candidates is complicated by the interference and overlap of resonant structures in the final-state Dalitz plot [12,13]. The 2D kernel estimation probability density function (KeysPDF)

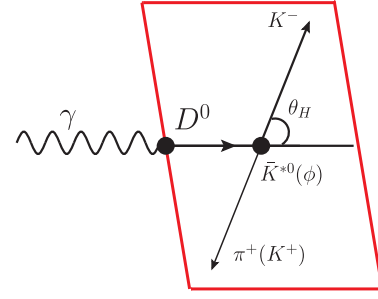


FIG. 2. Definition of the helicity angle of K^- diagram in the rest frame of $\bar{K}^{*0}$ or ϕ . The horizontal arrow denotes the direction of $\bar{K}^{*0}$, and the slanted arrow denotes the direction of K^- .

for the signal is obtained from the MC simulation and modeled using the signal MC shape, which is derived from inclusive MC samples after applying the same selection criteria as in data. The dominant backgrounds are $D^0 \rightarrow K^- \pi^+ \pi^0$ (amplitude analysis model, following the method of Ref. [41]) and $D^0 \rightarrow \phi \pi^0$ (SVS model: scalar to a vector and a scalar meson [27,42]) for $D^0 \rightarrow \gamma \bar{K}^{*0}$ and $D^0 \rightarrow \gamma \phi$, respectively. The background distributions as functions of ΔE_{sig} and the helicity angle θ_H are obtained from the inclusive MC sample. In the $D^0 \rightarrow \gamma \bar{K}^*(892)^0$ mode, the dominant backgrounds include $D^0 \rightarrow \bar{K}^{*0} K_L^0$, $D^0 \rightarrow \pi^+ \pi^- \pi^0$, $D^0 \rightarrow K^- \pi^+ \eta$, the semileptonic decays

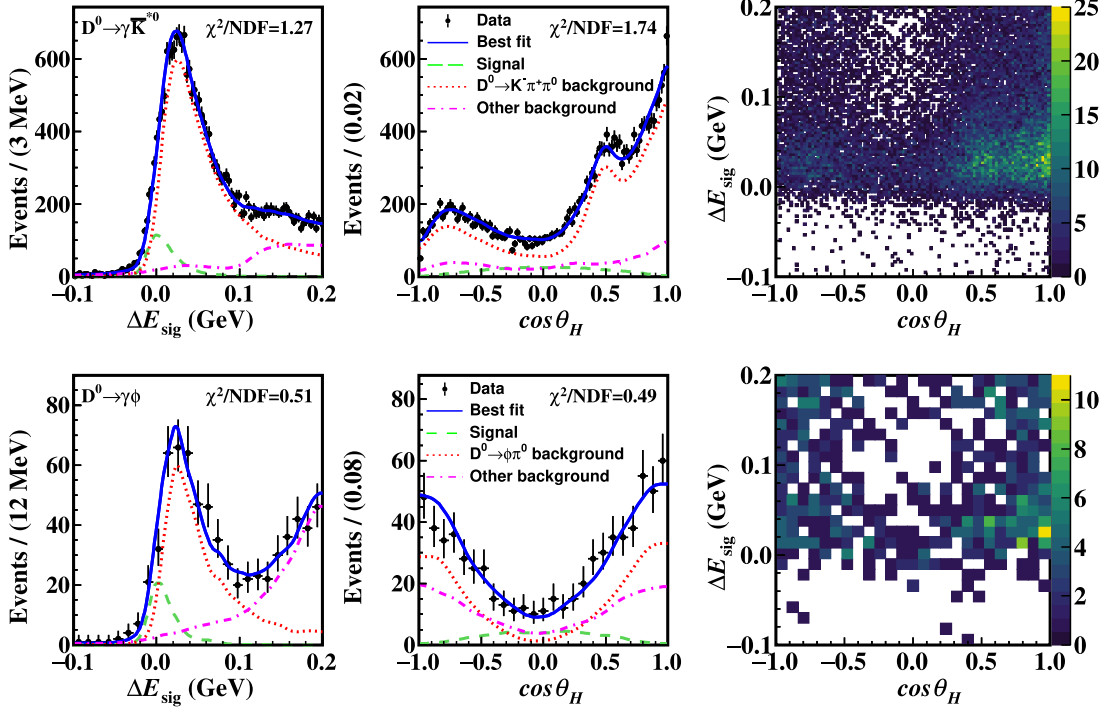


FIG. 3. Projections onto ΔE_{sig} (left column) and $\cos \theta_H$ (middle column) of the 2D fits and the 2D distributions (right column) for $D^0 \rightarrow \gamma \bar{K}^{*0}$ (top row) and $D^0 \rightarrow \gamma \phi$ (bottom row) candidate events in data. The points with error bars are data. The blue solid curves are the fit results. The green dashed curves are the fitted signal shapes, the red dotted curves are the $D^0 \rightarrow K^- \pi^+ \pi^0$ or $D^0 \rightarrow \phi \pi^0$ backgrounds, and the pink dash-dotted curves are the other processes. The events in the 2D distributions are data.

TABLE III. The DT yields in data (N_{DT}), statistical significances, signal efficiencies (ϵ_{sig}), and $\mathcal{B}_{\text{sig}}$ (in unit of $\times 10^{-5}$). The efficiencies do not include the BF of $\bar{K}^{*0}$ and ϕ decays. The first uncertainties are statistical and the second systematic.

Decay mode	N_{DT}	Significance	ϵ_{sig} (%)	$\mathcal{B}_{\text{sig}}$ (This work)	$\mathcal{B}_{\text{sig}}$ (Belle) [13]	$\mathcal{B}_{\text{sig}}$ (BABAR) [12]
$D^0 \rightarrow \gamma \bar{K}^{*0}$	1653 ± 77	26.8σ	32.17 ± 0.07	$38.1 \pm 1.8 \pm 2.0$	$46.9 \pm 2.0 \pm 2.0$	$33.3 \pm 2.0 \pm 2.8$
$D^0 \rightarrow \gamma \phi$	69 ± 12	7.9σ	27.29 ± 0.07	$2.51 \pm 0.44 \pm 0.11$	$2.71 \pm 0.19 \pm 0.09$	$2.83 \pm 0.31 \pm 0.27$

$D^0 \rightarrow K^- e^+ \nu_e$ and $D^0 \rightarrow K^{*-} \mu^+ \nu_\mu$, as well as the non-resonant hadronic decay $D^0 \rightarrow K_L^0 \pi^+ \pi^-$. Similarly, for the $D^0 \rightarrow \gamma \phi$ mode, the primary backgrounds consist of $D^0 \rightarrow K^+ K^- \pi^0$, $D^0 \rightarrow K_L^0 K^+ K^-$, $D^0 \rightarrow \phi \eta$, and $D^0 \rightarrow K_S^0 K^+ K^-$. All yields are allowed to float in the fits. The spectra in the left and middle columns of Fig. 3 show the projections onto ΔE_{sig} and $\cos \theta_H$ from the 2D fits to data. From the fits, the signal yields for $D^0 \rightarrow \gamma \bar{K}^{*0}$ and $D^0 \rightarrow \gamma \phi$ are determined to be 1653 ± 77 and 69 ± 12 events, respectively, where the uncertainties

are statistical only. For each signal decay, the statistical significance is evaluated by comparing the likelihood values from fits with and without the signal component, accounting for the change in degrees of freedom (NDF). The statistical significances for $D^0 \rightarrow \gamma \bar{K}^{*0}$ and $D^0 \rightarrow \gamma \phi$ are 26.8σ and 7.9σ , respectively. The BFs for the decays $D^0 \rightarrow \gamma \bar{K}^{*0}$ and $D^0 \rightarrow \gamma \phi$ are measured to be $(3.81 \pm 0.18_{\text{stat}} \pm 0.20_{\text{syst}}) \times 10^{-4}$ and $(2.51 \pm 0.44_{\text{stat}} \pm 0.11_{\text{syst}}) \times 10^{-5}$, respectively. The systematic uncertainties are discussed in the next section.

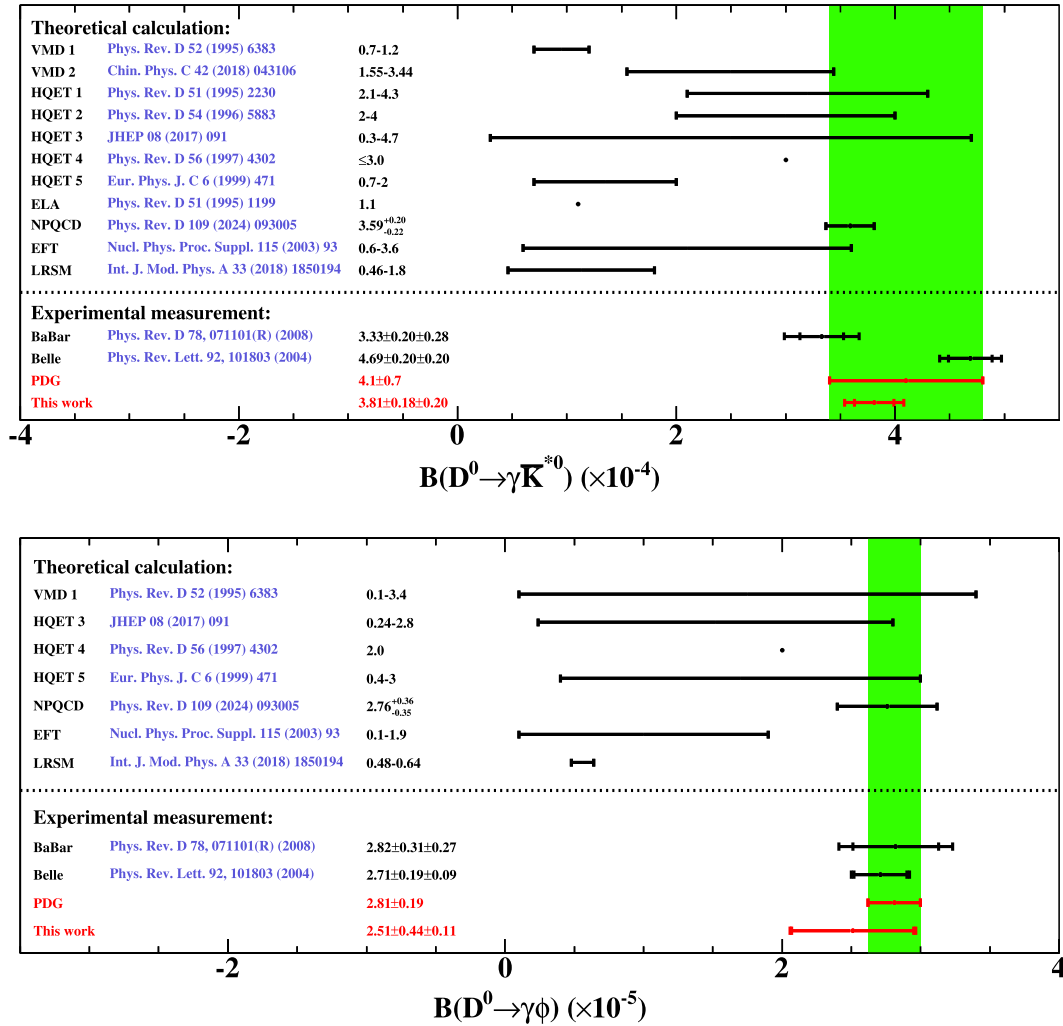


FIG. 4. Comparisons of the obtained BFs with theoretical calculations, other measurements, and the world average values (shown as green bands). For the measurements of BESIII, Belle, and BABAR, the inner error bars are statistical uncertainties, and the outer error bars are the combined statistical and systematic uncertainties in quadrature.

The obtained values of N_{DT} , ϵ_{sig} , and $\mathcal{B}_{\text{sig}}$ are summarized in Table III.

Figure 4 compares the measured BFs with previous measurements and the world average values. The BF of $D^0 \rightarrow \gamma \bar{K}^{*0}$ measured in this work is consistent with the predictions of the VMD2 [2], HQET [3–7], NPQCD [9], and EFT [10] models, while it deviates from those of the VMD1 [1], ELA [8], and LRSM [11] models. The BF of $D^0 \rightarrow \gamma \phi$ reported here is consistent with the predictions of the VMD1 [1], HQET [5–7], NPQCD [9], and EFT [10] models, and deviates from that of the LRSM model [11].

V. SYSTEMATIC UNCERTAINTIES

By exploiting the DT method, most uncertainties related to the ST selection cancel. The systematic uncertainties in the BF measurements arise from the following sources and are assigned relative to the measured BF.

The systematic uncertainty on the total ST $\bar{D}^0$ yield is estimated by varying the signal and background shapes. For the background, the endpoint of the ARGUS function is varied, resulting in an uncertainty of 0.02%. For the signal, the mean values, widths, and correlation coefficients of the three Gaussian functions are varied by 1σ , yielding an uncertainty of 0.25%. The total uncertainty from this source is taken as 0.3%.

The tag bias arises from different reconstruction environments of the tag side in the inclusive and signal MC samples [43,44]. We study the tracking/PID efficiencies in different multiplicities, and the combined differences between data and MC simulation are assigned as 0.2% for $D^0 \rightarrow \gamma \bar{K}^{*0}$ and 0.4% for $D^0 \rightarrow \gamma \phi$.

The tracking and particle identification (PID) efficiencies of $K^\pm$ and $\pi^\pm$ are studied using DT $D\bar{D}$ hadronic events [45]. A systematic uncertainty of 0.5% per $K^\pm$ and $\pi^\pm$ is assigned for tracking and PID. The systematic uncertainty associated with photon selection is taken as 1.0%, determined using $J/\psi \rightarrow \pi^+ \pi^- \pi^0$ events [46].

The systematic uncertainty associated with the $M_{\text{BC}}^{\text{sig}}$ requirement is evaluated using control samples of $D^0 \rightarrow K^- \pi^+ \pi^0$ and $D^0 \rightarrow K^- \pi^+$. The largest difference between data and the inclusive MC sample, 0.5%, is assigned as the systematic uncertainty.

The systematic uncertainties associated with the $\bar{K}^{*0}$ and ϕ mass windows are determined using control samples of $D^+ \rightarrow \bar{K}^{*0}(\rightarrow K^- \pi^+) e^+ \nu_e$ and $D^+ \rightarrow \phi(\rightarrow K^+ K^-) \pi^+$. The $M_{K^- \pi^+}$ and $M_{K^+ K^-}$ invariant mass spectra are fitted to the data and the MC simulation. The signal is modeled with a Breit-Wigner function and the background with a polynomial function. By comparing the yields inside and outside the signal mass regions, the differences in acceptance efficiencies between data and MC are determined to be 2.5% and 1.9%, respectively, and are assigned as systematic uncertainties.

The systematic uncertainties due to the requirements of no extra π^0 and no extra charged tracks are evaluated using

TABLE IV. Relative systematic uncertainties (%) in the BF measurements. The systematic uncertainties marked with an asterisk are independent of the CP asymmetry measurement.

Source	$D^0 \rightarrow \gamma \bar{K}^{*0}$	$D^0 \rightarrow \gamma \phi$
N_{tag}	0.3	0.3
Tag bias	0.2*	0.4
Tracking	1.0*	1.0
PID	1.0*	1.0
γ selection	1.0	1.0
$M_{\text{BC}}^{\text{sig}}$ requirement	0.5	0.5
$\bar{K}^{*0}$ or ϕ mass window	2.5	1.9
π^0 veto	1.3	1.3
2D fit	3.7*	2.7
Quoted BF	...	1.0
MC statistics	0.3*	0.3
$N_{\text{charge}}^{\text{extra}}$	1.6*	1.6
Total	5.3	4.4

$D^0 \rightarrow K^- \pi^+ \pi^0$ and $D^0 \rightarrow K^- \pi^+$ candidates. The largest differences in acceptance efficiencies between data and MC simulation, 1.3% and 1.6%, are assigned as the systematic uncertainties for the no-extra- π^0 and no-extra-track requirements, respectively.

The systematic uncertainty associated with the 2D fit is estimated by repeating the BF measurements using alternative signal and background shapes obtained by smearing with a Gaussian resolution function, varying the Gaussian resolution and the smoothness parameters of the KeysPDF, and changing the fit ranges. For $D^0 \rightarrow \gamma \bar{K}^{*0}$, the maximum variation of 3.7% in the BF is taken as the systematic uncertainty; for $D^0 \rightarrow \gamma \phi$, it is 2.7%.

The limited MC sample size contributes a 0.3% systematic uncertainty for both $D^0 \rightarrow \gamma \bar{K}^{*0}$ and $D^0 \rightarrow \gamma \phi$. The quoted BF of $\phi \rightarrow K^+ K^-$ is $(49.9 \pm 0.5)\%$ [28], corresponding to a 1.0% uncertainty.

Adding all contributions in quadrature, the total systematic uncertainties are 5.3% for $D^0 \rightarrow \gamma \bar{K}^{*0}$ and 4.4% for $D^0 \rightarrow \gamma \phi$, which summarized in Table IV.

VI. CP ASYMMETRY MEASUREMENT

Furthermore, the BFs of $D^0 \rightarrow \gamma \bar{K}^{*0}$ and $\bar{D}^0 \rightarrow \gamma K^{*0}$, denoted as $\mathcal{B}^+$ and $\mathcal{B}^-$, are measured separately to determine the CP asymmetry, defined as $\mathcal{A}_{CP} = \frac{\mathcal{B}^+ - \mathcal{B}^-}{\mathcal{B}^+ + \mathcal{B}^-}$. The $K_S^0 \pi^+ \pi^-$ ST channel is excluded because it cannot distinguish between D^0 and $\bar{D}^0$ mesons. Using the same method described above, we obtain DT yields, BF, and asymmetry, which are summarized in Table V.

In the determination of $\mathcal{A}_{CP}$, the systematic uncertainties associated with γ selection, π^0 veto, N_{tag} , the M_{BC} requirement, and the $\bar{K}^{*0}$ mass window are treated as correlated between charge-conjugated modes, while the remaining uncertainties are treated as uncorrelated. The

TABLE V. Signal yields (N_{net}), charge-separated BFs ($\mathcal{B}^+$ and $\mathcal{B}^-$), and their asymmetries ($\mathcal{A}_{CP}$). The first and second uncertainties are statistical and systematic, respectively.

Decay mode	N_{net}	$\mathcal{B}^\pm (\times 10^{-4})$	$\mathcal{A}_{CP} (\%)$	$\mathcal{A}_{CP} (\text{Belle}) (\%)$
$D^0 \rightarrow \gamma \bar{K}^{*0}$	754.4 ± 53.4	$3.72 \pm 0.26 \pm 0.20$	$-0.7 \pm 5.0 \pm 4.1$	$-0.3 \pm 2.0 \pm 0.0$
$\bar{D}^0 \rightarrow \gamma K^{*0}$	769.6 ± 53.2	$3.77 \pm 0.26 \pm 0.21$		

contributions are tag bias (0.4%, 0.4%), tracking (0.1%, 0.1%), PID (0.1%, 0.1%), 2D fit (5.6%, 5.3%), MC statistics (0.3%, 0.3%), and $N_{\text{charge}}^{\text{extra}}$ (1.7%, 1.7%), where the first value in each pair corresponds to $D^0 \rightarrow \gamma \bar{K}^{*0}$ and the second to $\bar{D}^0 \rightarrow \gamma K^{*0}$. The total systematic uncertainties, evaluated separately for the two charge states using the same procedure as described above, are (5.9%, 5.6%).

The resulting CP asymmetry is $\mathcal{A}_{CP} = (-0.7 \pm 5.0_{\text{stat}} \pm 4.1_{\text{syst}})\%$, which is consistent with zero and indicates no evidence for CP violation. Our result is consistent with the Belle measurement [13].

VII. SUMMARY

Using a data sample of 20.3 fb^{-1} collected at $\sqrt{s} = 3.773 \text{ GeV}$ with the BESIII detector, the absolute BF of the radiative decays $D^0 \rightarrow \gamma \bar{K}^{*0}$ and $D^0 \rightarrow \gamma \phi$ are measured for the first time, yielding $(3.81 \pm 0.18_{\text{stat}} \pm 0.20_{\text{syst}}) \times 10^{-4}$ and $(2.51 \pm 0.44_{\text{stat}} \pm 0.11_{\text{syst}}) \times 10^{-5}$, respectively. The measured value is consistent with the *BABAR* and Belle results within 1.1σ and 2.0σ , respectively, and achieves improved precision compared to the PDG average [28]. In addition, the CP asymmetry between $D^0 \rightarrow \gamma \bar{K}^{*0}$ and $\bar{D}^0 \rightarrow \gamma K^{*0}$ is measured to be $\mathcal{A}_{CP}(D^0 \rightarrow \gamma \bar{K}^{*0}) = (-0.7 \pm 5.0_{\text{stat}} \pm 4.1_{\text{syst}})\%$, which is consistent with CP conservation. Future experiments such as Belle II [47] and STCF [48,49] are expected to provide more precise measurements of radiative charm decays.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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