PROCEEDINGS OF SCIENCE

Quantum-correlation of neutral charmed mesons at BESIII

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BESIII has recently accumulated a large data sample near the $\psi(3770)$ production threshold corresponding to an integrated luminosity of $20\,\mathrm{fb}^{-1}$. Neutral $D^0\overline{D}^0$ pairs produced at the $\psi(3770)$ are in a C-odd correlated state, providing a unique laboratory to measure the strong-phase differences between D^0 and $\overline{D}^0$ decays. These parameters are essential inputs to the study of CP violation in heavy-flavor physics, primarily in the determinations of the CKM angle gamma and charm-mixing parameters. These proceedings report new measurements of strong-phase differences in different neutral D decays at BESIII, including new measurements of the strong phases in $D \to K^+K^-\pi^+\pi^-$ decays. Additionally reported is the first observation of correlated DD pairs produced at e^+e^- center-of-mass energies above the $\psi(3770)$ threshold, where $e^+e^- \to D^*\overline{D}$ and $e^+e^- \to D^*\overline{D}^*$ processes also occur. These processes produce both C-odd and C-even correlated $D\overline{D}$ pairs, which allow for new measurement techniques to determine strong-phases from previously unused datasets.

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Hadrons produced in electron-positron collisions are constrained to respect the charge-conjugation eigenvalue of the photon, $C = -1$, as the strong and electromagnetic interactions mediate $e^+e^- \to$ hadron processes. In the case of $e^+e^- \to D\overline{D}$ production[1], this constraint manifests through interference between the amplitudes of D^0 and $\overline{D}^0$ decays to the same final state[1]. The observed interference is sensitive to the ratio of the amplitudes between the D^0 and $\overline{D}^0$ to the specific final state and the CP-conserving "strong" phase between the amplitudes. These same parameters are important in the interpretation of CP violation in $B \to Dh$[2] decays and the interpretation of neutral-charm meson mixing[3]. Thus the measurements of strong phases from e^+e^- colliders running at open-charm thresholds provide crucial input to understanding the phenomena of CP violation and neutral-meson mixing.

The BESIII experiment [4] records data of symmetric e^+e^- collisions provided by the Beijing Electron Positron Collider Mk. II [5] (BEPCII). BEPCII produces collisions at center-of-mass energies of $2 - 5$ GeV with a design luminosity of 10^{33} cm^{-2}s^{-1} achieved in April 2016. The BESIII detector covers 93% of the full solid angle, and is equipped with gaseous tracking system, a plastic scintillator time-of-flight system for particle identification, a caesium-iodide calorimeter, and a resistive-plate-chamber muon system. A cross-sectional diagram of the BESIII Detector is shown in Fig. 1. BEPCII and BESIII finished construction in 2008, upgrading on the original Beijing Electron-Positrion Collider and BESII detector. BESIII began taking data in 2009, and has collected many large datasets in this energy regime[6]. Most relevant to these proceedings is the 20.3 fb^{-1} sample collected at the $\psi(3770)$ threshold, whose collection was completed in 2024. This contains the previous largest sample at this energy, a sample of 2.9 fb^{-1} collected in 2011. Results reported in these proceedings also employ a sample corresponding to 7.3 fb^{-1} between center-of-mass energies of $4.13 - 4.23$ GeV collected between 2013 to 2017.

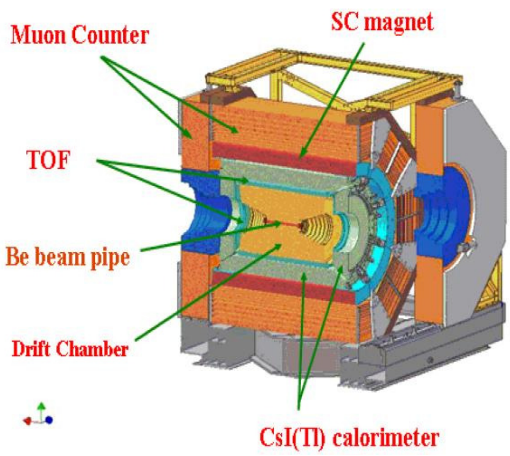

Figure 1: Cross-sectional view of the BESIII detector.

At the $\psi(3770)$ threshold, $D\overline{D}$ pairs are constrained to a $CP = -1$ state, since the threshold production ensures that no other particles are produced[2]. In this case, the probability of the $D\overline{D}$ pair

[1]The lack of charge superscripts here indicate the particles are produced as admixtures of D^0 and $\overline{D}^0$ mesons, with a similar convention taken for D^{*0} mesons.

[2]The only exception is $e^+e^- \to \gamma D\overline{D}$ production, which is estimated to occur at a rate of 10^{-8} relative to the $e^+e^- \to D\overline{D}$ production near the threshold, and so can be neglected.[7]

decaying to a final state X_1X_2 relative to the independent probabilities $P(D^0 \to X_1)\ P(\overline{D}^0 \to X_2)$ can be expressed as

$$\frac{P(D^0\overline{D}^0 \to X_1X_2)}{P(D^0 \to X_1)P(\overline{D}^0 \to X_2)} = 1 + \left(r_D^{X_1} r_D^{X_2}\right)^2 - 2r_D^{X_1} r_D^{X_2} \cos\left(\delta_D^{X_1} + \delta_D^{X_2}\right), \tag{1}$$

where r_D^X represents the ratio of amplitude magnitudes between D^0 and $\overline{D}^0$ decays to a final state X, and δ_D^X represents the strong phase between the two amplitudes. In order to determine the hadronic parameters of a decay $D \to X$, a variety of recoil D^0 decay (or “tag") modes must be reconstructed. These fall into three general categories:

1. Flavor and quasi-flavor tags, which satisfy $r_D \approx 0$
2. CP and quasi-CP tags, which satisfy $r_D \approx 1$ and $\delta_D \approx 0, \pi$
3. other indefinite tags, with a range of r_D and δ_D values

Examples of flavor tags include semileptonic D^0 decays, such as $D^0 \to K^-e^+\nu_e$ or the quasi-flavor tag decay $D^0 \to K^-\pi^+$. Quasi-CP eigenstate tags include $D^0 \to K^+K^-$, $D^0 \to K_S^0\pi^0$, and $D^0 \to \pi^+\pi^-\pi^0$.

For decays with three or more particles in the final state, the r_D and δ_D parameters vary as a function of the final-state phase space. As measurements of these processes cannot resolve single points in phase-space, such multi-body decays are often analyzed with some coarse-graining of the phase-space. This requires assigning an effective amplitude ratio and strong-phase for the coarse-grained region of phase-space, as well as a coherence factor that accounts for the sensitivity loss due to the coarse-graining, often referred to with the symbol κ or R. Alternative parameterizations of the phases, amplitudes, and coherence of the D meson decays are also often employed in certain final states, such as c_i and s_i parameters, defined as

$$c_i \propto \int_i d\Phi\ \left|\mathcal{A}_D(\Phi)\right| \left|\mathcal{A}_{\overline{D}}(\Phi)\right| \cos\left(\delta_D(\Phi)\right) \qquad s_i \propto \int_i d\Phi\ \left|\mathcal{A}_D(\Phi)\right| \left|\mathcal{A}_{\overline{D}}(\Phi)\right| \sin\left(\delta_D(\Phi)\right), \tag{2}$$

where the integral is performed of a subset of the total decay phase space Φ defined by i, and A_D or $A_{\overline{D}}$ correspond to the D^0 or $\overline{D}^0$ decay amplitude to the final state of interest, respectively. Another commonly used alternative parametrization is the CP-even fraction F_+ of the decay phase-space of multi-body quasi-CP eigenstate decays.

In 2022-2024, BESIII recorded a data sample at $E_{\rm cm} = 3.773$ GeV corresponding to an integrated luminosity of $17.4\,\mathrm{fb}^{-1}$, roughly five times larger than the previous largest sample of $2.9\,\mathrm{fb}^{-1}$ collected at the open-charm pair production threshold, which had been recorded by BESIII in 2011. The major increase in the number of quantum-correlated $D\overline{D}$ pairs provided by this sample will allow for significantly increased precision on strong-phase parameters in D^0 decays.

The full data sample including the 2011 and 2022-2024 datasets has been employed in Ref. [8] to produce the first measurement of c_i and s_i parameters in regions of the $D^0 \to K^+K^-\pi^+\pi^-$ phase space designed to optimize sensitivity to the CKM angle γ in decays of $B^\pm \to DK^\pm$ decays [9], and an updated measurement of the F_+ of the $D^0 \to K^+K^-\pi^+\pi^-$ decay integrated across the phase space. This analysis employs three quasi-flavour tag decay modes, ten CP and quasi-CP tag decay modes and the $K_{S/L}\pi^+\pi^-$ tag decay modes. Partially reconstructed $D \to K^+K^-\pi^+\pi^-$ decays were also incorporated into the analysis, where one of the kaons was not successfully identified in the detector. Yields of $D\overline{D} \to K^+K^-\pi^+\pi^-$ vs. the various tag decay modes are determined through fits to the beam-constrained mass of $D \to K^+K^-\pi^+\pi^-$ (M_{BC}) for fully reconstructed events, and the missing mass squared ($M^2_{\rm miss}$) for partially reconstructed events. Examples of these fits are shown in Fig. 2. The yields are then analyzed simultaneously to determine the c_i and s_i parameters defined in Eq. 2, using reparameterised form of Eq. 1. The resulting determinations of these parameters are shown in Fig. 2. The analysis also determines $F_+ = (0.754 \pm 0.010 \pm 0.008)$ for the $D^0 \to K^+K^-\pi^+\pi^-$ decay, and determines the branching fraction of $D^0 \to K^+K^-\pi^+\pi^-$ to be $(2.863 \pm 0.028 \pm 0.045) \times 10^{-3}$. These results have since been employed in a determination of the CKM angle γ with $B^\pm \to Dh^\pm$ decays by the LHCb collaboration [10].

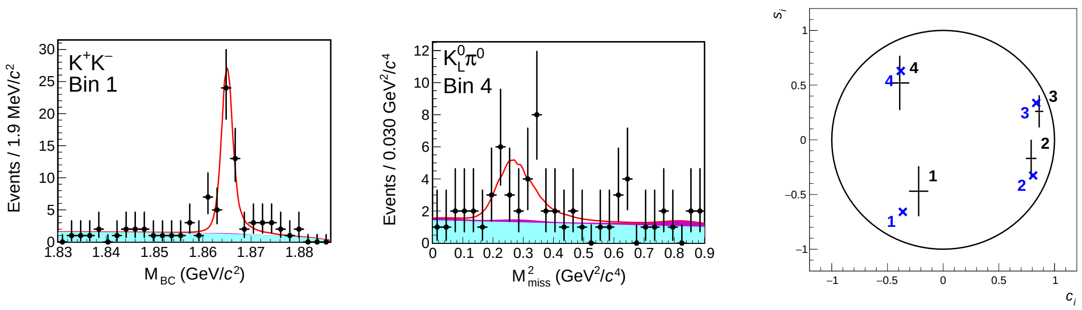

Figure 2: (Left, Center) Examples of fits to determine the yields of $D\overline{D} \to K^+K^-\pi^+\pi^-$vs. tag decay modes. (Right) Determinations of the c_i and s_i parameters as black points compared to predictions from an amplitude model[9] as blue crosses.

At energies above the open-charm pair production threshold, the processes $e^+e^- \to XD\overline{D}$ may occur, where X is an additional system of particles. If X is also a CP-eigenstate, then it has been predicted that the $D\overline{D}$ system will exhibit quantum correlations [1]. Additionally, if X is CP-odd, the $D\overline{D}$ pair is expected to be constrained to a C-even state, with opposite behavior to C-odd constrained $D\overline{D}$ pairs, such as those produced at the threshold energy. However, no experimental verification of this has previously been undertaken.

Using a data sample corresponding to an integrated luminosity of 7.3 fb^{-1} at center-of-mass energies ranging from $E_{\rm cm} = 4.13 - 4.23$ GeV, the presence of correlations in $D\overline{D}$ pairs produced through $e^+e^- \to XD\overline{D}$ processes has now been observed by the BESIII collaboration in Refs. [11, 12], specifically in $D\overline{D}$ pairs produced in five $e^+e^- \to XD\overline{D}$ production mechanisms expected to be C-definite: $D\overline{D}$ $[C = -1]$, $D^*\overline{D} \to \gamma D\overline{D}$ $[C = +1]$, $D^*\overline{D} \to \pi^0 D\overline{D}$ $[C = -1]$, $D^*\overline{D}^* \to \gamma\pi^0 D\overline{D}$ $[C = +1]$, and $D^*\overline{D}^* \to \gamma\gamma/\pi^0\pi^0 D\overline{D}$ $[C = -1]$. The yields are determined for $D\overline{D}$ final states that are expected to be forbidden or enhanced at a roughly twice the rate in the absence of correlations. Corrections are applied to the observed yields to account for reconstruction efficiencies and misidentification of the production mechanism hypothesis. The corrected yields for the final states expected to be significantly altered by the presence of correlations are compared to the corrected yields of the $D\overline{D} \to K^-\pi^+$ vs. $K^+\pi^-$ process, which is expected to be negligibly affected by the presence of the correlations. The ratios of corrected yields are shown in Fig. 3, which clearly demonstrates the presence of correlations in all of the observed final states.

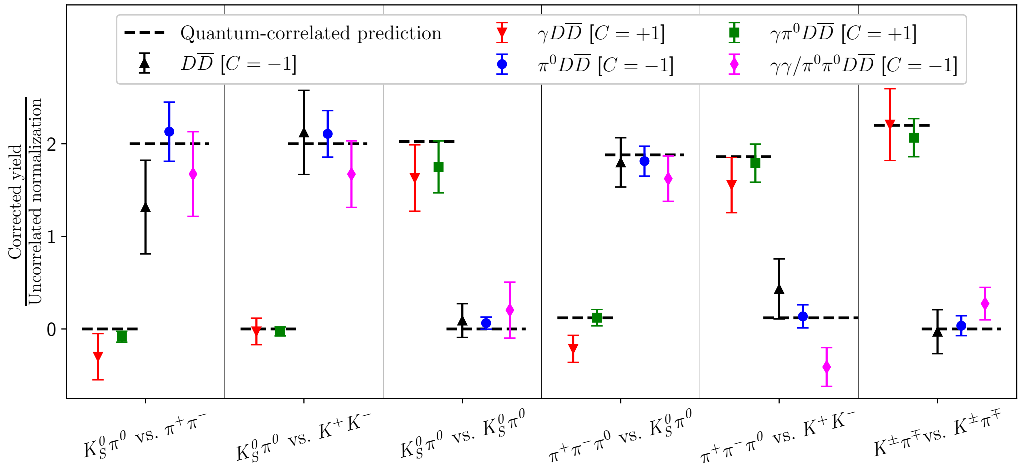

Figure 3: Corrected yields of $D\overline{D}$ final states expected to be significantly affected by the presence of quantum correlations normalized to the expectation in the absence of correlations. The predicted ratios of yields in the presence of correlations are shown for comparison.

The same data samples are employed to analyze decays of $D\overline{D} \to K^{\mp}\pi^{\pm}$ vs. Y, where Y is one of the following $\{\pi^+\pi^-\pi^0, K^+K^-, \pi^+\pi^-, K_S^0\pi^0, K_S^0\pi^+\pi^-\}$. Using a similar procedure to that employed to demonstrate the presence of quantum correlations in these samples, the effects of the correlations on the yields of these processes are studied to determine the strong phase between $D^0 \to K^-\pi^+$ and $\overline{D}^0 \to K^-\pi^+$ decays, $\delta_{K\pi}$. This results in a determination of $\delta_{K\pi} = \left(192.8^{+11.0+1.9}_{-12.4-2.4}\right)^\circ$, where the first listed uncertainties are statistical and the second are systematic. This result is compared to the most precise measurement performed at the $\psi(3770)$ resonance, $\delta^D_{K\pi} = \left(187.6^{+8.9+5.4}_{-9.7-6.4}\right)^\circ$ [13], where it is noted that the mixed C-even and C-odd sample allows for robust control of the systematic uncertainties. Given the similar sensitivities the two BESIII results are compared to determine $\delta^D_{K\pi} = (189.2^{+6.9+3.4}_{-7.4-3.8})^\circ$.

The demonstration of C-even correlations also has implications for the study of neutral charm meson mixing. C-even correlated $D\overline{D}$ pairs are significantly more sensitive to the effects of mixing than C-odd correlated $D\overline{D}$ pairs[14–17]. In light of this, the sensitivity to charm-mixing parameters from hadronic final states at the proposed Super-Tau Charm facility[18] is estimated in Ref. [11], where it is demonstrated that sensitivity on par with the current world averages would be well within reach.

The results presented in these proceedings are a small subset of recent BESIII results on quantum-correlated $D\overline{D}$ decays, with other results on the strong phases in $D^0 \to \pi^+\pi^-\pi^+\pi^-$ [19] using 2.9 fb^{-1} of data at the $\psi(3770)$ resonance, and in $D^0 \to \pi^+\pi^-\pi^0$[20], $D^0 \to K^+K^-\pi^0$[20], and $D^0 \to K^0_{S/L}\pi^+\pi^-$[21] decays using 7.9 fb^{-1} of data at the $\psi(3770)$ resonance, which both comprise a subset of the full 20.3 fb^{-1} sample that has recently been collected. Many other results on strong phases are expected to follow employing the full 20.3 fb^{-1} sample, which is projected to sufficiently improve the knowledge of strong phases in D^0 decays such that they do not limit the knowledge of the CKM angle γ or charm-mixing parameters in the near future.

References

[1] M. Goldhaber and J. L. Rosner, *Mixing of Neutral Charmed Mesons and Tests for CP Violation in their Decays*, Phys. Rev. D **15** (1977) 1254.

[2] LHCb, R. Aaij *et al.*, *Measurement of the CKM angle γ in $B^{\pm} \to DK^{\pm}$ and $B^{\pm} \to D\pi^{\pm}$ decays with $D \to K^0_S h^+h^-$*, JHEP **02** (2021) 169, arXiv:2010.08483.

[3] LHCb, R. Aaij *et al.*, *Observation of the mass difference between neutral charm-meson eigenstates*, Phys. Rev. Lett. **127** (2021) 111801, arXiv:2106.03744.

[4] BESIII, M. Ablikim *et al.*, *Design and Construction of the BESIII Detector*, Nucl. Instrum. Meth. A **614** (2010) 345, arXiv:0911.4960.

[5] C. Yu *et al.*, *BEPCII Performance and Beam Dynamics Studies on Luminosity*, in *7th International Particle Accelerator Conference*, TUYA01, 2016.

[6] BESIII, M. Ablikim *et al.*, *Future Physics Programme of BESIII*, Chin. Phys. C **44** (2020) 040001, arXiv:1912.05983.

[7] CLEO, D. M. Asner *et al.*, *Determination of the $D^0 \to K^+\pi^-$ relative strong phase using quantum-correlated measurements in $e^+e^- \to D^0\overline{D}^0$ at CLEO*, Phys. Rev. D **78** (2008) 012001, arXiv:0802.2268.

[8] BESIII, M. Ablikim *et al.*, *Measurement of the strong-phase difference between D0 and D0 $^-$→K+K-π+π- in bins of phase space*, Phys. Rev. D **112** (2025) 012015.

[9] LHCb, R. Aaij *et al.*, *A study of CP violation in the decays $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D h^{\pm}$ $(h = K, \pi)$ and $B^{\pm} \to [\pi^+\pi^-\pi^+\pi^-]_D h^{\pm}$*, Eur. Phys. J. C **83** (2023) 547, arXiv:2301.10328, [Erratum: Eur.Phys.J.C 83, 672 (2023)].

[10] LHCb, R. Aaij *et al.*, *A model-independent measurement of the CKM angle in the decays $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D h^{\pm}$ and $B^{\pm} \to [\pi^+\pi^-\pi^+\pi^-]_D h^{\pm}$ $(h = K, \pi)$*, arXiv:2509.15139.

[11] BESIII, M. Ablikim *et al.*, *First observation of quantum correlations in $e^+e^- \to XD\bar{D}$ and C-even constrained $D\bar{D}$ pairs*, Phys. Rev. Lett. **135** (2025) 171902, arXiv:2506.07906.

[12] BESIII, M. Ablikim *et al.*, *Novel measurement of the strong-phase difference between $D^0 \to K^-\pi^+$ and $\bar{D}^0 \to K^-\pi^+$ decays using C-even and C-odd quantum-correlated $D\bar{D}$ pairs*, Phys. Rev. **D112** (2025) 072006, arXiv:2506.07907.

[13] BESIII, M. Ablikim *et al.*, *Improved measurement of the strong-phase difference $\delta_D^{K\pi}$ in quantum-correlated $D\overline{D}$ decays*, Eur. Phys. J. C **82** (2022) 1009, arXiv:2208.09402.

[14] Z.-z. Xing, *D^0-$\overline{D}^0$ mixing and CP violation in neutral D meson decays*, Phys. Rev. D **55** (1997) 196, arXiv:hep-ph/9606422.

[15] A. Bondar, A. Poluektov, and V. Vorobiev, *Charm mixing in the model-independent analysis of correlated $D^0\overline{D}^0$ decays*, Phys. Rev. D **82** (2010) 034033, arXiv:1004.2350.

[16] M. Rama, *Measurement of strong phases, D–$\overline{D}$ mixing, and CP violation using quantum correlation at charm threshold*, Front. Phys. (Beijing) **11** (2016) 111404.

[17] P. Naik, *Novel correlated $D^0\overline{D}^0$ systems for c/b physics and tests of T/CPT*, JHEP **03** (2023) 038, arXiv:2102.07729.

[18] M. Achasov *et al.*, *STCF conceptual design report (Volume 1): Physics & detector*, Front. Phys. (Beijing) **19** (2024) 14701, arXiv:2303.15790.

[19] BESIII, M. Ablikim *et al.*, *Model-independent determination of the strong-phase difference between D^0 and $\overline{D}^0 \to \pi^+\pi^-\pi^+\pi^-$ decays*, Phys. Rev. D **110** (2024) 112008, arXiv:2408.16279.

[20] BESIII, M. Ablikim *et al.*, *Measurements of the CP-even fractions of $D^0 \to \pi^+\pi^-\pi^0$ and $D^0 \to K^+K^-\pi^0$ at BESIII*, Phys. Rev. D **111** (2025) 012007, arXiv:2409.07197.

[21] BESIII, M. Ablikim *et al.*, *Updated model-independent measurement of the strong-phase differences between D^0 and $\bar{D}^0 \to K^0_{S/L}\pi^+\pi^-$ decays*, arXiv:2503.22126.