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Quantum correlation of neutral charmed mesons at BESIII

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Abstract: BESIII has recently collected a large data sample at the $\psi(3770)$ energy point, with an integrated luminosity of 20 fb^{-1}. The neutral $D^0\bar{D}^0$ pairs produced at $\psi(3770)$ are in a C-odd correlated state, offering a unique laboratory for measuring the strong-phase differences between D^0 and $\bar{D}^0$ decays. These parameters are crucial inputs for *CP*-violation studies in heavy-flavor physics, such as determining the CKM angle γ and charm-mixing parameters, searching for indirect *CP* violtion in the charm sector. In this presentation, we report recent progresses on new or improved measurements of the strong-phase differences in various neutral D decays at BESIII. We also present results on the *CP*-even fractions for multi-body decays. Finally, we discuss measurements of strong phase difference from additional $D^0\bar{D}^0$ pairs produced at 4180 MeV.

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1. Overview

The BESIII detector records symmetric e^+e^- collisions provided by the BEPCII storage ring, covering center-of-mass energies from 1.84 to 4.95 GeV and reaching a peak luminosity of 1.1×10^{33} cm^{-2}s^{-1}. Charmed meson pairs such as $D^0\bar{D}^0$ are produced at the $\psi(3770)$ resonance (3.773 GeV), with an integrated luminosity of 20 fb^{-1} [1]. Furthermore, additional 7.13 fb^{-1} quantum-coherent $D^0\bar{D}^0$ events have been collected in the 4.13–4.23 GeV energy region, which are being used for the first time at BESIII to measure strong-phase differences. The hadronic decays of these mesons provide an excellent laboratory for amplitude analysis, branching fraction measurements, and quantum coherence studies. Most analyses employ the double-tag (DT) method, in which both charm mesons are fully reconstructed. The tagging schemes used include flavour-specific tags, *CP* tagstags, and self-conjugate tags.

2. *CP*-even fraction measurement

The BESIII experiment facilitates precise measurements of *CP*-even fractions with substantially suppressed background contamination. These measurements are conducted through the analysis of double-tag (DT) events, using both *CP* tags and $K_S^0\pi^+\pi^-$ tags. These results provide important inputs for measurements of strong phase differences and for studies of *CP* violation. Recently, BESIII has reported a series of *CP*-even fraction measurements in multi-body charm decays. For $D^0 \to \pi^+\pi^-\pi^0$ and $D^0 \to K^+K^-\pi^0$ [2], the *CP*-even fractions are determined to be $F_+(D^0 \to \pi^+\pi^-\pi^0) = 0.941 \pm 0.006_{\rm stat} \pm 0.003_{\rm syst}$ and $F_+(D^0 \to K^+K^-\pi^0) = 0.631 \pm 0.014_{\rm stat} \pm 0.011_{\rm syst}$, respectively. These analyses are based on a data set of 7.9 fb^{-1} and achieve a precision approximately 2.6 times better than previous results. For $D^0 \to K^+K^-\pi^+\pi^-$, the first model-independent measurement of the *CP*-even fraction has been performed using 2.93 fb^{-1} of data [3], yielding a value of $F_+(D^0 \to K^+K^-\pi^+\pi^-) = 0.730 \pm 0.037_{\rm stat} \pm 0.021_{\rm syst}$. For $D^0 \to K_S^0\pi^+\pi^-\pi^0$, the *CP*-even fraction has been measured using using 2.93 fb^{-1} of data. The value is $F_+(D^0 \to K_S^0\pi^+\pi^-\pi^0) = 0.235 \pm 0.010_{\rm stat} \pm 0.002_{\rm syst}$ [4].

3. Strong phase difference parameters measurement

For multi-body decays with significant resonant contributions, the Dalitz plane is commonly divided into bins to improve sensitivity in measurements of the CKM angle γ and studies of charm mixing and *CP* violation. Typical binning strategies include equal binning scheme for charm mixing and *CP*-violation analyses, the optimal binning scheme for γ measurement, the modified optimal binning scheme for γ measurements with small B statistics. The bin-averaged strong-phase difference parameters, c_i and s_i, are obtained from double-tag (DT) analyses using flavour-specific tags, *CP* tags, and self-conjugate tags. Fig. 1 presents the Dalitz distributions for the $K_S^0\pi\pi$ and $K_L^0\pi\pi$ final states, tagged with flavour eigenstates, *CP*-even tags and *CP*-odd tags. The patterns illustrate the influence of quantum coherence, which can be quantitatively extracted by comparing the different tagging channels.

The amplitude ratio between $D^0 \to K_S^0\pi\pi$ and $\bar{D}^0 \to K_S^0\pi\pi$ is close to unity, rendering this decay a "golden channel" for measuring the CKM angle γ. The strong-phase difference parameters

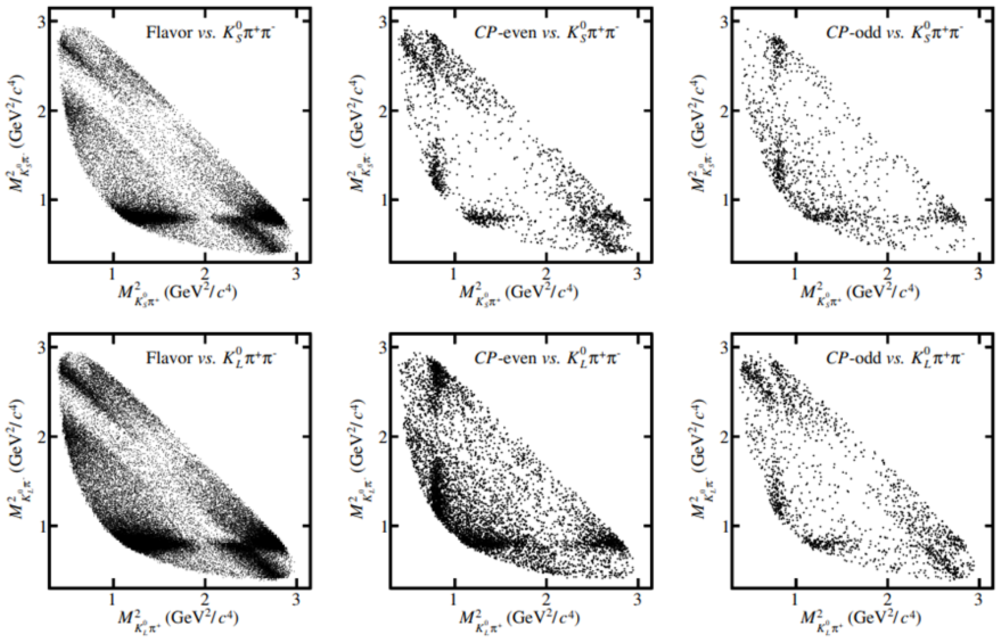

Figure 1: Dalitz plots for $K_S^0\pi\pi$ (top) and $K_L^0\pi\pi$ (bottom), tagged with flavour eigenstates (left), *CP*-even tags (middle), and *CP*-odd tags (right). The visible modulations reflect quantum coherent effects, which can be extracted through a combined analysis of the different tag categories.

extracted from D decays serve as critical inputs for γ determination and are widely used in studies of charm mixing and *CP* violation. Recently, BESIII has updated the strong-phase difference parameters for $D^0 \to K^0_{S/L}\pi\pi$ using a data set of 7.9 fb^{-1} under three distinct binning schemes [6]. These results are 1.5 times more precise than previous measurements, with an impact on γ estimated to be 0.9° for the optimal binning scheme—smaller than the projected statistical uncertainty of γ after LHCb Upgrade I (with 50 fb^{-1}, about 1.9°).

Notably, a model-dependent constraint on $\Delta c_i = c'_i - c_i$ and $\Delta s_i = s'_i - s_i$ was applied to to resolve two-fold ambiguity. With higher statistics, it is now feasible to remove this model-dependent constraint entirely. The corresponding results are shown in Fig. 2. Compared to the unconstrained determination of c_i and s_i, the constrained results align more closely with model predictions and exhibit significantly smaller uncertainties. Both sets of results are consistent within 2σ. Moreover, the shift in the central value of γ obtained using the constrained versus unconstrained strong-phase parameters is approximately 0.4° for the optimal binning scheme, motivating further analysis with increased luminosity.

The bin-averaged strong-phase differences for the decay $D^0 \to \pi^+\pi^-\pi^+\pi^-$ have been measured by BESIII using 2.93 fb^{-1} of data, employing both equal and optimal binning schemes [7]. The estimated contributions to the uncertainty in the CKM angle γ are 1.5° and 2.0° for the equal and optimal binnings, respectively. The *CP*-even fraction is determined to be $0.746 \pm 0.010_{\rm stat} \pm 0.004_{\rm syst}$, improving the precision by 30% over previous results.

In a separate analysis with 20.3 fb^{-1} data, BESIII has determined the strong-phase parameters for $D^0 \to K^+K^-\pi^+\pi^-$ [8]. These measurements provide supplementary constraints for γ, with

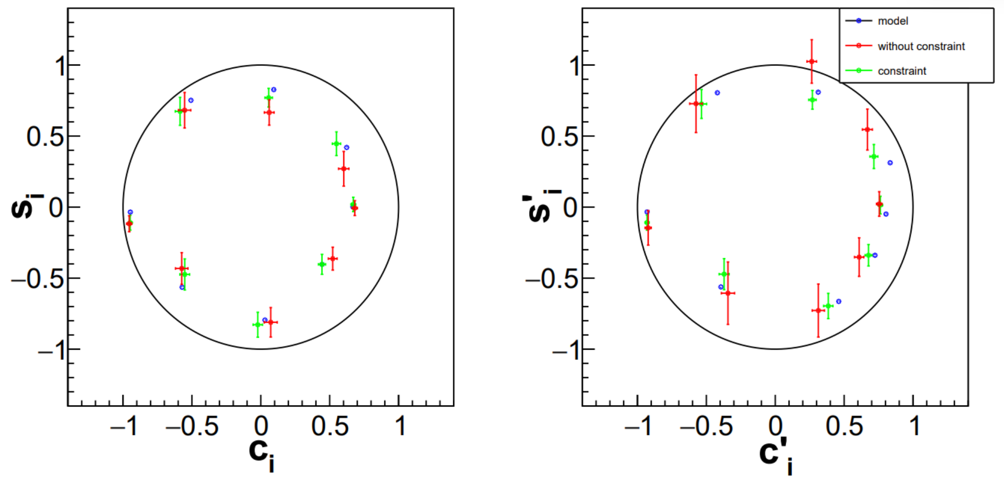

Figure 2: The measured $c_i^{(\prime)}$ and $s_i^{(\prime)}$ parameters obtained without constraints (red), with constraints (green), and predicted by the amplitude models [5] (blue), under the optimal binning scheme.

an estimated impact on its uncertainty of about 10°. The corresponding branching fraction is $(2.863 \pm 0.028_{\text{stat}} \pm 0.045_{\text{syst}}) \times 10^{-3}$, which is 3σ higher than the world average and twice as precise. The updated *CP*-even fraction, $0.754 \pm 0.010_{\text{stat}} \pm 0.008_{\text{syst}}$, represents a threefold improvement in precision.

4. Additional quantum coherent $D\bar{D}$ samples

In addition to the $D^0\bar{D}^0$ pairs produced at the $\psi(3770)$ resonance, the energy region between 4.13 and 4.23 GeV contains C-even final states such as $\gamma D\bar{D}$ and $\gamma\pi^0 D\bar{D}$, as well as C-odd final states including $\pi^0 D\bar{D}$, $\gamma\gamma D\bar{D}$, and $\pi^0\pi^0 D\bar{D}$. The separation of these samples proceeds in several stages [9]. First, events containing $D^0\bar{D}^0$ pairs are distinguished from other topologies using the missing energy $E_{\text{miss}} = E_{\text{cm}} - E_{D\bar{D}}$. The $\gamma D\bar{D}$ and $\pi^0 D\bar{D}$ channels are then selected via the recoil mass of the D meson, $\Delta M_{\text{rec},D}$, though the resolution is limited by initial-state radiation (ISR) effects. These two channels are further separated using the squared missing mass of the $D\bar{D}$ system, $M^2_{\text{miss},D\bar{D}}$. Finally, the combined $\gamma\gamma D\bar{D}$ and $\pi^0\pi^0 D\bar{D}$ sample is distinguished from $\gamma\pi^0 D\bar{D}$ by the squared missing mass $M^2_{\text{miss},\gamma D\bar{D}}$. The distributions of these variables are shown in Fig. 3 and are consistent with the expected behavior.

BESIII has performed the first measurement of the strong-phase-difference parameter $\delta_{K\pi}$ for the flavor-specific decay $K\pi$ by utilizing both C-even and C-odd samples. The analysis employs *CP* tags and $K^0_S\pi^+\pi^-$ tags, yielding $\delta_{K\pi} = \left(192.8^{+11.0}_{-12.4}\,(\text{stat})^{+1.9}_{-2.4}\,(\text{syst})\right)^\circ$. The use of both C-even and C-odd samples significantly reduces the systematic uncertainty, providing a valuable complement to the $\psi(3770)$ data set.

5. Summary and Prospects

Over the past two years, BESIII has produced a series of significant results in studies of quantum coherence, including determinations of *CP*-even fractions, binned strong-phase difference

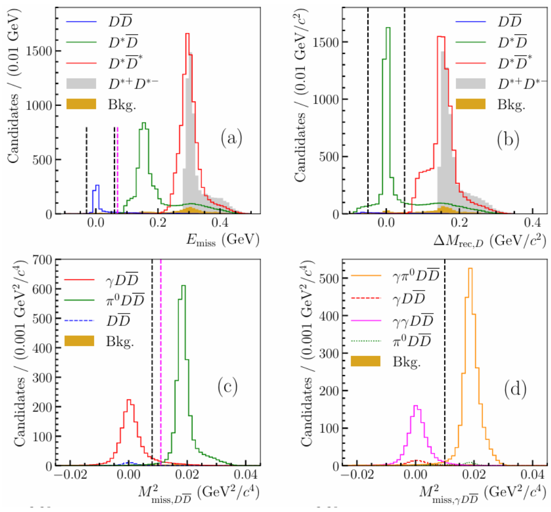

Figure 3: Distributions of (a) $E_{\rm miss}$, (b) $\Delta M_{{\rm rec},D}$, (c) $M^2_{{\rm miss},D\bar{D}}$, and (d) $M^2_{{\rm miss},\gamma D\bar{D}}$ for the $K^+\pi^-$ versus $K^-\pi^+$ double-tag sample in Monte Carlo simulation. The vertical dashed lines indicate the selection criteria used to separate the different production mechanisms [9].

parameters, and analyses with additional production channels. Utilizing the accumulated $D^0\bar{D}^0$ data sample of 20 fb^{-1} collected at $\sqrt{s}$ = 3.773 GeV, BESIII plans to conduct further amplitude analyses to deepen the understanding of decay dynamics and resonance properties, to improve precision of absolute branching fraction measurements, and to refine determination of strong-phase differences in neutral D decays. These efforts aim to reduce the uncertainty on the CKM angle γ originating from D-decay strong-phase effects to approximately 0.5°.

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