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Strong-phase results from quantum-correlated $D^0\overline{D}^0$ events

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Strong phases between D^0 and $\overline{D}^0$ mesons are essential inputs in interpreting D^0 mixing measurements and measurements of CP-violation in the charm and beauty sectors. Data from electron-positron colliders near the $\psi(3770)$ resonance allow for independent determinations of these strong phases in quantum-correlated $D^0\overline{D}^0$ produced through the mechanism $e^+e^- \to \gamma^* \to \ldots \to D^0\overline{D}^0$. The BESIII experiment accumulated 2.93 fb^{-1} of data near the $\psi(3770)$ production threshold in 2011, which continue to be used for measurements of strong phases in a number of final states. These proceedings discuss a number of results that have been published since the previous instalment of the BEAUTY conference in 2020. However, more data are needed to measure strong phases with sufficient precision so as they do not limit measurements of CP violation and charm-mixing from the large datasets currently being accumulated by the LHCb and Belle II experiments. Plans for the short-term and long-term futures of these measurements are also discussed.

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The contributions of strong interactions to D^0 meson decays occur in a flavour-basis, and as such, a phase is introduced between the amplitudes of D^0 and $\overline{D}^0$ mesons decaying to a common final state. If this final state is a CP-eigenstate, as in the decay of $D^0 \to P\overline{P}$, where P is a pseudoscalar meson such as K^+ or π^+, the determination of the strong phase is trivial. However, the strong phases between D^0 and $\overline{D}^0$ decaying to non-CP eigenstates are difficult to predict given the required low-energy QCD computations. Additionally, when D^0 decays to a multi (>2)-body final state, the strong phase varies across phase space, and is additionally complicated by the interference of the multiple resonances that contribute to the decay.

The BESIII experiment [1] records data of symmetric e^+e^- collisions provided by the Beijing Electron Positron Collider Mk. II (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.

In 2011, BESIII collected 2.93 fb^{-1} at $E_{\mathrm{CM}} = 3.773$ GeV, just above the threshold for producing $D^0\overline{D}^0$ mesons. As the $D^0\overline{D}^0$ pairs are produced through a virtual photon, i.e. $e^+e^- \to \gamma^* \to \ldots \to D^0\overline{D}^0$, and no other particles are produced in the final state, the $D^0\overline{D}^0$ pairs are constrained to be in a CP-odd state. This introduces entanglement between the two D mesons produced in the event, which can be leveraged to determine the strong phases of a specific D final state of interest. If both D mesons decay to flavour-indefinite final states, this entanglement results in interference which depends on a small number of other hadronic parameters, including the strong phases, between the D^0 and $\overline{D}^0$ decay amplitudes, δ_D. Using BESIII's samples at $E_{\mathrm{CM}} = 3.773$ GeV, these hadronic parameters can be determined by measuring the modified decay rate of the final state of interest against a variety of different tag decay modes of the other D meson in the event. While these measurements are of interest in their own right, they also serve as important inputs to studies of CP violation and mixing in decays of B and D mesons.

In 2022, an updated measurement of the strong phase between the processes $D^0 \to K^-\pi^+$ and $\overline{D}^0 \to K^-\pi^+$ [2] was published. This work supersedes the previous published measurement by BESIII in 2014 [3] and analyses a number of additional tag decay modes. These include the quasi-CP eigenstate $D^0 \to \pi^+\pi^-\pi^0$ and partially-reconstructed D^0 decays with a K^0_L in the final state. The effective branching fraction versus the CP-eigenstate and $\pi^+\pi^-\pi^0$ tag decay modes is shown in Fig.1, which clearly demonstrates the entanglement as there is a statistically significant difference in the effective branching fraction depending on the CP eigenvalue of the tag decay mode. The $K^0_S\pi^+\pi^-$ and $K^0_L\pi^+\pi^-$ tag modes also contribute significantly to the final determination. The updated measurement determines the strong phase as $\delta_D^{K\pi} = \left(187.6^{+8.9}_{-9.7}{}^{+5.4}_{-6.4}\right)^\circ$, consistent with the previous BESIII determination but significantly more precise. Here and throughout these proceedings, the first stated uncertainty corresponds to statistical uncertainty and the second to systematic uncertainty.

For the multi-body decays $D^0 \to K^0_S\pi^+\pi^-$ and $D^0 \to K^0_S K^+K^-$, the strong phases vary across the phase space of the final state. BESIII published updated measurements of the amplitude-weighted cosines and sines of the strong phases in (c_i and s_i, respectively) of both $D^0 \to K^0_S\pi^+\pi^-$ and $D^0 \to K^0_S K^+K^-$ in 2020 [4, 5]. The subscript i of the c_i and s_i parameters corresponds to the

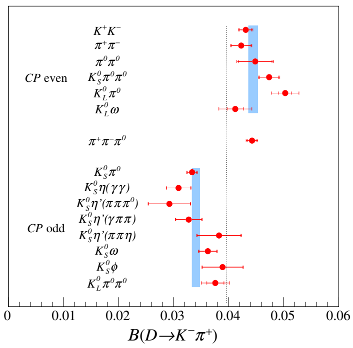

Figure 1: Effective branching fraction of $D \to K^-\pi^+$ against CP-eigenstate and $\pi^+\pi^-\pi^0$ tag modes [2].

bin of $K_S^0h^+h^-$ phase space. For $K_S^0\pi^+\pi^-$, two eight-bin binning schemes developed by the CLEO collaboration [6] are considered, one which minimizes variation of the strong phase across bins, and one which is constructed to maximize sensitivity to the CKM angle γ based on an amplitude model. For $K_S^0K^+K^-$, only a two-bin binning scheme which minimizes variation of the strong phase across bins is considered. The interference varies depending on the final state decaying against the $D \to K_S^0h^+h^-$. Seventeen opposite-side decays are studied, and can be broadly categorized into flavour tags, CP-even tags, CP-odd tags, $K_L^0\pi^+\pi^-$, and the double-tag $K_S^0h^+h^-$. The measured c_i and s_i parameters are shown in Fig. 2 and are compared to previous results and predictions.

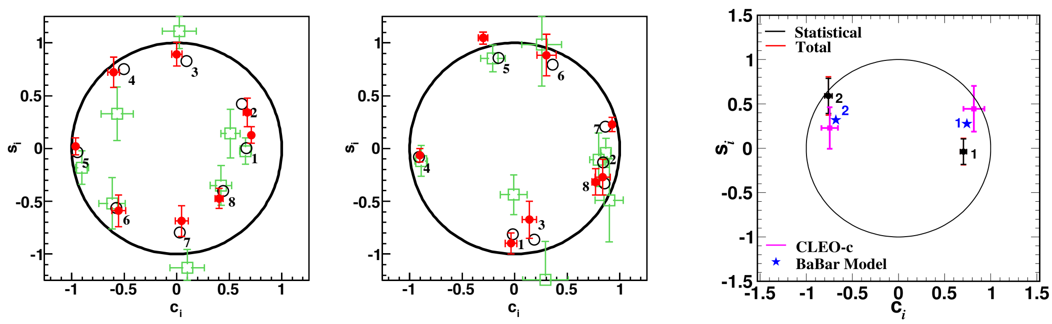

Figure 2: Comparison of c_i and s_i parameters between measured CLEO-c results [6] (open green squares in the left two plots), measured BESIII results [4, 5] (filled red circles in the left two plots), predictions from an amplitude model using *BABAR* and Belle data [7] for $D^0 \to K_S^0\pi^+\pi^-$ (open black circles in the left two plots), and predictions from an amplitude model using *BABAR* data [8] for $D^0 \to K_S^0K^+K^-$. Results are shown for the constant δ_D binning scheme of $D^0 \to K_S^0\pi^+\pi^-$ (left) , the optimal γ binning scheme of $D^0 \to K_S^0\pi^+\pi^-$ (center), and the constant δ_D binning scheme of $D^0 \to K_S^0K^+K^-$ (right).

BESIII also produced a study of U-spin breaking effects responsible for differences in the resonance structures of $D^0 \to K_S^0\pi^+\pi^-$ and $D^0 \to K_L^0\pi^+\pi^-$ decays [9]. Previous studies of strong phase measurements had relied on predictions of these effects, as they had never been studied experimentally. Through an amplitude analysis of the $D^0 \to K_L^0\pi^+\pi^-$ process and comparison to known results relating to the $D^0 \to K_S^0\pi^+\pi^-$ process, parameters related to the U-spin breaking are determined. The results of the $D^0 \to K_L^0\pi^+\pi^-$ amplitude analysis and comparison to the $D^0 \to K_S^0\pi^+\pi^-$ amplitudes are shown in Fig. 3. These results will allow for reduced systematic uncertainties in future strong phase measurements.

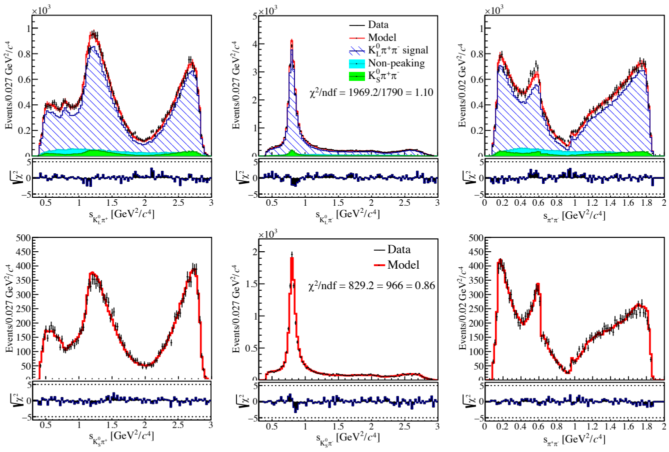

Figure 3: Projections of the amplitude fit to $D^0 \to K^0_L\pi^+\pi^-$ candidates (top), compared to the projections of data and an overlaid model prediction corresponding to $D^0 \to K^0_S\pi^+\pi^-$ events (bottom). Notable differences can be seen between the $K^0_L\pi^+\pi^-$ and $K^0_S\pi^+\pi^-$ distributions, which allow the determination of U-spin breaking parameters [9].

For the Cabibbo-favoured $D^0 \to K^-\pi^+\pi^+\pi^-$ and $D^0 \to K^-\pi^+\pi^0$ decays, interference is realised with the doubly-Cabbibo-suppressed decays $\overline{D}^0 \to K^-\pi^+\pi^+\pi^-$ and $\overline{D}^0 \to K^-\pi^+\pi^0$. BESIII published measurements [10] of the strong phases δ_D, the relative amplitude between the D^0 and $\overline{D}^0$ decay r_D, and the coherence of these parameters integrated across phase space R are mode for both $K3\pi$ and $K\pi\pi^0$. For $D^0 \to K3\pi$, these parameters are additionally measured in each bin of a four-bin binning scheme [11] which has been demonstrated to significantly increased sensitivity to the measurement of the CKM angle γ.

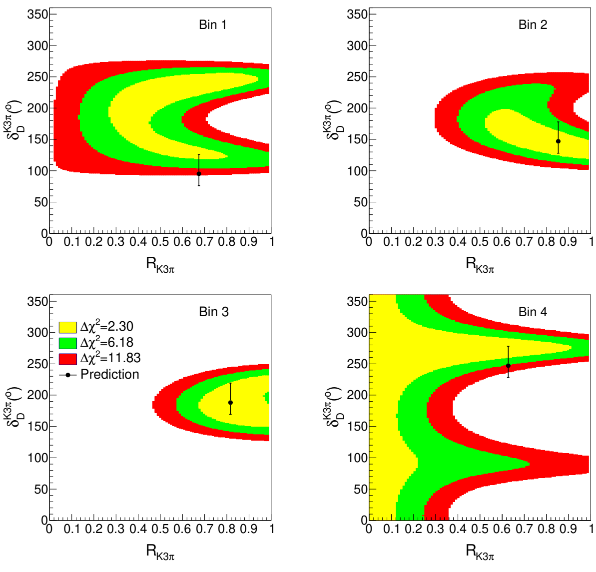

Figure 4: Measured results of the strong phase vs. the coherence factor for $K3\pi$ in the novel binning scheme [11] .

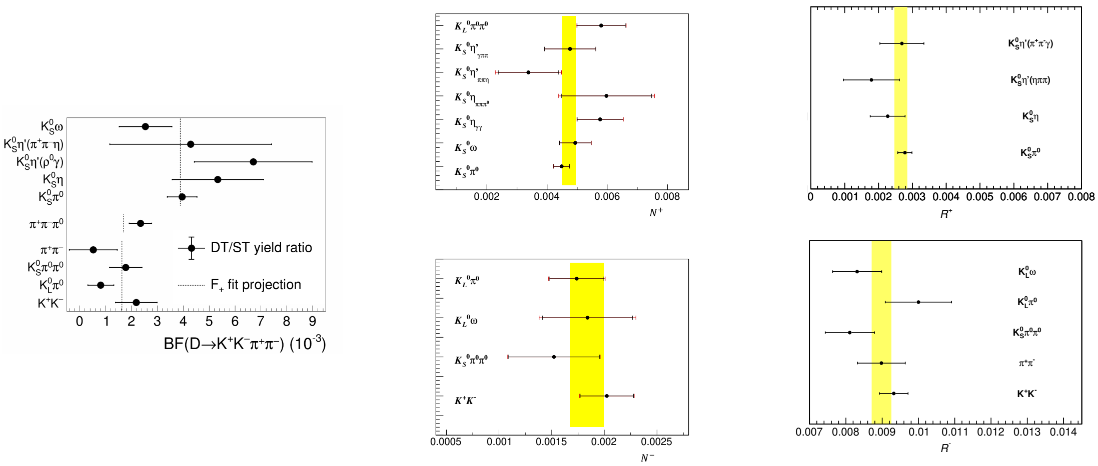

Figure 5: Effective branching fractions determined, or closely related parameters, against different tag modes for $D^0 \to K^+K^-\pi^+\pi^-$ (left), $D^0 \to \pi^+\pi^-\pi^+\pi^-$ (center), and $D^0 \to K^0_S\pi^-\pi^+\pi^0$ (right). In each case, CP-even tag modes are shown on top, and CP odd modes are shown on bottom.

Self-conjugate multi-body D^0 final states can be approximated as CP eigenstates, despite having intermediate states with both CP eigenvalues contributing to the total decay width. In this approximation, a correction must be determined for these decays to be used in studies of mixing and CP violation. The CP-even fraction F_+ of these decay channels quantifies the necessary correction, and can be determined using similar techniques to those used to determine strong phases and other hadronic parameters for the other final states described earlier in these proceedings. In 2022 and 2023, BESIII published determinations of F^+ for $D^0 \to K^+K^-\pi^+\pi^-$, $D^0 \to \pi^+\pi^-\pi^+\pi^-$, and $D^0 \to K^0_S\pi^-\pi^+\pi^0$ decays, finding $F_+ = 0.730\pm0.037\pm0.021$ [12], $F_+ = 0.753\pm0.028\pm0.010$ [13], and $F_+ = 0.235\pm0.010\pm0.002$ [14], respectively. The differences in the effective branching fraction (or a closely related parameter) against CP even and CP odd tag modes are shown for the three modes in Fig. 5.

These results serve as key inputs to the extracting the CKM angle γ from decays of $B \to DK$. The LHCb collaboration employed the updated strong phase measurements of $D^0 \to K^0_S h^+h^-$ in the analysis of $B^+ \to D[K^0_S h^+h^-]K^+$, which provides the world's most precise determination of γ to date [15] with $\gamma = \left(68.7^{+5.2}_{-5.1}\right)^\circ$. Uncertainties from the strong phase parameters contributed approximately 1° of uncertainty. In 2023, an LHCb measurement of $B^+ \to D[K^-\pi^+\pi^+\pi^-]K^+$, which employed the binning scheme laid out in Ref. [11] and the measured strong phase parameters from Ref. [10], produced the second-most precise determination of γ from any single measurement: $\gamma = \left(54.8^{+6.0}_{-5.8}{}^{+0.6}_{-0.6}{}^{+6.7}_{-4.3}\right)^\circ$ [16], where the first uncertainty arises from the LHCb sample size, the second uncertainty to LHCb systematics, and the third uncertainty to the propagated uncertainty from the $D^0 \to K^-\pi^+\pi^+\pi^-$ hadronic parameters. Additionally, LHCb recently employed the updated measurement of strong phase parameters of $D^0 \to K^0_S\pi^+\pi^-$ to produce the first measurement of a non-zero mass difference in the D^0 system [17].

These measurements of D^0 strong phases and other hadronic parameters provide crucial inputs for studies of CP violation and mixing in heavy-quark systems. At present, uncertainties from these measurement contribute subdominant uncertainties to the determination of γ in aggregate, however results from certain final states, such as $B^+ \to D[K^-\pi^+\pi^+\pi^-]K^+$ are limited by the associated D^0 hadronic parameter uncertainties. The propagated uncertainties of $D^0 \to K^0_S\pi^+\pi^-$ hadronic parameters currently contribute roughly half of the total uncertainty on the charm mixing parameters, x_{CP} and y_{CP}, and roughly 15% of the total uncertainty on the CP-violating parameters Δx and Δy. Further precision is needed for these uncertainties to remain subdominant as LHCb continues data collection in Run 3 of the LHC and Belle II accumulates data. As of the writing of these proceedings, BESIII has begun the collection of additional samples at $E_{\text{CM}} = 3.773$ GeV, with the goal of accumulating an additional 20 fb^{-1} of data at this energy. This sample will provide nearly seven times as many $D^{+/0}$ mesons than the current BESIII sample and will allow for the necessary improvement in precision on D^0 hadronic parameters.

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