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Charm physics at BESIII

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In these proceedings, three recent results on charm strong-phase measurements from BESIII are presented. These are necessary external inputs to model-independent measurements of the CKM angle γ. Furthermore, they can also be used in studies of D^0-$\bar{D}^0$ mixing and CP-violation measurements. First, the strong-phase difference in the decay $D \to K^-\pi^+$ is presented, and it is the most precise determination using quantum-correlated decays. Second, the decay mode $D \to K^-\pi^+\pi^-\pi^+$ has been analysed with a phase-space binned strategy, using a binning scheme optimised for sensitivity to γ. Finally, the first measurement of the CP-even fraction of $D^0 \to K^+K^-\pi^+\pi^-$ is discussed.

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1. Introduction

At BESIII, there is a wide charm physics programme, and in particular the strong-phase measurements in charm decays are of great interest in the studies of *CP*-violation at *B*-factories [1]. In measurements of the CKM angle γ, external measurements of the strong-phase difference between D^0 and $\bar{D}^0$ decays are required in order to extract a model-independent value of γ. The synergy between BESIII and *B*-factories is therefore crucial to precisely measure γ, as well as D mixing and *CP*-violation parameters.

BESIII is currently the only active charm factory with direct access to charm strong-phase information, using quantum-correlated $D^0\bar{D}^0$ pairs at the $\psi(3770)$ threshold. The results presented in these proceedings use a dataset with an integrated luminosity of 2.93 fb^{-1}. A double-tag (DT) method is employed, where a decay mode of interest is tagged with a set of known tag modes. Since the strong-phase content of the tag mode is known, the strong-phase information of the other D decay may be inferred from the suppression or enhancement due to quantum correlations.

2. Strong-phase measurement of $D \to K^-\pi^+$

In the decay $D \to K^-\pi^+$, the strong-phase difference $\delta_D^{K\pi}$ is defined as the strong-phase difference between the Cabbibo Favoured (CF) decay $\bar{D}^0 \to K^+\pi^-$ and the Doubly-Cabbibo Suppressed (DCS) decay $D^0 \to K^+\pi^-$.

Previously, the parameter $\cos(\delta_D^{K\pi})$ was measured using a set of eight *CP* tags [2]. In the recent analysis [3], the measurement is re-performed using the additional tag $D \to \pi^+\pi^-\pi^0$, which is approximately *CP*-even. Additionally, the partially reconstructed $D \to K_L^0\pi^0$, $K_L^0\pi^0\pi^0$ and $K_L^0\omega$ tags have also been included in the analysis. This allows for the determination of $\cos(\delta_D^{K\pi})$ with a much greater precision.

Since the tags involving a K_L^0 meson are partially reconstructed, their single-tag yield, which is used for normalisation, must be determined using the total number of $D\bar{D}$ pairs [4] and the branching fraction of the tag. These branching fractions are determined using a DT analysis of the same dataset by selecting $K_L^0\pi^0$, $K_L^0\pi^0\pi^0$ and $K_L^0\omega$ decays against *CP* tags of opposite *CP* content. The obtained branching fractions are

$$\begin{aligned}
\mathcal{B}(D^0 \to K_L^0\pi^0) &= (0.97 \pm 0.03 \pm 0.02) \times 10^{-2}, \\
\mathcal{B}(D^0 \to K_L^0\omega) &= (1.09 \pm 0.06 \pm 0.03) \times 10^{-2}, \\
\mathcal{B}(D^0 \to K_L^0\pi^0\pi^0) &= (1.26 \pm 0.05 \pm 0.03) \times 10^{-2},
\end{aligned}$$

where the first uncertainty is statistical and the second is systematic.

To measure $\cos(\delta_D^{K\pi})$, the tag $D \to K^-\pi^+$ is tagged against an ensemble of *CP*-even and *CP*-odd tags. The effective branching fraction may be measured for each tag separately, and due to quantum correlations, the effective branching fraction will either be enhanced or suppressed due to interference effects between CF and DCS amplitudes. A comparison between the *CP*-tag modes is shown on the left in Fig. 1, and the asymmetry is sensitive to $\cos(\delta_D^{K\pi})$.

In the final part of the measurement, the DT yields of $D \to K^-\pi^+$, tagged by $K_{S,L}^0\pi^+\pi^-$, are obtained for each bin in the $K_{S,L}^0\pi^+\pi^-$ phase space. These DT yields are related to $\delta_D^{K\pi}$ by

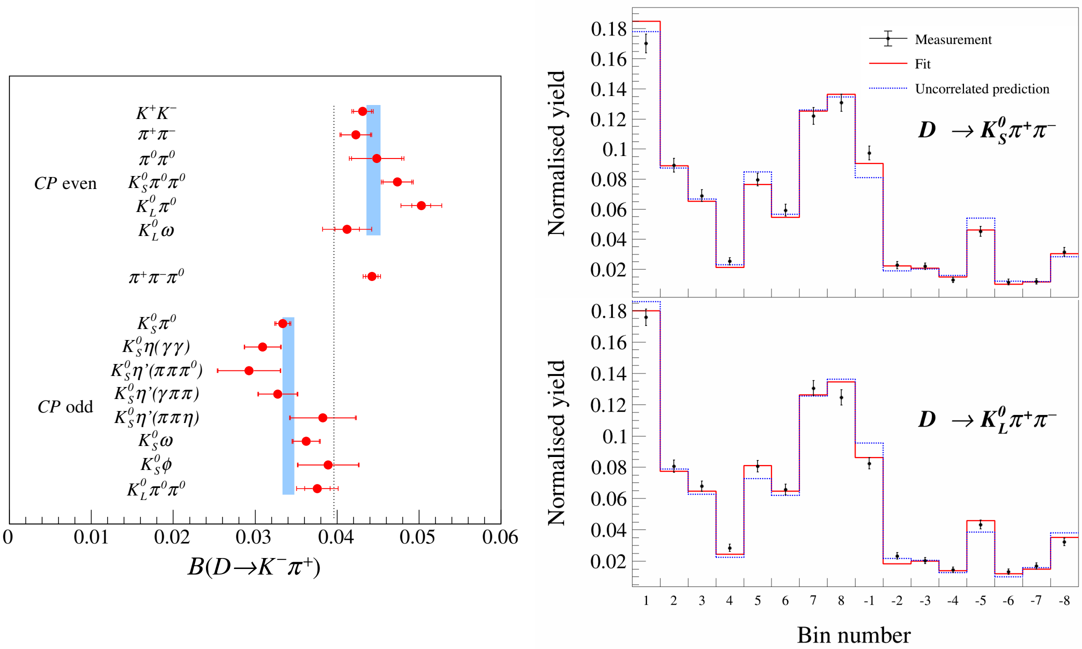

Figure 1: Left: Effective branching fraction of $D \to K^-\pi^+$ measured against CP tags. Right: Yields of $D \to K^-\pi^+$ decays tagged with (top) $D \to K_S^0\pi^+\pi^-$ and (bottom) $D \to K_L^0\pi^+\pi^-$ in bins of phase space.

$$Y_i \propto K_i + (r_D^{K\pi})^2 K_{-i} - 2r_D^{K\pi}\sqrt{K_i K_{-i}}\left[c_i \cos(\delta_D^{K\pi}) - s_i \sin(\delta_D^{K\pi})\right],$$

where K_i (K_{-i}) are the fractional bin yields of D^0 ($\bar{D}^0$) mesons decaying to $K_S^0\pi^+\pi^-$ in bin i, $r_D^{K\pi}$ is the ratio of the DCS and CF amplitudes, and c_i (s_i) is the amplitude-averaged cosine (sine) of the strong-phase difference between D^0 and $\bar{D}^0 \to K_S^0\pi^+\pi^-$. The equation for the $K_L^0\pi^+\pi^-$ tag is similar. The values of c_i, s_i and K_i for $K_{S,L}^0\pi^+\pi^-$ were measured using a DT analysis in Ref. [5], using $D \to K^-\pi^-$ as a tag mode. The same DT yields may be used for the measurement of $\delta_D^{K\pi}$. From the DT yields of $D \to K^-\pi^+$, tagged with $K_{S,L}^0\pi^+\pi^-$ in bins of phase space, the parameters $r_D^{K\pi}\cos(\delta_D^{K\pi})$ and $r_D^{K\pi}\sin(\delta_D^{K\pi})$ are determined. A comparison between the bin yields are shown on the right in Fig. 1.

The results from the CP tags and the self-conjugate multi-body tags are combined using maximum likelihood fit, and since both $\cos(\delta_D^{K\pi})$ and $\sin(\delta_D^{K\pi})$ are measured, a unique solution is obtained, $\delta_D^{K\pi} = 187.6^{+8.9+5.4}_{-9.7-6.4}$. This is the most precise measurement of $\delta_D^{K\pi}$ obtained from quantum-correlated $D\bar{D}$ decays, and it is complementary to that obtained at B-factories.

3. Phase-space binned analysis of $D \to K^-\pi^+\pi^-\pi^+$

The strong-phase of the decay $D \to K^-\pi^+\pi^-\pi^+$ can be defined in an analogous manner to that of $D \to K^-\pi^+$. However, since the final state has four spinless particles, the decay has a five-dimensional phase space, where the strong-phase difference $\delta_D^{K3\pi}$ can vary across the phase space.

In Ref. [6], the strong-phase difference $\delta_D^{K3\pi}$ was measured with an approach identical to that of $D \to K^-\pi^+$, but integrated over phase space. Since interference effects may be diluted when integrated over phase space, a coherence factor $R_{K3\pi}$ is introduced to parameterise this dilution. The results are $\delta_D^{K3\pi} = (167^{+31}_{-19})^\circ$ and $R_{K3\pi} = 0.52^{+0.12}_{-0.10}$. The latter result implies that around half of the interference effects are diluted when integrating over phase space.

By analysing the strong-phase difference in bins of phase space, using a binning scheme from Ref. [7], dilution effects can be reduced. The hadronic parameters are fitted simultaneously in all bins, and the resulting coherence factors and strong-phase differences are shown in Fig. 2. Clear enhancements in the coherence factor is seen, and this greatly improves the sensitivity to γ.

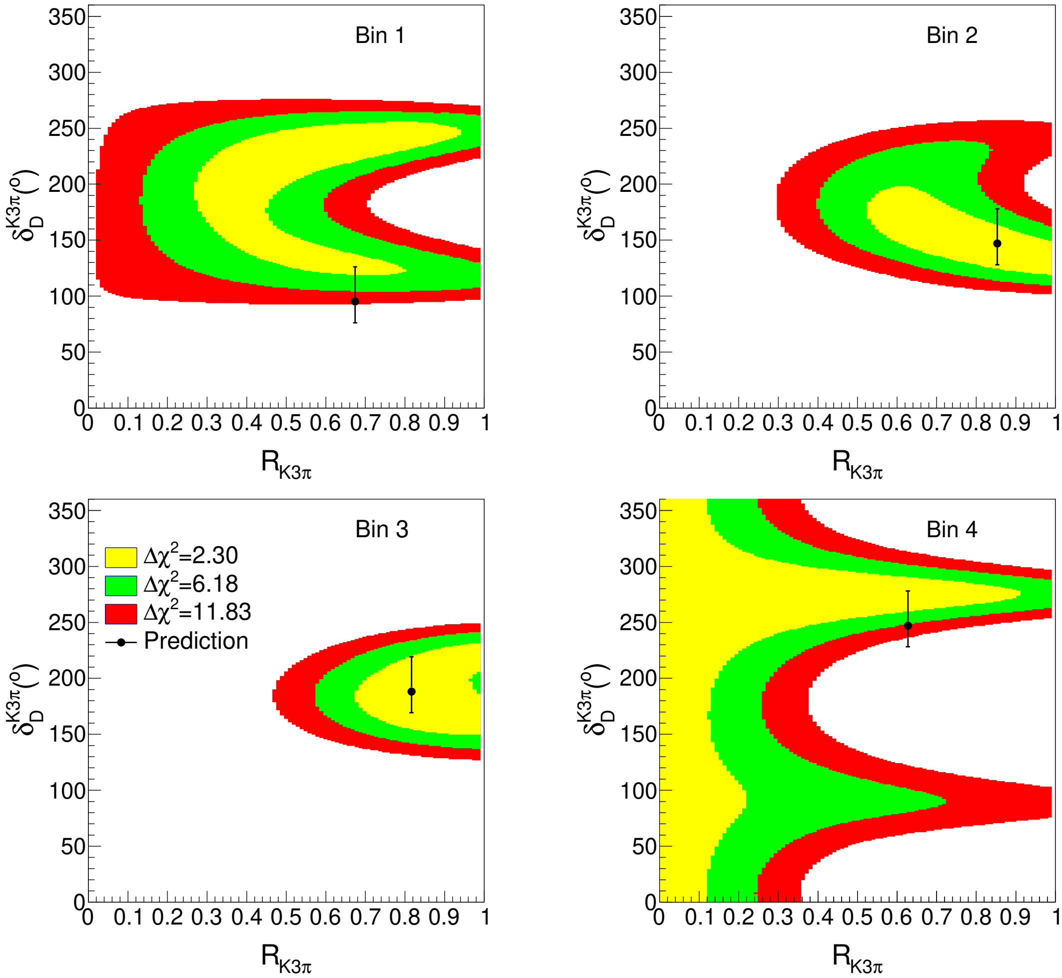

Figure 2: Binned fit of $\delta_{K3\pi}$ and $R_{K3\pi}$.

4. Measurement of the $D \to K^+K^-\pi^+\pi^-$ *CP*-fraction

The strong-phase difference of the decay $D \to K^+K^-\pi^+\pi^-$ has never been studied previously. In Ref. [8] this decay mode was shown to provide valuable information on γ, and LHCb has recently performed a first model-dependent measurement using this mode [9]. It is desirable to make direct measurements of the strong-phase difference of this mode in order to obtain a model-independent measurement of γ, and in Ref. [10] the *CP*-even fraction F_+ was studied for the first time.

The measurement of F_+ using *CP*-tags is analogous to that of $D \to K^-\pi^+$ and $D \to K^-\pi^+\pi^-\pi^+$. An effective branching fraction is determined, using 10 different *CP* tag modes. An asymmetry is seen, where the effective branching fraction obtained from *CP*-even (odd) tags are suppressed (enhanced). Furthermore, the self-conjugate multi-body tags $K^0_{S,L}\pi^+\pi^-$ are also analysed in bins of phase space, which provide additional constraints.

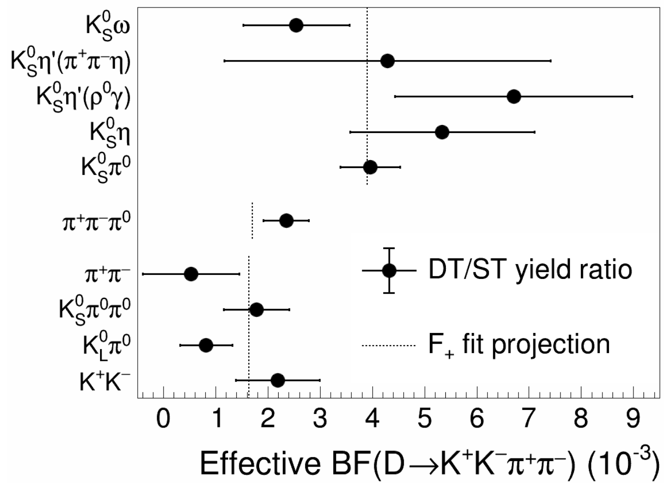

Figure 3: Effective branching fraction of $D \to K^+K^-\pi^+\pi^-$, tagged against *CP* tags.

The combined value of the *CP*-even fraction of this decay was found to be $F_+ = 0.73 \pm 0.04$, and it is dominated by statistical uncertainties. Furthermore, with more data this mode can also be analysed in bins of phase space, and this is expected to significantly enhance the sensitivity to γ at B-factories.

5. Summary and conclusion

BESIII has a performed a wide range of successful charm physics studies. Of particular importance is the measurement of strong-phase differences between D^0 and $\bar{D}^0$ decays, which are essential inputs to the measurement of the CKM angle γ at LHCb and Belle II. In addition, the same strong-phase parameters are also needed for studies of mixing and *CP*-violation in the charm system.

First, the analysis of the two-body decay $D \to K^-\pi^+$ has resulted in the most precise measurement of $\delta_D^{K\pi}$ from quantum-correlated $D\bar{D}$ pairs, and it is complementary with the value obtained from LHCb. A related decay mode, $D \to K^-\pi^+\pi^-\pi^+$, was analysed using an optimised binning scheme, and the coherence factor was found to increase significantly, compared with a phase-space integrated fit. Finally, for the decay $D \to K^+K^-\pi^+\pi^-$ the *CP*-even fraction has been measured, for the first time, to be $F_+ = 0.73 \pm 0.04$.

In the future, BESIII is expected to accumulate a datasample with integrated luminosity of 20 fb^{-1}. This will not only improve the precision of the current strong-phase measurements, but it will also allow for a binned analysis of the $D \to K^+K^-\pi^+\pi^-$ decay. Such analyses will be crucial since both LHCb and Belle II are expected to accumulate very large data samples of B decays, and measurements of γ and charm mixing will become limited by systematic uncertainty from the charm strong-phase inputs.

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