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Strong phase in $D^0 \to K\pi$ decay and y_{CP} measurements from CP-tagged D^0 decays at BESIII

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The preliminary results of $\cos\delta_{K\pi}$ and the $D^0 - \overline{D}^0$ mixing parameter y_{CP} from BESIII are presented in this paper, where $\delta_{K\pi}$ is the strong phase difference between the doubly Cabibbo-suppressed process $\overline{D}^0 \to K^-\pi^+$ and Cabibbo-favored $D^0 \to K^-\pi^+$. These measurements were carried out based on the quantum-correlated technique in studying the process of $D^0\overline{D}^0$ pair productions of 2.92 fb^{-1} e^+e^- collision data collected with the BESIII detector at $\sqrt{s}$ = 3.773 GeV. The preliminary results are $\cos\delta_{K\pi} = 1.03 \pm 0.12 \pm 0.04 \pm 0.01$ and $y_{CP} = (-1.6 \pm 1.3 \pm 0.6)\%$.

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1. Introduction

Mixing of neutral mesons occurs when the flavor eigenstates differ from the physical mass eigenstates. In charm sector, $D^0-\overline{D}^0$ mixing is a small effect in the Standard Model. While the short-distance effect is suppressed both by CKM matrix [1] and the GIM mechanism [2], charm mixing is expected to be dominated by long-distance process which make it difficult to be calculated reliably. To measure the charm mixing parameters helps to study the size of the long distance effect and search for new physics [3]. Many sophisticated experimental efforts have been made in the past decades, and these results indicate that D^0 and $\overline{D}^0$ do mix. Charm mixing is established by the LHCb [4] in 2013 and verified by the CDF experiment [5], subsequently.

Conventionally, charm mixing is described by two dimensionless parameters $x = 2\frac{M_1-M_2}{\Gamma_1+\Gamma_2}$ and $y = \frac{\Gamma_1-\Gamma_2}{\Gamma_1+\Gamma_2}$, where $M_{1,2}$ and $\Gamma_{1,2}$ are the masses and widths of two mass eigenstates. The mass eigenstates of D which are linear combinations of flavor eigenstates are expressed as $|D_{1,2}\rangle = p|D^0\rangle + q|\bar{D}^0\rangle$, where p and q are complex parameters and they have phase difference ϕ. With the help of the conventions $CP|D^0\rangle = |\overline{D}^0\rangle$, CP eigenstates can be written as $|D_{CP+}\rangle \equiv \frac{|D^0\rangle+|\overline{D}^0\rangle}{\sqrt{2}}$ and $|D_{CP-}\rangle \equiv \frac{|D^0\rangle-|\overline{D}^0\rangle}{\sqrt{2}}$. The parameter $y_{\rm CP}$ can also be defined to express the differences between effective lifetime of D decays to CP eigenstates and flavor eigenstates. In the absence of direct CP violation, but allowing for small indirect CP violation [6], we have

$$y_{\rm CP} = \frac{1}{2}[y\cos\phi(|\frac{q}{p}|+|\frac{p}{q}|) - x\sin\phi(|\frac{q}{p}|-|\frac{p}{q}|)]. \quad (1.1)$$

In case of no CPV, we have $|p/q| = 1$ and $\phi = 0$. Hence, $y_{\rm CP} = y$.

So far, most of our knowledge about $D^0-\overline{D}^0$ mixing are from time-dependent measurements. And the most precise determination of the size of the mixing are obtained by focusing on the time-dependent decay rate of the wrong-sign process $D^0 \to K^+\pi^-$. These analyses are sensitive to $y' \equiv y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$ and $x' \equiv x\cos\delta_{K\pi} + y\sin\delta_{K\pi}$ [4, 5, 7]. Where the $-\delta_{K\pi}$ is the relative strong phase between the doubly Cabibbo-suppressed (DCS) decay $D^0 \to K^+\pi^-$ and the corresponding Cabibbo-favored (CF) $\overline{D}^0 \to K^-\pi^+$

$$\frac{\langle K^-\pi^+|\overline{D}^0\rangle}{\langle K^-\pi^+|D^0\rangle} = -re^{-i\delta_{K\pi}}. \quad (1.2)$$

Here, $r = \left|\frac{\langle K^-\pi^+|\overline{D}^0\rangle}{\langle K^-\pi^+|D^0\rangle}\right|$. The measurement of $\delta_{K\pi}$ can allow x and y to be extracted from x' and y'. Determination of $\delta_{K\pi}$ is important for this extraction. Furthermore, finer precision of $\delta_{K\pi}$ helps the γ/ϕ_3 angle measurement in CKM matrix according to the so-called ADS method [8]. In the limit of CP conservation, $\delta_{K^-\pi^+}$ is the same as $\delta_{K^+\pi^-}$. We use the notation of $K^-\pi^+$, and its charge conjugation mode is always implied to be included throughout the report.

At BESIII, $\delta_{K\pi}$ and $y_{\rm CP}$ can be determined using the time-independent measurements. In the mass-threshold production process $e^+e^- \to D^0\overline{D}^0$, the $D^0\overline{D}^0$ pair is in a state of definite $C = -$, because of the initial state (the virtual photon) has $J^{PC} = 1^{--}$. Thus the D^0 and $\overline{D}^0$ mesons are quantum-correlated. This provides an unique way to probe $D^0-\overline{D}^0$ mixing as well as the strong phase differences between D^0 and $\overline{D}^0$ decays [9].

In this report, we present the preliminary results of $\delta_{K\pi}$ and $y_{\rm CP}$ by analysing coherent $D^0\overline{D}^0$ decays. These analyses are based on 2.92 fb^{-1} data at $\sqrt{s} = 3.773$ GeV in e^+e^- collisions collected with the BESIII detector. Details of the BESIII detector can be found elsewhere [10].

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2. Measurement of the relative strong phase $\delta_{K\pi}$

With the assumption of *CP* conservation, the relative strong phase $\delta_{K\pi}$ can be accessed using these following formula [11] [12]

$$2r\cos\delta_{K\pi} + y = (1+R_{\rm WS})\cdot\mathscr{A}_{CP\to K\pi}, \quad \mathscr{A}_{CP\to K\pi} = \frac{\mathscr{B}_{D_{CP-}\to K^-\pi^+} - \mathscr{B}_{D_{CP+}\to K^-\pi^+}}{\mathscr{B}_{D_{CP-}\to K^-\pi^+} + \mathscr{B}_{D_{CP+}\to K^-\pi^+}}, \tag{2.1}$$

where $R_{\rm WS}$ is the decay rate ratio of the wrong sign process $\overline{D}^0 \to K^-\pi^+$ and the right sign process $D^0 \to K^-\pi^+$ and $\mathscr{B}$ denotes branching fractions. Benefiting from quantum-coherence, at BESIII, we can use *CP* tagging method to measure the branching fractions

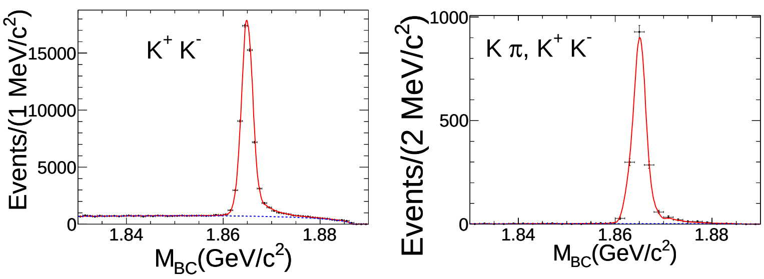
$$\mathscr{B}_{D^{CP\mp}\to K\pi} = \frac{n_{K\pi,CP\pm}}{n_{CP\pm}}\cdot\frac{\varepsilon_{CP\pm}}{\varepsilon_{K\pi,CP\pm}}, \tag{2.2}$$

In addition, most of systematic errors can be cancelled. Here, $n_{CP\pm}$ ($n_{K\pi,CP\pm}$) and $\varepsilon_{CP\pm}$ ($\varepsilon_{K\pi,CP\pm}$) are yields and detection efficiencies of single tags (ST) of $D \to CP\pm$ (double tags (DT) of $D^0\overline{D}^0 \to CP\pm;\ K\pi$), respectively. With external inputs of the parameters of r, y and $R_{\rm WS}$, one can extract $\delta_{K\pi}$.

In this analysis, 5 *CP*-even D^0 decay modes ($K^+K^-, \pi^+\pi^-, K^0_S\pi^0\pi^0, \pi^0\pi^0, \rho^0\pi^0$) and 3 *CP*-odd modes ($K^0_S\pi^0, K^0_S\eta, K^0_S\omega$) are used, with $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$, $K^0_S \to \pi^+\pi^-$ and $\omega \to \pi^+\pi^-\pi^0$. The key variable

$$M_{\rm BC} \equiv \sqrt{E_0^2/c^4 - |\vec{p}_{\rm D}|^2/c^2} \tag{2.3}$$

is used to identify signals. Here $\vec{p}_{\rm D}$ is the total momentum of the D^0 candidate and E_0 is the beam energy. Maximum likelihood fits are performed to $M_{\rm BC}$ distribution to get yields of the *CP* ST signals. Signals are modeled using the shape derived from MC simulation convoluted with a smearing Gaussian function, and backgrounds are described by the ARGUS function [13]. In the events of the *CP* ST modes, the $K\pi$ combinations are reconstructed using the remaining charged tracks with respect to the ST D candidates. Similar fits are performed to the distributions of $M_{\rm BC}(D \to CP\pm)$ in the survived DT events to estimate yields of DT signals. These fits are shown in Fig. 1. We get $\mathscr{A}_{CP\to K\pi} = (12.77 \pm 1.31^{+0.33}_{-0.31})\%$, where the first uncertainty is statistical



(a) ST $M_{\rm BC}$ fit of the $D \to K^+K^-$ (b) DT $M_{\rm BC}$ fit of the $K^+K^-; K\pi$

Figure 1: In both figures, data are shown in points with error bars. The solid red lines show the total fits and the dashed blue lines show the background shapes.

and the second is systematic. To measure the strong phase $\delta_{K\pi}$ in Eq. (2.1), we quote the external inputs of $R_{\rm D} = r^2 = (3.47 \pm 0.06)‰$, $y = (6.6 \pm 0.9)‰$, and $R_{\rm WS} = (3.80 \pm 0.05)‰$ from HFAG

2013 [14] and PDG [6]. Finally, we obtain $\cos\delta_{K\pi} = 1.03 \pm 0.12 \pm 0.04 \pm 0.01$, where the first uncertainty is statistical, the second uncertainty is systematic, and the third uncertainty is due to the errors introduced by the external input parameters. This result is more precise than CLEO's measurement [11, 14] and provides the world best constrain on $\delta_{K\pi}$.

3. Measurement of $y_{\rm CP}$

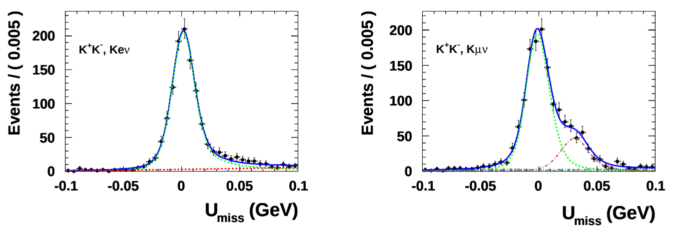
$y_{\rm CP}$ can be extracted by the semileptonic decays of $D^0 \to l$ using the following equation [12]

$$y_{\rm CP} = \frac{1}{4}\left(\frac{\mathscr{B}_{D_{CP-}\to l}}{\mathscr{B}_{D_{CP+}\to l}} - \frac{\mathscr{B}_{D_{CP+}\to l}}{\mathscr{B}_{D_{CP-}\to l}}\right), \tag{3.1}$$

where the branching ratios $\mathscr{B}_{CP\mp}$ can be obtained by

$$\mathscr{B}_{CP\mp} = \frac{n_{l;CP\pm}}{n_{CP\pm}} \cdot \frac{\varepsilon_{CP\pm}}{\varepsilon_{l;\,CP\pm}}. \tag{3.2}$$

To combine results from different tag modes, we determine $y_{\rm CP}$ using $\tilde{\mathscr{B}}_\pm$ which is obtained from $\chi^2 = \sum_\alpha \frac{(\tilde{\mathscr{B}}_\pm - \mathscr{B}^\alpha_\pm)^2}{(\sigma^\alpha_\pm)^2}$. Here, α denotes different CP-tag modes. 3 CP-even tag modes (K^+K^-, $\pi^+\pi^-$,



(a) $U_{\rm miss}$ fit for CP-tagged $Ke\nu$ (b) $U_{\rm miss}$ fit for CP-tagged $K\mu\nu$

Figure 2: $U_{\rm miss}$ distributions and fits to data.

$K_S\pi^0\pi^0$) and 3 CP-odd tag modes ($K^0_S\pi^0$, $K^0_S\omega$, $K^0_S\eta$)are used in this analysis. Similar to the analysis of $\delta_{K\pi}$, ST yields are estimated by fitting to the $M_{\rm BC}$ distributions. Semileptonic decays of $D \to Ke\nu$ and $D \to K\mu\nu$ are reconstructed with respect to the CP-tagged D candidates in ST events. These reconstruction are partial reconstruction due to the undetectable neutrino in the final states. Variable $U_{\rm miss}$ is defined to distinguish the semileptonic signals from backgrounds

$$U_{\rm miss} \equiv E_{\rm miss} - |\vec{p}_{\rm miss}|,$$

$$E_{\rm miss} \equiv E_0 - E_K - E_l, \quad \vec{p}_{\rm miss} \equiv -[\vec{p}_K + \vec{p}_l + \hat{p}_{\rm ST}\sqrt{E_0^2 - m_D^2}]. \tag{3.3}$$

Here, $E_{K/l}$ ($\vec{p}_{K/l}$) is the energy (three-momentum) of $K^\pm$ or lepton $l^\mp$, $\hat{p}_{\rm ST}$ is the unit vector in the reconstructed direction of the CP-tagged D and m_D is the nominal D^0 mass. $U_{\rm miss}$ of correctly-reconstructed signals should peaks at zero. $U_{\rm miss}$ fit plots are shown in Fig. 2.

In the $U_{\rm miss}$ fitting, for $Ke\nu$ mode, signal shape is modeled using MC shape convoluted with an asymmetric Gaussian and backgrounds are described with a 1st-order polynomial function. For $K\mu\nu$ mode, signal shape is modeled using MC shape convoluted with an asymmetric Gaussian.

Backgrounds of $Ke\nu$ are modeled using MC shape and their relative rate to the signals are fixed. Shape of $K\pi\pi^0$ backgrounds are taken from MC simulations with convolution of a smearing Gaussian function; parameters of the smearing function are fixed according to fits to the control sample of $D \to K\pi\pi^0$ events. Size of $K\pi\pi^0$ backgrounds are fixed by scaling the number of $K\pi\pi^0$ events in the control sample to the number in the signal region according to the ratio estimated from MC simulations. Other backgrounds are described with a 1st-order polynomial function. Finally, we obtain the preliminary result as $y_{\mathrm{CP}} = (-1.6 \pm 1.3 \pm 0.6)\%$, where the first uncertainty is statistical, the second uncertainty is systematic. The result is compatible with the previous measurements [14]. This is the most precise measurement of y_{CP} based on $D^0\overline{D}^0$ threshold productions. However, its precision is still statistically limited.

4. Summary

With the 2.92 fb^{-1} e^+e^- collision data collected with the BESIII detector at $\sqrt{s}$ = 3.773 GeV, we obtain the preliminary results of the strong phase difference $\cos\delta_{K\pi}$ in $D \to K\pi$ decays and the mixing parameter y_{CP}. These measurements were carried out based on the quantum-correlated technique. The preliminary results are given as $\cos\delta_{K\pi} = 1.03 \pm 0.12 \pm 0.04 \pm 0.01$ and $y_{\mathrm{CP}} = (-1.6 \pm 1.3 \pm 0.6)\%$. The result of $\cos\delta_{K\pi}$ is the most accurate to date. In the future, global fits can be implemented in order to best exploit BESIII data in the quantum-coherence productions [15].

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