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Measurements of CP asymmetries of $D^+ \to K^0_{S,L}X$ at BESIII

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Using 2.93 fb^{-1} of e^+e^- collision data taken at a center-of-mass energy of 3.773 GeV with the BESIII detector, we determine the absolute branching fractions $D^+ \to K^0_{S,L}K^+(\pi^0)$ and $D^0 \to K^0_{S,L}\pi^0(\pi^0)$, in which $\mathscr{B}(D^+ \to K^0_S K^+\pi^0)$, $\mathscr{B}(D^+ \to K^0_L K^+)$, $\mathscr{B}(D^+ \to K^0_L K^+\pi^0)$ and $\mathscr{B}(D^0 \to K^0_L\pi^0\pi^0)$ are measured for the first time. From results of $\mathscr{B}(D^+ \to K^0_{S,L}K^+(\pi^0))$, the CP asymmetries are measured and there are not an obvious deviation from zero. From results of $\mathscr{B}(D^0 \to K^0_{S,L}\pi^0(\pi^0))$, the branching fraction asymmetries in $D^0 \to K^0_S\pi^0(\pi^0)$ and $D^0 \to K^0_L\pi^0(\pi^0)$ are obtained. Combing the measured $\mathscr{B}(D^0 \to K^0_S\pi^0)$ and $\mathscr{B}(D^0 \to K^0_L\pi^0)$ with the results of $Ke\nu$ versus $K^0_{S,L}\pi^0$, we also determine y_{CP} value.

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1. Introduction

Experimental studies of the hadronic decays of charm mesons can shed light on the interplay between the strong and weak forces. In the standard model (SM), the singly Cabibbo-suppressed (SCS) D meson hadronic decays are predicted to exhibit CP asymmetries of the order of 10^{-3} [1]. Direct CP violation in SCS decays could arise from the interference between tree-level and penguin decay processes. Consequently, any observation of CP asymmetry greater than $\mathcal{O}(10^{-3})$ in any SCS D hardonic decay would be evidence for new physics beyond the SM [2]. This talk reports the measurements of the absolute branching factions and the CP asymmetries of the SCS decays of $D^+ \to K^0_S K^+$, $K^0_S K^+ \pi^0$, $K^0_L K^+$ and $K^0_L K^+ \pi^0$. Note that the decay rates of $D^+ \to K^0_S K^+(\pi^0)$ and $D^+ \to K^0_L K^+(\pi^0)$ are the same because there is no interference of $K^0 - \overline{K}^0$. The measurement of the branching fraction of the two body decay $D^+ \to \bar{K}^0 K^+$ is also helpful for better understanding SU(3)-violating effects in D meson decays [3].

Non-leptonic D decays and their strong phases have been of great interest as they are essentially related to the studies of CP violation (CPV), $D^0\bar{D}^0$mixing and SU(3) symmetry breaking effects in charm physics. As first pointed out by I.I.Bigi and H.Yamamoto [4], the decay rates of $D \to K^0_S \pi' s$ and $D \to K^0_L \pi' s$ are not the same because of the interference of the Cabibbo-favored (CF) component $D \to K^0 \pi' s$ with the doubly Cabibbo-suppressed (DCS) component $D \to \bar{K}^0 \pi' s$. Scale of the asymmetry is set by the doubly Cabibbo suppression factor $\tan^2\theta_C \approx 0.05$, where θ_C is the Cabibbo angle. The exact asymmetry is difficult to predict theoretically. A possible theory interpretation is based on flavor SU(3) with an estimate of symmetry-breaking effects [5].

2. Reconstruction method of K^0_L

The K^0_L is hard to be well reconstructed by BESIII as result of its long flight distance and rare decay rate in multi-layer drift chamber (MDC). Regardless of long flight distance, K^0_L interact with electromagnetic calorimeter (EMC) and deposit part of energy, thus giving position information. After reconstructing all other particles, K^0_L can be inferred from its position information and the constraint energy difference $\Delta E = 0$ ($\Delta E = E_D - E_{\rm beam}$).

In our previous work [6], some difference of the K^0_L reconstruction efficiencies between data and MC is found. Figure 1 shows the correction factors of K^0_L efficiency for the process of $K^0 \to K^0_L$ and $\overline{K}^0 \to K^0_L$, and the difference in most momentum ranges are larger than 10%. The reasons are that GEANT4 does not involve different nuclear cross sections for K^0 and $\bar{K}^0$, and the effects due to $K^0 - \bar{K}^0$ oscillations. In our analysis, the K^0_L reconstruction efficiencies are corrected to data.

3. Study of $D^+ \to K^0_{S,L} K^+(\pi^0)$ decays

3.1 Analysis technique

We employ the "double tag" (DT) technique first developed by the MARK-III Collaboration [7, 8] to measure the absolute branching fractions. First, we select the "single tag" (ST) events in which either a D or $\bar{D}$ is fully reconstructed by hadronic decays. Then we look for the D decays of interest in the presence of the ST $\bar{D}$ mesons; these are the DT events in which both the D and $\bar{D}$ mesons are fully reconstructed.

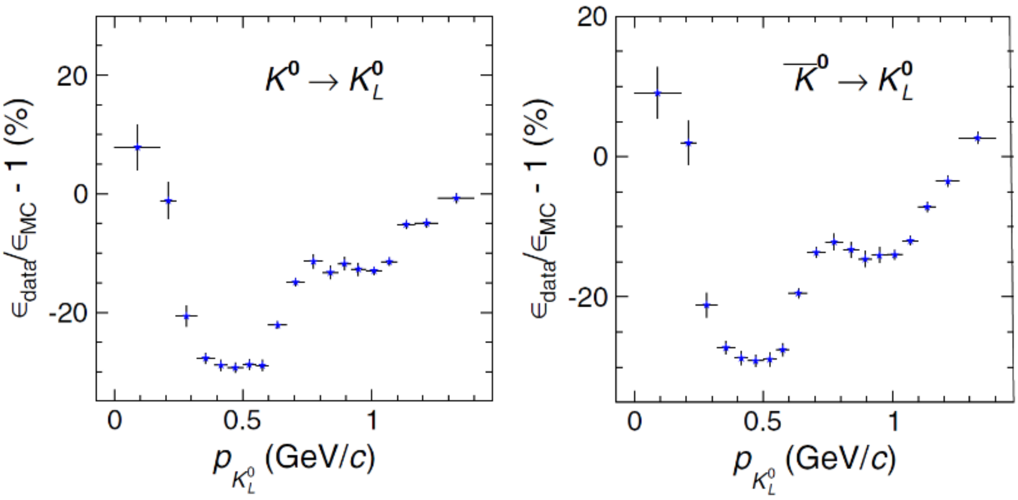

Figure 1: Comparisons of the correction factors of K^0_L efficiency for the process of $K^0 \to K^0_L$ and $\overline{K}^0 \to K^0_L$.

The absolute branching fraction for the signal decay is described by

$$\mathscr{B}_{\rm sig} = \frac{N_{\rm DT}/\varepsilon_{\rm DT}}{N_{\rm ST}/\varepsilon_{\rm ST}} = \frac{N_{\rm DT}/\varepsilon}{N_{\rm ST}}, \tag{3.1}$$

where the $N_{\rm ST}$ and $N_{\rm DT}$ are ST and DT yields, $\varepsilon_{\rm ST}$ and $\varepsilon_{\rm DT}$ are the efficiencies of reconstructing the ST and DT candidate events. With the measured absolute branching fractions of D^+ and D^- decays ($\mathscr{B}^+_{\rm sig}$ and $\mathscr{B}^-_{\rm sig}$), the *CP* asymmetry for the decay of interest can be determined by

$$\mathscr{A}_{CP} = \frac{\mathscr{B}^+_{\rm sig} - \mathscr{B}^-_{\rm sig}}{\mathscr{B}^+_{\rm sig} + \mathscr{B}^-_{\rm sig}}. \tag{3.2}$$

To identify ST D mesons, we use two variables: the energy difference ΔE and the beam energy constrained mass $M_{\rm BC}$, which are defined as

The ST $D^\pm$ mesons are reconstructed with six hadronic final states: $K^\mp\pi^\pm\pi^\pm$, $K^\mp\pi^\pm\pi^\pm\pi^0$, $K^0_S\pi^\pm$, $K^0_S\pi^\pm\pi^0$, $K^0_S\pi^\pm\pi^\pm\pi^\mp$ and $K^\mp K^\pm\pi^\pm$. To identify ST D mesons, we use two variables: the energy difference ΔE and the beam energy constrained mass $M_{\rm BC}$, which are defined as $\Delta E = E_D - E_{\rm beam}$ and $M_{\rm BC} \equiv \sqrt{E^2_{\rm beam}/c^4 - |\vec{p}_D|^2/c^2}$, where $\vec{p}_D$ and E_D are the reconstructed momentum and energy of the D candidate in the e^+e^- center-of-mass system, $E_{\rm beam}$ is the beam energy. To obtain the ST yields of data, a binned maximum likelihood fit is performed on the $M_{\rm BC}$ distribution. To extract the DT yield in data, we perform a two-dimensional (2D) maximum likelihood fit [9] on $M^{\rm tag}_{\rm BC}$ versus $M^{\rm sig}_{\rm BC}$ distribution, shown in Figure 2.

3.2 Results of branching fractions and *CP* asymmetries

Based on measurement method, we determine the average branching fraction of $D^+ \to K^0_{S,L}K^+(\pi^0)$ after considering charge conjugation, as well as the *CP* asymmetry for each decay with Eq. (3.2). These results are summarized in Table 1.

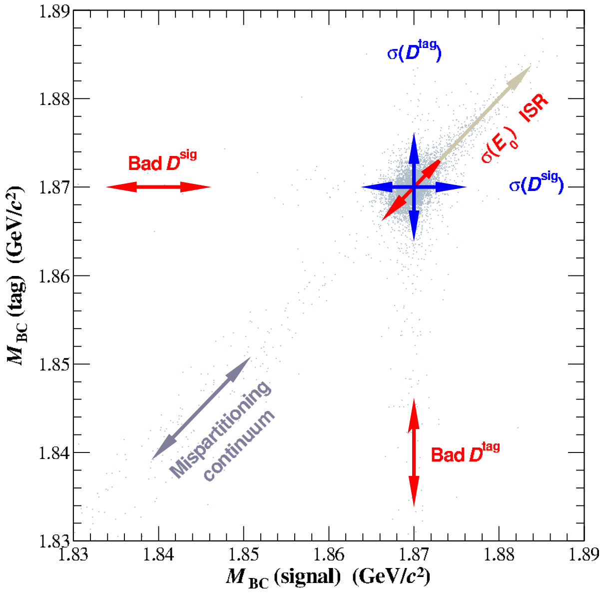

Figure 2: Scatter plot of $M^{\rm sig}_{\rm BC}$ versus $M^{\rm tag}_{\rm BC}$ for DT candidate events.

Table 1: Summary of the measured branching fractions and *CP* asymmetries, where the first and second uncertainties are statistical and systematic, respectively, and a comparison with the world average value [10].

Signal mode	$\mathcal{B}(D^+)$ ($\times 10^{-3}$)	$\mathcal{B}(D^-)$ ($\times 10^{-3}$)	$\overline{\mathcal{B}}$ ($\times 10^{-3}$)	$\mathcal{B}$ (PDG) ($\times 10^{-3}$)	$\mathcal{A}_{CP}$ (%)
$K^0_S K^\pm$	$3.01 \pm 0.12 \pm 0.08$	$3.10 \pm 0.12 \pm 0.08$	$3.06 \pm 0.09 \pm 0.08$	2.95 ± 0.15	$-1.5 \pm 2.8 \pm 1.6$
$K^0_S K^\pm \pi^0$	$5.23 \pm 0.28 \pm 0.24$	$5.09 \pm 0.29 \pm 0.22$	$5.16 \pm 0.21 \pm 0.23$	-	$1.4 \pm 4.0 \pm 2.4$
$K^0_L K^\pm$	$3.13 \pm 0.14 \pm 0.10$	$3.32 \pm 0.15 \pm 0.11$	$3.23 \pm 0.11 \pm 0.11$	-	$-3.0 \pm 3.2 \pm 1.2$
$K^0_L K^\pm \pi^0$	$5.17 \pm 0.30 \pm 0.21$	$5.26 \pm 0.30 \pm 0.21$	$5.22 \pm 0.22 \pm 0.21$	-	$-0.9 \pm 4.1 \pm 1.6$

4. Study of $D^0 \to K^0_{S,L}\pi^0(\pi^0)$ decays

4.1 Analysis technique

In branching fraction measurement of $D^0 \to K^0_{S,L}\pi^0(\pi^0)$, we employ the same method in Sec. 3.1. In the absence of CPV and $D^0\bar{D}^0$ mixing, the yields of CF ($D \to K^\pm\pi^\mp$, $K^\pm\pi^\mp\pi^\mp\pi^\pm$, $K^\pm\pi^\mp\pi^0$) ST sample, CP odd (CP$-$, $D \to K^0_S\pi^0$) ST sample, CP even (CP$+$, $D \to K^+K^-, \pi^+\pi^-$) ST sample and CF ($D \to K^\pm\pi^\mp$, $K^\pm\pi^\mp\pi^\mp\pi^\pm$, $K^\pm\pi^\mp\pi^0$) versus (vs) CP$\pm$ ($D \to K^+K^-, \pi^+\pi^-$, $K^0_L\pi^0$, $K^0_S\pi^0\pi^0$, $K^0_L\pi^0\pi^0$) DT sample can be denoted by

$$\begin{aligned} N_{\rm ST(\mathit{CF})} =& (1+r^2)\cdot 2N_{D^0\bar{D}^0}\cdot \mathcal{B}_{CF}\cdot \varepsilon_{\rm ST(\mathit{CF})} \\ N_{\rm ST(\mathit{CP}\pm)} =& 2N_{D^0\bar{D}^0}\cdot \mathcal{B}_{CP\pm}\cdot \varepsilon_{\rm ST(\mathit{CP}\pm)} \\ N_{\rm DT(\mathit{CF,CP}\pm)} =& (1+r^2\mp 2r\cos\delta)\cdot 2N_{D^0\bar{D}^0} \\ & \cdot \mathcal{B}_{CF}\cdot \mathcal{B}_{CP\pm}\cdot \varepsilon_{\rm DT(\mathit{CF,CP}\pm)}, \end{aligned} \tag{4.1}$$

where $N_{D^0\bar{D}^0}$ is the total number of $D^0\bar{D}^0$ pairs produced in data, $N_{\rm ST}$ and $N_{\rm DT}$ are the numbers of the ST and DT events (the ST and DT yields), $\varepsilon_{\rm ST}$ and $\varepsilon_{\rm DT}$ are the efficiencies of reconstructing the ST and DT events (the ST and DT efficiencies), $\mathscr{B}_{\rm CF}$ and $\mathscr{B}_{\rm CP\pm}$ are the branching fractions for the CF and CP$\pm$ decays, r is the ratio of the color-suppressed to color-favored amplitudes for $D^0(\bar{D}^0)$ decays to the same CF final state, and δ is the strong phase difference between the two amplitudes. The absolute branching fraction for the signal decay is extracted by

$$\mathscr{B}_{\mathrm{sig}(CP\pm)} = \frac{1}{1\mp C_f}\frac{N_{CF,CP\pm}/\varepsilon}{N_{CF}}, \quad (C_f \equiv \frac{2r\cos\delta}{1+r^2}) \tag{4.2}$$

where $\varepsilon = \varepsilon_{\rm DT}/\varepsilon_{\rm ST}$ is the efficiency of reconstructing the signal decay. C_f is a correction factor derived from r and δ. C_f can be measured using the CP$\pm$ ST events and CF vs. CP$\pm$ DT events.

$$C_f = \frac{\frac{N_{CP-,CF}/\varepsilon_{CP-,CF}}{N_{CP-}/\varepsilon_{CP-}} - \frac{N_{CP+,CF}/\varepsilon_{CP+,CF}}{N_{CP+}/\varepsilon_{CP+}}}{\frac{N_{CP-,CF}/\varepsilon_{CP-,CF}}{N_{CP-}/\varepsilon_{CP-}} + \frac{N_{CP+,CF}/\varepsilon_{CP+,CF}}{N_{CP+}/\varepsilon_{CP+}}} \tag{4.3}$$

With the measured $\mathscr{B}(D\to K^0_{S,L}\pi^0)$ and $\mathscr{B}(D\to K^0_{S,L}\pi^0\pi^0)$, the $K^0_{S,L}\pi^0$, $K^0_{S,L}\pi^0\pi^0$ decay branching fraction asymmetries can be determined by

$$\mathscr{R}(D\to K^0_{S,L}\pi^0(\pi^0)) = \frac{\mathscr{B}(D\to K^0_S\pi^0(\pi^0)) - \mathscr{B}(D\to K^0_L\pi^0(\pi^0))}{\mathscr{B}(D\to K^0_S\pi^0(\pi^0)) + \mathscr{B}(D\to K^0_L\pi^0(\pi^0))} \tag{4.4}$$

In measurement of $y_{\rm CP}$, oscillations between D^0 meson and $\bar{D}^0$ meson, also called mixing, can occur when the flavor eigenstates differ from the physical mass eigenstates. These effects provide a mechanism whereby interference in the transition amplitudes of mesons and antimesons may occur. The oscillations are conventionally characterized by two dimensionless parameters $x = \Delta m/\Gamma$ and $y = \Delta\Gamma/\Gamma$, where Δm and $\Delta\Gamma$ are the mass and width differences between the two mass eigenstates and Γ is the average decay width of those eigenstates. Mixing in D^0 decays to CP eigenstates gives rise to an effective lifetime that differs from that in decays to flavor eigenstates. The difference can be parameterized by y_{CP}. In the absence of CPV, one has $y_{CP} = y$.

We use the DT technique to measure y_{CP}. We partly reconstruct the D or $\bar{D}$ which decays to $Ke\nu$ and fully reconstruct the other $\bar{D}$ or D which decays to $K^0_{S,L}\pi^0$. When considering $D^0\bar{D}^0$ mixing without CPV, the yields of the CP$\pm$ ($K^0_S\pi^0$, $K^0_L\pi^0$) ST events and the $Ke\nu$ vs CP$\pm$ ($K^0_S\pi^0$, $K^0_L\pi^0$) DT events can be denoted by

$$\begin{aligned} N_{\mathrm{ST}(CP\pm)} =& (1\mp y_{CP})\cdot 2N_{D^0\bar{D}^0}\cdot \mathscr{B}_{CP\pm}\cdot \varepsilon_{\mathrm{ST}(CP\pm)} \\ N_{\mathrm{DT}(CP\pm,Ke\nu)} =& (1+y^2_{CP})\cdot 2N_{D^0\bar{D}^0}\cdot \mathscr{B}_{CP\pm} \\ & \cdot \mathscr{B}_{Ke\nu}\cdot \varepsilon_{\mathrm{DT}(CP\pm,Ke\nu)}. \end{aligned} \tag{4.5}$$

Here $\varepsilon_{\mathrm{DT}(CP\pm,Ke\nu)}$ and $\varepsilon_{\mathrm{ST}(CP\pm)}$ are the efficiencies of reconstructing the ST and DT candidate events, and $N_{\mathrm{DT}(CP\pm,Ke\nu)}$ and $N_{\mathrm{ST}(CP\pm)}$ are the DT and ST yields, $\mathscr{B}_{Ke\nu}$ and $\mathscr{B}_{CP\pm}$ are the branching fractions for $Ke\nu$ and CP$\pm$ decays. y_{CP} then can be determined by

$$y_{CP} = \frac{\frac{N_{K^0_L\pi^0,Ke\nu}/\varepsilon_{K^0_L\pi^0,Ke\nu}}{N_{K^0_L\pi^0}/\varepsilon_{K^0_L\pi^0}} - \frac{N_{K^0_S\pi^0,Ke\nu}/\varepsilon_{K^0_S\pi^0,Ke\nu}}{N_{K^0_S\pi^0}/\varepsilon_{K^0_S\pi^0}}}{\frac{N_{K^0_L\pi^0,Ke\nu}/\varepsilon_{K^0_L\pi^0,Ke\nu}}{N_{K^0_L\pi^0}/\varepsilon_{K^0_L\pi^0}} + \frac{N_{K^0_S\pi^0,Ke\nu}/\varepsilon_{K^0_S\pi^0,Ke\nu}}{N_{K^0_S\pi^0}/\varepsilon_{K^0_S\pi^0}}}. \tag{4.6}$$

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Since $K^0_L\pi^0$ can not be fully reconstructed as ST candidate, we obtain the ST yield using other CP+ (K^+K^-, $\pi^+\pi^-$) decays. According to Equation 4.1 and 4.5, one obtains

$$\frac{N_{K^0_L\pi^0}}{\varepsilon_{K^0_L\pi^0}} = N_{CP+}/\varepsilon_{CP+}\frac{N_{K^0_L\pi^0,CF}/\varepsilon_{K^0_L\pi^0,CF}}{N_{CP+,CF}/\varepsilon_{CP+,CF}}. \tag{4.7}$$

4.2 Results of branching fractions and y_{CP} asymmetries

The correction factor C_f and branching fractions for $D^0 \to K^0_S\pi^0(\pi^0)$ and $D^0 \to K^0_L\pi^0(\pi^0)$ are extracted by Equation 4.3 and 4.2. We obtain C_f and the branching fraction for each signal mode. The C_f are listed in Tables 2. By weighting the branching fractions measured with different ST modes, we obtain

$$\mathscr{B}(D^0 \to K^0_S\pi^0) = (1.237 \pm 0.020(\text{stat.}))\%,$$
$$\mathscr{B}(D^0 \to K^0_L\pi^0) = (0.993 \pm 0.019(\text{stat.}))\%,$$
$$\mathscr{B}(D^0 \to K^0_S\pi^0\pi^0) = (1.015 \pm 0.024(\text{stat.}))\%$$

and

$$\mathscr{B}(D^0 \to K^0_L\pi^0\pi^0) = (1.280 \pm 0.041(\text{stat.}))\%.$$

The branching fraction asymmetries are

$$\mathscr{R}(D^0 \to K^0_{S,L}\pi^0) = (10.94 \pm 1.24(\text{stat.}))\%,$$

and

$$\mathscr{R}(D^0 \to K^0_L\pi^0\pi^0) = (-11.56 \pm 1.95(\text{stat.}))\%.$$

Table 2: Correction factors $C_f = \frac{2r\cos\delta}{1+r^2}$ for CF modes, where the uncertainties are statistical only.

	C_f (%)
$K^\pm\pi^\mp$	-12.39±1.79
$K^\pm\pi^\mp\pi^\mp\pi^\pm$	-8.73±1.62
$K^\pm\pi^\mp\pi^0$	-7.02±1.25

According to Equation 4.7, $K^0_L\pi^0$ ST yields divided by efficiencies can be extracted. And along with the numbers of $N_{\text{ST}}(K^0_S\pi^0)$, $N_{\text{DT}}(K^0_{S,L}\pi^0, Ke\nu)$ and relative efficiencies, y_{CP} is extracted by Equation 4.6 to be

$$y_{CP} = (1.65 \pm 2.43(\text{stat.}))\%.$$

5. summary

From the analysis of 2.93 fb^{-1} data taken at 3.773 GeV with the BESIII detector, we present a measurement of the absolute branching fraction $\mathscr{B}(D^+ \to K^0_S K^+) = (3.06 \pm 0.09 \pm 0.08) \times 10^{-3}$, which is in agreement with the CLEO result [11], and the first measurements of the absolute branching fractions $\mathscr{B}(D^+ \to K^0_S K^+\pi^0) = (5.16 \pm 0.21 \pm 0.23) \times 10^{-3}$, $\mathscr{B}(D^+ \to K^0_L K^+) = (3.23 \pm 0.11 \pm$

$0.11) \times 10^{-3}$, $\mathscr{B}(D^+ \to K^0_L K^+ \pi^0) = (5.22 \pm 0.22 \pm 0.21) \times 10^{-3}$. We also determine the CP asymmetries in the four SCS decays, and no evidence for CP asymmetry is found. These provide helpful information to understand the SU(3)-flavor symmetry breaking effects and CP violation in D meson decays.

With the same data sample, we present measurements of the absolute branching fractions $\mathscr{B}(D^0 \to K^0_S \pi^0) = (1.237 \pm 0.020(\text{stat.}))\%$, $\mathscr{B}(D^0 \to K^0_L \pi^0) = (0.993 \pm 0.019(\text{stat.}))\%$, $\mathscr{B}(D^0 \to K^0_S \pi^0 \pi^0) = (1.015 \pm 0.024(\text{stat.}))\%$ and $\mathscr{B}(D^0 \to K^0_L \pi^0 \pi^0) = (1.280 \pm 0.041(\text{stat.}))\%$. The first two branching fractions are in agreement with the CLEO-c results [12]. The last one is measured for the first time. The $K^0_S \pi^0$, $K^0_L \pi^0$ branching fraction asymmetry agrees well with the prediction based on U-spin symmetry [4]. We also employ a CP-tagging technique ($K^0_{S,L} \pi^0$ vs $Ke\nu$) to obtain the y_{CP} parameter of $D^0 \bar{D}^0$ oscillations. Under the assumption of no direct CPV in the D sector, we obtain $y_{CP} = (1.65 \pm 2.43(\text{stat.}) \pm 0.56(\text{sys.}))\%$. The precision is still statistically limited. A previous y_{CP} measurement at BESIII using (K^+K^-, $\pi^+\pi^-$, $K^0_S \pi^0 \pi^0$, $K^0_S \pi^0$, $K^0_S \omega$, $K^0_S \eta$) vs ($Ke\nu$, $K\mu\nu$) gives $y_{CP} = (-2.0 \pm 1.3(stat.) \pm 0.7(syst.))\%$ [13]. The two results are compatible within 1.5 standard deviations.

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