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

Wenjing Zheng
Shandong University, Jinan, China
E-mail: zhengwj@ihep.ac.cn

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 $D^+ \rightarrow K^{0}_{S,L} K^+(\pi^0)$ and $D^0 \rightarrow K^{0}_{S,L} \pi^0(\pi^0)$, in which $B(D^+ \rightarrow K^{0}_{S} K^+ \pi^0)$, $B(D^+ \rightarrow K^{0}_{L} K^+)$, $B(D^+ \rightarrow K^{0}_{L} K^+ \pi^0)$ and $B(D^0 \rightarrow K^{0}_{S,L} \pi^0(\pi^0))$ are measured for the first time. From results of $B(D^+ \rightarrow K^{0}_{S,L} K^+(\pi^0))$, the $CP$ asymmetries are measured and there are not an obvious deviation from zero. From results of $B(D^0 \rightarrow K^{0}_{S,L} \pi^0(\pi^0))$, the branching fraction asymmetries in $D^0 \rightarrow K^{0}_{S} \pi^0(\pi^0)$ and $D^0 \rightarrow K^{0}_{L} \pi^0(\pi^0)$ are obtained. Combing the measured $B(D^0 \rightarrow K^{0}_{S} \pi^0)$ and $B(D^0 \rightarrow K^{0}_{L} \pi^0)$ with the results of $Ke\nu$ versus $K^{0}_{L,S}\pi^0$, we also determine $\gamma_{CP}$ value.
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 $10^{-3}$ \cite{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 \cite{2}. This talk reports the measurements of the absolute branching fractions and the $CP$ asymmetries of the SCS decays of $D^+ \rightarrow K_S^0 K^+$, $K_S^0 K^+ \pi^0$, $K_L^0 K^+ + \pi^0$, and $K_L^0 K^+ \pi^0$. Note that the decay rates of $D^+ \rightarrow K_S^0 K^+ (\pi^0)$ and $D^+ \rightarrow K_L^0 K^+ (\pi^0)$ are the same because there is no interference of $K^0 - \bar{K}^0$. The measurement of the branching fraction of the two body decay $D^+ \rightarrow K^0 \bar{K}^+$ is also helpful for better understanding SU(3)-violating effects in $D$ meson decays \cite{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 \cite{4}, the decay rates of $D \rightarrow K_L^0 \pi^0$ and $D \rightarrow K_S^0 \pi^0$ are not the same because of the interference of the Cabibbo-favored (CF) component $D \rightarrow K^0 \pi^0$ with the doubly Cabibbo-suppressed (DCS) component $D \rightarrow K^0 \pi^0$. Scale of the asymmetry is set by the doubly Cabibbo suppression factor $\tan^2 \theta_C \approx 0.05$, where $\theta_C$ 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 \cite{5}.

2. Reconstruction method of $K_L^0$

The $K_L^0$ 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, $K_L^0$ interact with electromagnetic calorimeter (EMC) and deposit part of energy, thus giving position information. After reconstructing all other particles, $K_L^0$ can be inferred from its position information and the constraint energy difference $\Delta E = 0$ ($\Delta E = E_{\text{beam}} - E_{\text{beam}}$).

In our previous work \cite{6}, some difference of the $K_L^0$ reconstruction efficiencies between data and MC is found. Figure \cite{7} shows the correction factors of $K_L^0$ efficiency for the process of $K^0 \rightarrow K_L^0$ and $\bar{K}^0 \rightarrow K_L^0$, and the difference in most momentum ranges are larger than 10%. The reasons are that $\text{GEANT}^4$ 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 $K_L^0$ reconstruction efficiencies are corrected to data.

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

3.1 Analysis technique

We employ the “double tag” (DT) technique first developed by the MARK-III Collaboration \cite{8,9} 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.
Measurements of CP asymmetries of $D^+ \to K^0_{S,L} X$ at BESIII

Wenjing Zheng

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 I.
Measurements of CP asymmetries of $D^+ \rightarrow K_S^0 L X$ at BESIII

Wenjing Zheng

Figure 2: Scatter plot of $M_{BC}^{sig}$ versus $M_{BC}^{tag}$ 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].

<table>
<thead>
<tr>
<th>Signal mode</th>
<th>$\mathcal{B}(D^+)$ ($\times 10^{-3}$)</th>
<th>$\mathcal{B}(D^-)$ ($\times 10^{-3}$)</th>
<th>$\mathcal{B}$ ($\times 10^{-3}$)</th>
<th>$\mathcal{B}$ (PDG) ($\times 10^{-3}$)</th>
<th>$\Delta$CP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^0 K^\pm$</td>
<td>$3.01 \pm 0.12 \pm 0.08$</td>
<td>$3.10 \pm 0.12 \pm 0.08$</td>
<td>$3.06 \pm 0.09 \pm 0.08$</td>
<td>$2.95 \pm 0.15$</td>
<td>$-1.5 \pm 2.8 \pm 1.6$</td>
</tr>
<tr>
<td>$K^0 K^{\mp}\pi^0$</td>
<td>$5.23 \pm 0.28 \pm 0.24$</td>
<td>$5.09 \pm 0.29 \pm 0.22$</td>
<td>$5.16 \pm 0.21 \pm 0.23$</td>
<td>-</td>
<td>$1.4 \pm 4.0 \pm 2.4$</td>
</tr>
<tr>
<td>$K^0 K^\pm$</td>
<td>$3.13 \pm 0.14 \pm 0.10$</td>
<td>$3.32 \pm 0.15 \pm 0.11$</td>
<td>$3.23 \pm 0.11 \pm 0.11$</td>
<td>-</td>
<td>$-3.0 \pm 3.2 \pm 1.2$</td>
</tr>
<tr>
<td>$K^0 K^{\mp}\pi^0$</td>
<td>$5.17 \pm 0.30 \pm 0.21$</td>
<td>$5.26 \pm 0.30 \pm 0.21$</td>
<td>$5.22 \pm 0.22 \pm 0.21$</td>
<td>-</td>
<td>$-0.9 \pm 4.1 \pm 1.6$</td>
</tr>
</tbody>
</table>

4. Study of $D^{0} \rightarrow K_{S,L}^{0} \pi^{0}(\pi^{0})$ decays

4.1 Analysis technique

In branching fraction measurement of $D^{0} \rightarrow K_{S,L}^{0} \pi^{0}(\pi^{0})$, 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 ($D \rightarrow K^\pm \pi^\mp$, $K^\pm \pi^\mp \pi^\mp \pi^\pm$, $K^\pm \pi^\mp \pi^0$) ST sample, CP odd ($D \rightarrow K^0 \pi^0$) ST sample, CP even ($D \rightarrow K^+ K^-$, $\pi^+ \pi^-$) ST sample and CF ($D \rightarrow K^\pm \pi^\mp$, $K^\pm \pi^\mp \pi^\mp \pi^\pm$, $K^\pm \pi^\mp \pi^0$) versus (vs) CP $\pm$ ($D \rightarrow K^+ K^-$, $\pi^+ \pi^-$, $K^0 \pi^0$, $K^0 \pi^0 \pi^0$, $K^0 \pi^0 \pi^0$) DT sample can be denoted by

$$
N_{ST(CF)} = (1 + r^2) \cdot 2N_{D^{0}\bar{D}^{0}} \cdot \mathcal{B}_{CF} \cdot \epsilon_{ST(CF)}
$$

$$
N_{ST(CP\pm)} = 2N_{D^{0}\bar{D}^{0}} \cdot \mathcal{B}_{CP\pm} \cdot \epsilon_{ST(CP\pm)}
$$

$$
N_{DT(CF,CP\pm)} = (1 + r^2 + 2r \cos \delta) \cdot 2N_{D^{0}\bar{D}^{0}} \cdot \mathcal{B}_{CF} \cdot \mathcal{B}_{CP\pm} \cdot \epsilon_{DT(CF,CP\pm)},
$$

where $N_{D^{0}\bar{D}^{0}}$ is the total number of $D^{0}\bar{D}^{0}$ pairs produced in data, $N_{ST}$ and $N_{DT}$ are the numbers of
the ST and DT events (the ST and DT yields), \( \varepsilon_{ST} \) and \( \varepsilon_{DT} \) are the efficiencies of reconstructing the ST and DT events (the ST and DT efficiencies), \( \mathcal{B}_{CF} \) and \( \mathcal{B}_{CP\pm} \) are the branching fractions for the CF and CP\pm decays, \( r \) is the ratio of the color-suppressed to color-favored amplitudes for \( D^0(D^0) \) decays to the same CF final state, and \( \delta \) is the strong phase difference between the two amplitudes. The oscillations are conventionally characterized by two dimensionless parameters \( x \) and \( y \). Mixing in \( y \) is the average decay width of those eigenstates. Mixing in \( r \) and \( \delta \). \( C_f \) can be measured using the CP\pm ST events and CF vs. CP\pm DT events.

\[
C_f = \frac{N_{CP\pm}/\varepsilon_{CP\pm}}{N_{CP\pm}/\varepsilon_{CP\pm}} \frac{N_{CP\pm}/\varepsilon_{CP\mp}}{N_{CP\pm}/\varepsilon_{CP\mp}} \tag{4.3}
\]

With the measured \( \mathcal{B}(D \rightarrow K_{S,L}^0 \pi^0) \) and \( \mathcal{B}(D \rightarrow K_{S,L}^0 \pi^0 \pi^0) \), the \( K_{S,L}^0 \pi^0, K_{S,L}^0 \pi^0 \pi^0 \) decay branching fraction asymmetries can be determined by

\[
\mathcal{B}(D \rightarrow K_{S,L}^0 (\pi^0)) = \frac{\mathcal{B}(D \rightarrow K_{S}^0 \pi^0(\pi^0)) - \mathcal{B}(D \rightarrow K_{L}^0 \pi^0(\pi^0))}{\mathcal{B}(D \rightarrow K_{S}^0 \pi^0(\pi^0)) + \mathcal{B}(D \rightarrow K_{L}^0 \pi^0(\pi^0))} \tag{4.4}
\]

In measurement of \( y_{CP} \), oscillations between \( D^0 \) meson and \( D^0 \) 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 \( \Delta m \) and \( \Delta \Gamma \) are the mass and width differences between the two mass eigenstates and \( \Gamma \) 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 \( D \) which decays to \( K_S \) and fully reconstruct the other \( D \) or \( D \) which decays to \( K_{L}^0 \) \( \pi^0 \). When considering \( D^0(D^0) \) mixing without CPV, the yields of the CP\pm \( (K_{S}^0 \pi^0, K_{L}^0 \pi^0) \) ST events and the \( K_{S} \) vs \( K_{L} \) \( \pi^0 \) DT events can be denoted by

\[
N_{ST(CP\pm)} = (1 + y_{CP}) \cdot 2 N_{D^0(D^0)} \cdot \mathcal{B}_{CP\pm} \cdot \varepsilon_{ST(CP\pm)} \tag{4.5}
\]

\[
N_{DT(CP\pm,K_{S} \pi^0)} = (1 + y_{CP}) \cdot 2 N_{D^0(D^0)} \cdot \mathcal{B}_{CP\pm} \cdot \mathcal{B}_{K_{S} \pi^0} \cdot \varepsilon_{DT(CP\pm,K_{S} \pi^0)}
\]

Here \( \varepsilon_{DT(CP\pm,K_{S} \pi^0)} \) and \( \varepsilon_{ST(CP\pm)} \) are the efficiencies of reconstructing the ST and DT candidate events, and \( N_{DT(CP\pm,K_{S} \pi^0)} \) and \( N_{ST(CP\pm)} \) are the DT and ST yields. \( \mathcal{B}_{K_{S} \pi^0} \) and \( \mathcal{B}_{CP\pm} \) are the branching fractions for \( K_{S} \) and CP\pm decays. \( y_{CP} \) then can be determined by

\[
y_{CP} = \frac{N_{K_{S}^0 \pi^0}(\mathcal{B}_{K_{S}^0 \pi^0} / \varepsilon_{K_{S}^0 \pi^0})}{N_{K_{L}^0 \pi^0}(\mathcal{B}_{K_{L}^0 \pi^0} / \varepsilon_{K_{L}^0 \pi^0})} \tag{4.6}
\]

\[
= \frac{N_{K_{S}^0 \pi^0}(\mathcal{B}_{K_{S}^0 \pi^0} / \varepsilon_{K_{S}^0 \pi^0})}{N_{K_{L}^0 \pi^0}(\mathcal{B}_{K_{L}^0 \pi^0} / \varepsilon_{K_{L}^0 \pi^0})} \tag{4.6}
\]
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 (4.4) and (4.5), one obtains

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

### 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 (4.4). 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

$$\mathcal{B}(D^0 \to K^0_S\pi^0) = (1.237 \pm 0.020)\%,$$

$$\mathcal{B}(D^0 \to K^0_L\pi^0) = (0.993 \pm 0.019)\%,$$

$$\mathcal{B}(D^0 \to K^0_S\pi^0) = (1.015 \pm 0.024)\%,$$

and

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

The branching fraction asymmetries are

$$\mathcal{B}(D^0 \to K^0_S\pi^0) = (10.94 \pm 1.24)\%,$$

and

$$\mathcal{B}(D^0 \to K^0_L\pi^0) = (-11.56 \pm 1.95)\%.$$

### Table 2: Correction factors $C_f$ for CF modes, where the uncertainties are statistical only.

<table>
<thead>
<tr>
<th>$K^\pm \pi^\mp$</th>
<th>$C_f$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+\pi^-$</td>
<td>-12.39 ± 1.79</td>
</tr>
<tr>
<td>$K^+\pi^\mp\pi^+$</td>
<td>-8.73 ± 1.62</td>
</tr>
<tr>
<td>$K^+\pi^+\pi^0$</td>
<td>-7.02 ± 1.25</td>
</tr>
</tbody>
</table>

According to Equation (4.4), $K^0_L\pi^0$ ST yields divided by efficiencies can be extracted. And along with the numbers of $N_{ST}(K^0_S\pi^0)$, $N_{DT}(K^0_L\pi^0, Kev)$ and relative efficiencies, $y_{CP}$ is extracted by Equation (4.5) to be

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

### 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 $\mathcal{B}(D^+ \to K^0_S K^+)$ = $(3.06 \pm 0.09 \pm 0.08) \times 10^{-3}$, which is in agreement with the CLEO result [11], and the first measurements of the absolute branching fractions $\mathcal{B}(D^+ \to K^0_S K^+ \pi^0)$ = $(5.16 \pm 0.21 \pm 0.23) \times 10^{-3}$, $\mathcal{B}(D^+ \to K^0_L K^+)$ = $(3.23 \pm 0.11 \pm 0.08) \times 10^{-3}$. These results make a significant contribution to the study of CP violation in B mesons.
0.11) \times 10^{-3}, \mathcal{B}(D^+ \to K^0_S 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 \( \mathcal{B}(D^0 \to K^0_S \pi^0) = (1.237 \pm 0.020({\text{stat.}}) \%) , \mathcal{B}(D^0 \to K^0_L \pi^0) = (0.993 \pm 0.019({\text{stat.}}) \%) , \mathcal{B}(D^0 \to K^0_L \pi^0 \pi^0) = (1.015 \pm 0.024({\text{stat.}}) \%) \text{ and } \mathcal{B}(D^0 \to K^0_L \pi^0 \pi^0) = (1.280 \pm 0.041({\text{stat.}}) \%). \) 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 \([3]\). We also employ a CP-tagging technique (\( K^0_S \pi^0 \) vs \( K^0_L \)) 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 \( (K^+ K^-, \pi^+ \pi^-, K^0_S \pi^0 \pi^0, K^0_L \pi^0, K^0_S \omega, K^0_L \eta) \) vs (KeV, \( K \mu \nu \)) gives \( y_{CP} = (-2.0 \pm 1.3(\text{stat.}) \pm 0.7(\text{syst.}) \%) \) \([13]\). The two results are compatible within 1.5 standard deviations.

## References


