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Quantum-correlated measurements of $D^0 \to K^0_S\pi^+\pi^-\pi^0$ and consequences for the determination of γ

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Quantum-correlated measurements of the decay $D^0 \to K^0_S\pi^+\pi^-\pi^0$ are performed with a data sample corresponding to an integrated luminosity of 818 pb^{-1} collected at the $\psi(3770)$ resonance by the CLEO-c detector. Preliminary results are presented for the *CP*-even fraction F_+ and the strong-phase differences of this decay. The value of F_+ is measured to be 0.246 ± 0.018. The strong-phase differences are measured in different regions of $K^0_S\pi^+\pi^-\pi^0$ phase space by binning around the intermediate resonances present. The potential sensitivity of the results for determining the CKM angle γ from $B^\pm \to D(K^0_S\pi^+\pi^-\pi^0)K^\pm$ decays using data collected by the Belle detector is also shown.

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1. Introduction

Among the three CKM [1] angles γ is measured least precisely. This is due to the small branching fraction ($\mathcal{O}(10^{-4})$) of decays sensitive to γ. An improved measurement of γ is essential for testing the standard model description of CP violation. The decays $B^\pm \to DK^\pm$, where D indicates a neutral charm meson reconstructed in a final state common to both D^0 and $\bar{D}^0$, provide CP-violating observables that in turn can be used for measuring γ using data collected by detectors such as BaBar, Belle, LHCb or the upcoming Belle II experiment. The additional inclusion of multibody D meson final states will reduce the statistical uncertainty on γ. However, such final states require knowledge of the strong-phase difference between the D^0 and $\bar{D}^0$ that varies over the phase space. The required strong-phase information can be obtained by studying quantum-correlated $D\bar{D}$ pairs produced in e^+e^- collisions at an energy corresponding to the $\psi(3770)$ resonance at CLEO-c.

We present herein preliminary results for the decay $D^0 \to K^0_S\pi^+\pi^-\pi^0$, which has a large branching fraction of 5.2% [2]. This decay mode has not been used so far to determine γ. The mode is potentially useful in a quasi-GLW [3] analysis along with other CP eigenstates if its CP-even fraction F_+ is known [4]. Further, this multibody self-conjugate decay occurs via many intermediate resonances, such as $K^0_S\omega$ and $K^{*\pm}\rho^\mp$. Hence if the strong-phase difference variation over the phase space is known, a GGSZ-style [5, 6] analysis to determine γ from this final state alone is possible.

2. Quantum-correlated D mesons

The wave function for the decay of the vector meson $\psi(3770)$ to a pair of D mesons is anti-symmetric as the two daughters are produced in a P-wave state. Integrating over the whole phase space, the double-tagged yield, where the decays of both the D mesons are identified, for a signal (tag) decay f (g) can be written in terms of the CP-even fraction F^f_+ (F^g_+) and the branching fractions $\mathcal{B}(f)$ ($\mathcal{B}(g)$) as

$$M(f|g) = \mathcal{N}\mathcal{B}(f)\mathcal{B}(g)\varepsilon(f|g)\left[1-(2F^f_+-1)(2F^g_+-1)\right], \tag{2.1}$$

where $\mathcal{N}$ is the overall normalization factor and ε is the reconstruction efficiency. If f or g is a CP eigenstate, then the value $(2F_+-1)$ becomes the CP eigenvalue λ_{CP}. So there is two-fold enhancement in the yield if f and g have opposite CP eigenvalue whereas the yield becomes zero if f and g have the same CP eigenvalue. Thus the rate of the decays of the two D mesons are correlated to each other.

The single-tagged yield, where only one of the D mesons is reconstructed without any constraints on the other, is given by

$$S(g) = \mathcal{N}\mathcal{B}(g)\varepsilon(g). \tag{2.2}$$

Assuming $\varepsilon(f|g) = \varepsilon(f)\varepsilon(g)$, we write the ratios between the double and single-tagged yields, N^+ and N^-, when mode g is CP-odd ($\lambda^g_{CP} = -1$) or even ($\lambda^g_{CP} = 1$), as

$$N^\pm = \frac{M(f|g)}{S(g)} = \mathcal{B}(f)\varepsilon(f)\left[1\mp(2F^f_+-1)\right], \tag{2.3}$$

which leads to the definition of F_+^f in terms of N^+ and N^-:

$$F_+^f \equiv \frac{N^+}{N^+ + N^-}. \tag{2.4}$$

In addition, we can also use some tag modes whose CP-even fraction F_+^g is already known to determine F_+^f. For this, we define a quantity N^g as the ratio of double and single-tagged yields as

$$N^g = \mathscr{B}(f)\varepsilon(f)\left[1-(2F_+^f-1)(2F_+^g-1)\right]. \tag{2.5}$$

This is used along with N^+ to extract F_+^f as

$$F_+^f = \frac{N^+F_+^g}{N^g - N^+ + 2N^+F_+^g}. \tag{2.6}$$

The g mode can also be self-conjugate modes like $K^0_S\pi^+\pi^-$ or $K^0_L\pi^+\pi^-$. The phase space of these multibody states can be divided into different bins. The $K^0_{S,L}\pi^+\pi^-$ Dalitz plot is studied and binned according to the Equal δ_D scheme [7] based on the amplitude model reported in Ref. [8]. The double-tagged yield in each of these bins is

$$M_i(K^0_S\pi^+\pi^-\pi^0|K^0_{S,L}\pi^+\pi^-) = h_{K^0_{S,L}\pi^+\pi^-}\left[K_i^{K^0_{S,L}\pi^+\pi^-} + K_{-i}^{K^0_{S,L}\pi^+\pi^-} - 2c_i\sqrt{K_i^{K^0_{S,L}\pi^+\pi^-}K_{-i}^{K^0_{S,L}\pi^+\pi^-}}(2F_+^f-1)\right], \tag{2.7}$$

where K_i and K_{-i} are the fraction of flavour-tagged D^0 and $\bar{D}^0$ decays in each bin, c_i is the cosine of the strong phase difference for $K^0_{S,L}\pi^+\pi^-$, and $h_{K^0_{S,L}\pi^+\pi^-}$ is the normalization factor. With these F_+^f can be determined if the double-tagged yields in each of the $K^0_{S,L}\pi^+\pi^-$ bins are measured.

To perform a GGSZ analysis with a self-conjugate multibody final state f, the amplitude-weighted averages of $\cos\Delta\delta_D$ and $\sin\Delta\delta_D$ over regions of phase space [5, 6], referred to as c_i and s_i, respectively are required. Here $\Delta\delta_D$ is the strong-phase difference between CP conjugate points in the phase space. The values of c_i and s_i are obtained by tagging with CP and quasi-CP eigenstates and other self-conjugate modes. For CP eigenstate tag modes, the double-tagged yield is given by

$$M_i^{\pm} = h_{CP}\left[K_i + \bar{K}_i \mp 2\sqrt{K_i\bar{K}_i}c_i\right], \tag{2.8}$$

where h_{CP} is the normalization constant. If the tag is a quasi-CP eigenstate of known F_+, the c_i sensitive term is scaled by $(2F_+-1)$ rather than 1. For the self-conjugate tag mode $K^0_S\pi^+\pi^-$ [9, 10], the double-tagged yield is

$$M_{i\pm j}^{K^0_S\pi^+\pi^-} = h_{K^0_S\pi^+\pi^-}\left[K_iK_{\mp j}^{K^0_S\pi^+\pi^-} + \bar{K}_iK_{\pm j}^{K^0_S\pi^+\pi^-} - 2\sqrt{K_iK_{\pm j}^{K^0_S\pi^+\pi^-}\bar{K}_iK_{\mp j}^{K^0_S\pi^+\pi^-}}(c_ic_j^{K^0_S\pi^+\pi^-} + s_is_j^{K^0_S\pi^+\pi^-})\right], \tag{2.9}$$

and for a $K^0_L\pi^+\pi^-$ tag, the double-tagged yield is

$$M_{i\pm j}^{K^0_L\pi^+\pi^-} = h_{K^0_L\pi^+\pi^-}\left[K_iK_{\mp j}^{K^0_L\pi^+\pi^-} + \bar{K}_iK_{\pm j}^{K^0_L\pi^+\pi^-} + 2\sqrt{K_iK_{\pm j}^{K^0_L\pi^+\pi^-}\bar{K}_iK_{\mp j}^{K^0_L\pi^+\pi^-}}(c_ic_j^{K^0_L\pi^+\pi^-} + s_is_j^{K^0_L\pi^+\pi^-})\right]. \tag{2.10}$$

If both tag and signal states are the same, then

$$M_{ij} = h_f\left[K_i\bar{K}_j + \bar{K}_iK_j - 2\sqrt{K_i\bar{K}_j\bar{K}_iK_j}(c_ic_j + s_is_j)\right], \tag{2.11}$$

where h_f is the normalization constant.

Type	Modes
CP-even	K^+K^-, $\pi^+\pi^-$, $K^0_S\pi^0\pi^0$, $K^0_L\omega$, $K^0_L\pi^0$
CP-odd	$K^0_S\pi^0$, $K^0_S\eta$, $K^0_S\eta'$
Mixed CP	$\pi^+\pi^-\pi^0$, $K^0_S\pi^+\pi^-$, $K^0_L\pi^+\pi^-$
Flavour	$K^\pm e^\mp \nu_e$

Table 1: Different tag modes used in the analysis.

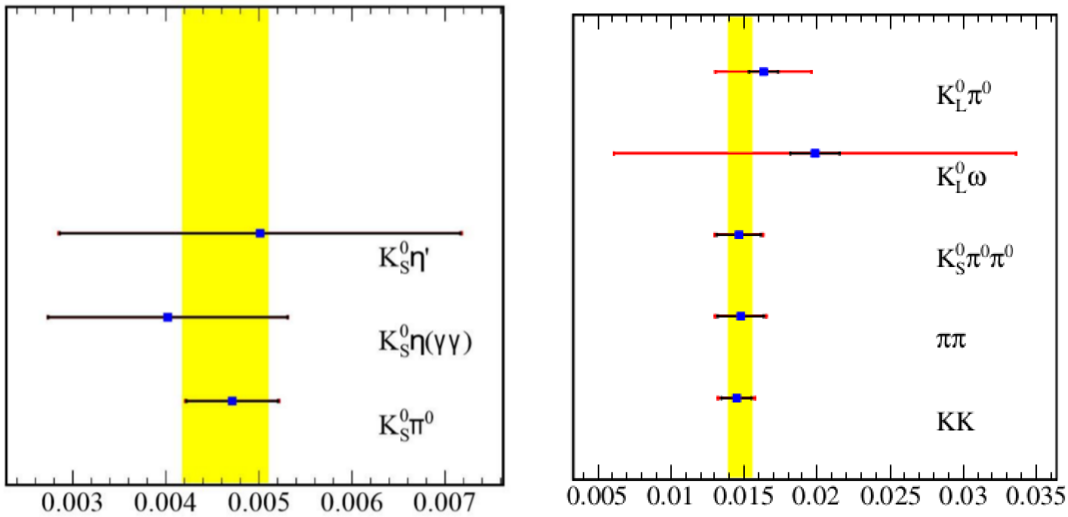

Figure 1: N^+ values for the CP-odd modes (left) and N^- values for the CP-even modes (right). The yellow region shows the average value. Horizontal black lines show the statistical uncertainty and red lines the total uncertainty.

3. Measurement of F_+ in $D^0 \to K^0_S\pi^+\pi^-\pi^0$ decays

A data sample corresponding to an integrated luminosity of 818 pb^{-1}, collected by the CLEO-c detector at the interaction point of CESR e^+e^- collider, consisting of $D\bar{D}$ pairs coming from the $\psi(3770)$ resonance is used in this analysis. The $D\bar{D}$ final state is reconstructed for the signal state $K^0_S\pi^+\pi^-\pi^0$ along with the tag modes listed in Table 1. All charged tracks and energy deposits associated with both the D mesons are reconstructed; the selection criteria for the tag modes are identical to those presented in Ref. [4]. Modes involving K^0_L or ν are reconstructed partially using a missing-mass squared technique [11].

With the double-tagged yields measured and single-tagged yields taken from Ref. [12], we calculate N^+ and N^- from the CP-odd and even modes, respectively. They are shown in Fig. 1. With the quasi-CP mode $\pi^+\pi^-\pi^0$, we calculate F_+ using Eqn. 2.6 with the input value $F_+^{\pi^+\pi^-\pi^0}$ = 0.973 $\pm$ 0.017 [12]. The value of F_+ obtained with CP and quasi-CP modes is 0.244 $\pm$ 0.021. This suggests that the mode $K^0_S\pi^+\pi^-\pi^0$ is significantly CP-odd. Using $K^0_{S,L}\pi^+\pi^-$ modes, F_+ is calculated with Eqn. 2.7. The values of K_i, K_{-i}, c_i, and s_i for $K^0_{S,L}\pi^+\pi^-$ are taken from Ref. [7]. The values of predicted and measured double-tagged yields in each of the $K^0_{S,L}\pi^+\pi^-$ bins are shown in Fig. 2; from these data F_+ is determined to be 0.265 $\pm$ 0.029 in our calculation. With all the three above mentioned methods, the average F_+ is 0.246 ± 0.018. The uncertainty includes statistical as well as systematic contributions.

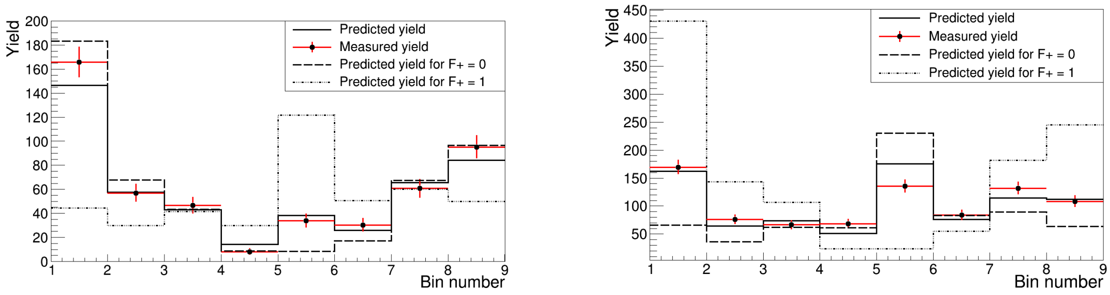

Figure 2: The predicted and measured yields for $K_S^0\pi^+\pi^-$ (left) and $K_L^0\pi^+\pi^-$ (right) in each bin obtained from a combined fit of both the modes. The histogram shows the predicted values, points show the measured values, dashed line corresponds to $F_+ = 0$ and the dotted line shows $F_+ = 1$.

4. Determination of c_i and s_i

The five-dimensional phase space of $D^0 \to K_S^0\pi^+\pi^-\pi^0$ is studied to extract c_i and s_i values. There is no trivial symmetry in the phase space to define the bins and hence the bins are constructed around the resonances present. The lack of an amplitude model for this channel makes a proper optimization difficult. An exclusive eight-bin scheme is followed around the resonances such as ω, K^* and ρ. The kinematic regions of the bins are listed in Table 2 along with the fraction of flavour-tagged D^0 and $\bar{D}^0$ decays in each of them. These values are determined from semileptonic flavour tag $K^\pm e^\mp \nu_e$.

Bin number	Specification	K_i	$\bar{K}_i$
1	$m(\pi^+\pi^-\pi^0) \approx m(\omega)$	0.222 ± 0.019	0.176 ± 0.017
2	$m(K_S^0\pi^-) \approx m(K^{*-})$ & $m(\pi^+\pi^0) \approx m(\rho^+)$	0.394 ± 0.022	0.190 ± 0.017
3	$m(K_S^0\pi^+) \approx m(K^{*+})$ & $m(\pi^-\pi^0) \approx m(\rho^-)$	0.087 ± 0.013	0.316 ± 0.021
4	$m(K_S^0\pi^-) \approx m(K^{*-})$	0.076 ± 0.012	0.046 ± 0.009
5	$m(K_S^0\pi^+) \approx m(K^{*+})$	0.057 ± 0.010	0.065 ± 0.011
6	$m(K_S^0\pi^0) \approx m(K^{*0})$	0.059 ± 0.011	0.092 ± 0.013
7	$m(\pi^+\pi^0) \approx m(\rho^+)$	0.045 ± 0.009	0.045 ± 0.009
8	Remainder	0.061 ± 0.011	0.070 ± 0.011

Table 2: The specifications for the eight exclusive bins of $D^0 \to K_S^0\pi^+\pi^-\pi^0$ phase space along with the fraction of D^0 and $\bar{D}^0$ events in each of them.

The yields for *CP*, quasi-*CP* and self-conjugate modes in each of the bins are measured and the c_i and s_i values are extracted using Eqns. 2.8-2.11. The migration of events from one bin to another due to the narrowness of each bin is considered in the fit. The preliminary results are summarized in Table 3 and Fig. 3. The uncertainties mentioned are statistical only.

Bin	c_i	s_i
1	-1.12 ± 0.12	0.12 ± 0.17
2	-0.29 ± 0.07	0.11 ± 0.13
3	-0.41 ± 0.09	-0.08 ± 0.18
4	-0.84 ± 0.12	-0.73 ± 0.34
5	-0.54 ± 0.13	0.65 ± 0.13
6	-0.22 ± 0.12	1.37 ± 0.22
7	-0.90 ± 0.16	-0.12 ± 0.40
8	-0.70 ± 0.14	-0.03 ± 0.44

Table 3: Preliminary results for c_i and s_i values obtained from the fit.

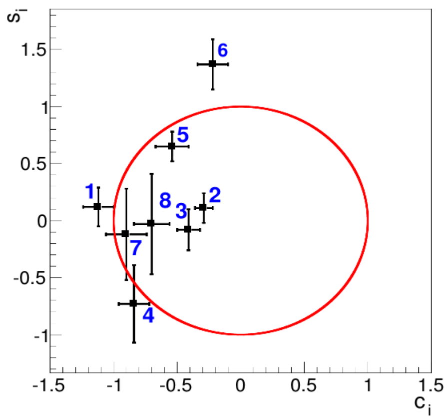

Figure 3: c_i and s_i values in each bin.

5. Estimation of γ sensitivity with $B^\pm \to D(K_S^0\pi^+\pi^-\pi^0)K^\pm$

We estimate the sensitivity of γ with the preliminary results of c_i and s_i values described in the previous section, in a GGSZ framework with $B^\pm \to D(K_S^0\pi^+\pi^-\pi^0)K^\pm$ decays from Belle ($\approx$ 1 ab^{-1}). We run 1000 pseudo-experiments with c_i, s_i, K_i, and $\bar{K}_i$ values as inputs with each experiment consisting of ≈ 1200 events. The sample sizes are determined from the Belle sample of $B^\pm \to D(K_S^0\pi^+\pi^-)K^\pm$ [13]. Here we assume that increase in branching fraction for $K_S^0\pi^+\pi^-\pi^0$ compared to $K_S^0\pi^+\pi^-$ is compensated by loss in efficiency due to a π^0 in final state. The estimated uncertainty on γ is $\sigma_\gamma = 25°$. The projection of this to a 50 ab^{-1} sample of Belle II gives $\sigma_\gamma = 3.5°$ (see Fig. 4).

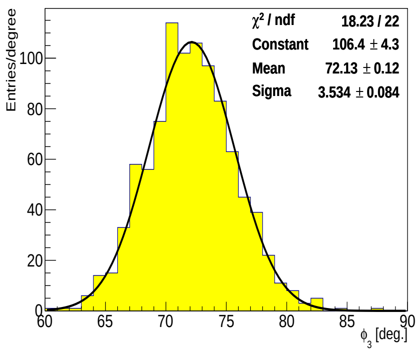

Figure 4: γ sensitivity with 50 ab^{-1} Belle II sample.

6. Conclusions

The studies of D meson final states open up additional avenues for measuring the CKM angle γ.

In particular, the decay $D^0 \to K^0_S\pi^+\pi^-\pi^0$ can serve as an additional mode in quasi-GLW methods, with the CP-even fraction F_+ measured to be 0.246 ± 0.018, reducing the statistical uncertainty on γ. Further, the measurement of strong phase differences of this mode in eight different phase space regions, allows a model-independent GGSZ estimation of γ from this mode alone. It is estimated that a single-mode uncertainty on γ of $\sigma_\gamma = 3.5^\circ$ is achievable with a 50 ab^{-1} sample of data at Belle II. This could be improved with optimized c_i and s_i values, provided a proper amplitude model is available and a finer binning using a larger sample of quantum correlated data from the BESIII experiment.

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