PROCEEDINGS OF SCIENCE

# Quantum-correlated $D$-decays at CLEO-c

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The 818 $\mathrm{fb}^{-1}$ dataset collected at the $\psi(3770)$ resonance at CLEO-c offers interesting possibilities for measuring strong phase differences in neutral $D$ decays. The measurements require that both $D$ mesons in the event are fully reconstructed, usually with one decaying to the signal mode of interest, and the other to a CP-eigenstate. The strong phase differences extracted from these decays are important inputs to measurements of the CKM angle $\gamma$ in $B \to DK$ decays. Results are presented from $D$ decays into $K_S^0\pi^+\pi^-$, $K_S^0K^+K^-$, and the impact of the $\gamma$ measurement is discussed. A summary is also given of measurements in other two- three- and four-body modes.

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## 1. Introduction

Studies which seek to determine the CKM angle $\gamma$ from measuring the CP-violation in $B \to DK$ decays, where $D$ indicates a $D^0$ or a $\bar{D}^0$ meson which is reconstructed in a common final state, in general require external information on the strong-phase difference between the $D^0$ and $\bar{D}^0$ decay. Examples include the so-called 'ADS' strategy [1] where the final state is a mode such as $K^{\mp}\pi^{\pm}$ and the strong phase difference is a single number, or the 'GGSZ' approach [2, 3], which uses decays such as $K^0_S h^+ h^-$ ($h = \pi$ or $K$), and the strong-phase difference varies over the Dalitz plot.

The strong-phase difference between $D^0$ and $\bar{D}^0$ decays may be measured in $e^+e^- \to \psi(3770) \to D\bar{D}$ data in which one meson is reconstructed in the final state of interest, and the other is reconstructed in a CP-eigenstate, e.g. $K^+K^-$, or $K^0_S\pi^0$. Such threshold production of $D\bar{D}$ pairs means that a quantum correlation exists between the charm mesons, and that if one $D$ is observed (or 'tagged') to be CP-even, then the other must be CP-odd, and vice versa. In this case the final state of interest is therefore a linear superposition of equal amounts of $D^0$ and $\bar{D}^0$, and thus the decay rate has a dependence on $\cos\Delta\delta_D$, where $\Delta\delta_D$ is the strong phase difference between the two amplitudes. In this manner 'CP-tagged' data from the $\psi(3770)$ can be used to determine these phase differences. The method can be generalised to use as a tag any hadronic final state, as all these modes can be accessed both by $D^0$ and $\bar{D}^0$ decays.

The CLEO-c experiment collected 818 pb$^{-1}$ of $e^+e^- \to \psi(3770) \to D\bar{D}$ data, delivered by the Cornell Electron Storage Ring. These data have been used to make measurements of strong-phase differences needed for the $B \to DK$ studies which will be performed at LHCb and $e^+e^-$ B-factories. Further measurements of this type will be possible with the BES-III data, where it is expected that the eventual $\psi(3770)$ sample size will be be significantly larger than at CLEO-c.

In Sec. 2 the recent CLEO measurement of the strong phase difference in $D \to K^0_S\pi^+\pi^-$ and $K^0_S K^+K^-$ decays [6] is discussed. In Sec. 3 a summary is made of other CLEO measurements.

## 2. Quantum-correlated studies of $D \to K^0_S\pi^+\pi^-$ and $K^0_S K^+K^-$ and impact on the $\gamma$ determination

A proposal to use $\psi(3770)$ data to make a model independent determination of the strong-phase differences in $D \to K^0_S\pi^+\pi^-$ decays can be found in [2] and is developed in [4]. A first measurement of these strong-phase differences has been pefromed by CLEO [5]. A recent update [6], summarised here, supersedes this first set of results, and also extends the study to $D \to K^0_S K^+K^-$.

The goal of the analysis is to find the quantities $c_i$ and $s_i$, which are the amplitude-weighted averages of the cosine and sine of the strong-phase differences between $D^0$ and $\bar{D}^0$ in bin $i$ of the Dalitz space. These quantities can then be used by other experiments in the analysis of $B \to DK$ data to extract the value of $\gamma$ in a model independent manner. This approach may be contrasted to the strategy pursued in $B \to DK$ measurements hitherto [7, 8], where the information on the strong-phase differences is obtained from an amplitude model fitted to flavour-tagged $D^* \to D\pi$, $D \to K^0_S h^+h^-$ data. The uncertainty associated with the amplitude model is difficult to assess, and therefore is an undesirable feature for future high precision measurements.

In the $K^0_S\pi^+\pi^-$ analysis the Dalitz space is divided into eight bins. The binning is defined from the flavour-tagged derived amplitude models developed at the B-factories. (This information

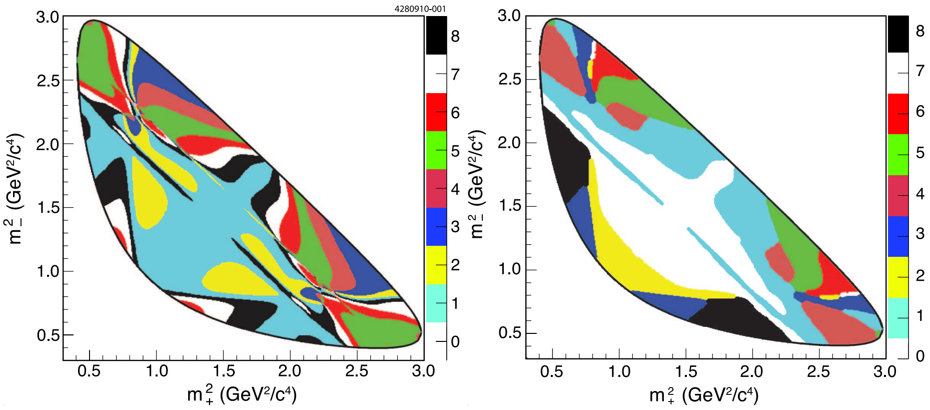


**Figure 1:** $D \to K_S^0 \pi^+ \pi^-$ binning. Left: BABAR equal $\Delta\delta_D$ binning. Right: modified optimal binning.

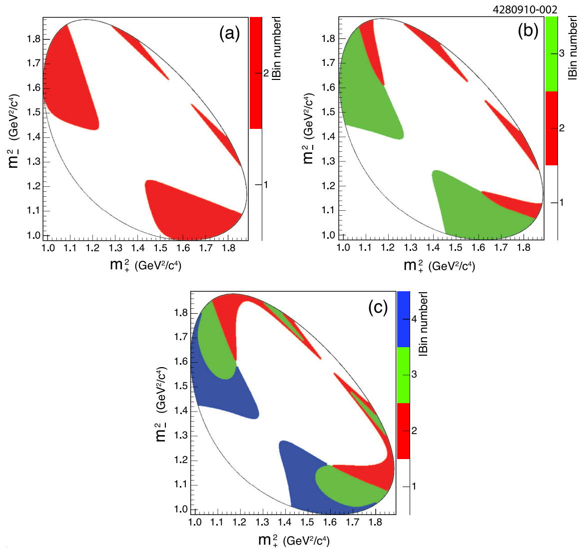


**Figure 2:** Two (a), three (b) and four (c) binning choices for the $D \to K_S^0 K^+ K^-$ analysis.

does not introduce any model dependent bias to the final results. If the models do not represent reality, the measurement will merely have lower sensitivity in the $\gamma$ measurement than expected.) In order to provide flexibility in the $B \to DK$ studies four different bin choices are considered. In two of these choices, one based on the BABAR model [9], one on the Belle model [8], each bin corresponds to a equal slice of strong-phase difference ('equal $\Delta\delta_D$ binning'). The two other choices ('optimal' and 'modified optimal'), derived from the BABAR model, have binnings which are constructed to provide higher statistical sensitivity in the $\gamma$measurement. The 'modified optimal' binning has been optimised assuming a background level in the $B \to DK$ analysis corresponding to that expected at LHCb. Two of these binning choices are show in Fig. 1.

In the $K_S^0 K^+ K^-$ analysis equal $\Delta\delta_D$ binnings are considered for two, three and four bins, all based on the flavour model found in [9]. These binnings are shown in Fig. 2.

The lack of fragmentation particles in threshold $D\bar{D}$ production, and the excellent hermiticity

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of the CLEO-c detector, enables final states containing $K_L^0$ mesons to be reconstructed, where the presence of the $K_L^0$ is inferred through the kinematics of the other particles in the event. This means that CP-tags such as $K_L^0\pi^0$ can be employed, and also $K_L^0\pi^+\pi^-$ events can be included. To first order a CP-odd $K_S^0\pi^+\pi-$ decay is the same as a CP-even $K_L^0\pi^+\pi^-$ decay. Small corrections to this equality are accounted for in the analysis and a systematic uncertainty assigned to the final results which is small.

Around 1600 CP-tagged $K^0\pi^+\pi^-$ events are selected, and around 1300 double tagged events of the sort $K_{S,L}^0\pi^+\pi^-$ vs. $K_S^0\pi^+\pi^-$. Quantum-correlations mean that this latter category can also be used in measurement. They are sensitive to $c_i$ and $s_i$ whereas the pure CP-tagged events are only sensitive to $c_i$.

In the $K_S^0K^+K^-$ analysis around 550 quantum-correlated double tags are used. They include events of the sort $K_{S,L}^0K^+K^-$ vs. $K_S^0\pi^+\pi^-$ and $K_S^0K^+K^-$ vs. $K_L^0\pi^+\pi^-$. In this manner the results of the $K^0\pi^+\pi^-$ analysis is used as a valuable input to the $K_S^0K^+K^-$ study.

The quantum-correlated yields are used to calculate the values of $c_i$ and $s_i$. In both analyses the statistical errors are the dominant contribution to the overall uncertainty. The results for the $K_S^0K^+K^-$ analysis are shown graphically in Fig. 3. It can be observed that there is reasonable agreement between the measured values and those predicted by the model. A similar picture emerges from the $K_S^0\pi^+\pi^-$ analysis [6].

Toy Monte Carlo studies have been conducted to assess the residual uncertainty in $\gamma$ analysis that will arise from the finite precision on the values of $c_i$ and $s_i$. This uncertainty is found to be between $1.7^\circ$ and $3.9^\circ$, depending on the binning, for $K_S^0\pi^+\pi^-$, and between $3.2^\circ$ and $3.9^\circ$ for $K_S^0K^+K^-$. These errors are small compared with the expected statistical uncertainties on these measurements at LHCb [10].

## 3. Other quantum-correlated studies, summary and prospects

The CLEO-c data set has also been used to determine the value of the strong-phase difference in decays to $K^\mp\pi^\pm$ [11, 12] and the average strong-phase difference and coherence factor [13] in decays to $K^\mp\pi^\pm\pi^+\pi^-$ and $K^\mp\pi^\pm\pi^0$.

All these results will be of great benefit in the measurement of the CKM angle $\gamma$ using $B\to DK$ strategies. They can also be used in model independent charm mixing studies [15]. Similar studies will be performed with decays to $K_S^0K^\pm\pi^\mp$ and $K_S^0\pi^+\pi^-\pi^0$. In future, these measurements can be repeated with higher statistical precision using data collected by the BES-III experiment.

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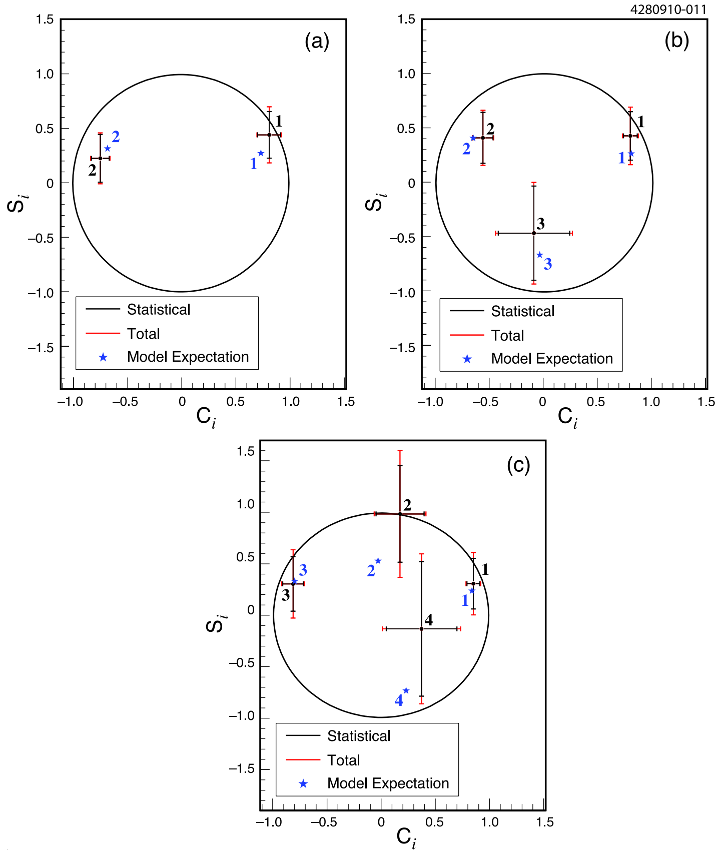


**Figure 3:** Measured values of $c_i$ and $s_i$ for $D \to K^0_S K^+ K^-$ data divided into (a) two, (b) three and (c) four equal $\Delta\delta_D$ bins. The expected values calculated from the models used are indicated by the stars. The circle indicates the boundary of the physical region $c_i^2 + s_i^2 = 1$.


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