The 818 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 $B \rightarrow DK$ 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.
1. Introduction

Studies which seek to determine the CKM angle $\gamma$ from measuring the CP-violation in $B \rightarrow DK$ decays, where $D$ indicates a $D^0$ or $\bar{D}^0$ 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 $K_S^0 h^+h^-$ ($h = \pi$ 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 $e^+e^- \rightarrow \psi(3770) \rightarrow D\bar{D}$ 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 $K_S^0\pi^0$. 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 $e^+e^- \rightarrow \psi(3770) \rightarrow D\bar{D}$ data, delivered by the Cornell Electron Storage Ring. These data have been used to make measurements of strong-phase differences needed for the $B \rightarrow DK$ 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 significantly larger than at CLEO-c.

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

2. Quantum-correlated studies of $D \rightarrow K_S^0\pi^+\pi^-$ and $K_S^0K^+K^-$ 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 $D \rightarrow K_S^0\pi^+\pi^-$ decays can be found in [2] and is developed in [4]. A first measurement of these strong-phase differences has been perfomed by CLEO [5]. A recent update [6], summarised here, supersedes this first set of results, and also extends the study to $D \rightarrow K_S^0K^+K^-$. 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 $B \rightarrow DK$ data to extract the value of $\gamma$ in a model independent manner. This approach may be contrasted to the strategy pursued in $B \rightarrow DK$ measurements hitherto [7, 8], where the information on the strong-phase differences is obtained from an amplitude model fitted to flavour-tagged $D^* \rightarrow D\pi$, $D \rightarrow K_S^0h^+h^-$ 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 $K_S^0\pi^+\pi^-$ 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
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Figure 1: $D \rightarrow K^0_S \pi^+ \pi^-$ 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 $D \rightarrow K^0_S K^+ K^-$ analysis.

The lack of fragmentation particles in threshold $D \bar{D}$ production, and the excellent hermiticity 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 $B \rightarrow DK$ 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 $B \rightarrow DK$ analysis corresponding to that expected at LHCb. Two of these binning choices are show in Fig. 1.

In the $K^0_S K^+ K^-$ 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.
of the CLEO-c detector, enables final states containing $K^0_L$ mesons to be reconstructed, where the presence of the $K^0_L$ is inferred through the kinematics of the other particles in the event. This means that CP-tags such as $K^0_L\pi^0$ can be employed, and also $K^0_L\pi^+\pi^-$ events can be included. To first order a CP-odd $K^0_L\pi^+\pi^-$ decay is the same as a CP-even $K^0_L\pi^+\pi^-$ 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 $K^0_0\pi^+\pi^-$ events are selected, and around 1300 double tagged events of the sort $K^0_0\pi^+\pi^- \text{ vs. } K^0_0\pi^+\pi^-$. 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 $K^0_0 K^+K^-$ analysis around 550 quantum-correlated double tags are used. They include events of the sort $K^0_0 K^+K^- \text{ vs. } K^0_0\pi^+\pi^- \text{ vs. } K^0_0\pi^+\pi^-$. In this manner the results of the $K^0_0\pi^+\pi^-$ analysis is used as a valuable input to the $K^0_0 K^+K^-$ study.

In both analyses the statistical errors are the dominant contribution to the overall uncertainty. The results for the $K^0_0 K^+K^-$ 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 $K^0_0\pi^+\pi^-$ 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 $K^0_0\pi^+\pi^-$, and between $3.2^\circ$ and $3.9^\circ$ for $K^0_0 K^+K^-$. 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 $K^\pm\pi^\mp$ [11, 12] and the average strong-phase difference and coherence factor [13] in decays to $K^\pm\pi^+\pi^- \text{ and } K^\mp\pi^+\pi^0$.

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 $K^0_0 K^+\pi^-$ and $K^0_0\pi^+\pi^-\pi^0$. In future, these measurements can be repeated with higher statistical precision using data collected by the BES-III experiment.

References


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Figure 3: Measured values of $c_i$ and $s_i$ for $D \rightarrow K_S^0K^+K^-$ 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 $c_i^2 + s_i^2 = 1$.