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Strong Phase Measurements - Towards γ at CLEO-c

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Strategies that utilise the interference effects within $B \to DK$ decays hold great potential for improving our sensitivity to the CKM angle γ. However, in order to exploit fully this potential, knowledge of parameters associated with the D decay, such as strong-phase differences, are required. This essential information can be obtained from the unique quantum-correlated $\psi(3770)$ datasets at CLEO-c. Results of such analyses involving the decay modes $D \to K\pi, K\pi\pi^0, K\pi\pi\pi$ and $K^0_S\pi\pi$ will be presented.

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1. Introduction

A theoretically clean method to extract the CKM-angle γ is to exploit the interference present in $B^{\pm} \to DK^{\pm}$, where the D is a D^0 or $\overline{D}^0$ decaying to a common final state, f. Decay rates in these channels are sensitive to the following amplitude ratios

$$\frac{A(B^- \to \overline{D}^0 K^-)}{A(B^- \to D^0 K^-)} = r_B e^{i(\delta_B - \gamma)}, \quad \frac{A(B^+ \to D^0 K^+)}{A(B^+ \to \overline{D}^0 K^+)} = r_B e^{i(\delta_B + \gamma)}. \tag{1.1}$$

which are functions of three parameters: the ratio of the absolute magnitudes of the amplitudes, r_B; a CP-invariant strong-phase difference, δ_B; and the weak phase γ. A variety of γ extraction strategies have been suggested depending on the D final state. Final states that can be used are: two-body modes such as $K^+K^-/\pi^+\pi^-$ [1, 2], $K^{\pm}\pi^{\mp}$ [3], as well as multi-body final states such as $K^0_S\pi^+\pi^-$ [4, 5] and $K^{\pm}\pi^{\mp}\pi^0/K^{\pm}\pi^{\mp}\pi^+\pi^-$ [6].[1] In all cases, the measurement of γ is affected by properties of the D decay amplitude. In order to exploit fully the sensitivity to the B-specific parameters (r_B, δ_B and γ) it is, therefore, highly advantageous to have prior knowledge of the parameters associated with the D decay. This is where CLEO-c plays a crucial role.

These proceedings describe three sets of measurements performed by CLEO-c of D-specific parameters relevant to the measurement of γ. Sec. 2 introduces the D parameters of interest in the context of the B decay rates. Sec. 3 then explains how one can exploit quantum-correlations at the $\psi(3770)$ in order to probe these D parameters. Sec. 4 describes the CLEO-c experiment and data sets used for the analyses. Secs. 5, 6 and 7 describe the experimental procedure and results.

2. *D* Parameters Associated with the ADS Method

In the case of the so-called *ADS method* [3], where $f = K^{\pm}\pi^{\mp}$, D-specific parameters contribute to the suppressed $B^{\pm}$ decay-rates as follows:

$$\Gamma(B^{\pm} \to (K^{\mp}\pi^{\pm})_D K^{\pm}) \propto r_B^2 + (r_D^{K\pi})^2 + 2\, r_B\, r_D^{K\pi} \cos(\delta_B + \delta_D^{K\pi} \pm \gamma), \tag{2.1}$$

where $r_D^{K\pi}$ and $\delta_D^{K\pi}$ are analogous to the $B^{\pm}$ parameters r_B and δ_B; $r_D^{K\pi}$ is the absolute ratio of the doubly Cabibbo suppressed (DCS) to Cabibbo favoured (CF) amplitudes and $\delta_D^{K\pi}$ is the corresponding D strong-phase difference. Futhermore, the extended method [6], which considers multi-body ADS modes i.e. $f = \{K^{\pm}\pi^{\mp}\pi^0,\ K^{\pm}\pi^{\mp}\pi^+\pi^-\}$, introduces an additional D parameter, R_f, the coherence factor:

$$\Gamma(B^{\pm} \to (\overline{f})_D K^-) \propto r_B^2 + (r_D^f)^2 + 2\, r_B\, r_D^f R_f \cos(\delta_B + \delta_D^f \pm \gamma), \tag{2.2}$$

where R_f satisfies the condition $\{R_f \in \mathbb{R} \mid 0 \leq R_f \leq 1\}$. This dilution term results from accounting for the resonant sub-structure of the multi-body mode. For modes whose intermediate resonances interfere constructively, R_f tends to unity, however if the resonances interfere destructively, then R_f tends to zero.

[1] For a review of all these methods, and a summary of current and future $B^{\pm} \to DK^{\pm}$ γ measurements, see Refs. [7] and [8].

3. Quantum Correlations at the $\psi(3770)$

Determination of strong-phase differences and coherence factors can be made from analysis of quantum-correlated $D^0\bar{D}^0$ pairs. Such an entangled state, with $C = -1$, is produced in e^+e^- collisions at the $\psi(3770)$ resonance. To conserve this charge-conjugation state, the final state of the $D^0\bar{D}^0$ pair must obey certain selection rules. For example, both D^0 and $\bar{D}^0$ cannot decay to CP-eigenstates with the same eigenvalue. However, decays to CP-eigenstates of opposite eigenvalue are enhanced by a factor of two. More generally, final states that are accessible by both D^0 and $\bar{D}^0$ (such as $K^-\pi^+$) are subject to similar interference effects. Consequently, by considering time-integrated decay rates of double tag (DT) events, where both the D^0 and the $\bar{D}^0$ are reconstructed, one is sensitive to interference dependent parameters such as strong-phases and coherence factors. Furthermore, these decay rates are also sensitive to charm mixing. Charm mixing is described by two dimensionless parameters: $x \equiv (M_1 - M_2)/\Gamma$ and $y \equiv (\Gamma_1 - \Gamma_2)/2\Gamma$, where $M_{1,2}$ and $\Gamma_{1,2}$ are the masses and widths, respectively, of the neutral D meson CP-eigenstates. The explicit dependence on the mixing parameters can be seen by considering the generalised, time-integrated, DT rate. That is, for a $D^0\bar{D}^0$ pair decaying to the final state (f, g):

$$\Gamma(f|g) = Q_M|A_f\bar{A}_g - \bar{A}_f A_g|^2 + R_M|A_f A_g - \bar{A}_f\bar{A}_g|^2, \tag{3.1}$$

where $A_i \equiv \langle i|D^0\rangle$, $\bar{A}_i \equiv \langle i|\bar{D}^0\rangle$. The coefficients Q_M and R_M posses the dependence on the mixing parameters, where $Q_M \equiv 1-(x^2-y^2)/2$ and $R_M \equiv (x^2+y^2)/2$ [11].

3.1 Probing strong-phases and coherence factors

Letting f represent the signal D decay of interest, it is possible to obtain access to strong-phases and coherence factors by considering specific states of the 'tag', g. As an example, we demonstrate here how sensitivity to strong-phases can be obtained by considering g to be in a CP-eigenstate with eigenvalue λ_{CP}. For the purpose of this discussion, we simplify the problem by ignoring D-mixing effects, i.e. $x, y \to 0$. In this scenario, $Q_M \to 1$, $R_M \to 0$. Consequently, for $f = K^-\pi^+$, Eqn.(3.1) reduces to:

$$\begin{aligned}\Gamma(K^-\pi^+|CP) &\propto |A_{K\pi}A_{CP} - \bar{A}_{K\pi}A_{CP}|^2 \\ &= |A_{K\pi}|^2|A_{CP}|^2\big(1+(r_D^{K\pi})^2 - 2\,\lambda_{CP}\, r_D^{K\pi}\cos(\delta_D^{K\pi})\big).\end{aligned} \tag{3.2}$$

Therefore, with a knowledge of $|A_{K\pi}|$, $|A_{CP}|$ and $r_D^{K\pi}$, the observed asymmetry between the rates for $\lambda_{CP} = +1$ and $\lambda_{CP} = -1$ provides direct sensitivity to $\cos(\delta_D^{K\pi})$. When a multi-body signal mode is considered, such as $f = \{K^\pm\pi^\mp\pi^0,\ \ K^\pm\pi^\mp\pi^+\pi^-\}$, the amplitude A_f must be integrated over all phase-space. This has the effect of modifying Eqn. (3.2) through the transformation $\cos(\delta_D^f) \to R_f\cos(\delta_D^f)$. Therefore, for $f = K^-\pi^+\pi^0$:

$$\Gamma(K^-\pi^+\pi^0|CP) = |A_{K\pi\pi^0}|^2|A_{CP}|^2\big(1+(r_D^{K\pi\pi^0})^2 - 2\,\lambda_{CP}\, r_D^{K\pi\pi^0}\, R_{K\pi\pi^0}\cos(\delta_D^{K\pi\pi^0})\big). \tag{3.3}$$

To give a more concrete overview, expressions from evaluating Eqn. (3.1) are listed in Table 1 for various tag modes against $f = K^-\pi^+$. As is demonstrated in Ref.[9], while $|A_{K\pi}|^2$ has direct correspondence to the CF branching fraction ($\mathscr{B}_{K\pi}^{CF}$), $|\bar{A}_{K\pi}|^2$ and $|A_{CP}|^2$ possess dependence on the mixing parameters x and y, i.e. $|\bar{A}_{K\pi}|^2 = \mathscr{B}_{K\pi}^{DCS}(1+\mathscr{O}(x,y))$. Consequently, a linear dependence on x and y is observed in some of the quantum correlated branching fractions quoted in Table 1.

Mode	**Relative Correlated Branching Fraction**
$K^-\pi^+$ vs. $K^-\pi^+$	R_M
$K^-\pi^+$ vs. $K^+\pi^-$	$(1+R_W)^2 - 4r\cos\delta_D^{K\pi}(r\cos\delta_D^{K\pi}+y)$
$K^-\pi^+$ vs. $CP\pm$	$1+R_{WS}\pm 2r\cos\delta_D^{K\pi}+y$
$K^-\pi^+$ vs. e^-	$1-ry\cos\delta_D^{K\pi}-rx\sin\delta_D^{K\pi}$
$CP\pm$ vs. $CP\pm$	0
$CP+$ vs. $CP-$	4
$CP\pm$ vs. e^-	$1\pm y$

Table 1: Correlated ($C=-1$) effective $D^0\bar{D}^0$ branching fractions to leading order in x, y and r^2. The rates are normalised to the multiple of the uncorrelated branching fractions. Some rates show dependence to the wrong-sign rate ratio, $R_{WS}=r^2+ry'+R_M$, where $y'=(y\cos\delta_D^{K\pi}-x\sin\delta_D^{K\pi})$.

4. CLEO-c

All measurements presented are made with $e^+e^-\to\psi(3770)$ data accumulated at the Cornell Electron Storage Ring (CESR). The CLEO-c detector was used to collect these data. Details of the experiment can be found elsewhere [10]. The total integrated luminosity of the data is 818 pb^{-1}, however, only 281 pb^{-1} have been used so far for the measurement of $\delta_D^{K\pi}$ presented in Sec. 5.

5. Measurement of the strong-phase difference in $D\to K^-\pi^+$

The first analysis presented is that of the strong-phase difference in $D\to K^-\pi^+$. Implementing the method described in Ref. [11], this analysis has performed the first measurements of y and $\cos(\delta_D^{K\pi})$ in quantum-correlated $\psi(3770)$ data. By comparing the correlated event yields, whose rates are listed in Table 1, with the uncorrelated expectations, we are able to extract r^2, $r\cos(\delta_D^{K\pi})$, y and x^2. To achieve this, a knowledge of the relevant uncorrelated branching-ratios are needed. This information is gathered by averaging results of single-tagged yields at the $\psi(3770)$ with external measurements using incoherently-produced D^0 mesons. In addition, to extract $\cos(\delta_D^{K\pi})$ from $r\cos(\delta_D^{K\pi})$, knowledge of r is required. This necessary information is obtained by including R_{WS} and R_M as external inputs to the least-squares fit. Furthermore, external measurements of the mixing parameters are used as constraints. All correlations amongst the inputs are accounted for.

The analysis has considered a total of seven CP-eigenstates reconstructed against the $K^\pm\pi^\mp$ signal mode: K^+K^-, $\pi^+\pi^-$, $K_s^0\pi^0$, $K_s^0\omega$, $K_s^0\pi^0\pi^0$, $K_s^0\eta$ and $K_L^0\pi^0$. In those DTs without a K_L^0, the signal is identified using two kinematic variables: the beam-constrained mass, $M\equiv\sqrt{E_{\rm Beam}^2-\mathbf{p}_D^2}$, and $\Delta E\equiv E_D-E_{\rm Beam}$, where $E_{\rm Beam}$ is the beam energy, $\mathbf{p}_D$ and E_D are the D^0 candidate momentum and energy, respectively. The reconstruction of $K_L^0\pi^0$ events utilises the missing-mass technique described in Ref. [12]. The analysis finds a result of $\delta_D^{K\pi}=(22^{+11+9}_{-12-11})^\circ$ from using 281 pb^{-1} of data, which is the first direct determination of this phase [13]. An updated result following analysis of the full 818 pb^{-1} dataset is in preparation.

6. Measurement of the coherence factor and average strong-phase difference in $D \to K^{\pm}\pi^{\mp}\pi^{0}$ and $D \to K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$

Determination of the average strong-phase difference and associated coherence factors for the modes $f = \{K\pi\pi^0, K3\pi\}$ have been made using an analogous technique to that described in Sec. 5 [14]. As shown in Eqn.(3.3), *CP*-tagged multi-body rates provide sensitivity to the product $R_f \cos(\delta_D^f)$. A means of decoupling these parameters fortunately comes from considering the rate $\Gamma(f|f)$. Evaluating Eqn.(3.1) for $g = f$, one obtains:

$$\Gamma(f|f) = Q_M |A_f|^2 |\bar{A}_f|^2 \left(1 - (R_f)^2\right) + |A_f|^4 R_M \left(1 - 2(r_D^f)^2 + (r_D^f)^4\right). \tag{6.1}$$

In the case of the two-body mode, $f = K^{\pm}\pi^{\mp}$, $R_f = 1$ and Eqn.(6.1) reduces to $|A_f|^4 R_M$ as quoted in Table 1. However, for multi-body final states, one observes that $(1 - R_f^2)$ is the leading term in Eqn.(6.1). Consequently, the rate $\Gamma(f|f)$ provides direct sensitivity to R_f and allows for a decoupling of the parameters. All the *CP*-tags listed in Sec. 5 are employed in this analysis, as well as $K_S^0\phi$, $K_S^0\eta'$ and $K_L^0\omega$.

As was done in the $K^{\pm}\pi^{\mp}$ analysis, a least-squares fit has been used to extract both mixing and strong-phase parameters. Likelihood contours in R_f, δ_D^f parameter space are shown in Fig. 1(a) for $f = K\pi\pi^0$, and Fig. 1(b) for $f = K3\pi$. The best-fit values of the coherence factors and average strong-phases are $R_{K\pi\pi^0} = 0.84 \pm 0.07$, $\delta_D^{K\pi\pi^0} = (227^{+14}_{-17})^\circ$, $R_{K3\pi} = 0.33^{+0.20}_{-0.23}$ and $\delta_D^{K3\pi} = (114^{+28}_{-23})^\circ$. The uncertainties quoted are a combination of statistical and systematic errors.

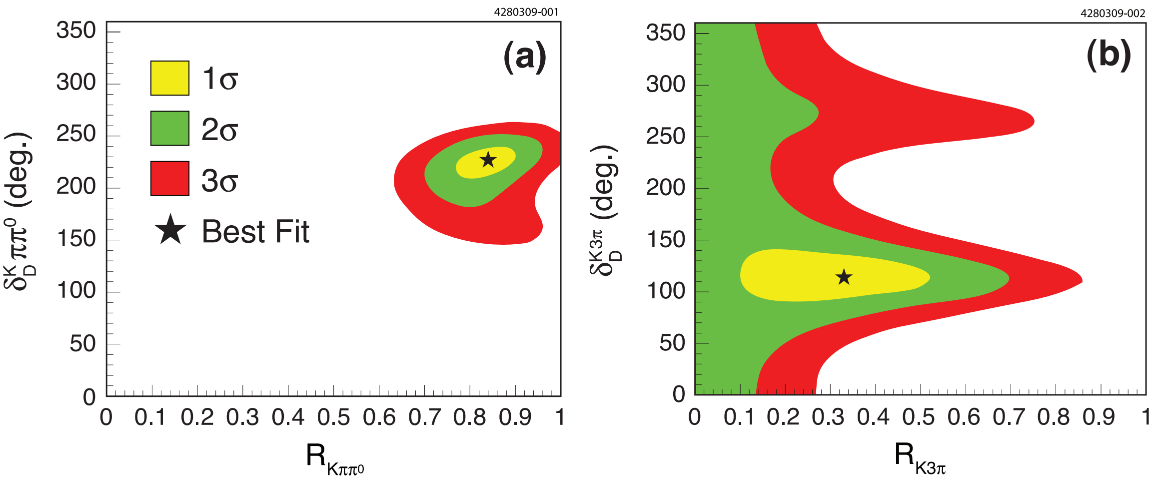


Figure 1: The limits determined on (a) $(R_{K\pi\pi^0}, \delta_D^{K\pi\pi^0})$ and (b) $(R_{K3\pi}, \delta_D^{K3\pi})$ at the 1, 2 and 3σ levels.

The results show significant coherence for $D^0 \to K\pi\pi^0$, but much less so for $D^0 \to K\pi\pi\pi$. These results will improve the measurement of γ and the amplitude ratio r_B in $B^{\pm} \to DK^{\pm}$, where the D decays to $K\pi\pi^0$ and $K\pi\pi\pi$. Earlier preliminary results of $R_{K3\pi}$ and $\delta_D^{K3\pi}$ [15] combined with CLEO-c's measurement of $\delta_D^{K\pi}$ were shown to improve the expected sensitivity to γ at LHCb in a combined ADS analysis of $K\pi$ and $K\pi\pi\pi$ final states by up to 40% [16].

7. Measurement of strong-phase variations in $D \to K_S^0\pi^+\pi^-$

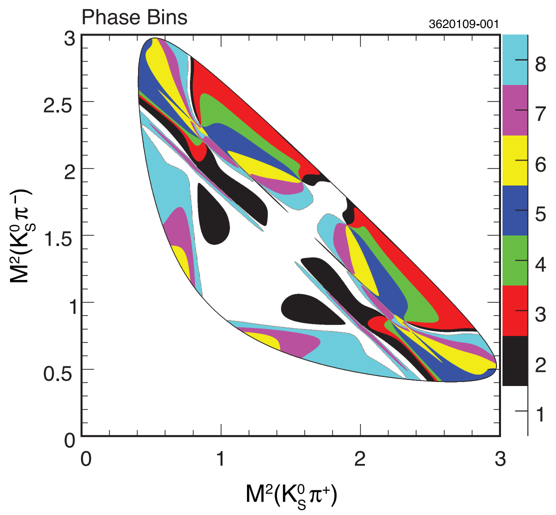
The current best constraints on γ come from measurements in $B^{\pm} \to D(K_S^0\pi^+\pi^-)K^{\pm}$ and related modes [17, 18] by performing likelihood fits to the $K^0_S\pi^+\pi^-$ Dalitz plot [4]. These fits require models to represent the $D^0 \to K^0_S\pi^+\pi^-$ resonant amplitude structure. Since these models are based on certain assumptions, an inherent systematic uncertainty is associated with this technique. Current estimates predict this error to be between 5° and 9°, meaning the γ measurement would soon become systematically limited at the next generation of flavour-physics experiment. However, an alternative *model-independent* method has been proposed where events are counted in specified regions of the $K^0_S\pi^+\pi^-$ Dalitz plot [4, 5], thus eliminating the model-uncertainty. This method relies on necessary strong-phase parameters having been determined at CLEO-c.

As Dalitz plot variables we use the invariant-mass squared of the $K^0_S\pi^-$ and $K^0_S\pi^+$ pairs, which we label as s_- and s_+, respectively. The strong-phase at a given point in the $K^0_S\pi^+\pi^-$ Dalitz plot is then $\delta_D(s_-,s_+)$. For the phase difference between $D^0 \to K^0_S\pi^+\pi^-$ and $\bar{D}^0 \to K^0_S\pi^+\pi^-$ at the same point in the Dalitz plot, we define

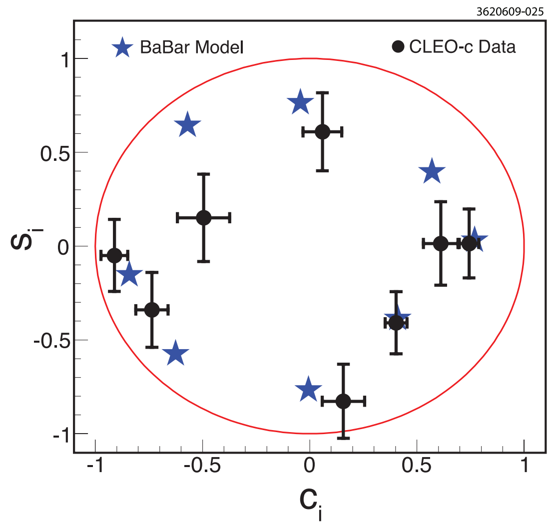
$$\Delta\delta_D \equiv \delta_D(s_-,s_+) - \delta_D(s_+,s_-). \tag{7.1}$$

The quantities measured by CLEO-c that provide input to the model-independent γ determination are the averages of $\cos(\Delta\delta_D)$ and $\sin(\Delta\delta_D)$ in the ith Dalitz plot bin. We denote these terms c_i and s_i, respectively. In a completely analogous manner to the analyses presented in Secs. 5 and 6, c_i can be determined from CP-tagged decay rates, while s_i is extracted from considering the double Dalitz plot of $K^0_S\pi^+\pi^-$ vs. $K^0_S\pi^+\pi^-$. Furthermore, additional constraints on c_i and s_i are obtained through $K^0_L\pi^+\pi^-$ events.

The choice of Dalitz plot binning affects the statistical precision of the analysis. It has been demonstrated in Ref. [5] that it is beneficial to choose bins such that $\Delta\delta_D$ varies as little as possible across each bin. The binning used in this analysis, with eight-pairs of bins uniformly dividing $\Delta\delta_D$ over the range $[0,2\pi]$, is shown in Fig. 2(a). The location of these bins in phase space are chosen based on the BaBar isobar model given in Ref. [19].



(a)



(b)

Figure 2: In (a), the uniform $|\Delta\delta_D|$ binning of the $K^0_S\pi^+\pi^-$ Dalitz plot. In (b), the comparison of the measured c_i and s_i (circles with error bars) to the predictions from the BaBar isobar model (stars).

The values of c_i and s_i from the combined analysis of $K_S^0\pi^+\pi^-$ and $K_L^0\pi^+\pi^-$ tagged events are shown graphically in Fig 2(b). When used as input to the γ measurement, these results are expected to replace the current model uncertainty of $5^\circ - 9^\circ$ with an uncertainty due to the statistically dominated error on c_i and s_i of 1.7° [20].

8. Conclusion

The importance of CLEO-c's quantum-correlated $\psi(3770)$ dataset in the context of measuring the CKM angle γ has been described. Analysis of a variety of two- and multi-body D^0 decays with these data have provided vital measurements of D^0 strong-phases, and associated parameters, for model-independent γ measurements at LHCb. In addition to the modes presented here, results are in preparation for other promising final states, such as $D^0 \to K_S^0 K^+ K^-$.

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