QUANTUM-CORRELATED MEASUREMENTS RELATED TO THE DETERMINATION OF $\gamma/\phi_3$

J. LIBBY*1

1Department of Physics, Indian Institute of Technology Madras, Chennai 600028, Tamil Nadu, India
libby@iitm.ac.in

(Dated: 13th December 2010)

Abstract

Measurements of $D^0$ meson strong-phase parameters in quantum-correlated $\psi(3770) \rightarrow D^0\overline{D}^0$ decays by the CLEO collaboration are presented. These measurements play an important role in the determination of the unitarity triangle angle $\gamma/\phi_3$ from $B$-meson decays. Measurements of the strong-phase parameters for $D^0 \rightarrow K^0\pi^+\pi^-$, $D^0 \rightarrow K^0K^+K^-$, $D^0 \rightarrow K^--\pi^+\pi^0$, and $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$ decays are described along with their impact on the determination of $\gamma/\phi_3$.

* Proceedings of an invited talk at CHARM 2010, Beijing, China, Oct 21-24 2010, given on behalf of the CLEO Collaboration.
I. INTRODUCTION

One of the primary goals of flavor physics is to determine the angle $\gamma/\phi_3$ of the $b - d$ CKM triangle [1]. Aside from being the least well known angle of the unitarity triangle (UT), it can be determined in tree-level processes that have negligible contributions from beyond the standard model physics, unlike most other constraints on the UT [2]. Therefore, any disagreement between the tree-level measurement of $\gamma/\phi_3$ with predictions derived from other measurements is a signature of new physics.

The most promising decay to determine $\gamma/\phi_3$ at tree level is $B^- \rightarrow \bar{D}^0 K^-$ where $\bar{D}^0$ is a $D^0$ or $\bar{D}^0$ decaying to the same final state $[3,1]$. The sensitivity to $\gamma/\phi_3$ arises from the interference between the decay $B^- \rightarrow D^0 K^-$ and the color and CKM-suppressed decay $B^- \rightarrow \bar{T}^0 K^-$. The most precise measurements $[4,5]$ of $\gamma/\phi_3$ come from decays where $\bar{D}^0 \rightarrow K^0_s h^+ h^- [6,7]$. Here, $h$ is $\pi$ or $K$. Other promising $D^0$ final states are $K^- \pi^+$, $K^- \pi^+ \pi^0$, and $K^- \pi^+ \pi^+ \pi^-$ $[8,9]$. All these measurements depend on parameters related to the decay of the $D^0$ meson. Knowledge of the $D$-decay parameters a priori can greatly improve the determination of $\gamma/\phi_3$. These proceedings summarise the measurements $[10,11]$ of these parameters made by the CLEO collaboration and estimates their impact on the determination of $\gamma/\phi_3$.

II. MEASUREMENT OF THE STRONG-PHASE PARAMETERS OF $D^0 \rightarrow K^0 h^+ h^-$ DECAYS

The sensitivity to $\gamma/\phi_3$ in $B^- \rightarrow \bar{D}^0 (K^0_s h^+ h^-) K^-$ comes from studying differences between the $\bar{D}^0 \rightarrow K^0_s h^+ h^-$ Dalitz plot for both $B^-$ and $B^+$ decays. Current measurements of $\gamma/\phi_3$ require a model of the $\bar{D}^0 \rightarrow K^0_s h^+ h^-$ Dalitz plot, which is derived from flavor-tagged samples of $D^0 \rightarrow K^0_s h^+ h^-$. The assumptions used to determine the model introduce a systematic uncertainty on $\gamma/\phi_3$ which is estimated to be between $3^\circ$ and $9^\circ [4,5]$. This is significantly less than the current statistical uncertainty but it will be a limiting factor in future measurements $[12,13]$. Therefore, it is desirable to perform the measurement in a model-independent manner. Such a method was proposed in Ref. [6] and has been developed significantly by Bondar and Polnekov [14]. The method requires determining yields in bins of the $\bar{D}^0 \rightarrow K^0_s h^+ h^-$ Dalitz plot for $B^-$ and $B^+$ decay, which depend on the $B$-decay parameters and two new parameters $c_i$ and $s_i$, which are the amplitude-weighted averages over the bin of the cosine and sine of the difference in strong-phase difference, $\Delta \delta_D$, between Dalitz-plot points $(m^2, m^2)$ and $(m^2, m^2)$. Here $m_{\pm}$ is the invariant-mass of the $K^0_s h^\pm$ pair. It can be shown $[10,14]$ that between 80% to 90% of the statistical sensitivity to $\gamma/\phi_3$ of the unbinned method can be obtained by choosing bins corresponding to equal intervals of $\Delta \delta_D$ according to an amplitude model. An example of such a binning is shown in Fig. [11].

The values of $c_i$ and $s_i$ can be measured in quantum-correlated $D^0\bar{D}^0$ decays of the $\psi(3770)$. The $D^0\bar{D}^0$ are produced in a $C = -1$ state. Therefore, if one $D$ meson decays to a $CP$-eigenstate the other $D$-meson is in the opposite $CP$-eigenstate. The difference between $CP$-even and $CP$-odd tagged Dalitz plots in each bin is related to the $c_i$ parameters. In addition, the Dalitz plot of quantum-correlated events where both $D$-mesons decay to $K^0_s h^+ h^-$ is sensitive to both $c_i$ and $s_i$. The strong-phase parameters for the decay $D^0 \rightarrow$
$K^0_L h^+ h^-$ ($c'_i$ and $s'_i$) are closely related to $c_i$ and $s_i$ such that using decays of the type $K^0_S h^+ h^-$ vs. $K^0_L h^+ h^-$ greatly improve the precision on $c_i$ and $s_i$.

The CLEO-c experiment [15] collected $e^+ e^- \rightarrow \psi(3770) \rightarrow D\bar{D}$ data corresponding to an integrated luminosity of 818 pb$^{-1}$. The fact that all particles arise from $D$-meson decay in the final state leads to both $D$ mesons being reconstructed exclusively with high efficiency and purity. For $D^0 \rightarrow K^0_S \pi^+ \pi^-$ ($D^0 \rightarrow K^0_S K^+ K^-$) decay the numbers of CP-tagged and $K^0 h^+ h^-$ vs. $K^0 h^+ h^-$ candidates selected are 1661 and 1674 (219 and 335), respectively.

A maximum-likelihood fit is performed to the bin yields of the CP-tagged and $K^0 h^+ h^-$ vs. $K^0 h^+ h^-$ events to extract $c_i^{(0)}$ and $s_i^{(0)}$. The results are presented in detail elsewhere [10]. The values of $c_i^{(0)}$ and $s_i^{(0)}$ are determined for several binning variations for both $D^0 \rightarrow K^0_S \pi^+ \pi^-$ and $D^0 \rightarrow K^0_S K^+ K^-$. These binnings allow flexibility given different scenarios for the amount of $B$ data and the background environment. The measured values of $c_i$ and $s_i$ are found to be in reasonable agreement with the values predicted by the amplitude models presented in Refs. [4, 16]. The largest systematic uncertainties arise from the modelling of the background. However, none of these measurements are systematically limited.

![Dalitz-plot binning for $D^0 \rightarrow K^0_S \pi^+ \pi^-$ in region of similar $\Delta \delta_D$.](image-url)

FIG. 1: Dalitz-plot binning for $D^0 \rightarrow K^0_S \pi^+ \pi^-$ in region of similar $\Delta \delta_D$. 

\[ \text{4280910-001} \]
The rate of decays $B^- \to D^0 (K^+ \pi^-) K^-$ is particularly sensitive to $\gamma/\phi_3$ because the two interfering amplitudes are of similar size due to the doubly-Cabibbo suppressed (DCS) $D^0$ decay coming from the favored $B^-$ amplitude [8]. The rate depends not only on $\gamma/\phi_3$ but on the strong-phase difference between the Cabibbo-favored and DCS $D^0 \to K^+ \pi^-$ decays. The measurement of this parameter by the CLEO collaboration is described elsewhere in these proceedings [18].

Via the same mechanism there is potential sensitivity to $\gamma/\phi_3$ from $B^- \to D^0 K^-$, where $D^0 \to K^+ \pi^- \pi^0$ or $D^0 \to K^+ \pi^- \pi^+ \pi^0$ [8]. These modes have significantly larger branching fractions than $D^0 \to K^+ \pi^- [17]$. However, the dynamics are more complicated because there is variation of the strong-phase difference over the multi-body phase-space. This leads to the introduction of a new parameter referred to as the coherence factor $R_F$ ($F = K \pi \pi^0$ or $K3\pi$), which multiplies the interference term sensitive to $\gamma/\phi_3$. The value of $R_F$ can vary between zero and one. If there is only a single intermediate resonance or a few non-interfering resonances the coherence factor will be close to one and the decay will behave just like $D^0 \to K^+ \pi^-$. If there are many overlapping intermediate resonances the coherence factor will tend toward zero, limiting the sensitivity to $\gamma/\phi_3$. However, even if there is limited sensitivity to the phases when $R \sim 0$ there is enhanced sensitivity to the magnitude of the amplitude ratio between the $B^- \to D^0 K^-$ and $B^- \to \overline{D^0} K^-$ decays; improved knowledge of this parameter will then lead to better overall sensitivity to $\gamma/\phi_3$ in a global fit to all $B^- \to D^0 K^-$ decays.

The values of $R_F$ and the average-strong phase difference $\delta_F^s$ have been measured by CLEO-c [11]. Sensitivity comes from the quantum-correlated $D^0 \overline{D^0}$ events with $F$ tagged by either $C_P$-eigenstates or $K^- \pi^+\pi^0$, $K^- \pi^+\pi^+$, and $K^- \pi^+\pi^-\pi^+$, where the tag kaon charge is the same as the signal. A $\chi^2$ fit to the yields gives: $R_{K^+\pi^0} = 0.84 \pm 0.07$, $\delta_{D^0}^{K^+\pi^0} = (227^{+114}_{-17})^\circ$, $R_{K^+\pi^0} = 0.33^{+0.26}_{-0.23}$, and $\delta_{D^0}^{K^+\pi^0} = (114^{+26}_{-23})^\circ$. Figure 2 shows the 1$\sigma$, 2$\sigma$, and 3$\sigma$ regions of $(R_{K^+\pi^0}, \delta_{D^0}^{K^+\pi^0})$ parameter space; the coherence of $D^0 \to K^- \pi^+\pi^0$ is clearly observed. The impact of these results on the measurements of $\gamma/\phi_3$ is discussed in the following section.

### IV. IMPACT OF RESULTS ON THE MEASUREMENT OF $\gamma/\phi_3$

The determination of the $c_i$ and $s_i$ in quantum-correlated $D$-decay allows the measurement of $\gamma/\phi_3$ without a model induced systematic uncertainty. However, this is replaced by uncertainty due to the limited statistics used to measure $c_i$ and $s_i$ at CLEO-c. This uncertainty is estimated to be between 1.7$^\circ$ and 3.9$^\circ$ (3.2$^\circ$ and 3.9$^\circ$) depending on the binning of the $D^0 \to K_S^0 \pi^+\pi^+$ ($D^0 \to K_S^0 K^- \pi^+$) Dalitz plot. The systematic uncertainty on $\gamma/\phi_3$ can be reduced by about a factor of three if BES-III collects 10 fb$^{-1}$ of integrated luminosity at the $\psi(3770)$ resonance [19]. This would reduce the uncertainty to the order of 1$^\circ$, which would not only be adequate for LHCb but also for future higher luminosity facilities [13, 20].

The impact of the measurements of $R_F$ and $\delta_F^s$ at LHCb is evaluated using the yield estimates for $B^- \to \overline{D^0}(K^+\pi^+)K^-$ and $B^- \to \overline{D^0}(K^+\pi^+\pi^-\pi^+)K^-$ decays in a dataset corresponding to 2 fb$^{-1}$ of integrated luminosity at a center-of-mass energy of 14 TeV [21]. In addition, the yield of $B^- \to \overline{D^0}(K^+\pi^+\pi^-\pi^+)K^-$ is assumed to be half that of $B^- \to \overline{D^0}(K^+\pi^+\pi^-\pi^-)K^-$ with the same level of background reflecting the difficulties
associated with $\pi^0$ reconstruction in the hadronic environment. The sensitivity to $\gamma/\phi_3$ from LHCb data alone is 9.7°. Including the CLEO-c constraints on $R_F$ and $\delta_D^F$ this improves to 7.5°. The introduction of the CLEO-c constraints is equivalent to 70% more LHCb data. This clearly illustrates the power of quantum-correlated measurements in aiding the determination of $\gamma/\phi_3$. BES-III data could lead to at least a further 10% reduction of the uncertainty on $\gamma/\phi_3$.

In conclusion, the first quantum-correlated measurements of strong-phase parameters of $D$-decay at CLEO-c have been presented and their positive impact on the determination of $\gamma/\phi_3$ at LHCb has been illustrated. Further improvements are possible by exploiting the larger sample of quantum-correlated decays that will be available at BES-III. Furthermore, there are other $\bar{D}^0$ decay modes of interest to the measurement of $\gamma/\phi_3$ for which the strong-phase parameters have yet to be determined: $K_S^0\pi^+\pi^-\pi^0$, $\pi^+\pi^-\pi^+\pi^-$, $K_S^0 K^\pm K^\mp$, and $K^+K^-\pi^+\pi^-$. 

![Diagram](image.png)

**FIG. 2:** The 1σ, 2σ, and 3σ allowed regions of $(R_{K\pi\pi_0},\delta_D^{K\pi\pi_0})$ parameter space.
Acknowledgments

I would like to thank the CHARM 2010 organisers for their financial assistance that allowed my participation in an excellent conference.

[1] N. Cabibbo, *Phys. Rev. Lett.* **10**, 531 (1963); M. Kobayashi and T. Maskawa, *Prog. Theor. Phys.* **49**, 652 (1973).

[2] CKMfitter Group, (A. Höcker et al.), *Eur. Phys. J. C* **21**, 225 (2001); CKMfitter Group (J. Charles et al.), *Eur. Phys. J. C* **41**, 1 (2005), and updates at [http://ckmfitter.in2p3.fr/](http://ckmfitter.in2p3.fr/); M. Ciuchini et al., *J. High Energy Phys.* 0107 (2001) 013; UTfit Collaboration (M. Bona et al.), *J. High Energy Phys.* 081 (2006) 10, and updates at [http://www.utfit.org/](http://www.utfit.org/).

[3] M. Gronau and D. Wyler, *Phys. Lett. B* **265**, 172 (1991); M. Gronau and D. London, *Phys. Lett. B* **253**, 483 (1991).

[4] Belle Collaboration (A. Poluektov et al.), *Phys. Rev. D* **81**, 112002 (2010).

[5] BABAR Collaboration, (P. del Amo Sanchez et al.), *Phys. Rev. Lett.* **105**, 121801 (2010).

[6] A. Giri, Y. Grossman, A. Soffer, and J. Zupan, *Phys. Rev. D* **68**, 054018 (2003).

[7] A. Bondar, *Proceedings of BINP Special Analysis Meeting on Dalitz Analysis*, 24-26 Sep. 2002, unpublished.

[8] D. Atwood, I. Dunietz, and A. Soni, *Phys. Rev. Lett.* **78**, 3257 (1997); D. Atwood, I. Dunietz, and A. Soni, *Phys. Rev. D* **63**, 036005 (2001).

[9] D. Atwood and A. Soni, *Phys. Rev. D* **68**, 033003 (2003).

[10] CLEO Collaboration (J. Libby et al.), arXiv:1010.2817 [hep-ex], accepted by Phys. Rev. D.

[11] CLEO Collaboration (N. Lowrey et al.), *Phys. Rev. D* **80**, 031105 (2009).

[12] J. Libby, CERN-LHCb-2007-141; V. Gibson, C. Lazzeroni, and Y.-Y. Li, CERN-LHCb-2008-028.

[13] T. Aushev et al., KEK-Report 2009-12; M. Bona et al., SLAC-R-856.

[14] A. Bondar and A. Poluektov, *Eur. Phys. J. C* **47**, 347 (2006); A. Bondar and A. Poluektov, *Eur. Phys. J. C* **55**, 51 (2008).

[15] CLEO Collaboration (Y. Kubota et al.), *Nucl. Instrum. Methods Phys. Res., Sect. A* **320**, 66 (1992); D. Peterson et al., *Nucl. Instrum. Methods Phys. Res., Sect. A* **478**, 142 (2002); M. Artuso et al., *Nucl. Instrum. Methods Phys. Res., Sect. A* **554**, 147 (2005).

[16] BABAR Collaboration (B. Aubert et al.), *Phys. Rev. D* **78**, 034023 (2008).

[17] Particle Data Group (K. Nakamura et al.), *J. Phys. G* **37**, 075021 (2010).

[18] D. Asner, these proceedings.

[19] H. Liu, these proceedings.

[20] LHCb Collaboration, CERN-LHCb-2008-019.

[21] LHCb Collaboration (B. Adeva et al.), LHCb-PUB-2009-029.