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Charm inputs from CLEO-c for γ measurements

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The measurements of D^0 strong phase parameters in quantum correlated $\psi(3770) \rightarrow D^0\overline{D}^0$ decays by the CLEO collaboration are presented here. These measurements can be used as inputs to model independent measurements of the unitary angle γ. Measurements of strong phase difference parameters in the decays $D^0 \rightarrow K^-\pi^+$, $D^0 \rightarrow K^-\pi^+\pi^0$, $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$, $D^0 \rightarrow K_SK^-\pi^+$, $D^0 \rightarrow K_S\pi^+\pi^-$, and $D^0 \rightarrow K_SK^+K^-$ decays are described along with their impact on future measurements of γ.

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1. Introduction

One of the primary goals of flavour physics is to improve the knowledge of the unitary triangle angle γ [1]. Not only is this the least well measured angle [2], but it is also the one that can be determined using tree level processes where the contribution of physics beyond the standard model is expected to be negligible. A disagreement between measurements of γ using tree and loop level processes would indicate the presence of new physics. At tree level one key way to measure γ is through the decay $B^- \to \widetilde{D^0}K^-$[1] where $\widetilde{D^0}$ is either D^0 or $\overline{D^0}$ decaying to the same final state, for example $K_S\pi^+\pi^-$ or $K^-\pi^+$[3]. The sensitivity to γ comes from the interference of $b \to c$ and $b \to u$ transitions. These measurements also require knowledge of the $\widetilde{D^0}$ decay parameters including the strong phase difference between the D^0 and $\overline{D^0}$ meson decay. If these can be determined accurately and independently of the γ measurement then there can be a significant improvement on the measurement of γ.

The CLEO-c experiment [4] collected $e^+e^- \to \psi(3770) \to D\overline{D}$ decays corresponding to 818 pb^{-1} of integrated luminosity. These data can be used to determine the strong phase difference as the $\psi(3770)$ is in a CP odd state and therefore the decay of the two D mesons is quantum correlated. To give an example of how this gives sensitivity to the strong phase difference, one can consider the Dalitz plot distribution of $D^0 \to K_S\pi^+\pi^-$. In the case of the decay of $\psi(3770)$ to two D mesons, where one D meson decays to the CP even final state $\pi\pi$, and the other to $K_S\pi^+\pi^-$, the effect of quantum correlation forces the decay of the D meson decaying to $K_S\pi^+\pi^-$ into a CP odd state. The amplitude for this decay is given by a superposition of D^0 and $\overline{D^0}$ amplitudes and hence the Dalitz plot density description includes a term proportional to the cosine of the strong phase difference. The full reconstruction of both D meson decays is known as a double tag. Other double tags besides those containing one D meson decay to a CP eigenstate also have sensitivity to the strong phase differences. The CLEO detector allows for full reconstruction of many double tags. The signal to background ranges from 10–100 depending on the decay considered. The presence of K_L^0 can also be determined via a missing mass technique, which allows the use of CP tags including a K_L such as $K_L\pi^0$. These proceedings summarise the various measurements performed by the CLEO collaboration and gives estimates on their impact on the determination of γ.

2. Measurements in self conjugate modes

One of the most promising decay channels to measure γ in is the decay $B^- \to \widetilde{D^0}K^-, \widetilde{D^0} \to K_S h^+h^-$ where $h = K, \pi$. The sensitivity to γ comes from the differences between the $\widetilde{D^0} \to K_S h^+h^-$ Dalitz plot for B^+ and B^- decays. These differences can be analysed using an amplitude model of the D decay, and this method has been used by the Belle and BABAR collaborations [5, 6]. The use of amplitude models introduces a systematic uncertainty estimated to be between 3 – 9°[5, 6]. This uncertainty will limit the precision in future measurements.

A model independent method has been proposed in [7] and developed further in [8]. This method requires determining yields of B^+ and B^- in bins of the $\widetilde{D} \to K_S\pi^+\pi^-$ Dalitz plot such as those shown in Figure 1. These yields can be related to the B decay parameters (including γ) and the parameters c_i and s_i, which are the amplitude-weighted averages over the bin of the cosine and

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[1] Throughout this paper the charge conjugate state is implied unless otherwise stated

sine of the difference in strong phase difference, $\Delta\delta_D$, between the Dalitz plot points (m_-^2, m_+^2) and (m_+^2, m_-^2) where $m_\pm$ is the invariant mass of the $K_S h^\pm$ pair.

In this binned analysis, the choice of the bin regions is important to minimise the loss in statistical sensitivity in comparison to the unbinned amplitude analysis. It has been shown that binning in intervals of expected strong phase gives around 80% of the statistical sensitivity compared to the unbinned amplitude analysis. Further binnings have been developed via an optimsation which takes into account the expected B statistics and background distributions. These optimal binnings retain around 90% of the statistical sensitivity [8, 9]. While the construction of the binnings does use the amplitude models it should be emphasised that this does not introduce a model uncertainty to the analysis. Any descrepancy between the model and the true decay description will result in an increased statistical uncertainty on a γ measurement as the bins will not truly be optimal.

CLEO has measured c_i and s_i for both $D^0 \to K_S\pi^+\pi^-$ and $K_S K^+K^-$ in a variety of binning regimes. The different binning choices are useful as they allow for cross checks and some binning regimes may be better than others depending on the background levels in the B data. The c_i are determined from analysing bin yields in double tags, where one D meson decays to $K_S h^+h^-$ and the other to a CP eigenstate. Analysing the bin yields in double tags where both D mesons decay to $K_S h^+h^-$ gives sensitivity to s_i as well. As the strong phase parameters for the decay $D^0 \to K_L^0 h+h^-$ (c_i', s_i') are closely related to c_i and s_i, double tags where one D meson decays to $K_S h^+h^-$ and the other to $K_L h^+h^-$ are included as they greatly improve the precision on c_i and s_i. For the $D^0 \to K_S\pi^+\pi^-$ ($D^0 \to K_S K^+K^-$) decay the numbers of CP-tagged and $K_S h^+h^-$ vs. $K^0 h^+h^-$ candidates selected are 1661 and 1674 (219 and 335), respectively.

In Figure 1 one of the binning regimes is shown. These bins are determined by using intervals of expected $\Delta\delta_D$ of the $D^0 \to K_S\pi\pi$ decay from the BABAR 2008 model [10]. The results for the measured c_i and s_i are plotted with the model predictions shown by the blue stars, and there is good agreement between the measured and expected values. The measurements are statistically limited. The full results including other binning regimes and results for $K_S KK$ are presented in detail in Ref. [9]

3. Non self conjugate modes

Non self conjugate decays of D mesons such as $D^0 \to K^\pm\pi^\mp$ can also be used to determine γ [11], as the measured rates are sensitive to γ as shown in the following equations

$$\Gamma(B^\mp \to \widetilde{D}(K^\mp\pi^\pm)K^- \propto 1 + (r_B r_D^{K\pi})^2 + 2 r_B r_D^{K\pi}\cos(\delta_B - \delta_D^{K\pi} \mp \gamma), \tag{3.1}$$

$$\Gamma(B^\mp \to \widetilde{D}(K^\pm\pi^\mp)K^- \propto (r_B)^2 + (r_D^{K\pi})^2 + 2 r_B r_D^{K\pi}\cos(\delta_B + \delta_D^{K\pi} \mp \gamma), \tag{3.2}$$

where r_B is the absolute amplitude ratio between the $B^- \to D^0K^-$ and $B^- \to \overline{D^0}K^-$ decay and δ_B is the strong phase difference. The parameters r_D and δ_D are similar quantities between the Cabibbo favoured decay $D^0 \to K^-\pi^+$ and the doubly Cabibbo suppressed decay $D^0 \to K^+\pi^-$. The strong phase difference $\delta_D^{K\pi}$ has been measured at CLEO-c using 281 pb^{-1} of data via analysing the yields of a number of double tags. Sensitivity to the strong phase comes from analysing the yields of various double tags in quantum correlated decays of the $\psi(3770)$ meson. With the inclusion of external constraints on the D mixing parameters, the strong phase difference is measured to be

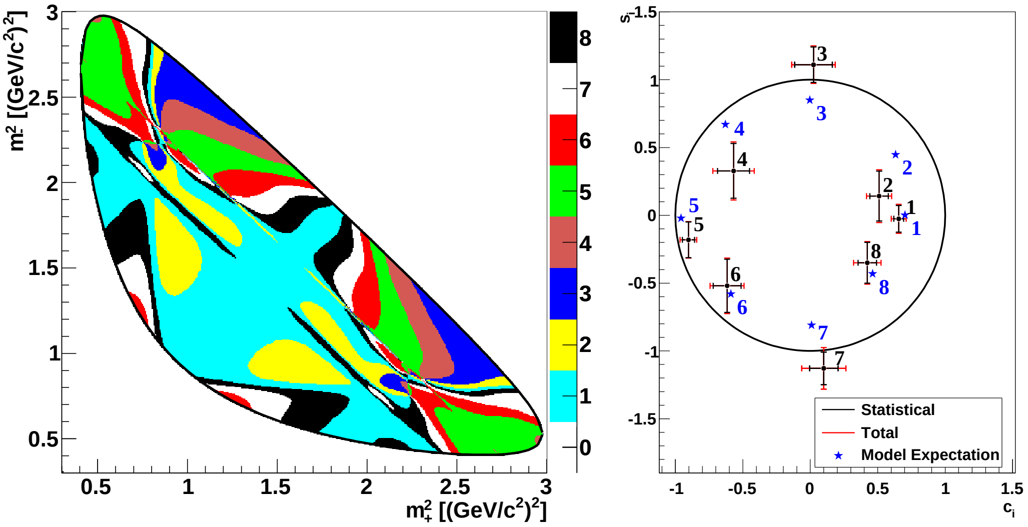

Figure 1: This diagram shows the bin divisions where the bins are divided into regions of $\Delta\delta_D$ according to the 2008 BABAR model [10]. The left plot shows the measured values of c_i and s_i corresponding to the bins on the right [9]. The model predictions are given by the blue star markers.

$\delta^{K\pi} = (22^{+11+9}_{-12-11})^\circ$ [12]. A new preliminary result uses the full $\psi(3770)$ data set of 818 pb^{-1} and also includes several double tags that were not used in the previous measurement such as CP eigenstates with a K_L^0 in the final state. This analysis allows for the measurement of r_D and the cosine and sine of the strong phase difference. The preliminary result using external D mixing constraints is $\delta^{K\pi} = 15^{+15}_{-7} \pm 7^\circ$.

In the case of multibody decays, such as $D^0 \to K\pi\pi^0$, $D^0 \to K\pi\pi\pi$, the strong phase difference and the amplitude ratio varies across the Dalitz plot. These decay channels can still be used to determine γ without using amplitude models if the coherence factor and average strong phase difference are known or can be determined [13]. The rate equations are modified and become:

$$\Gamma(B^\mp \to \widetilde{D}(F^-)K^- \propto 1 + (r_B r_D^F)^2 + 2r_B r_D^F R_F \cos(\delta_B - \delta_D^F \mp \gamma), \tag{3.3}$$

$$\Gamma(B^\mp \to \widetilde{D}(F^+)K^- \propto (r_B)^2 + (r_D^F)^2 + 2r_B r_D^F R_F \cos(\delta_B + \delta_D^F \mp \gamma), \tag{3.4}$$

where $F^\pm$ denotes the final state under analysis and the charge relates to the charge of the Kaon, R_F is the coherence factor, and δ_D^F is now the average strong phase difference over the Dalitz plot.

The coherence factor can range from 0 to 1. If the value is close to 1, then the decay is made of a few resonances with little interference between them and the decays will have good sensitivity to γ. The coherence factor and average strong phase have been measured by CLEO in the decay to final states $K\pi\pi^0$ and $K\pi\pi\pi$ [14]. Both these decay channels have r_D around 0.05 and large branching fractions (13% and 8%) [15], respectively. A preliminary measurement of the coherence factor for the final state $K_S K\pi$ has also been made. Although this decay channel has a lower branching fraction 0.35% [15], both the favoured and suppressed decay channels are singly Cabibbo supressed leading to a large value of r_D around 0.7. Hence if the coherence is also high, the per-event sensitivity to γ could be significant and make this a promising additional channel in which to measure γ. The coherence factor is determined from yields of double tags. The sensitivity comes mainly from the yield of CP tags which are sensitive to $R_F \cos\delta_D^F$. For $K\pi\pi^0$ and $K\pi\pi\pi$ the yield of double tags where each D meson decays to state F is sensitive to R_F^2. Due to the low branching fractions there are no events where both D mesons decay to $K_SK\pi$. However, with the determination of the c_i and s_i values it is possible to use the $K_0\pi\pi$ tag yield in each bin which are sensitive to a sum of $c_iR_F\cos\delta_D^F$ and $s_iR_F\sin\delta_D^F$. The various yields are combined in a χ^2 fit to determine the best fit values of the coherence factor and average strong phase difference. The fitted results give $R_{K\pi\pi^0} = 0.84\pm0.07$, $\delta_D^{K\pi\pi^0} = (227^{+14}_{-17})^\circ$, $R_{K\pi\pi\pi} = 0.33^{+0.20}_{-0.23}$, and $\delta_D^{K\pi\pi\pi} = (114^{+26}_{-23})^\circ$ [14]. The coherence for $D^0 \to K\pi\pi^0$ is high which means that the B data will have a high sensitivity to γ. In the case of $D^0 \to K\pi\pi\pi$ the coherence is low. However, this decay channel can then be used to improve the knowledge of r_B using equation 3.3 as the last terms tend to zero. In the case of $K_SK\pi$ the preliminary results for the coherence factor are $R_{K_SK\pi} = 0.73\pm0.09$ and $\delta_D^{K_SK\pi} = 8.2\pm15.2^\circ$. The coherence is large indicating that this should be promising channel in which to make an additional γ measurement. As the coherence is expected to be large in regions dominated by one resonance the measurement of $R_{K_SK\pi}$ has also been made in a bin where the invariant mass of the $K_S\pi$ combination lies within 789 to 993 MeV/c^2 i.e., around the $K^*(892)^\pm$ resonance. In this bin we find the coherence factor to be $R_{K_SK\pi} = 0.96\pm0.17$ and $\delta_D^{K_SK\pi} = 25.8\pm17.6^\circ$. As expected the coherence in this region is higher.

4. Impact on gamma measurements

The measurements of c_i and s_i allow for a measurement of γ which does not have a model dependence systematic uncertainty. These measurements have already been used by Belle [16]. The uncertainty on the measurements of c_i and s_i lead to an uncertainty on a measurement of γ. In the limit of large B statistics, these systematic uncertainties will be between 1.7 and 3.9° (dependent on binning choice) for measurements using the D meson decay to $K_S\pi\pi$, and between 3.2 and 3.9° (dependent on binning choice) for measurements using the decay to K_SKK [9]. These uncertainties are of similar size to those applied in a model dependent analysis. As the dominant contribution of uncertainty comes from the statistics available to measure c_i and s_i it will be possible to improve these measurements with the larger data sample that will become available at BES III.

The impact of the measurements of the coherence factor and strong phase at LHCb have been evaluated using the yield estimates of $B^- \to \widetilde{D^0}(K^\pm\pi^\mp)K^-$ and $B^- \to \widetilde{D^0}(K^-\pi^+\pi\pi)K^-$ decays in a data set corresponding to 2 fb^{-1} of data at a center of mass energy of 14TeV [17]. The yield of $B^- \to \widetilde{D^0}(K^-\pi^+\pi^0)K^-$ is assumed to be half of the $K\pi\pi\pi$ final state due to π^0 reconstruction, with the same level of background. Using only LHCb data the sensitivity to γ is 9.7°. If the CLEO-c constraints on coherence factors and strong phase differences are included the uncertainty on γ reduces to 7.5°. This estimate does not include the sensitivity from the $K_SK\pi$ channel.

In summary the quantum correlated measurements of the strong phase parameters in many D^0 decay channels from the CLEO-c experiment are presented here. Their use to improve measurement of the unitary angle γ has also been demonstrated. Further, similar measurements could also be pursued in other decay channels such as $D^0 \to \pi^+\pi^-\pi^0$ and $D^0 \to K_S\pi^+\pi^-\pi^0$.

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