γ/φ_3 Impact from CLEO-c Using CP-Tagged $D \rightarrow K_{S,L} \pi \pi$ Decays

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Charm 07
Path to Measuring $\gamma/\varphi_3$

- Use $B^\pm \rightarrow DK^\pm$ decays, followed by Dalitz plot analysis of $D \rightarrow K_s \pi^+ \pi^-$. 
- Developed by Giri, Grossman, Soffer, Zupan (GGSZ)[1] / Belle [2] -- exploit interference between $D^0$ and $\overline{D^0}$ channels

\[ N \sim |f_D|^2 + r_B^2 |\overline{f_D}|^2 + 2|f_D||\overline{f_D}| r_B [\cos(\delta_D)\sin(\delta_B - \gamma) - \sin(\delta_D)\cos(\delta_B - \gamma)] \]

5 parameters: $r_B, \delta_B, \gamma, \cos(\delta_D), \sin(\delta_D)$ Measure at CLEO-c

Current $\gamma/\varphi_3$ Measurements

**BaBar:** $92^\circ \pm 41^\circ$(stat) $\pm 11^\circ$(syst) $\pm 12^\circ$(model)

$(211 \text{ fb}^{-1})$

BaBar Collaboration, B. Aubert *et al.* hep-ex/0607104

**Belle:** $53^\circ \pm 17^\circ$(stat) $\pm 3^\circ$(syst) $\pm 9^\circ$(model)

$(357 \text{ fb}^{-1})$


Statistical uncertainty will go down to about $\sim 6^\circ$ with projected $2 \text{ ab}^{-1}$ ($r_B = 0.16$)

(LHCb projects $\sim 3^\circ$-$5^\circ$ uncertainty after 5 years… )

$10^\circ$ model uncertainty will dominate $\rightarrow$ CLEO-c can help lower this number
Correlated $D\bar{D}$ pairs ($C = -1$) are produced at CLEO-c. We tag the $K_S\pi\pi$ sample by reconstructing $D\rightarrow CP\pm$ eigentstates.

\[
D_{CP\pm} = \frac{D^0 + D^0}{\sqrt{2}}
\]

For $CP$-tagged Dalitz plots, number of events in Dalitz plot is

\[
M \sim |f_D|^2 + |\bar{f}_D|^2 \pm 2|f_D||\bar{f}_D| \cos(\delta_D)
\]

Divide the $(K_S\pi\pi)D$ Dalitz plot into bins, symmetric under interchange of $\pi^+ \leftrightarrow \pi^-$ interchange.

Define $\rightarrow c_i = \langle \cos(\delta_D) \rangle_i$

$c_i$ can be determined by counting $CP$-tagged bins
**Tagged $K_S\pi^+\pi^-$ Data from CLEO-c**

We use 398 pb$^{-1}$ of correlated $\Psi(3770)\rightarrow D\bar{D}$ decays.

Flavor-tagging modes: $D^0\rightarrow K\pi^+, K\pi^+\pi^0, K\pi^+\pi^-\pi^+$ (plus charge-conjugate)

<table>
<thead>
<tr>
<th>Event selection cuts</th>
<th>Only two-body $CP$ tags are used – provide clean signal with very little background</th>
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<tbody>
<tr>
<td>$</td>
<td>\Delta E</td>
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<td>$</td>
<td>K_S$ mass$</td>
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<td>M_{bc} - M_D</td>
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<tr>
<td>$M_{bc} \equiv \sqrt{(E_{beam})^2 - (p_D)^2}$</td>
<td>$K_S\eta$</td>
</tr>
</tbody>
</table>

Very low background

**Mode** | **Yield**
---|---
$K^+K^-$ | 61
$\pi^+\pi^-$ | 33
$K_S\pi^0$ | 108
$K_S\eta$ | 29

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**Flavor Tagged Data**

**CP+ Tagged Data**

**CP- Tagged Data**
What about $K_L \pi\pi$?

- Why not use $K_L \pi\pi$?

- Similar structure, opposite $CP$

- More than doubles overall statistics
Use same flavor and CP tag modes as \( K_s \pi \pi \), with same basic event selection.

\( K_L \pi \pi \) events are reconstructed using “missing mass” technique.

Require additional \( \pi^0, \eta \) veto.

Same two-body CP tags are used as \( K_s \pi \pi \):  

- CP+ tags:  
  - \( K^+ K^- \)
  - \( \pi^+ \pi^- \)

- CP- tags:  
  - \( K_S \pi^0 \)
  - \( K_S \eta \)

**Data**

- **CP+ Tagged Data**: \( m_K^2 = 0.247 \)
- **CP- Tagged Data**: 

**Mode** | **Yield**
---|---
\( K^+ K^- \) | 194 
\( \pi^+ \pi^- \) | 90 
\( K_S \pi^0 \) | 263 
\( K_S \eta \) | 21
Additionally, we use $K_L\pi^0$ as $CP$-even tag for $K_S\pi\pi$ mode

Similar event selection, with additional cuts:
- Require zero tracks
- $3\sigma$ cut on $\pi^0$ mass
- Additional $\pi^0$s vetoed

Reconstruct missing mass of $K_L$

Doubles number of $CP$-even tags

This mode contains highest background level $\sim 5\%$

Yield: 190 events

$m_{K^2}$ (GeV)$^2$
CP-tagged $K_S\pi^+\pi^-$ Dalitz Plots

$K_S\rho^0$ resonance enhanced in CP-odd Dalitz plot

CP-odd $K_S\rho^0$ resonance absent in CP-even Dalitz plot
Since CP of $K_L$ is opposite to $K_S$, $K_L\pi\pi$ Dalitz plot contains opposite CP structure to that of $K_S\pi\pi$.

$K_{L}\rho^0$ resonance enhanced in CP-even Dalitz plot.
The $K_{S,L}^{\pi\pi}$ Dalitz plots are not exactly equal.

There is a clear difference in the DCS $K^{*+}$ peak.

Appears constructively in $K_L^{\pi\pi}$, and destructively in $K_S^{\pi\pi}$.

Must take this into account before combining $c_i$ measurements for $K_L^{\pi\pi}$ and $K_S^{\pi\pi}$ samples.
Combining $c_i$ from $K_S\pi\pi$ and $K_L\pi\pi$

$K_S$ and $K_L$ can be expressed:

\[
A(D^0 \rightarrow K_S^0\pi^+\pi^-) = \frac{1}{\sqrt{2}}[A(D^0 \rightarrow \bar{K}^0\pi^+\pi^-) + A(D^0 \rightarrow K^0\pi^+\pi^-)]
\]

\[
A(D^0 \rightarrow K_L^0\pi^+\pi^-) = \frac{1}{\sqrt{2}}[A(D^0 \rightarrow \bar{K}^0\pi^+\pi^-) - A(D^0 \rightarrow K^0\pi^+\pi^-)]
\]

Define $r$ as the magnitude of DCS/CF ratio

$r$ is small (~ 0.06), but is the phase known?

\[
A(D^0 \rightarrow K_S\pi\pi) = K^*-(CF) + K^*(DCS) + f_0 + \rho_0 + \ldots
\]

\[
A(D^0 \rightarrow K_L\pi\pi) = K^*-(CF) - K^*(DCS) + (1-2re^{i\theta})f_0 + (1-2re^{i\theta})\rho_0 + \ldots
\]

Value of $c_i$ is in general different for $K_L\pi\pi$ and $K_S\pi\pi$, but can be related through U-spin symmetry

By varying each unknown phase and recalculating $c_i$, we can determine a measure of the systematic uncertainty for $K_L\pi\pi$
s_i can be determined from \( c_i \rightarrow s_i = \pm \sqrt{1 - c_i^2} \)

Provided fluctuations of phase difference \( \delta_D \) across bins are small

Variation of \( \delta_D \) phase can be minimized by choosing a more intelligent, model-inspired binning:

\[
2\pi(i - 1/2)/N < \Delta\delta_D(m^2_+, m^2_-) < 2\pi(i + 1/2)/N
\]

We use \( N = 8 \) bins in this analysis

Comparing $c_i$ for $K_{S,L}^{+\pi^-}$

- Obtain $K_L^{\pi\pi}$ model by changing sign of DCS terms → $K^{*+}(892), K^{*+}(1410)$…
- Calculate $c_i$ from $K_S^{\pi\pi}$ and $K_L^{\pi\pi}$ models
- Vary phase for each resonance, keep largest difference in $c_i$

- Systematic uncertainty from $K_L^{\pi\pi}$ is small compared to $c_i$ difference
- Good agreement of $c_i$ difference in data
Sensitivity to $c_i$

- We combine $K_L\pi\pi$, $K_S\pi\pi$ Dalitz plots into an improved overall measurement of $c_i$
- Scale statistical uncertainty up to full 750 pb$^{-1}$
- Combine with $K_L\pi\pi$ systematic uncertainty to determine overall expected sensitivity from CLEO-c measurement

Error bars represent expected uncertainty, as projected from current data sample
- $K_L\pi\pi, K_S\pi\pi$ samples can be combined

- Good sensitivity to $c_i$

- Total $D_{CP}$ expected to be $\sim 1,530$ for 750 pb$^{-1}$

- Combined BaBar/Belle (2 ab$^{-1}$) statistical uncertainty $\rightarrow \pm 6^o$

- CLEO-c can reduce model uncertainty from $\pm 10^o$ down to $\pm 4^o$ in $\gamma/\phi_3$ measurement
Following modes will also be used to measure $c_i$ and $s_i$

\[
\begin{align*}
K_S\pi\pi & \text{ vs. } K_S\pi\pi \ (\sim 480) \\
K_S\pi\pi & \text{ vs. } K_L\pi\pi \ (\sim 1240)
\end{align*}
\]
\{ Expected yields $(750 \text{ pb}^{-1})$ \}