Improving the Precision of $\gamma/\phi_3$ via CLEO-c Measurements

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Status of the Measurement of the CKM phase $\gamma$

- Of the three CKM phases, $\gamma$ is the least constrained.
- A precision measurement of $\gamma$ is essential in order to test the internal consistency of the CKM triangle.
- In addition, tree measurements of $\gamma$ compared to loop measurements may provide a first indication of New Physics in the flavor sector.
- The precision measurement of $\gamma$ is one of the most important measurements of LHCb and $e^+e^-$ flavor factories.

$\gamma : (76.8^{+30.4}_{-31.5})^\circ$

Fit from direct measurements only
(CKM Fitter, Summer 2007)

CKMfitter Group (J. Charles et al.),
Measuring the CKM phase $\gamma$ via $B \to D K$

The CKM phase $\gamma$ can be determined through the interference between the $b \to c$ and $b \to u$ transitions.

- Require the neutral D mesons to decay to the same final state $f(D)$.
- This method is theoretically clean.
- Success of this method requires that the D decay is well understood.

\[
\frac{\langle B^- \to \bar{D}^0 K^- \rangle}{\langle B^- \to D^0 K^- \rangle} = r_B e^{i(\delta_B - \gamma)}
\]

Color Suppressed

\[
r_B \equiv \left| \frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)} \right| \sim 0.1
\]
The role of CLEO-c

- CLEO-c analyses are vital for the purpose of CKM phase $\gamma$ extraction strategies via $B^{\pm} \to D_{\text{multi-body}}K^{\pm}$
- We present a first determination of the $D \to K\pi\pi\pi$ coherence factor, $R_{K3\pi}$ (and its associated global strong phase $\delta_{D^{K3\pi}}$)
  - Will significantly increase precision on $\gamma$ in future measurements
- CLEO-c has also measured the bin-averaged cosines ($c_{i}$) and sines ($s_{i}$) of $D \to K^{0}_{S}\pi\pi$ strong phase differences to allow a model-independent determination of $\gamma$ with $B^{\pm} \to D_{K^{0}_{S}\pi\pi} K^{\pm}$
  - Will reduce the largest systematic error for $\gamma$ via $B^{\pm} \to D_{K^{0}_{S}\pi\pi} K^{\pm}$
  - $c_{i}$ determined from CP-tagged decays
  - $c_{i}$ and $s_{i}$ determined from $K^{0}_{S}\pi\pi$-tagged decays
- CLEO-c measurement of the $D \to K\pi$ strong phase $\delta_{D^{K\pi}}$ also helps to determine $\gamma$ via $B^{\pm} \to D_{K\pi} K^{\pm}$ decays
Hermetic detector based at CESR (the Cornell Electron Storage Ring)

Operating at energies around $c\bar{c}$ threshold

We study $e^+e^- \rightarrow \psi(3770) \rightarrow D^0\bar{D}^0$ decays

- $C = -1$ for these decays at $\psi(3770)$ threshold
- Total integrated luminosity of this sample is 818 pb$^{-1}$

Quantum correlated (QC) states

- Example: Properly reconstructing one neutral $D$ decay to a CP eigenstate uniquely identifies the other $D$ decay to be of opposite CP

Double Tag

- We fully reconstruct the event for both neutral $D$ decays in our analyses

CP-Tagged

- Reconstruct other neutral $D$ to a CP eigenstate
The study of neutral D decays at CLEO-c is useful for measurements of the CKM phase $\gamma$ via $B^\pm \to D K^\pm$ decays

Atwood-Dunietz-Soni (ADS) Method uses $f(D) = K^+\pi^-$ (non-CP eigenstate)

The four rates for the different combinations of $B^\pm$ and neutral D decays to $K\pi$, together with those from D decays to CP eigenstates ($KK$ and $\pi\pi$), determine $\gamma$

A key measurement of LHCb and flavor factories

- 10° statistical precision with one year of LHCb running [LHCb-2008-011]

The ADS method can be extended to the mode $f(D) = K^+\pi^-\pi^+\pi^-$

However, we need to account for the resonant substructure

In principle, each point in phase space has a different strong phase associated with it
Using $D \to K\pi\pi\pi$ Decays at CLEO

- Atwood and Soni [Phys. Rev. D 68 (2003) 033003] showed how to modify the ADS formalism for the case of $K^+\pi^-\pi^+\pi^-$
- Introduce the **coherence parameter** $R_{K3\pi}$ which dilutes the interference term sensitive to $\gamma$

$$\Gamma(B^- \to (K^+\pi^-\pi^-\pi^+)_{D}K^-) \propto r_B^2 + (r_D^{K3\pi})^2 + 2r_B r_D^{K3\pi} R_{K3\pi} \cos(\delta_B + \delta_D^{K3\pi} - \gamma)$$

- $R_{K3\pi}$ then ranges between:
  - $0 = \text{incoherent (several significant resonant components)}$
  - $1 = \text{coherent (dominated by a single mode)}$

- **If** $R_{K3\pi}$ **is close to 0**, the rates still provide an extremely useful constraint on $r_B$.
  So, still a very informative measurement!

- **Determinations of** $R_{K3\pi}$ **and** $\delta_D^{K3\pi}$ **can be made at CLEO-c** from an analysis of double-tagged neutral D decays at threshold.

$$A(D^0 \to K^-\pi^+\pi^-\pi^+) \quad R_{K3\pi} e^{i\delta_D^{K3\pi}} \quad = \frac{\int A(s)\bar{A}(s)e^{i\delta(s)} ds}{\sqrt{\int |A(s)|^2 ds \int |\bar{A}(s)|^2 ds}}$$
Preliminary Results for $R_{K3\pi}$ at CLEO-c

1) $K^{\pm} \pi^\mp \pi^+ \pi^-$ vs. $CP$

![Diagram showing $\chi^2$/n.d.f. = 9.7/8]

$<R_{K3\pi}\cos(\delta_{K3\pi})> = -0.60 \pm 0.19 \pm 0.24$

2) $K^{\pm} \pi^\mp \pi^+ \pi^-$ vs. $K^{\pm} \pi^\mp \pi^+ \pi^-$

$(R_{K3\pi})^2 = -0.20 \pm 0.23 \pm 0.09$  

$(R_{K3\pi} < 0.22 \text{ at 1 sigma})$

3) $K^{\pm} \pi^\mp \pi^+ \pi^-$ vs. $K^{\pm} \pi^\mp$

$R_{K3\pi} \cos(\delta_{K\pi} - \delta_{K3\pi}) = 0.00 \pm 0.16 \pm 0.07$

- We use result (3) to constrain $R_{K3\pi}$ and $\delta_{K3\pi}$ using $\delta_{K\pi}$ from CLEO-c


CLEO-c Preliminary (818 pb$^{-1}$)

arXiv:0805.1722v1 (hep-ex)
Improving the Precision of $\gamma/\phi$ via CLEO-c Measurements

$\delta_{D^{K_3\pi}}$ vs. $R_{K_3\pi}$ Parameter Space Constraints

- We combine the results to make confidence plots for $R_{K_3\pi}$
- Low coherence is preferred
- Allows accurate determination of $r_B$ useful for all $B^{\pm} \to DK^{\pm}$ decays
- Improving the measurement of $r_B$ improves the measurements of $\gamma$ via ADS 2-body and Dalitz plot methods.
Example: Impact of CLEO-c Kππ at LHCb

These D→K3π measurements have been input to ADS simulation studies by LHCb

Estimated yields documented in LHCb-2006-066 and LHCb-2007-004

One nominal year of LHCb running: results see significant improvement with the addition of B→D(K3π)K and the CLEO-c constraints

- Added info from CLEO equivalent to ~doubling the LHCb data!
Using $D \rightarrow K_S\pi\pi$ Decays at CLEO

- $f(D) = K_S\pi\pi$ can be used as well
- Then a Dalitz plot analysis may be used to extract $\gamma$.
- Now, the interference depends on the $D^0, \overline{D^0}$ phase difference ($\delta_{x,y} - \delta_{y,x}$), as a function of position in the Dalitz plot.
- To date, this has been taken from results of uncorrelated Dalitz plot analyses, which suffer from a model dependence.
- **CLEO-c data has an essential role in the model-independent approach.**
Binned Analysis of $D \to K^0_{S\pi^+\pi^-}$ at CLEO-c

It can be shown that:

$$c_i = \frac{(M_i^+/S_+ - M_i^-/S_-) (K_i + K_{\bar{i}})}{(M_i^+/S_+ + M_i^-/S_-) 2\sqrt{K_i K_{\bar{i}}}}.$$ 

$s_+(s_-)$, number of single tags for CP even(odd) modes. $M_i^+(M_i^-)$, yields in each bin of Dalitz plot in CP even(odd) modes. $K_i(K_{\bar{i}})$, yields in each bin of Dalitz plot in flavor modes.

Instead of square bins, we use bins of some range in $\delta_D$

$$c_i = \frac{1}{\sqrt{T_i T_{\bar{i}}}} \int_{D_i} |A_D(x, y)||A_D(y, x)| \cos(\delta_{x, y} - \delta_{y, x}) dx dy$$

$$s_i = \frac{1}{\sqrt{T_i T_{\bar{i}}}} \int_{D_i} |A_D(x, y)||A_D(y, x)| \sin(\delta_{x, y} - \delta_{y, x}) dx dy$$

$T_i \equiv \int |A_D(x, y)|^2 dx dy$
Improving the Precision of $\gamma/\phi_3$ via CLEO-c Measurements

Preliminary CP tagged $K_{S}\pi^+\pi^-$ results

- Results for $c_i$ using 8 bins:

CLEO-c Preliminary (818 pb$^{-1}$)

http://beach2008.sc.edu/includes/documents/sessions/he.talk.pdf

- ~ 800 CP-tagged events

BABAR Collaboration, Arxiv:hep-ex/0607104
The CP-tagged sample of $K^0_S \pi^+ \pi^-$ can only give us values for $c_i$

Using a $K^0_S \pi^+ \pi^-$ vs. $K^0_S \pi^+ \pi^-$ sample, we can extract $c_i$ and $s_i$ simultaneously

$$M_{i,j} = \frac{1}{2N_D, D B_f^2} (K_i K_{\bar{j}} + K_j K_{\bar{i}} - 2\sqrt{K_i K_{\bar{j}} K_j K_{\bar{i}}} (c_i c_j + s_i s_j)).$$

Combine CP-tagged $K^0_S \pi^+ \pi^-$ and $K^0_S \pi^+ \pi^-$ vs. $K^0_S \pi^+ \pi^-$ samples: systematic uncertainty on $\gamma$ from $c_i, s_i$ expected to be $\sim 2^\circ$. Adding $K^0_L \pi^+ \pi^-$ statistics reduces this to $\sim 1^\circ$.

CLEO-c Preliminary (818 pb$^{-1}$)

http://beach2008.sc.edu/includes/documents/sessions/he.talk.pdf
Summary

- CLEO-c data is vital for the purpose of \( \gamma \) extraction strategies with \( B^\pm \rightarrow D_{\text{multi-body}}K^\pm \).
- A **first determination** of the \( D \rightarrow K\pi\pi\pi \) coherence factor, \( R_{K3\pi} \), has been made (and its associated global strong phase \( \delta_{D^{K3\pi}} \)).
  - Results already have a significant impact; further improvements to this result are foreseen with the addition of \( K_L \) CP modes in the selection.
  - Additional ADS modes are being studied (\( D \rightarrow K\pi\pi^0 \)).
- CLEO-c is also **measuring the average cosine and sine of** \( D \rightarrow K_0^{*}\pi\pi \) strong phase differences to allow a model-independent determination of \( \gamma \) with \( B^\pm \rightarrow D_{Ks\pi\pi} K^\pm \).
  - Further improvements to this result are foreseen with the addition of \( K_0^{*}\pi\pi \) candidates.
  - D decay-model systematic error of 6°-15° from currently available \( D \rightarrow K_0^{*}\pi\pi \) Dalitz plot analyses will be replaced with a residual D decay systematic error of 1°-2°!
Improving the Precision of $\phi_3$ via CLEO-c Measurements

Measuring $R_{K^3\pi}$ at CLEO-c

- Determinations of $R_{K^3\pi}$ and $\delta_D^{K^3\pi}$ can be made from analysis of double-tagged $D^0\overline{D^0}$ at CLEO-c.

- The coherent production of this state causes the double-tagged rates of $K\pi\pi\pi$ vs. $X$ to be altered in the following ways:

<table>
<thead>
<tr>
<th>Double Tag Rate</th>
<th>Sensitive To</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ vs. $K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$</td>
<td>$(R_{K^3\pi})^2$</td>
</tr>
<tr>
<td>$K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ vs. $CP$</td>
<td>$R_{K^3\pi}\cos(\delta^{K^3\pi})$</td>
</tr>
<tr>
<td>$K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ vs. $K^{\pm}\pi^{\mp}$</td>
<td>$R_{K^3\pi}\cos(\delta^{K\pi} - \delta^{K^3\pi})$</td>
</tr>
</tbody>
</table>

- We perform selections of these double-tags

- In addition, it is also necessary to perform selections of the opposite sign $K^\pm$ modes to determine normalisation factors
Improving the Precision of $\gamma/\phi_3$ via CLEO-c Measurements

Uncertainty due to $K^0\pi\pi$ decay

Bondar, et al. says uncertainty due to $K^0\pi\pi \sim 5^\circ$

<table>
<thead>
<tr>
<th>Binning</th>
<th>Q</th>
<th>$B$-stat. err.</th>
<th>$D_{CP}$-stat. err.</th>
<th>$(K_S^0\pi^+\pi^-)^2$-stat. err.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N = 8$</td>
<td>0.79</td>
<td>0.027</td>
<td>0.037</td>
<td>0.004</td>
</tr>
</tbody>
</table>

$x_\pm = r_B \cos(\delta_B \pm \gamma)$

$y_\pm = r_B \sin(\delta_B \pm \gamma)$

$5^\circ$ uncertainty assumed $\sigma_x = \sigma_y = 0.010$

Model-independent studies have been performed for LHCb with 8 $\Delta\delta_d$ bins (LHCb-2007-141). We use the same code to evaluate $\gamma$ systematic uncertainties from the measured $c_i$ and $s_i$.

These uncertainties have less impact (using Belle’s central values)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>RMS toy</th>
<th>RMS B&amp;P (scaled to actual yields)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_i$</td>
<td>0.005</td>
<td>0.004</td>
</tr>
<tr>
<td>$y_i$</td>
<td>0.005</td>
<td>0.007</td>
</tr>
<tr>
<td>$x_-$</td>
<td>0.005</td>
<td>0.004</td>
</tr>
<tr>
<td>$y_-$</td>
<td>0.014</td>
<td>0.007</td>
</tr>
</tbody>
</table>

arXiv:0803.3375 [hep-ex]