Results on CP violation in the charm sector

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Motivation
Data and methodology
Indirect CP violation
CP violation in decays
Summary and outlook

* Replacement for N.K. Nisar

Motivation

- CP violation in charm decays provides an interesting test bed for new physics as the standard model (SM) expects a small asymmetry owing to
  - Large GIM/CKM suppression
  - Lack of a large hierarchy in the down-type quark masses

- Typical SM value of the order of $10^{-3}$ most promising candidates to study are singly Cabibbo-suppressed (SCS) decays

- While talking about percentage effect, one needs a good control on the SM predictions, something that is in general lacking in this sector due to long-distance effects

  An example of “short vs. long”

- Further, with $D^0$-$\bar{D}^0$ mixing being firmly established, could there be any CPV in the mixing or due to interference between mixing and decay?
Current expectation for direct CP violation

\[ A_{\Gamma}^f \equiv \frac{\tau(D^0 \to f) - \tau(D^0 \to f)}{\tau(D^0 \to f) + \tau(D^0 \to f)} \approx -a_{C_P}^{\text{ind}} \]

\[ A_{C_P}^f \equiv \frac{\Gamma(D^0 \to f) - \Gamma(D^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(D^0 \to f)} \]

\[ \Delta A_{C_P} \equiv A_{C_P}(K^+ K^-) - A_{C_P}(\pi^+ \pi^-) = \left( 1 + y \cos \phi \frac{\langle t \rangle}{\tau} \right) \Delta a_{C_P}^{\text{dir}} + \left( \frac{\Delta \langle t \rangle}{\tau} \right) a_{C_P}^{\text{ind}} \]

\[ x \equiv \Delta m/\bar{\Gamma}, \ y \equiv \Delta \Gamma/2\bar{\Gamma} \text{ and } \phi \equiv \text{Arg}(q/p), \text{ where } \Delta m \text{ and } \Delta \Gamma \text{ are the mass and width difference between two D-meson mass eigenstates, } \bar{\Gamma} \text{ is their average width and } (p, q) \text{ are the two complex coefficients that relate mass with flavor eigenstates} \]

\[ a_{C_P}^{\text{ind}} = (\pm 0.015 \pm 0.052)\% \]

\[ \Delta a_{C_P}^{\text{dir}} = (-0.333 \pm 0.120)\% \]

- No CPV (0,0) point: \[ \Delta \chi^2 = 7.8, \text{ CL = 2\%} \] (excluded at 2\sigma)
Dataset and Methodology

Charge of the slow pion in the $D^*$ decay ($D^{*+} \rightarrow D^0\pi^+$ or $D^{*-} \rightarrow \bar{D}^0\pi^-$) can tell us flavor of the $D$ meson.

For a CP study, we need to keep in mind a) $D^*$ production and b) the kinematics of the accompanying charged pion.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>$\mathcal{L}_{\text{int}}$ (fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Upsilon(1S)$</td>
<td>6</td>
</tr>
<tr>
<td>$\Upsilon(2S)$</td>
<td>25</td>
</tr>
<tr>
<td>$\Upsilon(3S)$</td>
<td>3</td>
</tr>
<tr>
<td>$\Upsilon(4S)$</td>
<td>711</td>
</tr>
<tr>
<td>$\Upsilon(5S)$</td>
<td>121</td>
</tr>
<tr>
<td>Off-res.</td>
<td>100</td>
</tr>
<tr>
<td>Total</td>
<td>966</td>
</tr>
</tbody>
</table>
Study of the wrong-sign decay $D^0 \rightarrow K^{+}\pi^{-}\pi^{+}\pi^{-}$

- Contributions from both a doubly-Cabibbo suppressed (DCS) decay and $D^0$-$\bar{D}^0$ mixing followed by a Cabibbo favored (CF) decay

- Measurement performed relative to the CF decay $D^0 \rightarrow K^{-}\pi^{+}\pi^{+}\pi^{-}$

\[
R_{WS} = \frac{\Gamma(D^0 \rightarrow K^{+}\pi^{-}\pi^{+}\pi^{-})}{\Gamma(D^0 \rightarrow K^{-}\pi^{+}\pi^{+}\pi^{-})} = R_D + \alpha y' \sqrt{R_D} + \frac{1}{2}(x^2 + y^2)
\]

$R_D$: ratio of the DCS to CF decay amplitude squared

$\alpha$: coherence factor that accounts for strong phase variation over the phase space ($0 \leq \alpha \leq 1$)

$y' = y \cos \delta - x \sin \delta$ where $\delta$ is strong-phase difference between DCS and CF decays

- A 2D binned maximum likelihood fit to the $M_{K^3\pi}$ and $Q = M_{D^{*}\pi} - M_D$ distributions

\[
R_{WS} = (0.324 \pm 0.008 \pm 0.007)\%
\]

\[
\mathcal{B}_{WS} = (2.61 \pm 0.06^{+0.09}_{-0.08}) \times 10^{-4}
\]

With $\alpha$ and $\delta$ from CLEOc:

\[
R_D = (0.327^{+0.019}_{-0.016})\%
\]
We measure here: \[ A_{\text{rec}}^{K_S K^+} = A_{CP}^{K_S K^+} + A_{FB} + A_{\varepsilon}^{K^+} + A_{K^0} \]

Worry about the detection efficiency asymmetry for charged kaons and the asymmetry owing to difference in interactions of $K^0$ and $\bar{K}^0$ inside detector.

Obtain the charged kaon detection asymmetry using the self-tagged decay channels $D^0 \rightarrow K^- \pi^+$ ($\bar{D}^0 \rightarrow K^+ \pi^-$) and $D_s^+ \rightarrow \phi \pi^+$ ($D_s^- \rightarrow \phi \pi^-$)

\[ A^{K\pi} = A_{FB} + A_{\varepsilon}^{K^-} + A_{\varepsilon}^{\pi^+} \]
\[ A^{\phi \pi} = A_{FB} + A_{\varepsilon}^{\pi^+} \]

Take symmetric and antisymmetric combinations in $\cos \theta^*$ to calculate $A_{CP}$ and $A_{FB}$ respectively ($f \equiv K_S K^+$)

\[ A_{CP}^f = \frac{1}{2}[A_{\text{rec}}^{f, \text{cor}}(\cos \theta^*) + A_{\text{rec}}^{f, \text{cor}}(-\cos \theta^*)] \]
\[ A_{FB}^f = \frac{1}{2}[A_{\text{rec}}^{f, \text{cor}}(\cos \theta^*) - A_{\text{rec}}^{f, \text{cor}}(-\cos \theta^*)] \]

After considering CPV due to $K^0-\bar{K}^0$ mixing

\[ A_{CP} = (+0.08 \pm 0.28 \pm 0.14)^\% \]
Search for CP violation in $D^+ \rightarrow K_S \pi^+$

- We measure here: $A_{K_S \pi^+}^{rec} = A_{K_S \pi^+}^{CP} + A_{FB} + A_\varepsilon + A_{K^0}$

  Complication arises due to difference in interactions of $K^0$ and $\bar{K}^0$ inside the detector

- Obtain the charged pion detection asymmetry using $D \rightarrow K\pi\pi$ decays

  $A(D^+ \rightarrow K^- \pi^+ \pi^+) = A_{FB} + A_\varepsilon^{K^- \pi^+} + A_\pi^+$
  $A(D^0 \rightarrow K^- \pi^+ \pi^0) = A_{FB} + A_\varepsilon^{K^- \pi^+}$

- Calculate $A_{CP}$ and $A_{FB}$ from the symmetric and antisymmetric combinations in $\cos \theta^*$ ($f \equiv K_S \pi^+$)

  $A_{CP}^f = \frac{1}{2}[A_{rec}^{f,cor}(\cos \theta^*) + A_{rec}^{f,cor}(-\cos \theta^*)]$
  $A_{FB}^f = \frac{1}{2}[A_{rec}^{f,cor}(\cos \theta^*) - A_{rec}^{f,cor}(-\cos \theta^*)]$

- After considering CPV due to $K^0$-$\bar{K}^0$ mixing

  $A_{CP} = (-0.024 \pm 0.094 \pm 0.067)\%$
Mixing and CPV results from $D^0 \rightarrow K_S \pi^+ \pi^-$

- Time-dependent fit to the Dalitz plot (shown below together with one of its projections)

$$\chi^2/\text{ndf} = 1.207$$

<table>
<thead>
<tr>
<th>Fit case</th>
<th>Parameter</th>
<th>Preliminary (921 fb$^{-1}$)</th>
<th>PRL 99, 131803 (2007)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assuming</td>
<td>$x(%)$</td>
<td>$0.56 \pm 0.19^{+0.03}<em>{-0.09}{}^{+0.06}</em>{-0.09}$</td>
<td>$0.80 \pm 0.29^{+0.09}<em>{-0.07}{}^{+0.10}</em>{-0.14}$</td>
</tr>
<tr>
<td>no CPV</td>
<td>$y(%)$</td>
<td>$0.30 \pm 0.15^{+0.04}<em>{-0.05}{}^{+0.03}</em>{-0.06}$</td>
<td>$0.33 \pm 0.24^{+0.08}<em>{-0.12}{}^{+0.06}</em>{-0.08}$</td>
</tr>
<tr>
<td>No DCPV</td>
<td>$</td>
<td>q/p</td>
<td>$</td>
</tr>
<tr>
<td></td>
<td>$\phi(\degree)$</td>
<td>$-6 \pm 11^{+3}<em>{-3}{}^{+3}</em>{-4}$</td>
<td>$-14^{+16}<em>{-18}{}^{+5}</em>{-3}{}^{+2}_{-4}$</td>
</tr>
</tbody>
</table>

No DCPV $\Rightarrow A_f = \overline{A}_f$ when $f$ is a self-conjugate mode such as $K_S \pi^+ \pi^-$

- 2.5$\sigma$ away from the no-mixing hypothesis
- No evidence for indirect CP violation
Search for CP violation in $D^0 \rightarrow \pi^0\pi^0$

- Large CP asymmetries expected in this decay for NP scenarios having large penguin contributions and large chromo-magnetic dipole operators

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Large penguins</th>
<th>Large c.d.o.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \rightarrow \pi^+\pi^-$</td>
<td>3.96 (4.40)</td>
<td>5.18 (3.70)</td>
</tr>
<tr>
<td>$D^0 \rightarrow \pi^0\pi^0$</td>
<td>0.93 (1.01)</td>
<td>8.63 (6.19)</td>
</tr>
</tbody>
</table>

- Large penguin contribution is predicted for $D^0 \rightarrow \pi^0\pi^0$

- Some NP models e.g., triplet model, predict a sizeable CP asymmetry in $D^0 \rightarrow \pi^0\pi^0$

- Need a precise measurement that can only be done at the $e^+e^-$ flavor factories
Based on a 13.7 fb\(^{-1}\) data, CLEO has measured \(A_{CP} = ( +0.1 \pm 4.8 \)\)%

Using 470.5 fb\(^{-1}\) of data BABAR found the branching fraction \(BF(D^0 \rightarrow \pi^0 \pi^0) = \left[8.4 \pm 0.1\text{ (stat.)} \pm 0.4\text{ (syst.)} \pm 0.3\text{ (norm.)}\right] \times 10^{-4}\), no attempt is made for \(A_{CP}\)
Signal component is parametrized as a sum of Gaussian and an asymmetric Gaussian function with common mean, while the background as a threshold function $f(x) = (x - m_0)^\alpha \exp[-\beta(x - m_0)]$

- Expected statistical error on $A_{CP}$ is 0.64% (an order of magnitude better than CLEO)
Summary and Outlook

- presented a sample of results related to CP violation in charm from

1) Measured the rate for “wrong-sign” decay $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$ relative to the “right-sign” decay $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$ decays

$$R_{WS} = (0.324 \pm 0.008 \pm 0.007)\%$$
$$B_{WS} = (2.61 \pm 0.06^{+0.09}_{-0.08}) \times 10^{-4}$$

2) Searched for CP violation in $D^+ \rightarrow K_S K^+$ consistent with no CPV

3) Story is same for $D^+ \rightarrow K_S \pi^+$ as well as $D^0 \rightarrow K_S \pi^+ \pi^-$ (indirect CP violation)

4) Conducting the most precise measurement of CP violation in the decay $D^0 \rightarrow \pi^0\pi^0$, which can be only done at $e^+e^-$ flavor factories

- Many other related studies are ongoing with the data recorded with Belle

- With being on track, the future looks bright for this exciting area in flavor physics
Bonus slides
Systematic uncertainties in $D^0 \rightarrow K_S \pi^+ \pi^-$

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta x \times 10^{-4}$</th>
<th>$\Delta y \times 10^{-4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best candidate selection</td>
<td>+1.05</td>
<td>+1.87</td>
</tr>
<tr>
<td>Signal and background yields</td>
<td>±0.30</td>
<td>±0.27</td>
</tr>
<tr>
<td>Wrong tagged event fraction</td>
<td>−0.67</td>
<td>−0.45</td>
</tr>
<tr>
<td>Time resolution of signal</td>
<td>−1.39</td>
<td>−0.92</td>
</tr>
<tr>
<td>Efficiency</td>
<td>−1.13</td>
<td>−2.09</td>
</tr>
<tr>
<td>Combinatorial PDF</td>
<td>+1.90</td>
<td>+2.28</td>
</tr>
<tr>
<td></td>
<td>−4.82</td>
<td>−3.88</td>
</tr>
<tr>
<td>$K^*(892)$ DCS/CF fraction</td>
<td>−7.28</td>
<td>+2.29</td>
</tr>
<tr>
<td>$K_2^*(1430)$ DCS/CF fraction</td>
<td>+1.71</td>
<td>−0.67</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>+2.78</strong></td>
<td><strong>+3.74</strong></td>
</tr>
<tr>
<td></td>
<td><strong>−8.94</strong></td>
<td><strong>−4.58</strong></td>
</tr>
</tbody>
</table>

- Improved systematic uncertainties together with statistical with respect to the previous publication

**Belle, PRL 99, 131803 (2007)**