Searches for CP violation in charm decays

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CP violation in charm

- 3 types of CPV
  - In decay: amplitudes for a process and its conjugate differ (Covered here)
  - In mixing: rate of $D^0 \rightarrow \bar{D}^0$ and $\bar{D}^0 \rightarrow D^0$ differ (Covered yesterday Chris Thomas)
  - In interference between mixing and decay diagrams
- Direct CPV negligible in Cabibbo-favoured modes (SM tree dominates)
- Direct CPV in SCS charm decays can be incorporated in SM
  - generally up to $\sim O(10^{-3})$ although $\sim O(10^{-2})$ cannot be ruled out
  - Can be significantly enhanced by NP
- Discovery of CPV in charm would be very exciting with or without NP

Looking for direct CPV

- Need at least two contributing amplitudes with different strong and weak phases to get CPV
- Singly-Cabibbo-suppressed modes with gluonic penguin diagrams very promising
  - Several classes of NP can contribute
  - ... but non-negligible SM contribution

CPV from tree-penguin interference:

\[ A_f = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})} = 2r_f \sin \phi_f \sin \delta_f \]

\( r_f \) is the ratio of penguin/tree amplitudes

\( \phi_f \) is the weak phase difference

\( \delta_f \) is the strong phase difference

Direct CP violation searches at LHCb

- **Global** asymmetries (two-body modes)
  
  \[ A_{CP} = \frac{\Gamma(D \rightarrow f) - \Gamma(\bar{D} \rightarrow \bar{f})}{\Gamma(D \rightarrow f) + \Gamma(\bar{D} \rightarrow \bar{f})} \]

  - \( \Delta A_{CP} : \Delta A_{CP}(D^0 \rightarrow KK, D^0 \rightarrow \pi\pi) \)
  
  - \( A_{CP} : D^+ \rightarrow \Phi\pi^+, D^+ \rightarrow K_S^0\pi^+, D^0 \rightarrow K^+K^-, \text{ and } D^0 \rightarrow \pi^+\pi^- \) (ongoing)

- **Local** asymmetries (multi-body modes)

  - **Model-independent:**
    
    - **Binned:** \( D^+ \rightarrow \pi^+\pi^+\pi^-, D^0 \rightarrow \pi^+\pi^+\pi^-\pi^-, D^0 \rightarrow K^+K^-\pi^-\pi^+, D^+ \rightarrow K^-K^+\pi^+ \)
    
    - **Unbinned:** \( D^+ \rightarrow \pi^+\pi^+\pi^- \)

  - **Triple products**

    - **T-odd moments:** \( D^0 \rightarrow K^+K^-\pi^-\pi^- \) (BaBar \( \sim \) 47k events)

  - **Model-dependent**

    - **Amplitude analysis:** \( D^0 \rightarrow K^+K^-\pi^-\pi^+ \) (CLEO \( \sim \) 3k events)

LHCb result
Global
ΔACP Tagging

LHCb uses two methods to tag the D⁰ flavour

**D* decays (Prompt)**
Use slow pion from D* decays to tag D flavour \( D^{*+} \rightarrow D^0 \pi^+ \) or 
\( D^{*-} \rightarrow \bar{D}^0 \pi^- \)

**Semileptonic B decay (Secondary)**
Use muon charge to tag D flavour
\( B \rightarrow \bar{D}^0 \mu^+ \nu \mu X \) or
\( B \rightarrow D^0 \mu^- \nu \mu X \)
\[ \Delta A_{CP} \]

\[ A_{RAW}(f) \simeq A_{CP}(f) + A_D(f) + A_D(\pi_s^+) + A_p(D^{*+}) \]

want  f’s detection asymmetry  \( \pi_s \) detection asymmetry  Production asymmetry
$\Delta A_{\text{CP}}$ from $D^*$ decays

$$A_{\text{RAW}}(f) \simeq A_{\text{CP}}(f) + A_{\text{D}}(f) + A_D(\pi^+_s) + A_p(D^{*+})$$

want

- $f$'s detection asymmetry
- $\pi_s$ detection asymmetry
- Production asymmetry

Zero for self-conjugate final states $(K^+K^-/\pi^+\pi^-)$
$\Delta A_{CP}$ from $D^*$ decays

$$A_{RAW}(f) \simeq A_{CP}(f) + A_D(f) + A_D(\pi^+) + A_p(D^{*+})$$

$\pi_s$ detection asymmetry

Production asymmetry

Taking $A_{RAW}(f) - A_{RAW}(f')$ the production and slow pion detection asymmetries will cancel to first order

$$A_{RAW}(K^-K^+) - A_{RAW}(\pi^-\pi^+) = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) \equiv \Delta A_{CP}$$
$\Delta A_{CP}$ from semileptonic B decays

$$A_{RAW}(f) = A_{CP}(f) + A_D(\mu^+) + A_p(B)$$

Detection and production asymmetries **independent** from $D^*$ analysis

Taking $A_{RAW}(f) - A_{RAW}(f')$ the production and muon detection asymmetries will cancel if kinematics of muon and B meson are the same for both $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$

$$A_{RAW}(K^-K^+) - A_{RAW}(\pi^-\pi^+) = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) \equiv \Delta A_{CP}$$
In order to obtain the same kinematic differences in the momentum distributions. The background has been subtracted using the sPlot method. In order to obtain the same kinematic differences in the momentum distributions. The background has been statistically subtracted using the sPlot method. In order to obtain the same kinematic differences in the momentum distributions. The background has been statistically subtracted using the sPlot method.

Since the detection and production asymmetry may have a kinematic dependence, the cancellation in Eq. (4) is only valid if the kinematic distributions of the muon and the trigger and selection requirements are identical. Nevertheless, due to the different hadron and selection requirements the kinematic distributions for the two decay modes are different for the two decay modes. Therefore, detection and production asymmetries may not cancel completely in the calculation of the asymmetry fit is overlaid, showing the contribution.

Figure 1:

\[ \Delta A_{\text{CP}} \]

**Prompt**

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<th>( D^0 \to K K )</th>
<th>( D^0 \to \pi \pi )</th>
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<td><strong>LHCb Preliminary</strong></td>
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<td>Events / (0.1 MeV/c^2)</td>
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<td>2000</td>
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<tr>
<td>10</td>
<td>1000</td>
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<tr>
<td>( \delta m ) (MeV/c^2)</td>
<td>( \delta m ) (MeV/c^2)</td>
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**Semileptonic**

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<tr>
<td>( M_{KK} ) [MeV/c^2]</td>
<td>( M_{\pi\pi} ) [MeV/c^2]</td>
</tr>
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LHCb-CONF-2013-003

\[ \Delta A_{CP} \]

Where we were last year

![Graph showing \( \Delta a_{CP} \) vs. \( a_{CP}^{ind} \) with various data points and error bands.]
Where we are today

$\Delta A_{CP} = (-0.34 \pm 0.15 \pm 0.10)\%$

$\Delta A_{CP} = (0.49 \pm 0.30 \pm 0.14)\%$

$A_{\Gamma} \, \pi\pi$ (see yesterdays talks)

$A_{\Gamma} \, KK$ (see yesterdays talks)

Semil $\Delta A_{CP}$

Prompt $\Delta A_{CP}$

CDF $\Delta A_{CP}$

$\Delta A_{CP} = +0.015 \pm 0.052\%$

$\Delta A_{CP} = -0.333 \pm 0.120\%$
A\textsubscript{CP}

- Work is ongoing to separate A\textsubscript{CP}(D\textsubscript{0} \rightarrow KK) and A\textsubscript{CP}(D\textsubscript{0} \rightarrow \pi\pi)

- Need to separate real CP asymmetry from nuisance asymmetries:
  - Production asymmetry of D vs \bar{D}
  - Efficiency asymmetry of f vs \bar{f}

- Work on isolating production and efficiency asymmetries using control modes

- D\textsubscript{0} \rightarrow K\textsubscript{s}^0K\textsubscript{s}^0
  - Only existing measurement CLEO A\textsubscript{CP} = (-23 \pm 19) \%
  - Work in progress

- D^+ \rightarrow \phi\pi^+ and D_{s}^+ \rightarrow K\textsubscript{s}^0\pi^+
CP violation in $D^+ \rightarrow \phi \pi^+$ and $D_{s}^+ \rightarrow K_{s}^0 \pi^+$

- Define $A_{CP}$ for $D^+ \rightarrow \phi \pi^+$

$$A_{CP}(D^+ \rightarrow \phi \pi^+) = A_{\text{raw}}(D^+ \rightarrow \phi \pi^+) - A_{\text{raw}}(D^+ \rightarrow K_{s}^0 \pi^+) + A_{CP}(K^0/\bar{K}^0)$$
CP violation in $D^+ \rightarrow \phi \pi^+$ and $D_{s}^+ \rightarrow K_S^0\pi^+$

- Define $A_{CP}$ for $D^+ \rightarrow \phi \pi^+$

$$A_{CP}(D^+ \rightarrow \phi \pi^+) = A_{\text{raw}}(D^+ \rightarrow \phi \pi^+) - A_{\text{raw}}(D^+ \rightarrow K_S^0\pi^+) + A_{CP}(K^0/\bar{K}^0)$$

$$A_{\text{raw}} = \frac{N_{D^+} - N_{D^-}}{N_{D^+} + N_{D^-}}$$
CP violation in $D^+ \rightarrow \phi\pi^+$ and $D_{s}^+ \rightarrow K_{S}^0\pi^+$

- Define $A_{CP}$ for $D^+ \rightarrow \phi\pi^+$

$$A_{CP}(D^+ \rightarrow \phi\pi^+) = A_{raw}(D^+ \rightarrow \phi\pi^+) - A_{raw}(D^+ \rightarrow K_S^0\pi^+) + A_{CP}(K^0/\bar{K}^0)$$

$A_{raw} = \frac{N_{D^+} - N_{D^-}}{N_{D^+} + N_{D^-}}$

Control channel where CPV is negligible

Cancels detection/production asymmetries
CP violation in $D^+ \to \phi \pi^+$ and $Ds^+ \to K_S^0 \pi^+$

- Define $A_{CP}$ for $D^+ \to \phi \pi^+$

$$A_{CP}(D^+ \to \phi \pi^+) = A_{raw}(D^+ \to \phi \pi^+) - A_{raw}(D^+ \to K_S^0 \pi^+) + A_{CP}(K^0/\bar{K}^0)$$

$A_{raw} = \frac{N_{D^+} - N_{D^-}}{N_{D^+} + N_{D^-}}$

- Control channel where CPV is negligible

- Correction due to CPV in neutral Kaon system

Cancels detection/production asymmetries
CP violation in $D^+ \rightarrow \phi\pi^+$ and $D_{s^+} \rightarrow K_S^0\pi^+$

- Define $A_{CP}$ for $D^+ \rightarrow \phi\pi^+$

\[
A_{CP}(D^+ \rightarrow \phi\pi^+) = A_{raw}(D^+ \rightarrow \phi\pi^+) - A_{raw}(D^+ \rightarrow K_S^0\pi^+) + A_{CP}(K^0/\bar{K}^0)
\]

- Control channel where CPV is negligible

- Also for $D_{s^+} \rightarrow K_S^0\pi^+$

\[
A_{CP}(D_{s^+} \rightarrow K_S^0\pi^+) = A_{raw}(D_{s^+} \rightarrow K_S^0\pi^+) + A_{CP}(K^0/\bar{K}^0) - A_{raw}(D_{s^+} \rightarrow \phi\pi^+)
\]

- No mixing in $D^+$ - any CPV signal = direct CPV
CP violation in $D^+ \rightarrow \phi\pi^+$ and $D_s^+ \rightarrow K_S^0\pi^+$

- Very low background levels
  
  $1.6M \; D^+ \rightarrow \phi\pi^+ \; 1.1M \; D^+ \rightarrow K_S^0\pi^+$
  
  $26K \; D_s^+ \rightarrow K_S^0\pi^+ \; 3.6M \; D_s^+ \rightarrow \phi\pi^+$

JHEP 1306 (2013) 112
1.0fb$^{-1}$ collected during 2011

LHCb
CP violation in $D^+ \to \phi \pi^+$ and $D_{s}^+ \to K_S^0 \pi^+$

- Very low background levels
  - $1.6 \text{M} \ D^+ \to \phi \pi^+$
  - $1.1 \text{M} \ D^+ \to K_S^0 \pi^+$
  - $2.6 \text{M} \ D_{s}^+ \to K_S^0 \pi^+$
  - $3.6 \text{M} \ D_{s}^+ \to \phi \pi^+$

- No evidence of CPV observed
  - $A_{\text{CP}}(D^+ \to \phi \pi^+) = (-0.04 \pm 0.14 \pm 0.14)\%$
  - $A_{\text{CP}}(D_{s}^+ \to K_S^0 \pi^+) = (+0.61 \pm 0.83 \pm 0.14)\%$

JHEP 1306 (2013) 112
1.0 fb$^{-1}$ collected during 2011
Going local
CP violation in $D^+ \rightarrow \phi \pi^+$ and $D_s^+ \rightarrow K_S^0 \pi^+$

- Split up phase space across $\Phi$ resonance into 4 bins
  - minimise the strong phase difference across each bin
  - can improve sensitivity to certain CPV
- Define a third variable

$$A_{CP|S} = \frac{1}{2} (A^A_{raw} + A^C_{raw} - A^B_{raw} - A^D_{raw})$$

$$A_{CP|S}(D^+ \rightarrow \phi \pi^+) = (-0.18 \pm 0.17 \pm 0.18)\%,$$
Local CP searches

• Mainly focused around the binned technique
  • Split the phase space into independent volumes. For each volume, define
    
    \[ S_{CP}^i = \frac{N_i(D^0) - \alpha N_i(D^0)}{\sqrt{\alpha \left( \sigma_{D^0}^2 + \sigma_{\bar{D}^0}^2 \right)}} \]
    \[ \alpha = \frac{\sum_i N_i(D^0)}{\sum_i N_i(D^0)} \]
  
  • The significance of a CP asymmetry in bin i, correcting for global asymmetry with \( \alpha \)
    
    \[ \chi^2 = \sum_i (S_{CP}^i)^2 \]
  
  • Chi2 and p-value calculated with ndof = number of bins - 1 (due to constraint from \( \alpha \))

• This method is applied to
  • three-body (2D phase space)
    • \( D^+ \to \pi^- \pi^+ \pi^+ \) decays (which also uses an unbinned technique)
    • control channel \( D_s^+ \to \pi^- \pi^+ \pi^+ \)
  • four-body (5D phase space)
    • \( D^0 \to \pi^- \pi^+ \pi^- \pi^+ \) and \( D^0 \to K^- K^+ \pi^- \pi^+ \) decays
    • control channel CF \( D^0 \to K^- \pi^+ \pi^- \pi^+ \)
$D^0 \rightarrow \pi^- \pi^+ \pi^- \pi^+$ and $D^0 \rightarrow K^- K^+ \pi^- \pi^+$

- $D^0 \rightarrow K^- K^+ \pi^- \pi^+$ 57,000 signal events
- $D^0 \rightarrow \pi^- \pi^+ \pi^- \pi^+$ 330,000 signal events

- S-weight these distributions to extract the signal phase space distribution
$D^0 \rightarrow \pi^- \pi^+ \pi^+ \pi^-$ and $D^0 \rightarrow K^- K^+ \pi^- \pi^+$

$LHCb$ 

$D^0 \rightarrow K^+ K^- 2 \pi^\pm 3 \pi^\mp 4$

$D^0 \rightarrow K^- K^+ 2 \pi^- 3 \pi^+ 4$

$LHCb$ 

$D^0 \rightarrow \pi^- 1 \pi^+ 2 \pi^+ 3 \pi^- 4$

$D^0 \rightarrow \pi^+ 1 \pi^- 2 \pi^- 3 \pi^+ 4$

$LHCb$
Simulation

- Introduce CPV in the amplitude model of the D decay

![Simulation graphs](image)

- Sensitivity a phase difference of $O(10^0)$ or a magnitude difference of $O(10\%)$
  - between $D^0 \rightarrow \phi \rho^0$ and $\overline{D}^0 \rightarrow \phi \rho^0$ decays for the $D^0 \rightarrow K^- K^+ \pi^- \pi^+$ mode
  - between $D^0 \rightarrow a_1(1260)^+ \pi^-$ and $\overline{D}^0 \rightarrow a_1(1260)^- \pi^+$ decays for the $D^0 \rightarrow \pi^- \pi^+ \pi^+ \pi^-$ mode.
Results

- p-value under no CPV hypothesis
  - 80.0% for CF $K^-\pi^+\pi^-\pi^+$
  - Control channel (2.9mil signal events)
  - 9.1% for $K^-K^+\pi^-\pi^+$
  - 41% for $\pi^-\pi^+\pi^-\pi^+$

- In no bin is there a CP asymmetry greater than
  - 6.5% for $K^-K^+\pi^-\pi^+$ (32 bins each with ~1800 decays)
  - 5.5% for $\pi^-\pi^+\pi^-\pi^+$ (128 bins each with ~2500 decays)
$D^0 \to \pi^-\pi^+\pi^-\pi^+$ and $D^0 \to K^-K^+\pi^-\pi^+$

- Current search uses 1.0 fb$^{-1}$
  - 2011+2012 have $\sim$250,000 $K^-K^+\pi^-\pi^+$ and $\sim$1.4mil $\pi^-\pi^+\pi^-\pi^+$ signal decays (from $D^*$ decays)

Possibilities with this data

- Measure T-odd moments in $K^-K^+\pi^-\pi^+$ (BarBar $\sim$47k events)
- Can carry out binned analysis
  - Possibly bin in lifetime
- $\Delta A_{CP} = A_{CP}(K^-K^+\pi^-\pi^+) - A_{CP}(\pi^-\pi^+\pi^-\pi^+)$
  or something similar to make use of the correlations between 2 modes
T-odd moments

- Define the following triple products
  \[ C_T \equiv \mathbf{p}_{K^+} \cdot (\mathbf{p}_{\pi^+} \times \mathbf{p}_{\pi^-}) \]
  \[ \overline{C}_T \equiv \mathbf{p}_{K^-} \cdot (\mathbf{p}_{\pi^-} \times \mathbf{p}_{\pi^+}) \]

- The following asymmetries are odd under $T$ transformation
  \[ A_{CT} = \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)} \]
  \[ \overline{A}_{CT} = \frac{\Gamma(-\overline{C}_T > 0) - \Gamma(-\overline{C}_T < 0)}{\Gamma(-\overline{C}_T > 0) + \Gamma(-\overline{C}_T < 0)} \]

- Although $T$-odd not a true CP-violating parameter
  \[ A_{CT} \propto \sin (\phi + \delta) \]

- Define the following CP-violating parameter
  \[ A_T = \frac{1}{2} \left( A_{CT} - \overline{A}_{CT} \right) \]
  \[ A_T \propto \sin (\phi) \cos (\delta) \]
Search for CPV in $D^+ \to \pi^- \pi^+ \pi^+$

- Uses same technique as applied to $D^0 \to \pi^- \pi^+ \pi^- \pi^+$ and $D^0 \to K^- K^+ \pi^- \pi^+$
- In addition uses an unbinned method

- Use CF $D_s^+ \to \pi^- \pi^+ \pi^+$ as control channel
Unbinned method

- Unbinned k-nearest neighbour analysis technique
- Compare probability distribution function of phase space for D+ and D-
  - Determine distance between events in Dalitz space
  - Find the k-nearest neighbour events to each point
  - For each event calculate a test statistic \( T \)

\[
T = \frac{1}{n_k(N_+ + N_-)} \sum_{i=1}^{N_+ + N_-} \sum_{k=1}^{n_k} I(i, k),
\]

- \( I(i, k) = 1 \) if \( i^{th} \) event and its \( k^{th} \) nearest neighbour have same charge, \((D^+ - D^+)\)
- \( I(i, k) = 0 \) if pair have opposite charge \((D^+ - D^-)\)

- \( T \) is the mean fraction of like pairs in the pooled sample of the two data sets
- Calculate p-value by comparing test statistic \( T \) with case of no CPV
Searches for CPV in $D^+ \rightarrow \pi^- \pi^+ \pi^+$

- A total of 3.1 million $D^+/D^-$ candidates
- Sensitive in general to $\sim 1, 2^0$ in phase and $\sim 2\%$ in amplitude
  - Similar sensitivity in binned and unbinned methods
Searches for asymmetries in $D_{s}^{+}\rightarrow\pi^{-}\pi^{+}\pi^{+}$ control channel

- Use CF $D_{s}^{+}\rightarrow\pi^{-}\pi^{+}\pi^{+}$ as control channel
  - No evidence for asymmetry in control channel

Binned

LHCb-PAPER-2013-057
Preliminary
Searches for asymmetries in $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ control channel

First point is whole of phase space

Show the p-value for each region
Searches for asymmetries in $D_{s}^{+} \rightarrow \pi^{-} \pi^{+} \pi^{+}$ control channel
Searches for asymmetries in $D_s^+ \to \pi^- \pi^+ \pi^+$ control channel

No visible asymmetry in any of the regions for the control mode.
Results

- Binned
  - Uniform and adaptive bins
- Unbinned
  - All p-values for null CPV above 30%
  - p-value under no CP Asymmetry hypothesis

- p-values for null CPV hypothesis in the range of 50%-99%

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Adaptive binning

Correlated results (same sample different bins)
Overview of time-integrated searches for CPV in charm decays at LHCb

- No evidence for CP violation in charm decays
  - Two-body modes \((D^0 \rightarrow K K, D^0 \rightarrow \pi \pi, D^+ \rightarrow \Phi \pi^+, D^+ \rightarrow K_{S}^{0} \pi^+ )\)
  - Three- and Four-body modes \((D^+ \rightarrow \pi^+ \pi^+ \pi^-, D^0 \rightarrow \pi^+ \pi^+ \pi^- \pi^-, D^0 \rightarrow K^+ K^- \pi^+ \pi^-)\)

- Huge samples available.
  - Potential to update analysis to include the 2012 data set.
  - Plenty of additional search techniques can be applied.

- Hopefully CP violation in Charm isn’t far away