Searches for $CP$ violation in multibody D decays

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Introduction

- CPV is an interference effect:
  at least two amplitudes with different strong and weak phases.
- CPV in charm decays is CKM suppressed in the SM, $\lesssim 0.1\%$.
- Multibody charm decays are a good place to search for CPV:
  very rich resonant structures of interfering amplitudes can give large effects.
  allow to probe CPV in different phase space regions.

Searches at LHCb:

$D^+ \rightarrow \pi^- \pi^+ \pi^+$
$D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$
$D^0 \rightarrow K^+ K^- \pi^+ \pi^-.$

Two model-independent methods are applied:

Miranda and $T$-odd correlations (New)
Miranda method

- Phase space splitted into different bins. Significance defined between \( CP \) conjugate decays for each bin:

\[
S_{CP}^i = \frac{N_i(D^0) - \alpha N_i(D^0)}{\sqrt{\alpha \left( \sigma_i^2(D^0) + \sigma_i^2(D^0) \right)}} , \quad \alpha = \frac{\sum_i N_i(D^0)}{\sum_i N_i(D^0)} .
\]

\( \alpha \), removes sensitivity of global production and detection asymetries.

\( \sigma_i \), uncertainty of \( N_i \) determination

- A \( \chi^2 \) statistic constructed, from which a \( p \)-value calculated with \( N_{\text{bins}} - 1 \) degree of freedom.

\[
\chi^2 = \sum_i (S_{CP}^i)^2
\]

\( CP \) conserved: pass \( \chi^2 \) test.

\( CPV \): deviation from \( \chi^2 \) distribution.
Miranda analysis $D^+ \rightarrow \pi^- \pi^+ \pi^+$

Reconstructed with a data set of 1 fb$^{-1}$. Sensitive to 1$^\circ$ in phase difference or 2% in amplitude difference.

Control sample 2.7M $D^+_s \rightarrow \pi^- \pi^+ \pi^+$

Tested with adaptive binning schemes of 20, 30, 40, 49 and 100 bins. Results consistent with no CPV at current sensitivities with the $p$-values above 50%.

Tested with uniform binning schemes of 20, 32, 52 and 98 bins. Results consistent with no CPV with the $p$-values above 90%.

No single bin in any of the binning schemes presents an absolute $S_{CP}$ value larger than 3.
$D^0 \rightarrow K^+ K^- \pi^+ \pi^-$, $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$

- Reconstructed with a data set of 1 fb$^{-1}$. Sensitive to 10° in phase difference or 10% in amplitude difference.
- Two-dimensional unbinned likelihood fits to $m(hhhh)$ and $\Delta m$, sPlot method for signal and background separation.

57k $D^0 \rightarrow K^- K^+ \pi^+ \pi^-$

330k $D^0 \rightarrow \pi^- \pi^+ \pi^+ \pi^-$
Miranda analysis $D^0 \rightarrow K^+K^-\pi^+\pi^-, D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$

- The phase space more complicated than 3-body decays, can be described with five invariant mass-squared combinations of final particles.

- An adaptive binning algorithm devised to partition the phase space into 5-dimensional hypercubes.

- Results consistent with no CPV with $p$-values of 9.1% for $D^0 \rightarrow K^+K^-\pi^+\pi^-$, and 41% for $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$. 

- Cross checked with 16, 64 and 256 binning schemes, all results consistent with no CPV.
$T$-odd correlations method: $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ (New)

- $T$-odd triple products: in $D^0$ ($\bar{D}^0$) rest frame.
  \[
  C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}), \text{ for } D^0 \\
  \bar{C}_T \equiv \vec{p}_{K^-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+}), \text{ for } \bar{D}^0
  \]

- $T$-odd observable:
  \[
  A_T \equiv \frac{\Gamma(C_T>0) - \Gamma(C_T<0)}{\Gamma(C_T>0) + \Gamma(C_T<0)}, \text{ measured in } D^0 \text{ decays}
  \]
  \[
  \bar{A}_T \equiv \frac{\Gamma(-\bar{C}_T>0) - \Gamma(-\bar{C}_T<0)}{\Gamma(-\bar{C}_T>0) + \Gamma(-\bar{C}_T<0)}, \text{ measured in } \bar{D}^0 \text{ decays}
  \]
  True $CP$-violating observable: cancel FSI effects
  \[
  a^{T-\text{odd}}_{CP} = \frac{1}{2} (A_T - \bar{A}_T)
  \]

Sensitivity using $T$-odd correlations

- Measurement of $a_{CP}^{T-odd}$ is different from $S_{CP}$:
  - Complementary approach to the search for $CPV$.
  - $a_{CP}^{T-odd} \propto \sin(\phi) \cos(\delta)$, $S_{CP} \propto \sin(\phi) \sin(\delta)$. 
    
    $\phi$ weak phase, $\delta$ strong phase of two interfering amplitudes.
  - Different sensitivity to $CPV$:
    $S_{CP}$ vanishes for $\delta = 0$, while $a_{CP}^{T-odd}$ is maximal.

- The measurement $a_{CP}^{T-odd}$ is affected by small systematic uncertainties:
  - $a_{CP}^{T-odd}$ is not sensitive to $D^0/\bar{D}^0$ production asymmetry.
  - $a_{CP}^{T-odd}$ is not sensitive to detector charge reconstruction asymmetry.
**Experimental status**

- Previous measurements of $a_{CP}^{T-\text{odd}}$ consistent with no CPV.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$N_{\text{sig}}$</th>
<th>$a_{CP}^{T-\text{odd}}(D^0)$</th>
<th>$a_{CP}^{T-\text{odd}}(D^+)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \rightarrow K^+ K^- \pi^+ \pi^-$</td>
<td>FOCUS(2005) 800</td>
<td>$(1.0 \pm 5.7 \pm 3.7)%$</td>
<td>$(2.3 \pm 6.2 \pm 2.2)%$</td>
</tr>
<tr>
<td></td>
<td>Babar(2010) 47k</td>
<td>$a_{CP}^{T-\text{odd}}(D^0)$ = $(1.0 \pm 5.7 \pm 3.7)%$</td>
<td>$a_{CP}^{T-\text{odd}}(D^0)$ = $(0.10 \pm 0.51 \pm 0.44)%$</td>
</tr>
<tr>
<td>$D_{(s)}^+ \rightarrow K^+ K_S^0 \pi^+ \pi^-$</td>
<td>FOCUS(2005) 500</td>
<td>$a_{CP}^{T-\text{odd}}(D^+)$ = $(2.3 \pm 6.2 \pm 2.2)%$</td>
<td>$a_{CP}^{T-\text{odd}}(D^+)$ = $(−3.6 \pm 6.7 \pm 2.3)%$</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>$a_{CP}^{T-\text{odd}}(D^+)$ = $(2.3 \pm 6.2 \pm 2.2)%$</td>
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</tr>
<tr>
<td></td>
<td>BaBar(2011) 20k</td>
<td>$a_{CP}^{T-\text{odd}}(D^+)$ = $(−1.20 \pm 1.00 \pm 0.46)%$</td>
<td>$a_{CP}^{T-\text{odd}}(D^+)$ = $(−1.36 \pm 0.77 \pm 0.34)%$</td>
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<tr>
<td></td>
<td>30k</td>
<td>$a_{CP}^{T-\text{odd}}(D^+)$ = $(−1.20 \pm 1.00 \pm 0.46)%$</td>
<td>$a_{CP}^{T-\text{odd}}(D^+)$ = $(−1.36 \pm 0.77 \pm 0.34)%$</td>
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$T$-odd correlations analysis: $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ (New)

- $D^0$ tagged using semileptonic B decays $B \rightarrow D^0 \mu^- X$.
- 171k $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ reconstructed with a data set of 3 fb$^{-1}$.
- Preliminary results, LHCb-PAPER-2014-046 is in preparation.
Analysis Strategy

- Dataset split into 4 samples depending on $D^0$ flavor and $C_T$ value, the number of signal events retrieved by simultaneous fit to the four distributions of $m(K^+K^-\pi^+\pi^-)$. Asymmetry parameters $A_T$, $\bar{A}_T$ extracted from the fit.

\[
N_{D^0, C_T>0} = \frac{1}{2} N_{D^0} (1 + A_T),
\]

\[
N_{D^0, C_T<0} = \frac{1}{2} N_{D^0} (1 - A_T),
\]

\[
N_{\bar{D}^0, -\bar{C}_T>0} = \frac{1}{2} N_{\bar{D}^0} (1 + \bar{A}_T),
\]

\[
N_{\bar{D}^0, -\bar{C}_T<0} = \frac{1}{2} N_{\bar{D}^0} (1 - \bar{A}_T).
\]

- Measurements of asymmetry parameters in different regions of the phase space by dividing the 5-dimensional Dalitz plots. The compatibility with no $CPV$ hypothesis tested by $\chi^2 = X^T V^{-1} X$, $X$, array of $a_{CP}^{T-odd}$ residuals of each bin w.r.t 0.

$V$, sum of the statistical and the systematic error matrix. $a_{CP}^{T-odd}$, Gaussian distributed variables, systematic errors are mainly Gaussian.

- Measurements of asymmetry parameters as a function of $D^0$ proper time.
Phase space integrated measurement (1) (New)

The simultaneous fit to the full data sample for the integrated measurement.
Asymmetries parameters: Preliminary

\[ A_T = (-7.18 \pm 0.41 \text{(stat)} \pm 0.13 \text{(syst)})\% \]
\[ \bar{A}_T = (-7.55 \pm 0.41 \text{(stat)} \pm 0.12 \text{(syst)})\% \]
\[ a_{CP}^{T-\text{odd}} = (0.18 \pm 0.29 \text{(stat)} \pm 0.04 \text{(syst)})\% \]

consistent with measurements at Babar\[^1\], with a precision improved by more than a factor of 2.

Large asymmetries observed in \( A_T \) and \( \bar{A}_T \) are due to FSI effect\[^2\].

The phase space is divided into 32 bins following a binning scheme based on the Cabibbo-Maksimowicz variables: 
\[ m_{\pi^+\pi^-}^2, m_{K^+K^-}^2, \cos(\theta_\pi), \cos(\theta_K), \text{ and } \phi. \]

The number of events is consistent in different bins. Other phase space divisions with 8 and 16 bins have been considered for control checks.
Asymmetries over the phase space (New)

\[ \text{Asymmetry in } \phi, \cos(\theta_K), \cos(\theta_\pi) \text{ is due to the dynamics of the decay} \]
Results over phase space regions (New)

- Results consistent with no CPV hypothesis with a probability of 74% based on $\chi^2/ndof = 26.4/32$.
- Control checks: results are compatible with no CPV hypothesis at 24% probability for the case of 8 bins and at 28%, 62%, 82% probability for cases of three different 16 bins.
- $A_T$ and $\bar{A}_T$ are significantly different among the different bins: rich resonant structure produce different FSI effects.

$LHCb$ Phase space region

$\chi^2/ndof = 26.4/32$
Measurement of $a_{CP}^{T-\text{odd}}$ as a function of $D^0$ proper time

- First time measurement of $a_{CP}^{T-\text{odd}}$ as a function of $D^0$ proper time.
- Proper time divided into 10 bins with similar signal events. Asymmetries measured in each bin.
- The compatibility with no CPV hypothesis verified by means of the $\chi^2$ test.
- $a_{CP}^{T-\text{odd}}$ is consistent with no indirect CPV at 72% probability.
- $A_T$ and $\bar{A}_T$ do not show any significant dependence on the proper time, compatible with a constant at 80% and 34% probability, respectively.
Summary

- A search for $CP$ violation using the Miranda method is performed with a data set of $1 \text{ fb}^{-1}$:
  \[ D^+ \rightarrow \pi^- \pi^+ \pi^+ \]
  \[ D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^- \]
  \[ D^0 \rightarrow K^+ K^- \pi^+ \pi^- \]

- A search for $CP$ violation using the $T$-odd correlations method is performed in $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ decays with a data set of $3 \text{ fb}^{-1}$. Search for $CPV$ in different regions of five dimensional phase space and as a function of $D^0$ proper time are also presented for the first time. (New)

- All results are consistent with no $CPV$ in $D$ decays.
- Further improvements expected with more statistics at the LHCb.