Searches for CP violation in multibody charm decays

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Local Asymmetries in Charm Decays

Results of two-body CP violation searches in charm sector were previously discussed in this section.

Let's move to multibody decays, as they have a very rich resonance structure, we can see something in the interplay at a given local point.

CPV is an interference effect. Rate for interfering amplitudes $A_1$, $A_2$:

$$|A_1|^2 + |A_2|^2 + 2|A_1||A_2|\cos(\Delta\delta + \phi_{\text{CPV}})$$

What should we do about variations? Currently we have two model independent methods: binned and unbinned.

Additional benefit: these rely on shape across Dalitz space, not on absolute rates - robust against global detection and production effects.
Binned (also known as) Miranda method provides a model independent mapping of local CP asymmetries. This method studies the significance in the difference between corresponding Dalitz plot bins:

\[ S_{CP}^i = \frac{N_i(D) - \alpha N_i(\bar{D})}{\sqrt{\alpha \sigma_i^2(D) + \sigma_i^2(\bar{D})}} \]

\[ \alpha = \frac{\sum_i N_i(D)}{\sum_i N_i(\bar{D})} \]

\( \alpha \) removes the sensitivity to global asymmetries, \( \sigma_i \) – uncertainty of \( N_i \) determination.

If \( CP \) is conserved, \( \Sigma(S_{CP}^i)^2 \) pass a \( \chi^2 \) test with \( N_{\text{bins}} - 1 \) degrees of freedom.

The deviation from a \( \chi^2 \) distribution will give us a \( p \)-value of CPV. For example, in case of reasonable \( CP \) violation in \( D^+ \rightarrow \pi \pi \pi \), we will see.

We make use of this method in the analysis of Cabibbo-suppressed decay, $D^+ \rightarrow \pi^+\pi^+\pi^-$, using the 2011 data sample of 1 fb$^{-1}$.

We also reconstruct $D_s^+ \rightarrow \pi^+\pi^+\pi^-$ as a control channel, where CPV is expected to be negligible.

After applying kinematic selection criteria, we obtain:

<table>
<thead>
<tr>
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<th>$D^+ \rightarrow \pi^+\pi^+\pi^-$</th>
<th>$D_s^+ \rightarrow \pi^+\pi^+\pi^-$</th>
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<tbody>
<tr>
<td>$N_{\text{sig}}, 10^3$</td>
<td>2678±7</td>
<td>2704±8</td>
</tr>
<tr>
<td>Purity</td>
<td>82%</td>
<td>87%</td>
</tr>
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</table>

The high yield and purity allow us to have sensitivities down to 1° in phase and 2% in amplitudes.
We define a set of bins (from 40 to 100 bins in a set) on the Dalitz plain. Here, the adaptive (equal population) binning is shown:

The analysis is also cross-checked for uniform binning. No single bin in any of the binning schemes presents an absolute $S_{CP}^i$ value larger than 3.

Both $D^+$ and $D_s^+$ samples manifest the absence of CP violation at current sensitivities with the p-value of this hypothesis is typically greater than 0.5.
We can also use this technique in to analyse four body decays. In this case, $D^0$ should be tagged with $D^*+\rightarrow D^0\pi^+$ decays. This reduces number of events but gives a powerful observable: $\Delta m = m_{D^*} - m_{D^0}$.

Signal and background distributions are separated using sPlot method. We are able to see the rich resonant structure:
Decay | \( D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^- \) | \( D^0 \rightarrow K^+ K^- \pi^+ \pi^- \) (control channel) | 
--- | --- | --- |
\( N_{\text{sig}}, 10^3 \) | 330 | 57 | 2900

The sensitivity to CPV phase is down to 10° or a magnitude difference of O(10%) between \( D^0 \rightarrow \phi \rho \) and \( \bar{D}^0 \rightarrow \phi \rho \).

We use adaptive binning to calculate \( S_{CP} \) for 32-128 bins. All results are consistent with CP conservation at the current sensitivity.
D$^+\rightarrow\pi^+\pi^+\pi^-$ channel was also analysed in an unbinned way using a k-nearest neighbour algorithm.

In this method, to test the hypothesis of no CPV in D$^+$ and D$^-$ in a sample with N events, we calculate:

$$ T = \frac{1}{n_kN} \sum_{i=1}^{N} \sum_{k=1}^{n_k} I(i, k) $$

$I(i,k)=1$, if $i$ and $k$ are like sign candidates,
$I(i,k)=0$, if $i$ and $k$ are opposite sign candidates.

We know that the test statistics $T$ for our case should have:

- Mean $\mu_T \sim 0.5$
- Deviation $\sigma_T^2 \sim 0.5/(n_k \cdot N)$

We thus construct a “pull” observable to test the absence of CPV:

$$ (T-\mu_T)/\sigma_T $$

and test it in different amount of bins. Our estimations predict 2° sensitivity for CPV phase and 2% sensitivity to CPV amplitudes.
We define several sets of bins based on the known Dalitz plot structure:
- $R_0$: Full Dalitz Plot,
- $R_1$-$R_7$: selecting resonant regions,
- $P_1$-$P_3$: selecting broader structures.

Analysing for $n_k=20$, we do not see any deviations from no CPV.
LHCb has started to explore a rich field of multibody charm meson decays.

We test the presence of CP Violation effects in:
- $D^+ \rightarrow \pi^+\pi^+\pi^-$
- $D_s^+ \rightarrow \pi^+\pi^+\pi^-$
- $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$
- $D^0 \rightarrow K^+K^-\pi^+\pi^-$
- $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$

using model-independent binned and unbinned approaches with sensitivities down to $1^\circ$ or $1\%$ for 3-body decays and $10^\circ$ or $10\%$ for 4-body decays.

Previously, LHCb also showed search for CP Violation in $D^+ \rightarrow K^+K^-\pi^+$ (Phys Rev D 84(2011) 112008).

In all cases, the p-value of no CPV hypothesis stays high, excluding large CP violation effects.

We are currently analysing unprecedented charm samples, more analyses to come soon.