Searching for direct CPV in charm at LHCb

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In the Standard Model (SM), charge-parity violation (CPV) in the quark sector comes only from the phase in the CKM matrix.

Order of magnitudes too small to explain our matter dominated universe

→ Look for New Physics (NP) processes that enhance CPV

Direct CPV (or CPV in the decay)

Difference of decay rate between two CP conjugated states

\[ |A(D^0 \to f)|^2 \neq |A(\bar{D}^0 \to \bar{f})|^2 \]
Introduction

Why look for \( CPV \) in charm ?
- Prediction of \( CPV \) in charm from the SM are small
  → Lots of room for NP enhancement
- Only way to probe for \( CPV \) in up-type hadrons
  → Complementary to other searches in \( B \) or \( K \)

Why look for \( CPV \) in charm at LHCb ?
- Largest sample of charm decays
  - Large \( cc \) cross-section:
    \[
    \sigma(pp \to ccX) = (2369 \pm 3 \pm 152 \pm 118) \mu b,
    \]
    at 13 TeV and for \( p_T < 8 \text{ GeV}/c, 2.0 < y < 4.5 \) [JHEP 03 (2016) 159]
  → Large charm yields (\( \mathcal{O}(100 \text{ M}) \) \( D^0 \to K^- \pi^+ \) tagged decays)
- Good momentum resolution (0.5 – 1%)
- Good tracking efficiency (over 95%)
- Excellent vertex resolution (IP resolution \( (15 + 29/p_T) \mu m \))
The experimental observable is not directly $A_{CP}$, but $A_{raw}$:

$$A_{raw} = A_{CP} + A_P + A_D + A_{tag}$$

- The production asymmetry $A_P$: In $pp$ collisions there is an initial anti-quark deficit.
- The detection asymmetry $A_D$: Mesons and anti-mesons have different behaviours in matter.
- The tagging asymmetry $A_{tag}$: The tagging particle also has different behaviour in matter according to its charge.
- The $CP$ asymmetry $A_{CP}$: What we want to measure.

$$A_{CP} = \frac{\Gamma(D^0 \rightarrow f) - \Gamma(D^0 \rightarrow \bar{f})}{\Gamma(D^0 \rightarrow f) + \Gamma(D^0 \rightarrow \bar{f})}$$
At LHCb, we use 2 independent tagging methods:

**Prompt**

\[ D^{*+} \rightarrow D^0 \pi^+ \]

**Semileptonic**

\[ B^- \rightarrow D^0 \mu^- \bar{\nu}_\mu X \]
Detection asymmetry

- Detection asymmetry reduced by flipping magnet polarity regularly
- Residual detection asymmetry due to intrinsic different cross-section between particles of opposite charge when interacting with the detector’s material

C. Patrignani et al. (PDG), CPC 40, 100001 (2016) and 2017 update.
Experimental trick

- Difficult to measure the detector asymmetries
- One solution is to analyse 2 similar decays
  - They need to have the same tagging channel
  - e.g. \( D^0 \to K^+K^- \) and \( D^0 \to \pi^+\pi^- \)
  - Cancel the detector asymmetries by subtracting the two raw asymmetries

\[
\Delta A_{CP} = A_{raw}(D^0 \to K^+K^-) - A_{raw}(D^0 \to \pi^+\pi^-) = A_{CP}(D^0 \to K^+K^-) + A_P(D^*+) + A_D(K^+K^-) + A_{tag}(\pi^+) \\
- A_{CP}(D^0 \to \pi^+\pi^-) - A_P(D^*+) - A_D(\pi^+\pi^-) - A_{tag}(\pi^+) \\
= A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)
\]
Experimental status

- Most precise measurements to date
  - Based on Run 1 data
  - Updated analyses with Run 2 data under way

A_{CP}(D^0 \rightarrow K^+K^-) = (0.4 \pm 1.2 \pm 1.0) \times 10^{-3}  

A_{CP}(D^0 \rightarrow \pi^+\pi^-) = (0.7 \pm 1.4 \pm 1.1) \times 10^{-3}  

\Delta A_{CP}(D^0 \rightarrow h^+h^-) = (1.0 \pm 0.8 \pm 0.3) \times 10^{-3}  

In the following slides, I will present a highlight of the latest results
A measurement of the $CP$ asymmetry difference between $\Lambda_c^+ \rightarrow pK^-K^+$ and $\Lambda_c^+ \rightarrow p\pi^-\pi^+$

[JHEP 03 (2018) 182]
**ΔACP in Λ⁺ₐc decays**

- Dataset: 3.0 fb⁻¹, Run 1
- Production mode: $Λ₀ᵇ → Λ⁺ₐc μ⁻ X$
- Raw asymmetry:
  
  $$A_{raw}(f) = A_{CP}(f) + A_P(Λ₀ᵇ) + A_{tag}(μ) + A_D(f)$$
  
  where $f = pK^+K^-, pπ^+π^−$

- Removing experimental asymmetries by taking the difference between the two final states
  
  $$ΔA_{CP} = A_{raw}(pK^+K^-) - A_{raw}(pπ^+π^-)$$
  
  $$= A_{CP}(pK^+K^-) - A_{CP}(pπ^+π^-)$$

- Assuming the kinematics is the same for the two final states
The kinematics of the two final states are not the same

→ Reweight the kinematics of $p\pi^+\pi^-$ to $pK^+K^-$
  - Reweight with decision trees with gradient boosting (GBDT)
  - Reweight for $\Lambda_c^+$ transverse momentum and pseudorapidity and $p$ transverse momentum
  - limited by statistics of $pK^+K^-$ final state

Quote a weighted asymmetry:

$$\Delta A_{CP}^{wgt} = A_{raw}(pK^+K^-) - A_{raw}(p\pi^+\pi^-)$$

- Weight function published in order to compare with theoretical predictions
\[ \Delta A_{CP} \text{ in } \Lambda_c^+ \text{ decays} \]

**Yields**

\[ \Lambda_c^+ \rightarrow pK^-K^+ \]
\[ N_{\text{sig}} = 25190 \pm 200 \]

\[ \Lambda_c^+ \rightarrow p\pi^-\pi^+ \]
\[ N_{\text{sig}} = 161390 \pm 580 \]

**Results**

\[ \Delta A_{CP}^{\text{wgt}} = (3.0 \pm 9.1 \pm 6.1) \times 10^{-3} \]

- First measurement of \( CPV \) parameters in 3-body \( \Lambda_c^+ \) decays.
- No \( CPV \) observed
Search for CP violation in the phase space of $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ decays

$CPV$ in $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$

- Dataset : 3.0 $fb^{-1}$, Run 1
- Production mode : $D^{*+} \rightarrow D^0 \pi^+$
- $N_{\text{sig}} = (1008 \pm 1) \times 10^3$

Parametrisation of the phase space

- Ordering of the particles:
  - For the $D^0$: $\pi_1 \pi_2 \pi_3 \pi_4 = \pi^+ \pi^- \pi^+ \pi^-$, where largest $m(\pi^+ \pi^-) = m(\pi_3 \pi_4)$
  - For the $\bar{D}^0$: $CP$ is applied $\pi_1 \pi_2 \pi_3 \pi_4 = \pi^- \pi^+ \pi^- \pi^+$
- 5D phase space:
  - $m(\pi_1 \pi_2), m(\pi_1 \pi_4), m(\pi_2 \pi_3), m(\pi_1 \pi_2 \pi_3), m(\pi_1 \pi_2 \pi_4)$
**The energy test**  

- Sensitive to local CPV in the phase space
- Model independent unbinned method
- Define a metric to compute the distance between 2 points in the phase space
- Define a test statistic, $T$

\[
T = \sum_{i,j>i}^n \frac{\psi_{ij}}{n(n-1)} + \sum_{i,j>i}^{\bar{n}} \frac{\psi_{ij}}{\bar{n}(\bar{n}-1)} - \sum_{i,j}^{n,\bar{n}} \frac{\psi_{ij}}{n\bar{n}}
\]

- Build the "no CPV" hypothesis as a set of random permutations of the data
- Compare the value in data to the "no CPV" hypothesis

This is the first application of the energy test to a 4-body decay
2 tests are performed

- **P-even test:** $D^0$ vs $\bar{D}^0$ (*i.e.* I+II vs III+IV)

Definition of the triple-product:

For the $D^0$:  
$$C_T = \vec{p}_1 \cdot (\vec{p}_2 \times \vec{p}_3)$$

For the $\bar{D}^0$:  
$$\text{CP}(C_T) = -C(C_T) = -\bar{C}_T$$

- **P-odd test:** $C_T > 0$ vs $C_T < 0$ (*i.e.* I+IV vs II+III)

<table>
<thead>
<tr>
<th></th>
<th>$D^0$</th>
<th>$\bar{D}^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$C_T &gt; 0$</td>
<td>$-\bar{C}_T &gt; 0$</td>
</tr>
<tr>
<td>II</td>
<td>$C_T &lt; 0$</td>
<td>$-\bar{C}_T &lt; 0$</td>
</tr>
</tbody>
</table>
Results

**P-even test**

\[ p\text{-value} = (4.6 \pm 0.5)\% \]

**P-odd test**

\[ p\text{-value} = (0.6 \pm 0.2)\% \]

P-odd test corresponds to a significance of CPV of 2.7\(\sigma\).
Results
Local asymmetry exceeding $2\sigma$ seen in the region of the $\rho(770)^0$
Measurement of the time-integrated $CP$ asymmetry in $D^0 \rightarrow K^0_s K^0_s$ decays

Submitted to JHEP, [arXiv:1806.01642]
$A_{CP}$ in $D^0 \rightarrow K_S^0 K_S^0$ decays

- Dataset : 2.0 fb$^{-1}$, 2015-2016
- Production mode : $D^{*+} \rightarrow D^0 \pi^+$
- Raw asymmetry :
  \[
  A_{\text{raw}}(K_S^0 K_S^0) = A_{CP}(K_S^0 K_S^0) + A_P(D^{*+}) + A_{\text{tag}}(\pi^+)
  \]
- No detection asymmetries from the daughters of the $D^0$ since they are symmetric
- Removing production and tagging asymmetries by using a control channel $D^0 \rightarrow K^+ K^-$:
  \[
  \Delta A_{CP} = A_{\text{raw}}(K_S^0 K_S^0) - A_{\text{raw}}(K^+ K^-)
  = A_{CP}(K_S^0 K_S^0) - A_{CP}(K^+ K^-)
  \]
Various possible tracks in LHCb:

For this analysis:
- LL: the two $K_S^0$ decay in the VELO and both form long tracks
- LD: one $K_S^0$ decays inside and one decays downstream of the VELO
Removing specific backgrounds:
\( A_{CP} \) in \( D^0 \to K_S^0 K_S^0 \) decays

\[ N_{\text{sig}}^{LL} = 759 \pm 32 \quad \text{LL} \]

\[ N_{\text{sig}}^{LD} = 308 \pm 26 \quad \text{LD} \]

Results

- \( A_{CP} = (4.2 \pm 3.4 \pm 1.0)\% \)
- Compatible with Run 1 result: \( A_{CP} = (-2.9 \pm 5.2 \pm 2.2)\% \)
- Average: \( A_{CP} = (2.0 \pm 2.9 \pm 1.0)\% \)
- → Catching up with the Belle result
Conclusion

- This was a highlight of 3 recent analyses from LHCb
- No CPV has been observed in charm yet
- Reaching the precision of the theory predictions ($10^{-3} - 10^{-4}$)
  - New estimate of direct CPV in charm: $\mathcal{O}(10^{-4})$ [Khodjamirian and Petrov, PLB 774 (2017), 235-242]
- More promising results with Run 2 are coming
  - Already collected 3.7 fb$^{-1}$ between 2015 and 2017
  - Expect to have a total dataset (Run 1 + Run 2) of $\sim 9.0$ fb$^{-1}$ at the end of this year
- Working hard towards the upgrade for even better results
BACKUP
The LHCb detector
Removing specific backgrounds:

\[ D^0 \to K_{S}^0 K_{S}^0 \]

\[ D^0 \to K_{S}^0 \pi^+\pi^- \]