Searches for direct CPV in charm at LHCb

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On behalf of the LHCb collaboration

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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

\[ |A(D^0 \rightarrow f)|^2 \neq |A(\bar{D}^0 \rightarrow \bar{f})|^2 \]
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 $c\bar{c}$ cross-section:
    $$\sigma(pp \rightarrow c\bar{c}X) = (2369 \pm 3 \pm 152 \pm 118) \mu b,$$
    at 13 TeV and for $p_T < 8\text{ GeV}/c, 2.0 < y < 4.5$ [JHEP 03 (2016) 159]
  → Large charm yields ($\mathcal{O}(100 \text{ M}) D^0 \rightarrow K^- \pi^+$ tagged decays)
- Good momentum resolution (0.5 – 1%)
- Good tracking efficiency (over 95%)
- Excellent vertex resolution (IP resolution $(15 + 29/p_T) \text{ \mu m}$)
Experimental observable

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

$$A_{CP} = \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\bar{D}^0 \rightarrow \bar{f})}{\Gamma(D^0 \rightarrow f) + \Gamma(\bar{D}^0 \rightarrow \bar{f})}$$
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

![Graph showing cross-section vs. p_{lab} in GeV/c](image)

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]
Dataset: 3.0 fb$^{-1}$, Run 1

Production mode: $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- X$

Raw asymmetry:

$$A_{raw}(f) = A_{CP}(f) + A_P(\Lambda_b^0) + A_{tag}(\mu) + A_D(f)$$

where $f = pK^+K^-, p\pi^+\pi^-$

Removing experimental asymmetries by taking the difference between the two final states

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

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

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:

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

- Weight function published in order to compare with theoretical predictions
ΔA_{CP} in Λ_c^+ decays

Yields

Λ_c^+ → pK^−K^+

N_{sig} = 25190 ± 200

Λ_c^+ → pπ^−π^+

N_{sig} = 161390 ± 580

Results

\[ ΔA_{CP}^{wgt} = (3.0 ± 9.1 ± 6.1) \times 10^{-3} \]

- First measurement of CPV parameters in 3-body Λ_c^+ decays.
- No CPV observed.

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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:
  - $m(\pi_1 \pi_2), m(\pi_1 \pi_4), m(\pi_2 \pi_3), m(\pi_1 \pi_2 \pi_3), m(\pi_1 \pi_2 \pi_4)$

- 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 $\bar{D}^0$: \[ CP(C_T) = -C(C_T) = -\bar{C}_T \]

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

<table>
<thead>
<tr>
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<th>D^0</th>
<th>\bar{D}^0</th>
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<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 2σ seen in the region of the ρ(770)^0
Measurement of the time-integrated CP asymmetry in $D^0 \to K_S^0 K_S^0$ 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 :

$$A_{raw}(K_S^0 K_S^0) = A_{CP}(K_S^0 K_S^0) + A_P(D^{*+}) + A_{tag}(\pi^+)$$

- No detection asymmetries from the daughters of the $D^0$ since they are symmetric
- Removing production and tagging asymmetries by using a control channel $D^0 \rightarrow K^+ K^-$:

$$\Delta A_{CP} = A_{raw}(K_S^0 K_S^0) - A_{raw}(K^+ K^-) = A_{CP}(K_S^0 K_S^0) - A_{CP}(K^+ K^-)$$
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
$A_{CP}$ in $D^0 \rightarrow K_S^0 K_S^0$ decays

Removing specific backgrounds:
$A_{CP}$ in $D^0 \rightarrow K_S^0 K_S^0$ decays

$D^0 \rightarrow K_S^0 K_S^0$

$\bar{D}^0 \rightarrow K_S^0 K_S^0$

$N_{\text{sig}}^{LL} = 759 \pm 32$ \hspace{1cm} LL

$N_{\text{sig}}^{LD} = 308 \pm 26$ \hspace{1cm} 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: $A_{CP} = (2.0 \pm 2.9 \pm 1.0)\%$
- $\rightarrow$ Catching up with the Belle result
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

ECAL
HCAL
Muon Chambers
Magnet
RICH1
VeLo
TT
T1 T2 T3
RICH2

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\[ D^0 \to K^0_S K^0_S \]

\[ D^0 \to K^0_S \pi^+ \pi^- \]