Searches for CPV in $D^+$ decays at LHCb

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on behalf of the LHCb collaboration

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**CP violation in charm**

- CPV not yet observed in charm - unique probe for CPV in the up-quark sector
  - In the Standard Model, CPV in mixing expected to be small and universal
  - Direct CPV dependent on the final state


- Sizeable direct CPV (above $10^{-3}$) can be accommodated within Standard Model and beyond-SM pictures
  - Non-perturbative effects may be relevant
  - New Physics contributions, e.g., in gluonic penguin

- Need to **look at many decays** with comparable sensitivity
  - We don’t know where CPV might show up first
  - Key to interpret experimental results (SM or NP?)
Hadronic decays and CPV

● D mesons decay dominantly into hadronic final states, a large fraction of which are two-body modes (P P, V P, V V, A P)
  \( P = \text{pseudoscalar}, \ V = \text{vector}, \ A = \text{axial} \)

● In the SM only Singly-Cabibbo-Suppressed decays can possibly involve diagrams with different weak phases
  \[
  \text{Amp} = V_{cd}V_{ud}^*(\text{trees + penguins}) + V_{cs}V_{us}^*(\text{trees + penguins})
  \]

● CPV in SCS decays are expected only at $10^{-4}$ to $10^{-3}$ level
  \[
  a_{CP}^{dir} = \left| \frac{V_{cb}^* V_{ub}}{V_{cd}^* V_{ud}} \right| \sin \gamma \left| \frac{A_2}{A_1} \right| \sin \delta \sim 10^{-3} \left| \frac{A_2}{A_1} \right| \sin \delta
  \]
  \( (\delta = \text{relative strong phase}) \)

CPV in SCS $D_{(s)}^+ \rightarrow PP$ decays


<table>
<thead>
<tr>
<th>Modes</th>
<th>$a_{CP}$(FSI)</th>
<th>$a_{CP}$(diagram)</th>
<th>$a_{tree}^{CP}$</th>
<th>$a_{tot}^{CP}(\times 10^{-3})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^+ \rightarrow \pi^+\pi^0$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$-0.23$</td>
</tr>
<tr>
<td>$D^+ \rightarrow K^+\overline{K}^0$</td>
<td>$-0.51\pm0.30$</td>
<td>$-0.38$</td>
<td>$-0.08$</td>
<td>$-0.93$</td>
</tr>
<tr>
<td>$D^+ \rightarrow \pi^+\eta$</td>
<td>$-0.65$</td>
<td>$-0.46$</td>
<td></td>
<td>$0.63$</td>
</tr>
<tr>
<td>$D^+ \rightarrow \pi^+\eta'$</td>
<td>$0.41$</td>
<td>$0.30$</td>
<td>$1.28$</td>
<td></td>
</tr>
<tr>
<td>$D_S^+ \rightarrow \pi^0K^+$</td>
<td>$0.88$</td>
<td>$0.17$</td>
<td></td>
<td>$0.76$</td>
</tr>
<tr>
<td>$D_S^+ \rightarrow \pi^+K^0$</td>
<td>$0.52$</td>
<td>$-0.01$</td>
<td>$0.87$</td>
<td></td>
</tr>
<tr>
<td>$D_S^+ \rightarrow K^+\eta$</td>
<td>$-0.19$</td>
<td>$0.75$</td>
<td>$0.76$</td>
<td></td>
</tr>
<tr>
<td>$D_S^+ \rightarrow K^+\eta'$</td>
<td>$-0.41$</td>
<td>$-0.48$</td>
<td></td>
<td>$1.83$</td>
</tr>
</tbody>
</table>

$1^{[\text{LHCb collaboration, JHEP 10 (2014) 025}}$

$2^{[\text{LHCb collaboration, JHEP 06 (2013) 112}}$

Most have $\pi^0$, $\eta$, $\eta'$!
\( \text{D}_{s}^{\pm} \rightarrow \eta' \pi^{\pm} \) and \( \text{D}^{\pm} \rightarrow \eta' \pi^{\pm} \) decays

- **Cabibbo Favored (D\(_{s}\)) and Singly-Cabibbo-Suppressed (D)**

- Small asymmetries in SM: null for CF decays, O(0.1%) or below for SCS

- **Measurements at e\(^{+}\)e\(^{-}\) machines**
  
  - \( A_{\text{CP}} (\text{D}^{\pm} \rightarrow \eta' \pi^{\pm}) = (-0.12 \pm 1.12 \pm 0.17)\% \)
    

  - \( A_{\text{CP}} (\text{D}_{s}^{\pm} \rightarrow \eta' \pi^{\pm}) = (-2.2 \pm 2.2 \pm 0.6)\% \)
    
Charm with neutrals at LHCb

✓ Large production cross-section
   \( \sim 10^{12} \) D mesons in acceptance ⇒ \( \sim 10^{10} \) on tape

✓ Large boost and good time-res.

✗ Dedicated trigger required

✗ Hard to do neutrals

⇨ Mitigate disadvantage of hadronic environment: reconstruct neutral in a charged mode

<table>
<thead>
<tr>
<th>Mode</th>
<th>Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi^0 )</td>
<td></td>
</tr>
<tr>
<td>2( \gamma )</td>
<td>98.823 ± 0.034</td>
</tr>
<tr>
<td>( e^+ e^- \gamma )</td>
<td>1.174 ± 0.035</td>
</tr>
<tr>
<td>( \eta )</td>
<td></td>
</tr>
<tr>
<td>2( \gamma )</td>
<td>39.41 ± 0.20</td>
</tr>
<tr>
<td>3( \pi^0 )</td>
<td>32.68 ± 0.23</td>
</tr>
<tr>
<td>( \pi^+ \pi^- \pi^0 )</td>
<td>22.92 ± 0.28</td>
</tr>
<tr>
<td>( \pi^+ \pi^- \gamma )</td>
<td>4.22 ± 0.08</td>
</tr>
<tr>
<td>( \eta' )</td>
<td></td>
</tr>
<tr>
<td>( \pi^+ \pi^- \eta )</td>
<td>42.9 ± 0.7</td>
</tr>
<tr>
<td>( \rho^0 \gamma ) (including non-resonant ( \pi^+ \pi^- \gamma ))</td>
<td>29.1 ± 0.5</td>
</tr>
<tr>
<td>( \pi^0 \pi^0 \eta )</td>
<td>22.2 ± 0.8</td>
</tr>
<tr>
<td>( \omega \gamma )</td>
<td>2.75 ± 0.23</td>
</tr>
<tr>
<td>( \gamma \gamma )</td>
<td>2.20 ± 0.08</td>
</tr>
</tbody>
</table>
\(\eta'\) reconstructed in \(\pi^+\pi^-\gamma\) final state

- Most important peaking background: \(D_{(s)}^+ \rightarrow \phi \pi^+, \phi \rightarrow \pi^+\pi^-\pi^0\)
- \(\eta'\) natural width small compared to the \(\pi^+\pi^-\gamma\) resolution:
  \[m(\eta'\pi^+)\] calculated constraining \(m(\pi^+\pi^-\gamma)\) to known \(\eta'\) mass
Measured (raw) asymmetries

We measure the asymmetry in the observed number of positive and negative candidates, $A_{\text{raw}}$

$$A_{\text{raw}}(D_{(s)}^{\pm} \to f^{\pm}) = \frac{N(D_{(s)}^{+} \to f^{+}) - N(D_{(s)}^{-} \to f^{-})}{N(D_{(s)}^{+} \to f^{+}) + N(D_{(s)}^{-} \to f^{-})}$$

This is related to first order to CP asymmetries by:

$$A_{\text{raw}} \sim A_{\text{CP}} + A_{\text{det}} + A_{\text{prod}}$$
Difference of CP asymmetries: $\Delta A_{CP}$

$A_{det}$ and $A_{prod}$ cancel in the difference of asymmetries with control samples with similar production and decay topology.

cancellation relies on similar kinematic distributions

$n(D^\pm): 1165k$
$n(D_s^\pm): 6657k$
Improving cancellation of $A_{\text{det}}$

- Equalize bachelor pion selection for signal and control samples
- Perform the analysis in bins of the bachelor pion transverse momentum and pseudorapidity
Measurement of raw asymmetries

- Different samples for different beam and trigger conditions, fitted individually
- Simultaneous maximum likelihood fit to D+ and D- in all bins

Points with errors represent data, while the curves represent the fitted models (solid), the $D_s^\pm \rightarrow \phi\pi^\pm$ (dashed) and $D^\pm \rightarrow \phi\pi^\pm$ (long-dashed) components, and the sum of all background.
Systematic uncertainties

- Main systematic from background shape: several alternative models tested, maximum deviation as systematic uncertainty
- Uncertainties related to production mechanism negligible

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta A_{CP}(D_s^\pm \rightarrow \eta'\pi^\pm)$</th>
<th>$\Delta A_{CP}(D^\pm \rightarrow \eta'\pi^\pm)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-prompt charm</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Background model</td>
<td>0.19</td>
<td>0.50</td>
</tr>
<tr>
<td>Fit procedure</td>
<td>0.09</td>
<td>0.16</td>
</tr>
<tr>
<td>Sideband subtraction</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>$D_s$ production asymmetry</td>
<td>0.02</td>
<td>0.07</td>
</tr>
<tr>
<td>$K^0$ asymmetry</td>
<td>–</td>
<td>0.08</td>
</tr>
<tr>
<td>Total</td>
<td>0.24</td>
<td>0.55</td>
</tr>
<tr>
<td>Statistical uncertainties</td>
<td>0.36</td>
<td>0.72</td>
</tr>
</tbody>
</table>
Results

- $\Delta A_{CP}$ values from all kinematic bins are averaged together:

$A_{raw}(D^+_s \rightarrow \eta'\pi^+) - A_{raw}(D^+_s \rightarrow \phi\pi^+) = (-0.44 \pm 0.36 \pm 0.24)\%$

$A_{raw}(D^+ \rightarrow \eta'\pi^+) - A_{raw}(D^+ \rightarrow K^0_S\pi^+) = (-0.50 \pm 0.72 \pm 0.55)\%$

- To get $A_{CP}(D_{(s)}^+ \rightarrow \eta'\pi^+)$, must correct for the known CP asymmetries of control channels:

$A_{CP}(D^+ \rightarrow K^0_S\pi^+) = (-0.024 \pm 0.094 \pm 0.067)\%$


$A_{CP}(D^+_s \rightarrow \phi\pi^+) = (-0.38 \pm 0.26 \pm 0.08)\%$

[D0 collaboration, Phys. Rev. Lett. 112 (2014) 111804]

- $A_{raw}(D^+ \rightarrow K^0_S\pi^+)$ also contains a contribution from $K^0$ CP and detection asymmetries, $A(K^0) = (0.08 \pm 0.01)\%$, to be subtracted

[LHCb collaboration, JHEP 07 (2014) 041]
Results

\[ A_{CP}(D^{\pm} \rightarrow \eta'\pi^{\pm}) = (-0.61 \pm 0.72 \pm 0.55 \pm 0.12)\% \]
\[ A_{CP}(D_{s}^{\pm} \rightarrow \eta'\pi^{\pm}) = (-0.82 \pm 0.36 \pm 0.24 \pm 0.27)\% \]

Previous measurements at \( e^+e^- \) machines:

\[ A_{CP}(D^{\pm} \rightarrow \eta'\pi^{\pm}) = (-0.12 \pm 1.12 \pm 0.17)\% \]

\[ A_{CP}(D_{s}^{\pm} \rightarrow \eta'\pi^{\pm}) = (-2.2 \pm 2.2 \pm 0.6)\% \]
Conclusions

- Most precise (better than O(%)\)) measurement of CP asymmetries in $D_s^{\pm} \rightarrow \eta'\pi^\pm$ and $D^{\pm} \rightarrow \eta'\pi^\pm$ decays to date [LHCB-PAPER-2016-041]

- Consistent with no CP violation and SM expectations

- Analysis of charged decay modes of neutral mesons ($\pi^0, \eta, \eta'$) allows previously unanticipated measurements of CP asymmetries in $D^+$ and $D_s^+$ decays
D-candidates kinematic distributions

In each bachelor-pion kinematic bin, we reweight the D-meson pseudorapidity or Pt distribution in the control samples, and re-calculate $\Delta A_{\text{raw}}$.
Secondary charm

Secondary charm suppressed by cut on $\chi^2$ of the PV-constrained fit

Bias due to $D$ from $b$ is given by: 

$$A^D_{P(s)}(corr) = \frac{A^D_{P(s)} + f A^b_{P}}{1 + f},$$

and $f$ can differ in signal and control samples $\rightarrow$ no cancellation

$f$ is calculated from cross sections, branching fractions, efficiencies

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Simone Stracka - CHARM 2016 - Bologna - 07/09/2016
Control samples

![Graph showing control samples for LHCb Preliminary](image-url)
LHCb Yield (63k D⁺) is ~10 times higher than Belle (but also higher background)

\[ D^+ \to \pi^+ \eta', \quad \eta' \to \pi^+ \pi^- \eta_{\gamma\gamma} \]

Calorimeters

- **ECAL** made of shashlik blocks
  - Lead - scintillator stack (25 $X_0$)
  - ~6000 channels, readout by PMT
  - $\sigma(E)/E \sim 10\% / \sqrt{E} + 1\%$

- **HCAL**: scintillating tiles in iron
  - ~1500 channels, same readout and electronics as ECAL
  - $\sigma(E)/E \sim 70\% / \sqrt{E} + 9\%
  - Mainly used for trigger

- **SPD and PreShower**
  - Same geometry as ECAL
  - Scintillator tiles readout by MAPMT, separated by 2.5 $X_0$ lead sheet
  - Identify electron/photon, used in L0 trigger