LHCb results on *Mixing* and *CP violation* in Charm

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*on behalf of the LHCb collaboration*

Lake Louise Winter Institute - February 12th, 2019
Why study charm physics?

- If new physics (NP) exists it should violate CP symmetry

- **Up-type** quark: unique probe of NP in the flavor sector, **complementary** to studies in K and B systems

- Small CP asymmetries expected (0.1%÷1%)
  - CKM/GIM suppression
  - Large uncertainties due to low-energy strong interaction effects

- CP violation (CPV) in charm decays has not yet been observed

- Why at **LHCb**? Huge $c\bar{c}$ production cross-section:
  $$\sigma( pp \rightarrow c\bar{c} X )_{\sqrt{s} = 13 \text{ TeV}} \approx 2.4 \text{ mb}$$
  [JHEP 03 (2016) 159]
Mixing of neutral D mesons

- **Mass eigenstates are not the flavor eigenstates:**

\[
|D_{1,2}\rangle = p |D^0\rangle \pm q |\bar{D}^0\rangle
\]

- This causes \( D \leftrightarrow \bar{D} \) transitions described by

\[
x = \frac{m_1 - m_2}{\Gamma}
\]

\[
y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}
\]

Mixing of neutral D mesons

\[
|P^0(0)|P^0(t)|^2 \propto e^{-\Gamma t}[\cosh(y\Gamma t) + \cos(x\Gamma t)]
\]

\[
|P^0(0)|\bar{P}^0(t)|^2 \propto e^{-\Gamma t}[\cosh(y\Gamma t) - \cos(x\Gamma t)]
\]

Tiny mixing in charm!
Measurement of the charm-mixing parameter $y_{CP}$

- Compare decay widths of $D^0$ decaying to $CP$-eigenstates ($\Gamma^{CP}$) and to $CP$-mixed states ($\Gamma$):

  $$y_{CP} = \frac{\Gamma^{CP}}{\Gamma} - 1 = \Delta_{\Gamma}$$

  $$\Delta_{\Gamma} = \Gamma^{CP} - \Gamma$$

- Use $K^+K^-$ and $\pi^+\pi^-$ ($CP$-even) and $K^-\pi^+$ ($CP$-mixed) states

- $y_{CP}$ differs from 0 because of mixing

- if $CP$ symmetry is violated $y_{CP}$ differs from $y$
Strategy and results

- Use $D^0$ from semi-leptonic $B$ decays (Run-1 data)
- Determine the $K^+K^-$, $\pi^+\pi^-$ and $K^+\pi^-$ signal yields in bins of $D^0$ decay time
- Fit the acceptance-corrected ratio of $K^+K^-/K^+\pi^-$ and $\pi^+\pi^-/K^+\pi^-$ to measure $y_{CP}$
- Results are consistent between modes, and combined give:
  
  $$y_{CP} = (0.57 \pm 0.13 \text{(stat)} \pm 0.09 \text{(syst)})\%,$$

- Consistent and, as precise as, the world average
- Consistent with world average value of $y = (0.62 \pm 0.07)\%$
Direct $CP$ violation

- Corresponds to

$$A_{CP} = \frac{|A_f|^2 - |\overline{A}_f|^2}{|A_f|^2 + |\overline{A}_f|^2} \neq 0$$

- Most promising channels are **Cabibbo-suppressed** (CS) decays because $CPV$ may arise from the *interference* between the tree and the penguin amplitude
Experimentally...

- **Raw asymmetry** between the observed yields:

\[
A(D \rightarrow f) = \frac{N(D \rightarrow f) - N(\bar{D} \rightarrow \bar{f})}{N(D \rightarrow f) + N(\bar{D} \rightarrow \bar{f})}
\]

- Contributions other than \(A_{CP}\):

\[
A_P(D) = \frac{\sigma(D) - \sigma(\bar{D})}{\sigma(D) + \sigma(\bar{D})}
\]

\[
A_D(f) = \frac{\epsilon(f) - \epsilon(\bar{f})}{\epsilon(f) + \epsilon(\bar{f})}
\]
**CP asymmetries in the CS**

\(D_{s}^{+}\rightarrow K_{S}\pi^{+}, \ D^{+}\rightarrow K_{S}K^{+}\) and \(D^{+}\rightarrow \phi\pi^{+}\) decays

- Best measurements to date are from LHCb Run-1:
  - [JHEP 06 (2013) 112](none) and [JHEP 1410 (2014) 025](none)

<table>
<thead>
<tr>
<th>Channel</th>
<th>(A_{CP}) (%)</th>
<th>Dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D_{s}^{+}\rightarrow K_{S}^{0}\pi^{+})</td>
<td>(+0.38 \pm 0.46) (stat) (\pm 0.17) (syst)</td>
<td>2011-2012 (3.2/fb)</td>
</tr>
<tr>
<td>(D^{+}\rightarrow K_{S}^{0}K^{+})</td>
<td>(+0.03 \pm 0.17) (stat) (\pm 0.14) (syst)</td>
<td>2011-2012 (3.2/fb)</td>
</tr>
<tr>
<td>(D^{+}\rightarrow \phi\pi^{+})</td>
<td>(-0.04 \pm 0.14) (stat) (\pm 0.14) (syst)</td>
<td>2011 (1.1/fb)</td>
</tr>
</tbody>
</table>

- **NEW**

- Today, updated results using 3.8/fb of Run-2 data collected during 2015-2017
Strategy

- Correct raw asymmetries $A$ using kinematically weighted samples of Cabibbo-favored $D_{(s)^+}$ decays (where CPV can be neglected)

$$A_{CP}(D_s^+ \rightarrow K_S^0 \pi^+) = [A(D_s^+ \rightarrow K_S^0 \pi^+) - A_D(K^0)] - A(D_s^+ \rightarrow \phi \pi^+)$$

$$A_{CP}(D^+ \rightarrow K_S^0 K^+) = [A(D^+ \rightarrow K_S^0 K^+) - A_D(\bar{K}^0)] - [A(D^+ \rightarrow K_S^0 \pi^+) - A_D(\bar{K}^0)]$$

$$\quad - [A(D_s^+ \rightarrow K_S^0 K^+) - A_D(\bar{K}^0)] + A(D_s^+ \rightarrow \phi \pi^+)$$

$$A_{CP}(D^+ \rightarrow \phi \pi^+) = A(D^+ \rightarrow \phi \pi^+) - [A(D^+ \rightarrow K_S^0 \pi^+) - A_D(\bar{K}^0)]$$

where $K_S \rightarrow \pi^+ \pi^-$ and $A_D(K^0) = -A_D(\bar{K}^0)$ is the detection asymmetry of neutral kaons, which includes mixing and CPV effects

Production and detection asymmetries cancel out!
Determination of raw asymmetries

\[ K_S \pi^+ \]
LHCb preliminary

\[ K_S K^+ \]
LHCb preliminary

\[ \phi \pi^+ \]
LHCb preliminary

Raw asymmetries projection:
Systematics

Table 1: Summary of the systematic uncertainties (in units of $10^{-3}$) on the measured quantities. The total is the sum in quadrature of the different sources.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\mathcal{A}_{CP}(D^+_s \rightarrow K^0\pi^+)$</th>
<th>$\mathcal{A}_{CP}(D^+ \rightarrow K^0 K^+)$</th>
<th>$\mathcal{A}_{CP}(D^+ \rightarrow \phi\pi^+)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit model</td>
<td>0.39</td>
<td>0.44</td>
<td>0.24</td>
</tr>
<tr>
<td>Secondary decays</td>
<td>0.30</td>
<td>0.12</td>
<td>0.03</td>
</tr>
<tr>
<td>Kinematic diff.</td>
<td>0.09</td>
<td>0.09</td>
<td>0.04</td>
</tr>
<tr>
<td>Neutral kaon asym.</td>
<td>0.05</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>Charged kaon asym.</td>
<td>0.08</td>
<td>0.09</td>
<td>0.15</td>
</tr>
<tr>
<td>Total</td>
<td>0.51</td>
<td>0.48</td>
<td>0.29</td>
</tr>
</tbody>
</table>

LHCb preliminary
Results

- **CP asymmetries:**

\[ A_{CP}(D^+_s \rightarrow K^0_S \pi^+) = (1.3 \pm 1.9 \text{ (stat)} \pm 0.5 \text{ (syst)}) \times 10^{-3}, \]
\[ A_{CP}(D^+ \rightarrow K^0_S K^+) = (-0.09 \pm 0.65 \text{ (stat)} \pm 0.48 \text{ (syst)}) \times 10^{-3}, \]
\[ A_{CP}(D^+ \rightarrow \phi \pi^+) = (0.05 \pm 0.42 \text{ (stat)} \pm 0.29 \text{ (syst)}) \times 10^{-3}. \]

- When averaged with previous LHCb measurements they yield

\[ A_{CP}(D^+_s \rightarrow K^0_S \pi^+) = (1.6 \pm 1.7 \text{ (stat)} \pm 0.5 \text{ (syst)}) \times 10^{-3}, \]
\[ A_{CP}(D^+ \rightarrow K^0_S K^+) = (-0.04 \pm 0.61 \text{ (stat)} \pm 0.45 \text{ (syst)}) \times 10^{-3}, \]
\[ A_{CP}(D^+ \rightarrow \phi \pi^+) = (0.03 \pm 0.40 \text{ (stat)} \pm 0.29 \text{ (syst)}) \times 10^{-3}. \]

- No evidence of CPV is found
Summary

- Presented new results in Charm physics at LHCb

- Measurement of mixing parameter $y_{CP}$ as precise as the World average

- For the first time: a search for direct $CP$ violation in $D_{(s)}^{+}\rightarrow K_{S}h^{+}$ and $D^{+}\rightarrow \phi\pi^{+}$ decays

  In $D^{+}\rightarrow \phi\pi^{+}$ measured the most precise $A_{CP}$ in charm hadrons!

- All results so far are consistent with $CP$ symmetry

- However they are limited by statistics, and a large amount of data remains to be analyzed
LHCb results on Mixing and CP violation in Charm

Thanks for your attention!
Mixing and CP violation

- CPV in mixing
  Occurs if $|q/p| \neq 1$

- CPV in interference
  between mixing and decay
  Occurs if
  $\phi \overset{\text{def}}{=} \arg(q\bar{A}_f / pA_f) \neq 0$

- Charm-mixing parameter $y_{CP}$

$$y_{CP} \equiv \frac{1}{2} \left[ y \cos \phi \left( \frac{q}{p} + \frac{p}{q} \right) - x \sin \phi \left( \frac{|q|}{|p|} - \frac{|p|}{|q|} \right) \right]$$

CPV in mixing

CPV in interference
CP violation in Cabibbo-favored $D(\ell s)^+ \rightarrow K_\ell h^+$ decays

- $K_S$ reconstructed from two long tracks (LL)
  - Effect that we ignore
  - Effect that we consider

![Diagram showing decay processes and mixing effects](image-url)

$D^+$ decay modes:
- $\overline{K}^0 \rightarrow \pi^+$
- $K^0 \rightarrow \pi^+ \pi^-$
- $\pi^+ \rightarrow K^0$
- $K^0 \rightarrow \pi^+ \pi^-$

Time-dependent $A_{CP}(t)$

$A_{CP}(t) \times 10^{-3}$

$K_S^0$ LL
$K_S^0$ DD

$LHCb$-ANL-2013-055

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