Charm mixing and CPV

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on behalf of the LHCb collaboration

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Peniche, 19/06/2018
Outline

❖ CPV in charm @ LHCb

❖ Direct CPV:
 ➢ \( \Delta A_{CP}^{\Lambda_c \rightarrow p h^+ h^-} \) \[\text{JHEP 03(2018)182}\]
 ➢ \( A_{CP}^{D_0 \rightarrow K_S^0 K_S^0} \) \[\text{arXiv:1806.01642} \text{ submitted to JHEP NEW}\]
 ➢ \( A_{CP}^{D_0 \rightarrow h^+ h^- \mu^+ \mu^-} \) \[\text{LHCb-PAPER-2018-020} \text{ in preparation NEW}\]

❖ Charm mixing and indirect CPV:
 ➢ \( D_0^0 - \overline{D_0}^0 \) mixing and CPV with \( D^0 \rightarrow K^+ \pi^- \) \[\text{PRD 97(2018) 031101}\]

Giulia Tuci, 19/06/2018
CPV in charm

- Charm transitions are a unique portal for obtaining a novel access to flavor dynamics
  - complementarity wrt B and K mesons
  - CPV in charm predicted $\sim O(10^{-3})$:
    low SM background $\rightarrow$ sensitivity to “New Physics”

- CPV in charm decays has not yet been observed!

- Large samples of charm mesons decays needed $\rightarrow$ LHCb
  - $\sim 10^6 c\bar{c}$ pairs per second produced in LHCb acceptance ($2<\eta<4.5$, $0<p_T<8$ GeV/c) at LHC
  - Good momentum resolution (0.5% - 1%)
  - Excellent vertex resolution (IP resolution $(15+29/p_T)\mu$m)

\[
\begin{align*}
\sigma(pp \rightarrow D^0 X) &= 2072 \pm 2 \pm 124 \mu b \\
\sigma(pp \rightarrow D^+ X) &= 834 \pm 2 \pm 78 \mu b \\
\sigma(pp \rightarrow D_s^+ X) &= 353 \pm 9 \pm 76 \mu b \\
\sigma(pp \rightarrow D_s^{**+} X) &= 784 \pm 4 \pm 87 \mu b
\end{align*}
\]

JHEP 05 (2017) 074
Direct CPV

- Difference of decay rate between two CP conjugate states

\[ A^{CP}(f) = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})} \]

- Quantity measured in LHCb

\[ A^{raw} \equiv \frac{N_D - N_{\bar{D}}}{N_D + N_{\bar{D}}} \]

\[ A^{raw} \approx A^{CP} + A^{prod} + A^{det} \]
Direct CPV

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Production asymmetry: initial state pp is not CP symmetric

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Direct CPV

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- Quantity measured in LHCb

\[ A_{raw} \equiv \frac{N_D - N_{\bar{D}}}{N_D + N_{\bar{D}}} \]

Production asymmetry: initial state pp is not CP symmetric

Asymmetric detector acceptance + material interaction different for particles/antiparticles
$\Delta A^\text{CP}$ in $\Lambda_c \rightarrow p h^+ h^-$

- CPV in charm baryons almost unexplored

$A_{\text{CP}}(\Lambda_c^+ \rightarrow \Lambda^0 \pi^+) = (-7 \pm 31\%)$  
FOCUS, PLB 634 (2006) 165

$A_{\text{CP}}(\Lambda_c^+ \rightarrow \Lambda^0 e^+\nu_e) = (0 \pm 4\%)$  
CLEO, PRL 94 (2005) 191801

- Dataset: full Run1 sample (3 fb$^{-1}$)

- Production mode: $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- X$
  - requirements on $\Lambda_c^+ \mu^-$ vertex displacement suppress background

- Measured quantity: $\Delta A^\text{CP} = A_{\text{CP}}(\Lambda_c^+ \rightarrow p K^+ K^-) - A_{\text{CP}}(\Lambda_c^+ \rightarrow p \pi^+\pi^-)$
  - Detector and production asymmetries cancel if kinematics are identical
  - $p\pi^+\pi^-$ kinematics equalized to $pK^+K^-$ kinematics before extracting raw asymmetry, weights computed using GBDT
  - Per candidate weights provided for theoretical interpretation
ΔA^{CP} \text{ in } \Lambda_c \rightarrow ph^+h^-$

- Measured phase-space integrated CPV
- Cut-based selection to avoid creating kinematic differences between decay modes
- $A^{raw}$ extracted fitting $ph^+h^-$ mass distribution and corrected for efficiency variation across 5D phase-space → from simulated events

[1HEP 03(2018)182]
\[ \Delta A_{\text{CP}} \text{ in } \Lambda_c \rightarrow \phi^+ \phi^- \]

**Results**

\[ \Delta A_{\text{CP}} = (0.30 \pm 0.91 \pm 0.61)\% \]

Consistent with no-CPV hypothesis

Main systematic uncertainty arises from limited simulation sample-size.

Results consistent varying data-taking period (centre-of-mass energy) and magnet polarity
**$A^{CP}$ in $D^0 \rightarrow K_s^0 K_s^0$**

- Search of CPV in decay channels with high statistics not conclusive
- Different approach: search CPV in decay channels where amplitudes are suppressed

  ➢ $D^0 \rightarrow K_s^0 K_s^0$, where $A^{CP}$ could be enhanced at a level of ~1%

  B.R. ($D^0 \rightarrow K_s^0 K_s^0$) = $(1.8 \pm 0.4) \times 10^{-4}$

**Previous measurements**

<table>
<thead>
<tr>
<th>$A^{CP}(K_s^0 K_s^0)$ (%)</th>
<th>Yield</th>
<th>Collaboration</th>
</tr>
</thead>
<tbody>
<tr>
<td>-23. ± 19.</td>
<td>65 ± 14</td>
<td>CLEO</td>
</tr>
<tr>
<td>-2.9 ± 5.2 ± 2.2</td>
<td>635 ± 74</td>
<td>LHCb Run-1</td>
</tr>
<tr>
<td>-0.02 ± 1.53 ± 0.17</td>
<td>5399 ± 87</td>
<td>Belle</td>
</tr>
</tbody>
</table>

CLEO PRD 63 (2001) 071101
LHCb (Run1) JHEP 10 (2015) 055
Belle PRL 119 (2017) 171801

[arXiv:1806.01642]
A_{CP} in D^0 \rightarrow K_S^0 K_S^0

- D^{*+} \rightarrow D^0 \pi^+ decay used to tag D^0
- To remove production and detection asymmetries, D^0 \rightarrow K^+ K^- is used as a calibration channel

\[ \Delta A^{CP} \equiv A_{raw}(K_S^0 K_S^0) - A_{raw}(K^+ K^-) = A^{CP}(K_S^0 K_S^0) - A^{CP}(K^+ K^-). \]

\[ A^{CP}(K_S^0 K_S^0) = \Delta A^{CP} + A^{CP}(K^+ K^-). \]

Independently measured by LHCb with a precision of \sim 0.1%  
PLB767(2017)177
$A^{\text{CP}}$ in $D^0 \rightarrow K^0_S K^0_S$

- $D^{*+} \rightarrow D^0 \pi^+$ decay used to tag $D^0$
- To remove production and detection asymmetries $D^0 \rightarrow K^+ K^-$ is used as a calibration channel

\[
\Delta A^{\text{CP}} \equiv A^{\text{raw}}(K^0_S K^0_S) - A^{\text{raw}}(K^+ K^-) \\
= A^{\text{CP}}(K^0_S K^0_S) - A^{\text{CP}}(K^+ K^-).
\]

\[A^{\text{CP}}(K^0_S K^0_S) = \Delta A^{\text{CP}} + A^{\text{CP}}(K^+ K^-)\]

Independently measured by LHCb with a precision of $\sim 0.1\%$

PLB767(2017)177

- Data samples collected in 2015-2016 ($\sim 2\text{fb}^{-1}$)
  - **LL** sample: both $K^0_S$ are reconstructed from Long tracks
  - **LD** sample: one $K^0_S$ is Long and the other one is Downstream
$A^{CP}$ in $D^0 \rightarrow K_S^0 K_S^0$

- $A^{raw}$ extracted with a fit to $\Delta m = m(D^*) - m(D^0)$ distribution. **Total yields:** $1067 \pm 41$

**Results**

Consistent with no-CPV hypothesis and previous results. Main systematic uncertainty arises from fit model choice.
First observation of the rarest charm decays, agreement with SM

Now measured **angular and CP asymmetries** on data samples of 2011-2016 (5 fb$^{-1}$)

Asymmetries sensitive to SD in full range due to SD-LD interference

- negligible SM contribution with current precision
- O(few %) predictions for some NP models

Asymmetries compatible with zero, i.e. with SM prediction

No dependence on dimuon mass

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**Preliminary results**

$D^0 \rightarrow \pi^+ \pi^- \mu^- \mu^+$:

$A_{CP} = (4.9 \pm 3.8 \pm 0.7)\%$

$D^0 \rightarrow K^+ K^- \mu^- \mu^+$:

$A_{CP} = (0 \pm 11 \pm 2)\%$

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Further details on Jolanta Brodzicka presentation on “Rare Charm”
Mixing and indirect CPV

- Mass eigenstates linear combination of flavor eigenstates

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

\[ x \equiv \Delta m / \Gamma \]
\[ y \equiv \Delta \Gamma / 2\Gamma \]

Experimental status

- No evidence for non-zero Δm (x)
- No evidence for CP violation in mixing or interference (q/p ≠ 1)
Mixing parameters and search for CPV in $D^0 \rightarrow K^+\pi^-$

[PRD 97(2018) 031101]

- Data sample: 5fb$^{-1}$ (2011-2016)
- Used tagged $D^0 \rightarrow K^+\pi^-$ decays
- Measured the time dependent ratio of WS $D^0 \rightarrow K^+\pi^-$ and RS $D^0 \rightarrow K^-\pi^+$ decay rates

$$R(t) = \frac{N(D^0 \rightarrow K^+\pi^-)}{N(D^0 \rightarrow K^-\pi^+)}$$

$$R(t) \approx R_D + \sqrt{R_D} y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left( \frac{t}{\tau} \right)^2$$

- Approximation for $x, y \ll 1$
- $\tau$ is the average $D^0$ lifetime
- $R_D$ is the ratio of suppressed to favored decay rates
- $\delta$ is the strong-phase difference between suppressed and favored amplitudes

$\begin{align*}
x' &\equiv x \cos \delta + y \sin \delta \\
y' &\equiv y \cos \delta - x \sin \delta
\end{align*}$
Mixing parameters and search for CPV in $D^0 \rightarrow K^+\pi^-$

- Data sample: 5fb$^{-1}$ (2011-2016)
- Used tagged $D^0 \rightarrow K^+\pi^-$ decays
- Measured the time dependent ratio of WS $D^0 \rightarrow K^+\pi^-$ and RS $D^0 \rightarrow K^-\pi^+$ dominated by CF amplitude

$$R(t) = \frac{N(D^0 \rightarrow K^+\pi^-)}{N(D^0 \rightarrow K^-\pi^+)}$$

$$R^\pm(t) = R_D^\pm + \sqrt{R_D^\pm} y'^\pm t + \frac{(x'^\pm)^2 + (y'^\pm)^2}{4} t^2$$

Initial $D^0/\bar{D}^0$

$R_D^+ \neq R_D^- \rightarrow$ Direct CPV

$x'^+ \neq x'^- (y'^+ \neq y'^-) \rightarrow$ Indirect CPV
Mixing parameters and search for CPV in $D^0 \rightarrow K^+\pi^-$

- $R^\pm$ determined in 13 decay-time bins, fitting $\Delta m$ distribution
- Cuts applied to suppress problematic backgrounds, as:
  - ‘Ghost’ pions from mismatched track segments before and after the magnet
    - Possible peak in $\Delta m$ distribution
    - Wrong charge 50% of time: RS $\rightarrow$ WS migration
  - Backgrounds from mis-ID of $D^0$ daughters
  - Contamination from secondary decays: the $D^*$ is not coming from the primary vertex, but from a b-hadron decay

![Graphs showing data and fit](image)

- 1.8 $\times 10^8$ RS events
- 7.2 $\times 10^5$ WS events
Fitted efficiency-corrected data to extract $(x'^\pm,y'^\pm,R'^\pm_D)$ under three different hypotheses

- Main systematic uncertainty: residual secondary decays in the final sample
Mixing parameters and search for CPV in $D^{0} \rightarrow K^{+}\pi^{-}$

Results

- Fitted efficiency-corrected data to extract $(x'^{\pm}, y'^{\pm}, R_{D}^{\pm})$ under three different hypotheses
- Main systematic uncertainty: residual secondary decays in the final sample

\[
A_{D} = \frac{R_{D}^{+} - R_{D}^{-}}{R_{D}^{+} + R_{D}^{-}} = (-0.1 \pm 8.1(\text{stat}) \pm 4.2(\text{syst})) \times 10^{-3}
\]

Direct CPV

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<td>$y'^{+}$</td>
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<td>$y'$</td>
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Results

- Fitted efficiency-corrected data to extract \((x'^\pm,y'^\pm,R'^\pm_D)\) under three different hypotheses
- Main systematic uncertainty: residual secondary decays in the final sample

\[
A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} = (-0.1 \pm 8.1(\text{stat}) \pm 4.2(\text{syst}) \times 10^{-3}
\]

Direct CPV

No evidence for CPV

### Direct and indirect CPV

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### No direct CPV

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Conclusion

❖ Reached unprecedented precision on $D^0$-$\bar{D}^0$ mixing parameters

➢ $y' \rightarrow 5 \times 10^{-4}$  $x'^2 \rightarrow 3 \times 10^{-5}$ (still compatible with 0 within uncertainty)

❖ The search for CP violation in charm decays continues!

❖ With growing data samples **LHCb is reaching the precision to observe CP violation** as expected by SM

❖ New results from Run1 and Run2 data samples are coming

❖ Stay tuned!
Backup slides
The LHCb experiment

- **Calorimeters**: particle identification
- **Cherenkov detector**: particle identification
- **Muon chambers**
- **Vertex detector (VELO)**
- **Magnet**
- **Tracking stations**: trajectory of charged particles → momentum
\[ A^{\text{CP}} \text{ in } D^0 \rightarrow K^0_S K^0_S \]

- \( A^{\text{raw}} \) extracted with a fit to \( \Delta m = m(D^*) - m(D^0) \) distribution
- Peaking background reduced with cut based selection, e.g.
  - \( D^0 \rightarrow K^0_S \pi^+ \pi^- \), reduced performing selections on \( m(K^0_S) \) and flight distance
- Combinatorial background reduced using kNN classifier
- Results on LL and LD sample and on the two separate magnet polarities compatible within 2\( \sigma \)