Mixing and CP violation in charm

Louis Henry (IFIC, University of Valencia-CSIC)
On behalf of the LHCb collaboration
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Outline

- Introduction

- Recent results
  - A measurement of the CP asymmetry difference in $\Lambda_c^+ \to pK^+K^-$ and $p\pi^+\pi^-$ decays [arxiv:1712.07051]
  - Measurement of CP asymmetries in $D^\pm \to \eta'\pi^\pm$ and $D^+_s \to \eta'\pi^\pm$ decays (Phys. Lett. B 771 (2017) 21-30)
  - Updated determination of $D^0-\bar{D}^0$ mixing and CP violation parameters with $D^0 \to K^+\pi^-$ decays [arxiv:1712.03220]

- Conclusion
CP violation and mixing in charm decays

- CP violation (CPV) observed in down-quark sector (kaons, $B_{(s)}$ mesons).
  - Leading order for charm in Standard Model is $(1/m_c) \rightarrow$ non-observation is compatible with expectations.
  - However NP coupling solely to up-type quarks could enhance CPV effects.

- In the Standard Model (SM), no CPV in single amplitude processes.
  - Single-Cabibbo suppressed decays have different competing amplitudes $\rightarrow$ CPV possible
  - No CPV seen in charm as of yet.

- Charm mixing is very small in the SM
  \[ x = \Delta m / \Gamma, \quad y = \Delta \Gamma / 2 \Gamma \]

\[ x = (4.6^{+1.4}_{-1.5}) \times 10^{-3} \text{ and } y = (6.2 \pm 0.8) \times 10^{-3} \]

The LHCb detector


Recent results on CPV and mixing in charm decays at LHCb
\[ \Delta A_{\text{CP}} \text{ in } \Lambda_c^+ \rightarrow pK^+K^- \text{ and } p\pi^+\pi^- \text{ decays (Run 1)} \]

arxiv:1712.07051, submitted to JHEP

- Both modes are selected as part of the \( \Lambda_b^0 \rightarrow \Lambda_c^+\mu^{-}X \) decay chain.

- We measure \( A_{\text{raw}} \) as:

\[
A_{\text{raw}}(f) = \frac{N(f\mu^-) - N(\bar{f}\mu^+)}{N(f\mu^-) + N(f\mu^+)} \quad \text{related to } A_{\text{CP}} \text{ by: } A_{\text{raw}} = A_{\text{CP}} + A_{\text{detection}} + A_{\text{production}}
\]

- Measure \( A_{\text{raw}} \) for two modes and correct for kinematical differences in order to access to \( \Delta A_{\text{CP}} \).

Large source of systematic uncertainties

\( N_S \sim 2.5 \times 10^4 \)
\( \Delta A_{CP} \) in \( \Lambda_c^+ \rightarrow pK^+K^- \) and \( p\pi^+\pi^- \) decays (Run 1)

- 5-D efficiency and kinematic differences taken into account.

- Main systematics arise from the size of the simulated samples but measurement is statistically limited.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit signal model</td>
<td>0.20</td>
</tr>
<tr>
<td>Fit background model</td>
<td>—</td>
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<tr>
<td>Residual asymmetries</td>
<td>0.10</td>
</tr>
<tr>
<td>Limited simulated sample size</td>
<td>0.57</td>
</tr>
<tr>
<td>Prompt ( \Lambda_c^+ )</td>
<td>—</td>
</tr>
<tr>
<td>Total</td>
<td>0.61</td>
</tr>
</tbody>
</table>

\[
\Delta A_{CP}^{\text{raw}}(pK^+K^-) = (3.72 \pm 0.78)\% \\
\Delta A_{CP}^{\text{raw}}(p\pi^+\pi^-) = (3.42 \pm 0.47)\% \\
\Delta A_{CP} = (0.30 \pm 0.91 \pm 0.61)\%
\]

First measurement of CPV parameter in 3-body \( \Lambda_c^+ \) decays!

CPV in $D^\pm \to \eta'\pi^\pm$ and $D_s^\pm \to \eta'\pi^\pm$ decays (Run 1)


- We measure the difference in $A_{CP}$ between the studied modes and modes where $A_{CP}$ is already measured precisely.

\[
\Delta A_{CP}(D^\pm \to \eta'\pi^\pm) \equiv A_{CP}(D^\pm \to \eta'\pi^\pm) - A_{CP}(D^\pm \to K_s^0\pi^\pm) \\
= A_{\text{raw}}(D^\pm \to \eta'\pi^\pm) - A_{\text{raw}}(D^\pm \to K_s^0\pi^\pm) + A(K^0 - K^0), \\
\Delta A_{CP}(D_s^\pm \to \eta'\pi^\pm) \equiv A_{CP}(D_s^\pm \to \eta'\pi^\pm) - A_{CP}(D_s^\pm \to \phi\pi^\pm) \\
= A_{\text{raw}}(D_s^\pm \to \eta'\pi^\pm) - A_{\text{raw}}(D_s^\pm \to \phi\pi^\pm).
\]

- Three different trigger requirements:
  - Energy deposit in hadronic calorimeter from decay particle (T1)
  - Energy deposit in hadronic calorimeter from unrelated particle (T2)
  - Energy deposit in electromagnetic calorimeter or high-pT muon from unrelated particle (T3).

- \( \eta' \to \pi^+\pi^-\gamma \)
  - \( \phi \to K^+K^- \)
  - \( K_s^0 \to \pi^+\pi^- \)

CPV in $D^\pm \to \eta' \pi^\pm$ and $D^\pm_s \to \eta' \pi^\pm$ decays (Run 1)

- Fits are performed in nine bins of ($p_T$-$\eta$), then $A_{raw}$ are combined using a weighted average.

Consistent measurements through data-taking conditions and trigger requirements.

$$\Delta A_{CP}(D^\pm \to \eta' \pi^\pm) = (-0.58 \pm 0.72 \pm 0.53)\%,$$

$$\Delta A_{CP}(D^\pm_s \to \eta' \pi^\pm) = (-0.44 \pm 0.36 \pm 0.22)\%.$$

Most precise measurement to date

Charm mixing and CPV with $D^0 \to K^\pm \pi^\mp$ decays

- $D^0$ decay to $K^+\pi^-$ is doubly Cabibbo-suppressed (DCS) → interfere with $D^0 \to \bar{D}^0$ mixing.

- Analysis on Run 1 + 2015 + 2016

- $D^0$ flavor tagged at production by using $D^0$ from $D^*_\pm$

- Ratio of suppressed-to-favored decay rates approximated as:

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

$+(-)$ refers to the decay from a $D^0 (\bar{D}^0)$.

$x' = x \cos(\delta) + y \sin(\delta)$, $y' = y \cos(\delta) - x \sin(\delta)$,

$\delta$: strong-phase difference between the suppressed and favored amplitudes (CLEO-c, BESIII)

Charm mixing and CPV with $D^0 \rightarrow K^{\pm} \pi^{\mp}$ decays

- Separated in 13 bins of lifetime.

- Statistical uncertainty dominates, main sources of systematic uncertainties are residual $D^{*+}$ from B mesons and spurious soft pions $\rightarrow$ statistical in nature.

$$x' = (3.9 \pm 2.7) \times 10^{-5}, \quad y' = (5.28 \pm 0.52) \times 10^{-3}$$

$$R_D = (3.454 \pm 0.031) \times 10^{-3}$$

$$A_D = (-0.1 \pm 9.1) \times 10^{-3} \text{ and } 1.00 < |q/p| < 1.35$$

Twice as precise as previous LHCb measurement (Phys. Rev. Lett. 111 (2013))

Most stringent limits to date on charm CPV
Conclusion and prospects

- A lot of activity in Charm physics in LHCb.
  - Could not present all of the recent results, for instance:
  - Measurement of the CP violation parameter $A_{\Gamma}$ in $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ decays \(\text{(Phys. Rev. Lett. 118, 261803 (2017))}\)
  - Search for CP violation in the phase space of $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ decays \(\text{(Phys. Lett. B 769 (2017) 345-356)}\)
- Wealth of experience from Run 1 analyses → fast and improved analyses.
- Analysis of Run 2 data directly on trigger output! (“turbo” trigger).
- Systematic use of control modes, consistency checks and difference of observables allow to keep systematic uncertainties under control.
  → Despite often huge datasets (order $10^5$-$10^7$ signal candidates), presented measurements are all statistically limited.

Stay tuned!
Thank you!
The LHCb detector
The LHCb detector: tracking subsystems
The LHCb detector: particle identification

(also central in the hardware trigger)
CPV in $D^\pm \to \eta' \pi^\pm$ and $D_s^\pm \to \eta' \pi^\pm$ decays (Run 1)

- Eta or eta’: 30% of the BR
- CPV expected at the < 1% level.
- Tree-level:
  - $D_s^+ \to \eta\pi^+$ (CF): $V_{cd}^* V_{ud}(\sqrt{2} A \cos \phi - T \sin \phi)$;
  - $D_s^+ \to \eta'\pi^+$ (CF): $V_{cs}^* V_{ud}(\sqrt{2} A \sin \phi + T \cos \phi)$;
  - $D^+ \to \eta\pi^+$ (SCS): $\frac{1}{\sqrt{2}} V_{cd}^* V_{ud}(T' + C' + 2A') \cos \phi - V_{cs}^* V_{us} C' \sin \phi$;
  - $D^+ \to \eta'\pi^+$ (SCS): $\frac{1}{\sqrt{2}} V_{cd}^* V_{ud}(T' + C' + 2A') \sin \phi + V_{cs}^* V_{us} C' \cos \phi$;
  - $D_s^+ \to \eta K^+$ (SCS): $V_{cs}^* V_{us} \left[\frac{1}{\sqrt{2}} A'' \cos \phi - (T'' + C'' + A'') \sin \phi\right] + \frac{V_{cd}^* V_{ud}}{\sqrt{2}} C'' \cos \phi$;
  - $D_s^+ \to \eta' K^+$ (SCS): $V_{cs}^* V_{us} \left[\frac{1}{\sqrt{2}} A'' \cos \phi + (T'' + C'' + A'') \sin \phi\right] + \frac{V_{cd}^* V_{ud}}{\sqrt{2}} C'' \cos \phi$;
  - $D^+ \to \eta K^+$ (DCS): $V_{cd}^* V_{us} \left[\frac{1}{\sqrt{2}} (T'' + A'') \cos \phi - A'' \sin \phi\right]$;
  - $D^+ \to \eta' K^+$ (DCS): $V_{cd}^* V_{us} \left[\frac{1}{\sqrt{2}} (T'' + A'') \sin \phi + A'' \cos \phi\right]$;

CPV in $D^{\pm}\rightarrow\eta'\pi^{\pm}$ and $D_{s}^{\pm}\rightarrow\eta'\pi^{\pm}$ decays (Run 1)

- Signal form: Johnson distributions, tails shared between signals and $(p_{T}$-eta) bins
  
  $f(x; \mu, \sigma, \delta, \gamma) \propto \left[ 1 + \left( \frac{x - \mu}{\sigma} \right)^{2} \right]^{-\frac{1}{2}} \exp \left\{ -\frac{1}{2} [\gamma + \delta \sinh^{-1} \left( \frac{x - \mu}{\sigma} \right)]^{2} \right\}$.

- Background: 4th order polynomial with parameters Gaussian-constrained by sideband fit.

- Peaking backgrounds: all suppressed except $D_{s} \rightarrow \phi(\rightarrow \pi^{+}\pi^{-}\pi^{0})\pi$, $A_{CP}$ from control sample.

- $A_{CP}$ computed as inverse-variance weighted average over the $(p_{T}$-eta) bins.

- Dominant systematic: background model.
  - Background $\rightarrow$ second-order polynomial, ARGUS
  - Fix parameters from sideband, change peaking background contribution
  - Neglected contributions, signal leaking in sidebands, remaining nonresonant $(K^{+}K^{-})$ in control sample
  - Independently assessed by lifting constraints and observing increase of statistical uncertainty.
Charm mixing and CPV with $D^0 \rightarrow K^\pm \pi^\mp$ decays: systematics

<table>
<thead>
<tr>
<th>No CP violation</th>
<th>Source</th>
<th>$R_D$ $[10^{-3}]$</th>
<th>$y^+$ $[10^{-3}]$</th>
<th>$y^-$ $[10^{-3}]$</th>
<th>$x^{2+}$ $[10^{-3}]$</th>
<th>$x^{2-}$ $[10^{-3}]$</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Instrumental asymm.</td>
<td>$&lt; 0.001$</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.001$</td>
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<td></td>
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<tr>
<td></td>
<td>Peaking background</td>
<td>$\pm 0.003$</td>
<td>$\pm 0.04$</td>
<td>$\pm 0.002$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Secondary $D$ decays</td>
<td>$\pm 0.010$</td>
<td>$\pm 0.21$</td>
<td>$\pm 0.011$</td>
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<tr>
<td></td>
<td>Ghost soft pions</td>
<td>$\pm 0.008$</td>
<td>$\pm 0.15$</td>
<td>$\pm 0.008$</td>
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<tr>
<td></td>
<td>Total syst. uncertainty</td>
<td>$\pm 0.014$</td>
<td>$\pm 0.27$</td>
<td>$\pm 0.014$</td>
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</tr>
<tr>
<td></td>
<td>Statistical uncertainty</td>
<td>$\pm 0.028$</td>
<td>$\pm 0.45$</td>
<td>$\pm 0.023$</td>
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</tr>
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</table>

<table>
<thead>
<tr>
<th>No direct CP violation</th>
<th>Source</th>
<th>$R_D$ $[10^{-3}]$</th>
<th>$y^+$ $[10^{-3}]$</th>
<th>$y^-$ $[10^{-3}]$</th>
<th>$x^{2+}$ $[10^{-3}]$</th>
<th>$x^{2-}$ $[10^{-3}]$</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Instrumental asymm.</td>
<td>$&lt; 0.001$</td>
<td>$\pm 0.08$</td>
<td>$\pm 0.08$</td>
<td>$\pm 0.003$</td>
<td>$\pm 0.004$</td>
</tr>
<tr>
<td></td>
<td>Peaking background</td>
<td>$\pm 0.003$</td>
<td>$\pm 0.04$</td>
<td>$\pm 0.04$</td>
<td>$\pm 0.002$</td>
<td>$\pm 0.002$</td>
</tr>
<tr>
<td></td>
<td>Secondary $D$ decays</td>
<td>$\pm 0.010$</td>
<td>$\pm 0.21$</td>
<td>$\pm 0.21$</td>
<td>$\pm 0.011$</td>
<td>$\pm 0.012$</td>
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<tr>
<td></td>
<td>Ghost soft pions</td>
<td>$\pm 0.008$</td>
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<td>$\pm 0.009$</td>
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<tr>
<td></td>
<td>Total syst. uncertainty</td>
<td>$\pm 0.014$</td>
<td>$\pm 0.29$</td>
<td>$\pm 0.29$</td>
<td>$\pm 0.016$</td>
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<tr>
<td></td>
<td>Statistical uncertainty</td>
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<td>$\pm 0.48$</td>
<td>$\pm 0.48$</td>
<td>$\pm 0.026$</td>
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</table>

<table>
<thead>
<tr>
<th>Direct and indirect CP violation</th>
<th>Source</th>
<th>$R^+_D$ $[10^{-3}]$</th>
<th>$R^-_D$ $[10^{-3}]$</th>
<th>$y'^+$ $[10^{-3}]$</th>
<th>$y'^-$ $[10^{-3}]$</th>
<th>$x'^{2+}$ $[10^{-3}]$</th>
<th>$x'^{2-}$ $[10^{-3}]$</th>
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</thead>
<tbody>
<tr>
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<td>Instrumental asymm.</td>
<td>$\pm 0.006$</td>
<td>$\pm 0.006$</td>
<td>$\pm 0.04$</td>
<td>$\pm 0.04$</td>
<td>$\pm 0.03$</td>
<td>$\pm 0.002$</td>
</tr>
<tr>
<td></td>
<td>Peaking background</td>
<td>$\pm 0.003$</td>
<td>$\pm 0.003$</td>
<td>$\pm 0.04$</td>
<td>$\pm 0.04$</td>
<td>$\pm 0.04$</td>
<td>$\pm 0.002$</td>
</tr>
<tr>
<td></td>
<td>Secondary $D$ decays</td>
<td>$\pm 0.014$</td>
<td>$\pm 0.014$</td>
<td>$\pm 0.29$</td>
<td>$\pm 0.29$</td>
<td>$\pm 0.29$</td>
<td>$\pm 0.015$</td>
</tr>
<tr>
<td></td>
<td>Ghost soft pions</td>
<td>$\pm 0.012$</td>
<td>$\pm 0.012$</td>
<td>$\pm 0.21$</td>
<td>$\pm 0.21$</td>
<td>$\pm 0.21$</td>
<td>$\pm 0.011$</td>
</tr>
<tr>
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<td>Total syst. uncertainty</td>
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<td>$\pm 0.020$</td>
<td>$\pm 0.38$</td>
<td>$\pm 0.38$</td>
<td>$\pm 0.38$</td>
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<tr>
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<td>Statistical uncertainty</td>
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<td>$\pm 0.040$</td>
<td>$\pm 0.64$</td>
<td>$\pm 0.64$</td>
<td>$\pm 0.64$</td>
<td>$\pm 0.032$</td>
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</tbody>
</table>
What do we mean when we say that “asymmetries are small”?

\[
A_{CP}^{\text{Raw}}(f) = \frac{\mathcal{P}(\Lambda_b^0)\epsilon(\mu^-)\epsilon(f)\Gamma(f) - \mathcal{P}(\bar{\Lambda}_b^0)\epsilon(\mu^+)\epsilon(f)\Gamma(f)}{\mathcal{P}(\Lambda_b^0)\epsilon(\mu^-)\epsilon(f)\Gamma(f) + \mathcal{P}(\bar{\Lambda}_b^0)\epsilon(\mu^+)\epsilon(f)\Gamma(f)},
\]

\[
A_P^{\Lambda_b^0}(f) = \frac{\mathcal{P}(\Lambda_b^0) - \mathcal{P}(\bar{\Lambda}_b^0)}{\mathcal{P}(\Lambda_b^0) + \mathcal{P}(\bar{\Lambda}_b^0)},
\]

\[
A_D^{\mu}(f) = \frac{\epsilon(\mu^-) - \epsilon(\mu^+)}{\epsilon(\mu^-) + \epsilon(\mu^+)},
\]

\[
A_D^{f}(f) = \frac{\epsilon(f) - \epsilon(\bar{f})}{\epsilon(f) + \epsilon(\bar{f})},
\]

\[
x = \frac{1}{2}(x + y)(1 + X),
\]

\[
y = \frac{1}{2}(x + y)(1 - X).
\]

\[
A_{CP}^{\text{Raw}}(f) = \frac{A_P^{\Lambda_b^0} A_D^{\mu} A_D^{f} + A_P^{\Lambda_b^0} A_D^{\mu} A_{CP} + A_P^{\Lambda_b^0} A_D^{f} A_{CP} + A_D^{\mu} A_P^{\Lambda_b^0} A_D^{f} A_{CP} + A_D^{\mu} A_D^{f} A_{CP} + A_D^{\mu} A_D^{f} A_{CP}}{1 + A_P^{\Lambda_b^0} A_D^{\mu} + A_P^{\Lambda_b^0} A_D^{f} + A_P^{\Lambda_b^0} A_{CP} + A_D^{\mu} A_D^{f} + A_D^{\mu} A_{CP} + A_D^{f} A_D^{f} A_{CP}}.
\]