Mixing and CP violation results in charm decays at LHCb

Silvia Borghi
On behalf of the LHCb Collaboration
D⁰ mixing

* D⁰ oscillation is characterized by:

** mixing parameters: 
\[ x \equiv \frac{(m_2 - m_1)}{\Gamma} \] and 
\[ y \equiv \frac{(\Gamma_2 - \Gamma_1)}{2\Gamma} \]

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

* Theoretical expectation: \(|x|, |y| \lesssim O(10^{-2})\)

* Experimental status


** Mixing well established with more than 10 σ. Most recent and precise measurements at LHCb [PRL 111 (2013) 231802]
CP violation in charm

* CP-violating asymmetries in the charm sector provide a unique probe for physics beyond the Standard Model (SM)
* In the SM CP violation is expected to be small
* New Physics can enhance CP violating observables
* CP violation contributions:
  ★ In decay: amplitudes for a process and its conjugate differ
  ➔ direct CP violation

\[
\frac{|A_f|}{A_f} \approx 1 \pm A_d \quad \text{with } A_d \neq 0
\]

★ In mixing: rate of \( D^0 \to \bar{D}^0 \) and \( \bar{D}^0 \to D^0 \) differ:

\[
\frac{q}{p} \approx 1 \pm A_m \quad \text{with } A_m \neq 0
\]

★ In interference between mixing and decay diagrams

➔ indirect CP violation

\[
a_{CP}^{ind} = -\frac{A_m}{2} y \cos \phi + x \sin \phi
\]

Silvia Borghi
LHCP, Shanghai 14-20 May 2017
Direct CPV search in $D^+_{(s)} \rightarrow \eta' \pi^+$

arXiv:1701.01871; submitted to PLB
CP asymmetries in decays to $\eta'$ not yet measured at hadron collider

Strategy: subtract detector asymmetries using control channels

Main challenge: background modelling.

Main physics background from $D_{(S)}^* \rightarrow \pi(\phi \rightarrow \pi^+ \pi^- \pi^0)$

$$A_{CP}(D^+ \rightarrow \eta'\pi^+) \equiv A_{raw}(D^+ \rightarrow \eta'\pi^+) - A_{raw}(D^+ \rightarrow K_S\pi^+) + A_{CP}(D^+ \rightarrow K_S^0\pi^+) + A_{mix}(K_S^0)$$

$$A_{CP}(D_s^+ \rightarrow \eta'\pi^+) \equiv A_{raw}(D_s^+ \rightarrow \eta'\pi^+) - A_{raw}(D_s^+ \rightarrow \phi\pi^+) + A_{CP}(D_s^+ \rightarrow \phi\pi^+)$$

Fit $m(\pi\pi)$ to extract raw asymmetry

Control channel asymmetry

External input (D0, Belle)
Direct CPV search in $D^{+}(s) \rightarrow \eta' \pi^{+}$

- Separate by magnet polarity and collision energy
- Bin in $\eta(\pi)$, $p_{T}(\pi)$ to improve cancellation of detector asymmetries
- Statistically limited
- Largest systematic uncertainty from background model in fit
- Additional uncertainty from external $A_{CP}$ (control) input

Data sample: 63k $D^{\pm}$ and 152k $D^{\pm}_{s}$

$$A_{CP}(D^{\pm} \rightarrow \eta' \pi^{\pm}) = (-0.61 \pm 0.72 \pm 0.55 \pm 0.12)\%$$

$$A_{CP}(D^{\pm}_{s} \rightarrow \eta' \pi^{\pm}) = (-0.82 \pm 0.36 \pm 0.24 \pm 0.27)\%$$

Consistent with CP conservation

Most precise measurements to date
Search of CPV in $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ decays

Search of CPV in $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ decays

- Multi-body charm decays have rich resonant structure
  - Variation of strong phase difference among the Dalitz plot may enhance local CPV sensitivity
- The energy test: a model-independent unbinned method to search for local CPV in the decay phase space
  - Previously used in LHCb $D^0 \rightarrow \pi^+ \pi^- \pi^0$ [Phys. Lett B740 (2015) 158]
  - First time used in four-body decay
- $\pi$-tagged $D^0$ candidates on full Run 1 sample:
  - ~1M signal candidates with high purity
Energy tests

* Compare two distributions statistically
* Electric charge analogy
  ✷ +q and -q evenly distributed \(\Rightarrow\) potential energy \(E=0\)
  ✷ +q and -q differently distributed \(\Rightarrow\) potential energy \(E>0\)
* Construct test statistic based on difference in phase space separations \(d_{ij}\) between same and opposite charges:

\[
T = \sum_{i,j>i}^{n} \frac{\psi_{ij}}{n(n-1)} + \sum_{i,j>i}^{\bar{n}} \frac{\psi_{ij}}{\bar{n}(\bar{n}-1)} - \sum_{i,j}^{n,\bar{n}} \frac{\psi_{ij}}{n\bar{n}}
\]

where the interaction potential \(\psi(d_{ij}) = e^{-d_{ij}/d^2}\) and \(n, \bar{n}\) the number of \(D^0\) and \(\bar{D}^0\)
* Compare T-value from tested sample \((T^0)\) with T-values from no-CPV samples.
* P-value: fraction of permutation T-values above \(T^0\)
Search of CPV in $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ decays

* $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ phase space is 5D
* Chose five invariant masses with most sensitivity to CPV from dominant resonances
  - $D^0 \rightarrow a_1(1260)^+\pi^-$, $a_1^+\rightarrow\rho^0(770)\pi^+$
  - $D^0 \rightarrow \rho^0(770)\rho^0(770)$
* Standard test compare $D^0 - \overline{D^0}$, sensitive to only P-even
* In decays to four or more pseudo-scalars, there is the possibility of using P-odd observables for CPV searches
  - Introduce triple product $C_T$ as parity sensitive variable
    \[ C_T = \hat{p}(\pi_3) \cdot [\hat{p}(\pi_1) \times \hat{p}(\pi_2)] \]
  - Separate samples by triple product sign $\Rightarrow$ P-odd CPV

\[
A_{CP}^{P-even} = \frac{A_{CP}(C_T > 0) + A_{CP}(C_T < 0)}{2}, \quad A_{CP}^{P-odd} = \frac{A_{CP}(C_T > 0) - A_{CP}(C_T < 0)}{2}
\]
Search of CPV in $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ decays

*Results*

- **P-even CPV**: $p$-value = $(4.3 \pm 0.6)\%$ Consistent with CP asymmetry
- **P-odd CPV**: $p$-value = $(0.6 \pm 0.2)\%$ P-odd test marginally consistent with no-CPV hypothesis. Significance of $2.7 \sigma$ for CP non-conservation

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LHCb, Shanghai 14-20 May 2017

Silvia Borghi
Mixing and CPV in \(D^0 \rightarrow K^+ \pi^-\) decays


Poster of Adam Davis at this conference
Measurements of charm mixing and CP violation using \(D^0 \rightarrow K^+ \pi^-\) decays
Mixing and CPV in $D^0 \to K^+\pi^-$ decays

* $D^0 \to K^-\pi^+$ (right sign, RS) dominated by Cabibbo favoured decay; while wrong-sign (WS) has two possible paths w/o mixing

$D^0$  
\begin{center}
\begin{tikzcd}
\text{WS} \arrow[r, no mix] & \text{DCS} \arrow[r, mix] & K^+\pi^- \\
\text{RS} \arrow[r, no mix] & \text{DCS} \arrow[r, mix] & K^-\pi^+
\end{tikzcd}
\end{center}

* Considering $|x|$ and $|y| \ll 1$ and assuming no CPV, the time dependent ratio is

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

$R_D$ = magnitude squared of DCS/CF amplitudes

$\delta$ is the strong phase between CF and DCS amplitudes

$$x' = x \cos \delta + y \sin \delta$$

$$y' = y \cos \delta + x \sin \delta$$
Mixing and CPV in $D^0 \rightarrow K^+\pi^-$ decays

* $D^0 \rightarrow K^-\pi^+$ (right sign, RS) dominated by Cabibbo favoured decay; while wrong-sign (WS) has two possible paths w/o mixing

* Considering $|x|$ and $|y| \ll 1$ and allowing CPV the time dependent ratio is

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

* If $R^+(t) \neq R^-(t)$ $\Rightarrow$ CP violation
  
  ★ Indirect CPV: $x'^+ \neq x'^-$ and/or $y'^+ \neq y'^-$
  
  ★ Direct CPV: $R_D^+ \neq R_D^-$
Mixing and CPV in $D^0 \rightarrow K^+ \pi^-$ decays

* Search of CP violation in $D^0 - \overline{D^0}$ mixing by comparing the decay-time dependent ratio of $D^0$ and $\overline{D^0}$

* Double-tagged data sample of $D^0$ from $\overline{B} \rightarrow D^{*+} \mu^- X$ with $D^{*+} \rightarrow D^0 (\rightarrow K^+ \pi^-) \pi^+$

* Fit $D^*$ mass distributions to extract RS and WS yields in 5 time bins

* Correct for time-dependent detector effects

* 3 fit scenario considered:
  - CPV allowed
  - no direct CPV
  - no CPV allowed

Consistent with no CPV hypothesis
Mixing and CPV in $D^0 \rightarrow K^+\pi^-$ decays

* Simultaneous fit of the double-tagged sample and the prompt $\pi$-tagged $D^0$ sample [PRL 111 (2013) 231802]

Results for all CPV allowed

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_D^+$</td>
<td>$3.474 \pm 0.081$</td>
</tr>
<tr>
<td>$R_D^-$</td>
<td>$3.591 \pm 0.081$</td>
</tr>
<tr>
<td>$y'^+$</td>
<td>$5.97 \pm 1.25$</td>
</tr>
<tr>
<td>$y'^-$</td>
<td>$4.50 \pm 1.21$</td>
</tr>
<tr>
<td>$x'^+2$</td>
<td>$0.11 \pm 0.65$</td>
</tr>
<tr>
<td>$x'^-2$</td>
<td>$0.61 \pm 0.61$</td>
</tr>
</tbody>
</table>

* Precision improves by 10–20% when adding double tagged data (2.5% of signal)

* Gain from complementary decay-time coverage, and higher signal purity

Consistent with hypothesis of CP symmetry
$A_T$ measurement

arXiv:1702.06490; accepted by PRL
\[ A_{\Gamma} \text{ measurement} \]

- The time-dependent CP asymmetry is

\[
A_{CP}(t) = \frac{\Gamma(D^0(t) \rightarrow f) - \Gamma(\bar{D}^0(t) \rightarrow f)}{\Gamma(D^0(t) \rightarrow f) + \Gamma(\bar{D}^0(t) \rightarrow f)} \approx a_{\text{dir}}^f - A_{\Gamma} \frac{t}{\tau_D}
\]

$\Gamma$ is the final state $K^-K^+$ or $\pi^-\pi^+$; control channel $D^0 \rightarrow K^-\pi^+$

- Expectation: $A_{\Gamma} < O(10^{-3})$ in SM \[arXiv:1612.07233\]

- A significant non-zero value of $A_{\Gamma}$ would be a clear measurement of CP violation and could be a sign of new physics contribution.

- Prompt $\pi$-tagged $D^0$ sample with the full Run 1 integrated luminosity

- Two independent measurements using different approaches:
  - Binned fit versus decay time (full 3 fb\(^{-1}\) sample)
  - Unbinned fit (2 fb\(^{-1}\) @ 8 GeV). The 7 TeV analysis described in PRL 112 (2014) 041801
**$A_\Gamma$ measurement**

- Yield extracted by fitting the $\delta m = m(D\pi) - m(\pi)$ distribution in bins of $t(D^0)$
- Reweight events to have same soft pion distributions in production angle and curvature
- Validate on control channel $D^0 \rightarrow K^-\pi^+$
- Extract $A_\Gamma$ by linear fit of the asymmetry as function of the proper decay time

\[
A_\Gamma(K^+K^-) = (-0.30\pm0.32\pm0.10)x10^{-3}
\]
\[
A_\Gamma(\pi^+\pi^-) = (0.46\pm0.58\pm0.12)x10^{-3}
\]
- Assuming only indirect CP asymmetry contributes to $A_\Gamma$ the two results are average

\[
A_\Gamma = (-0.13\pm0.28\pm0.10)x10^{-3}
\]
The measurement of $A_{\Gamma}$ involves the following steps:

- Yield extracted by fitting the $\delta m = m(D\pi) - m(\pi)$ distribution in bins of $t(D^0)$
- Reweight events to have the same soft pion distributions in production angle and curvature
- Validate on control channel $D^0 \rightarrow K^-\pi^+$
- Extract $A_{\Gamma}$ by linear fit of the asymmetry as a function of the proper decay time

\[
A_{\Gamma}(K^+K^-) = (-0.30\pm0.32\pm0.10) \times 10^{-3}
\]
\[
A_{\Gamma}(\pi^+\pi^-) = (0.46\pm0.58\pm0.12) \times 10^{-3}
\]

- Assuming only indirect CP asymmetry contributes to $A_{\Gamma}$, the two results are averaged to

\[
A_{\Gamma} = (-0.13\pm0.28\pm0.10) \times 10^{-3}
\]

- Combining with the statistical independent data sample $\bar{B} \rightarrow D^{*+}\mu^-X$ [JHEP 1504 (2015) 043]

\[
A_{\Gamma} = (-0.29\pm0.28) \times 10^{-3}
\]

Consistent with no-CPV hypothesis.

Most precise measurements of CPV in charm system ever made.
Conclusion

✱ Comprehensive investigation of mixing and CPV in charm using LHCb Run 1 data
   ✫ No evidence for any CP violation so far
   ✫ Measurements still statistically limited
   ✫ Many systematics also scale inversely with sample size (control sample reweighting, background modelling, …)

✱ Run 2 and beyond offers significant opportunity for charm physics
   ✫ Run2: two times yield from energy plus gains from trigger optimization; as well new lifetime unbiased hadronic triggers
   ✫ Run3: upgraded detector will allow to deeply exploit the charm sector

Stay tuned: much more to come!
BACKUP
World average

\[ a_{\text{CP}}^{\text{ind}} = (0.056 \pm 0.040)\% \quad \text{and} \quad \Delta a_{\text{CP}}^{\text{dir}} = (-0.137 \pm 0.070)\% \]

⊙ Consistent with no CP violation at 6.5% C.L.