CP Violation and Mixing in Charm at LHCb
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Why are we interested in charm physics?

1. Precision measurements of CPV involving up-type quarks
   ⇒ studies complementary to K and B.

2. In Charm:
   ⇒ Expect very small CP asymmetry in the SM $\sim 10^{-3}$.
   Hints of NP if higher values are observed!
   ⇒ Mixing very slow therefore highly precise detector required.

3. Theoretical predictions are difficult since $m_c \approx \Lambda_{QCD}$ and $\alpha_s(m_c)$ is large.
Cabibbo-Kobayashi-Maskawa (CKM) Matrix and CPV

\[ V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \frac{1}{2} \lambda^2 & \lambda & A\lambda^3 (\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2} \lambda^2 & A\lambda^2 \\ A\lambda^3 (1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4) \]

1. Complex phase \( i\eta \Rightarrow \text{the only known source of CPV in the SM} \)

2. Relation relevant for \( D^0 \) meson decays and mixing:
   \[ \Rightarrow V_{ud}^* V_{cd} + V_{us}^* V_{cs} + V_{ub}^* V_{cb} = 0 \]

3. Scale of CPV related to the openness of the unitary triangle
   \[ D^0 : \beta_c \approx 0.03^\circ \]
   \[ B^0 : \beta \approx 22^\circ \]

\[ \beta_c \]

\[ V_{ud}^* V_{cd} \sim \lambda \]

\[ V_{us}^* V_{cs} \sim \lambda \]

\[ V_{ub}^* V_{cb} \sim \lambda^5 \]

\text{sine of Cabbibo angle} \( \lambda \approx 0.2 \)
All types of CPV

1. Direct (charm hadrons $M$):
   - CPV in decay $|A(M \to f)|^2 \neq |A(\bar{M} \to \bar{f})|^2$

2. Indirect (only for neutral mesons):
   - CPV in mixing $\Gamma(D^0 \to \bar{D}^0) \neq \Gamma(D^0 \to D^0)$
   - CPV in interference between mixing and decay $\Gamma(D^0 \to \bar{D}^0 \to f_{CP}) \neq \Gamma(\bar{D}^0 \to D^0 \to f_{CP})$
CKM Matrix and classification of decays

\[ V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \frac{1}{2} \lambda^2 & \lambda & A \lambda^3 (\rho - i \eta) \\ -\lambda & 1 - \frac{1}{2} \lambda^2 & A \lambda^2 \\ A \lambda^3 (1 - \rho - i \eta) & -A \lambda^2 & 1 \end{pmatrix} + O(\lambda^4) \]

1. \( \lambda \approx 0.2 \) defined as sine of the Cabibbo angle.

2. Decay classification: \( \lambda^n \) in decay amplitudes:
   - Cabibbo favoured (CF) \( \rightarrow n = 0 \),
   - singly Cabibbo suppressed (SCS) \( \rightarrow n = 1 \),
   - doubly Cabibbo suppressed (DCS) \( \rightarrow n = 2 \).

3. SCS decays (both tree and penguin contributions)
   \( \Rightarrow \) small CPV present in the SM

4. CF and DCS decays (only one diagram contributes)
   \( \Rightarrow \) no CPV in the SM
"LHCb Run1 (2011-2012) and Run2 (2015-2018)"

° World’s Largest sample of charm hadron decays:
  ⇒ \( \sigma(pp \rightarrow c\bar{c}X) \approx 2.4 \text{mb} @ \sqrt{s} = 13 \text{ TeV} [\text{JHEP 05 (2017) 074}] \)
  ⇒ Run1 \( \rightarrow 3 \text{fb}^{-1} @ \sqrt{s} = 7-8 \text{ TeV} \); 
  ⇒ Run2 \( \rightarrow 6 \text{fb}^{-1} @ \sqrt{s} = 13 \text{ TeV} \)

° Excellent particle identification, tracking and vertexing:
  ⇒ Momentum resolution \( \Delta p/p = 0.5\% \) at low momentum.
  ⇒ Impact parameter resolution: \( (15 + 29/p_T) \mu m \)
  ⇒ Decay time resolution: \( 45\text{fs} \sim 0.1\tau_{D_0} \).
Experimental status - CPV in the decay

- In 2019 LHCb reported first observation of CPV in charm.
  \[ \Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-15.4 \pm 2.9) \cdot 10^{-4} \ (5.3\sigma) \ [PRL \ 122, \ 211803] \]

- In 2023 evidence of CPV in \( D^0 \rightarrow \pi^+\pi^- \) decay.
  \[ a^d_{\pi^+\pi^-} = (23.2 \pm 6.1) \cdot 10^{-4} \ (3.8\sigma) \ [PRL \ 131, \ 091802] \]

- Interpretation within the SM still debated.
energy-test

- CPV in $D^0 \rightarrow K_S^0 K^\pm \pi^\mp$ with energy test [JHEP 03 (2024) 107]
- CPV in $D^0 \rightarrow \pi^0 \pi^- \pi^+$ with energy test [JHEP 09 (2023) 129]
Outline

energy-test

° CPV in $D^0 \rightarrow K^0 S K^{\pm} \pi^{\mp}$ with energy test [JHEP 03 (2024) 107]
° CPV in $D^0 \rightarrow \pi^0 \pi^- \pi^+$ with energy test [JHEP 09 (2023) 129]

time-dependent

° Mixing and CPV in $D^0 \rightarrow K^+ \pi^-$ [LHCb-PAPER-2024-008]
° CPV in $D^0 \rightarrow \pi^0 \pi^- \pi^+$ decays [arXiv:2405.06556]
Search for CPV with multibody decays - experimental idea

1. Multibody decays:
   ⇒ Strong-phase differences varying across the phase-space
   ⇒ CP asymmetries may appear locally

2. Three body decay $M \to m_1 m_2 m_3 \to$ visual representation Dalitz plot
   ⇒ $m_{ij}$ is an invariant mass for $m_i$ and $m_j$

3. We want to compare CP conjugated $D^0$ and $\overline{D^0}$ statistically.

4. Analysis tools for local CPV studies:
   ⇒ Amplitude models (sys. uncertainties assessment difficult)
   ⇒ Model independent methods $\to$ Energy test (today)
Energy test method (unbinned method) [JHEP 03 (2024) 107]

1. Energy test uses distance weight $\Psi$ to compute $T$ test statistic.
2. $T$ quantifies average distance between pairs of events in the phase-space.

$$T = \frac{1}{2} \frac{1}{n(n-1)} \sum_{i \neq j}^{n} \psi_{ij} + \frac{1}{2} \frac{1}{\bar{n}(\bar{n}-1)} \sum_{i \neq j}^{\bar{n}} \psi_{ij} - \frac{1}{n\bar{n}} \sum_{i,j}^{n,\bar{n}} \psi_{ij},$$

- Average distance in the first sample. For example in the sample of $D^0$.
- Average distance in the second sample. For example in the sample of $\bar{D}^0$.
- Average distance between the two samples. Distances between $D^0$ and $\bar{D}^0$ pairs.

3. Distance weight $\psi_{ij} = e^{-d_{ij}^2/2\delta}$
4. Phase-space distance $d_{ij}^2 = (s_{12,i} - s_{12,j})^2 + (s_{13,i} - s_{13,j})^2 + (s_{23,i} - s_{23,j})^2$.
5. Phase-space parametrised with invariant masses of pairs of decay products: $s_{12}, s_{13}, s_{23}$.
6. For $D^0 \rightarrow K^0_s K^\pm \pi^\mp$: $s_{12} = m^2(K^0_s K^\pm)$, $s_{13} = m^2(K^0 S \pi^\pm)$, $s_{23} = m^2(K^\pm \pi^\mp)$.
Test idea [JINST 13 (2018) P04011]

- Permuted T-values (null hypothesis) $\rightarrow$ randomly assign flavours to data
- Measure p-value $\Rightarrow$ fraction of T-values $\geq$ Data T-value.
- No CPV $\Rightarrow$ Data T-value $\approx 0$, p-value large
- Large CPV $\Rightarrow$ Data T-value large and $> 0$, p-value $\approx 0$
CPV in $D^0 \rightarrow K_S^0 K^{\pm} \pi^\mp$ Phase-space [JHEP 03 (2024) 107], dataset (2016-2018)

- $D^{*+} \rightarrow D^0 \pi^+$ strong decays, $\pi^+$ tagging
- Two signal states:
  - **SS**: $K^0_S K^+ \pi^-$ (same-sign)
  - **OS**: $K^0_S K^+ \pi^-$ (opposite-sign)
- $K^0_S$ identified via $\pi^+ \pi^- \pi^0$ decay
- Control channels:
  - $D^0 \rightarrow K^- \pi^+ \pi^- \pi^0$
  - $D^0 \rightarrow K_S^0 \pi^+ \pi^-$

Sample 7x larger than [PRD 94, 0502019 (2016)]
CPV in $D^0 \to \pi^0\pi^0\pi^+$ Phase-space [JHEP 09 (2023) 129], dataset (2015-2018)

- $D^{*+} \to D^0 \pi^+$ strong decays, $\pi^+$ tagging
- Two $\pi^0$ reconstruction modes:
  - **resolved**: low $p_T(\pi^0)$
  - **merged**: high $p_T(\pi^0)$
- Control channel:
  $D^0 \to K^- \pi^+\pi^-$

Sample 4x larger than [PLB 740 (2015) 158]
Measurement of CPV with $D^0 \rightarrow K^+\pi^-$ [LHCb-PAPER-2024-008]

Signal yields for LHCb Run2: $\sim 400$M events in RS and $\sim 1.6$M in WS

$$R^+_{K\pi} = \frac{\Gamma(D^0(t) \rightarrow K^+\pi^-)}{\Gamma(D^0 \rightarrow K^-\pi^+)}; \quad R^-_{K\pi} = \frac{\Gamma(D^0(t) \rightarrow K^-\pi^+)}{\Gamma(D^0 \rightarrow K^+\pi^-)};$$

For small theoretical mixing parameters $x_{12}, y_{12} \ll 1$:

$$R^\pm_{K\pi}(t) \approx R_{K\pi} (1 \pm A_{K\pi}) + R_{K\pi} (1 \pm A_{K\pi}) (c_{K\pi} \pm \Delta c_{K\pi}) \left( \frac{t}{\tau_{D^0}} \right) + (c'_{K\pi} \pm \Delta c'_{K\pi}) \left( \frac{t}{\tau_{D^0}} \right)^2$$

CPV observables: $A_{K\pi}$ (in decays), $\Delta c_{K\pi}$ (in interference), $\Delta c'_{K\pi}$ (in mixing).

Mixing observables: $c_{K\pi}, c'_{K\pi}$
Measurement of CPV with $D^0 \rightarrow K^+\pi^-$ [LHCb-PAPER-2024-008]

Total uncertainty improved 1.6x compared to [PRD97.031101 (2018)]

LHCb Run1+Run2 (stat+sys)

$R_{K\pi} = (342.7 \pm 1.9) \times 10^{-5}$

$c_{K\pi} = (52.8 \pm 3.3) \times 10^{-4}$

$c'_{K\pi} = (12.0 \pm 3.5) \times 10^{-6}$

$A_{K\pi} = (-6.6 \pm 5.7) \times 10^{-3}$

$\Delta c_{K\pi} = (2.0 \pm 3.4) \times 10^{-4}$

$\Delta c'_{K\pi} = (-0.7 \pm 3.6) \times 10^{-6}$
Search for time-dependent CPV in $D^0 \rightarrow \pi^+\pi^-\pi^0$ decays


First measurement of time-dependent CPV with $\pi^0$

$$A_{CP}(f_{CP}, t) = \frac{\Gamma_{D^0 \rightarrow f_{CP}}(t) - \Gamma_{D^0 \rightarrow f_{CP}}(t)}{\Gamma_{D^0 \rightarrow f_{CP}}(t) + \Gamma_{D^0 \rightarrow f_{CP}}(t)} \approx a_{f_{CP}}^{dir} + \frac{\Delta Y_{f_{CP}}}{\tau_{D^0}} t$$

$$\Delta Y = \eta_{f_{CP}} \Delta Y_{f_{CP}}$$

Universal across decay modes. Related to mixing and CPV.

1. $A_{CP}(t) \Rightarrow 21$ bins of $t/\tau_{D^0}$
   - Filled with $\Delta m = m(D^*) - m(D^0)$ signal yields.
2. $\Delta Y$ fit validated in $D^0 \rightarrow K^+\pi^-\pi^+$.
3. Account for CP-odd cont. $\Delta Y_{eff} = (2F_{\pi\pi\pi}^+ - 1)\Delta Y$:
   - $F_{\pi\pi\pi}^+ \approx 0.973 \pm 0.017$ [PLB. 747 (2015) 9–17]

Result: $\Delta Y = (-1.3 \pm 6.3 \pm 2.4) \cdot 10^{-4}$

WA: $\Delta Y = (0.9 \pm 1.1) \cdot 10^{-4}$ [PRD. 107,052008]
Summary and Future prospects

1. LHCb collected the largest sample of charm decays leading to new world-best measurements (2011-2018, Run1+Run2)

2. Four analysis were presented.

3. No new evidence of CPV $\rightarrow$ results agree with the SM within $1\sigma$.

4. In the analysis of $D^0 \rightarrow K^+\pi^-$ decays [LHCb-PAPER-2024-008]: $\rightarrow (3\sigma)$ evidence of quadratic mixing term.

5. Uncertainties dominated by statistical effects. $\rightarrow$ improvement expected in the context of Run3.