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CP Violation and Mixing in Charm at LHCb

The 10th International Conference on Quarks and Nuclear Physics

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On behalf of the LHCb collaboration

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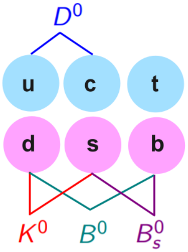
Why are we interested in charm physics?

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.

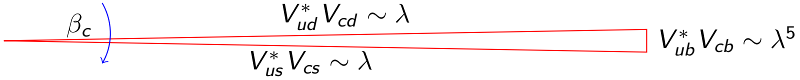
Cabibbo-Kobayashi-Maskawa (CKM) Matrix and CPV

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

1. Complex phase $i\eta$ $\Rightarrow$ 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
   $D^0 : \beta_c \approx 0.03^\circ$
   $B^0 : \beta \approx 22^\circ$



sine of Cabbibo angle $\lambda \approx 0.2$

All types of CPV

1. Direct (charm hadrons M):

   ◦ CPV in decay $|A(M \to f)|^2 \neq |A(\overline{M} \to \overline{f})|^2$

2. Indirect (only for neutral mesons):

   ◦ CPV in mixing $\Gamma(D^0 \to \overline{D^0}) \neq \Gamma(\overline{D^0} \to D^0)$

   ◦ CPV in interference between mixing and decay
   $\Gamma(D^0 \to \overline{D^0} \to f_{\mathrm{CP}}) \neq \Gamma(\overline{D^0} \to D^0 \to f_{\mathrm{CP}})$

CKM Matrix and classification of decays

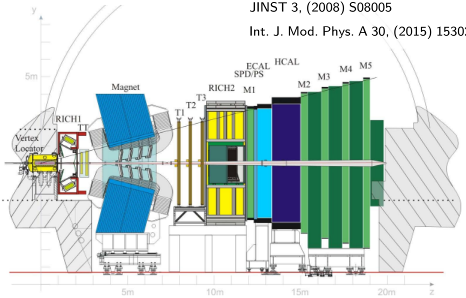
$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 &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

1. $\lambda \approx 0.2$ defined as sine of the Cabibbo angle.
2. Decay classification: λ^n in decay amplitudes:
   - Cabibbo favoured (CF) $\to n = 0$,
   - singly Cabibbo suppressed (SCS) $\to n = 1$,
   - doubly Cabibbo supressed (DCS) $\to n = 2$.
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)

JINST 3, (2008) S08005

Int. J. Mod. Phys. A 30, (2015) 153022



- World's Largest sample of charm hadron decays:
  - $\Rightarrow \sigma(pp \to c\bar{c}X) \approx 2.4mb$ @ $\sqrt{s} = 13$ TeV [JHEP 05 (2017) 074]
  - $\Rightarrow$ Run1 $\to$ 3fb^{-1} @ $\sqrt{s}$ =7-8 TeV;
  - $\Rightarrow$ Run2 $\to$ 6fb^{-1} @ $\sqrt{s}$ =13 TeV
- Excellent particle identification, tracking and vertexing:
  - $\Rightarrow$ Momentum resolution $\Delta p/p = 0.5\%$ at low momentum.
  - $\Rightarrow$ Impact parameter resolution: $(15 + 29/p_T)\mu m$
  - $\Rightarrow$ Decay time resolution: 45fs $\sim 0.1\tau_{D^0}$.

Experimental status - CPV in the decay

- In 2019 LHCb reported first observation of CPV in charm.

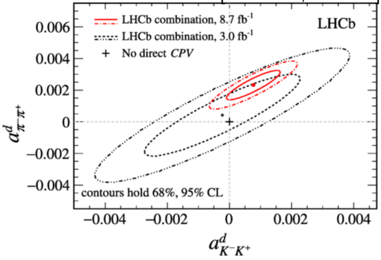
  $\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-15.4 \pm 2.9) \cdot 10^{-4}$ (5.3σ) [PRL 122, 211803]

- In 2023 evidence of CPV in $D^0 \to \pi^+\pi^-$ decay.

  $a^d_{\pi^+\pi^-} = (23.2 \pm 6.1) \cdot 10^{-4}$ (3.8σ) [PRL 131, 091802]

- Interpretation within the SM still debated.

[PRL 131, 091802]



Outline

energy-test

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

Outline

energy-test

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time-dependent

- Mixing and CPV in $D^0 \to K^+ \pi^-$ [LHCb-PAPER-2024-008]
- CPV in $D^0 \to \pi^0 \pi^- \pi^+$ decays [arXiv:2405.06556]

Search for CPV with multibody decays - experimental idea

1. Multibody decays:

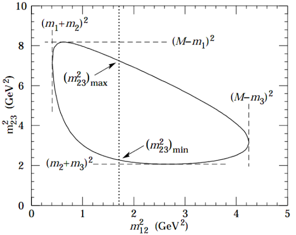
   ⇒ Strong-phase differences varying across the phase-space

   ⇒ CP asymmetries may appear locally

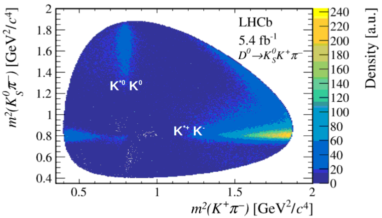
2. Three body decay $M \to m_1 m_2 m_3 \to$ visual representation Dalitz plot

⇒ m_{ij} is an invariant mass for m_i and m_j

DOI:10.13140/RG.2.2.17128.37124



JHEP 03 (2024) 107



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 → Energy test (today)

Energy test method (unbinned method) [JHEP 03 (2024) 107]

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

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

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 $\overline{D^0}$.

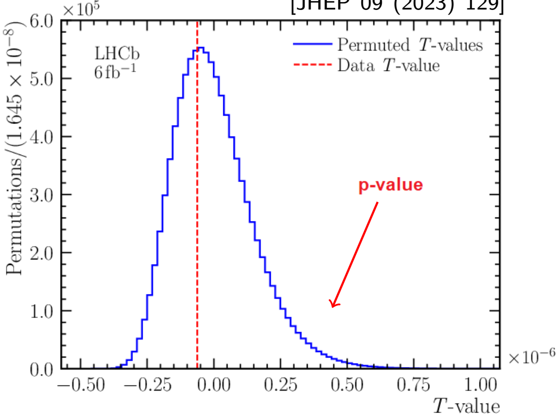
Average distance between the two samples. Distances between D^0 and $\overline{D^0}$ pairs.

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 $D^0 \to K_s^0 K^{\pm}\pi^{\mp}$: $s_{12} = m^2(K_s^0 K^{\pm})$, $s_{13} = m^2(K^0 S\pi^{\mp})$, $s_{23} = m^2(K^{\pm}\pi^{\mp})$.

Test idea [JINST 13 (2018) P04011]

- Permuted T-values (null hypothesis) → randomly assign flavours to data
- Measure p-value ⇒ fraction of T-values > Data T-value.
- No CPV ⇒ Data T-value ≈ 0, p-value large
- Large CPV ⇒ Data T-value large and > 0, p-value ≈ 0

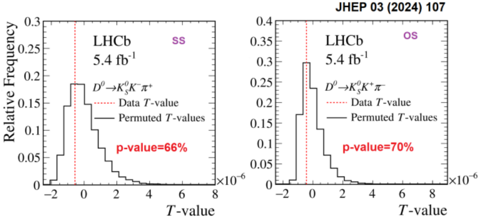
[JHEP 09 (2023) 129]



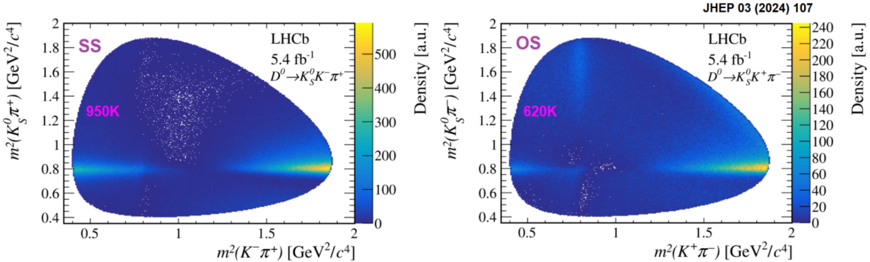
CPV in $D^0 \to K_S^0 K^{\pm}\pi^{\mp}$ Phase-space [JHEP 03 (2024) 107], dataset (2016-2018)

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

No Evidence of CPV



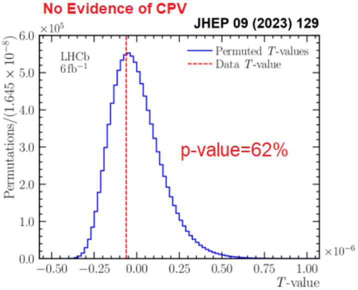
Sample 7x larger than [PRD 94, 0502019 (2016)]

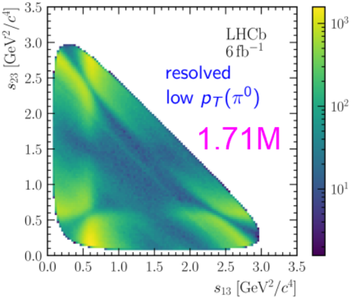


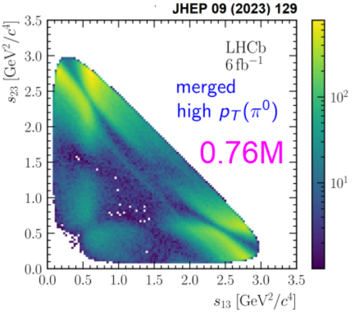
CPV in $D^0 \to \pi^0\pi^-\pi^+$ Phase-space [JHEP 09 (2023) 129], dataset (2015-2018)

- $D^{*+} \to D^0\pi^+$ strong decays, π^+ tagging
- Two π^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]

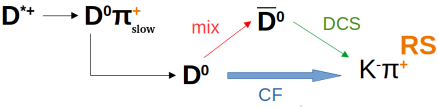


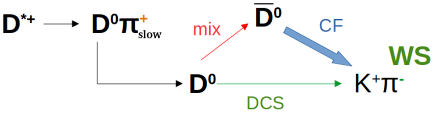




Measurement of CPV with $D^0 \to K^+\pi^-$ [LHCb-PAPER-2024-008]

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





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

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

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

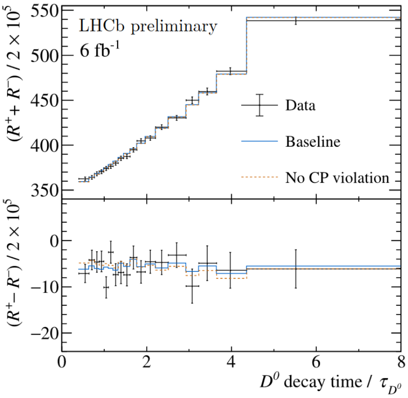
CPV observables: $A_{K\pi}$ (in decays), $\Delta c_{K\pi}$ (in interference), $\Delta c'_{K\pi}$ (in mixing).

Mixing observables: $c_{K\pi}$, $c'_{K\pi}$

Measurement of CPV with $D^0 \to K^+\pi^-$ [LHCb-PAPER-2024-008]

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

LHCb Run1+Run2 (stat+sys)
$R_{K\pi} = (342.7 \pm 1.9) \times 10^{-5}$
$c_{K\pi} = (52.8 \pm 3.3) \times 10^{-4}$
$c'_{K\pi} = (12.0 \pm 3.5) \times 10^{-6}$
$A_{K\pi} = (-6.6 \pm 5.7) \times 10^{-3}$
$\Delta c_{K\pi} = (2.0 \pm 3.4) \times 10^{-4}$
$\Delta c'_{K\pi} = (-0.7 \pm 3.6) \times 10^{-6}$



FIRST EVIDENCE OF QUADRATIC TERM IN MIXING (3σ)

NO EVIDENCE OF CPV

Search for time-dependent CPV in $D^0 \to \pi^+\pi^-\pi^0$ decays

(2012 and 2015-2018 dataset) [LHCb-PAPER-2024-003, arXiv:2405.06556]

First measurement of time-dependent CPV with π^0

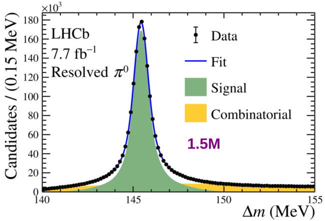
$$A_{CP}(f_{CP}, t) = \frac{\Gamma_{D^0\to f_{CP}}(t) - \Gamma_{\overline{D^0}\to f_{CP}}(t)}{\Gamma_{D^0\to f_{CP}}(t) + \Gamma_{\overline{D^0}\to f_{CP}}(t)} \approx a^{dir}_{f_{CP}} + \Delta Y_{f_{CP}} \frac{t}{\tau_{D^0}}$$

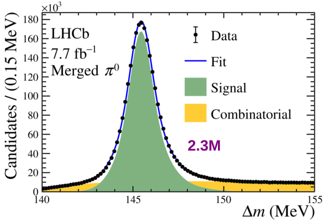
$$\Delta Y = \eta_{f_{CP}} \Delta Y_{f_{CP}}$$

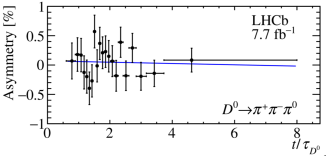
Universal across decay modes.
Related to mixing and CPV.

1. $A_{CP}(t) \Rightarrow$ 21 bins of t/τ_{D^0}
   - Filled with $\Delta m = m(D^*) - m(D^0)$ signal yields.
2. ΔY fit validated in $D^0 \to K^+\pi^-\pi^+$.
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)

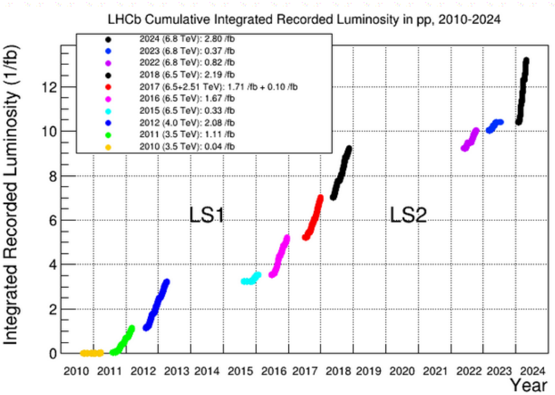
2. Four analysis were presented.

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

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

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

BACKUP


LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2024
2024 (6.8 TeV): 2.80 /fb
2023 (6.8 TeV): 0.37 /fb
2022 (6.8 TeV): 0.82 /fb
2018 (6.5 TeV): 2.19 /fb
2017 (6.5+2.51 TeV): 1.71 /fb + 0.10 /fb
2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.33 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb
LS1
LS2
Integrated Recorded Luminosity (1/fb)
0
2
4
6
8
10
12
2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024
Year