Recent measurement of CP violation and mixing with wrong-sign and right-sign $D^0 \to K\pi$ decays

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On behalf of the LHCb collaboration

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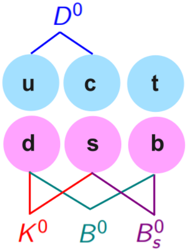
Why are we interested in charm physics?

1. Precision measurements of CPV involving up-type quarks

   $\Rightarrow$ studies complementary to K and B.

2. In Charm:

   $\Rightarrow$ Expect very small CP asymmetry in the SM $\sim 10^{-3}$.
   Hints of NP if higher values are observed!
   $\Rightarrow$ 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.

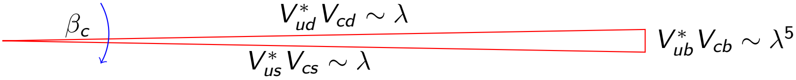
Cabibbo-Kobayashi-Maskawa (CKM) Matrix and CPV

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

1. Complex phase $i\eta \Rightarrow$ 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
   $\Gamma(D^0 \to \overline{D^0} \to f_{\mathrm{CP}}) \neq \Gamma(\overline{D^0} \to D^0 \to f_{\mathrm{CP}})$

Mixing and CPV in Charm

$$i\,\frac{d}{dt}\begin{pmatrix} M^0(t) \\ \bar{M}^0(t) \end{pmatrix} = \left[\begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{pmatrix}\right]\begin{pmatrix} M^0(t) \\ \bar{M}^0(t) \end{pmatrix}$$

1. Oscillations governed by:

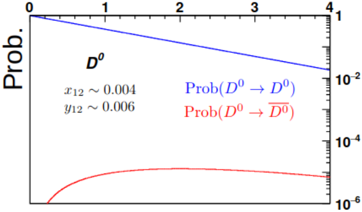
   $\rightarrow x_{12} = \frac{2|M_{12}|}{\Gamma},\ y_{12} = \frac{|\Gamma_{12}|}{\Gamma}.$

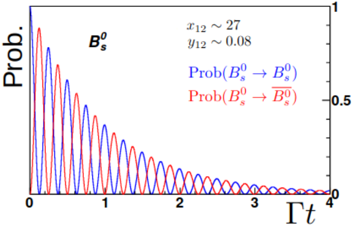
2. CPV described with dispersive and absorptive phases:

   $\rightarrow \phi_2^M \sim \arg(M_{12}),\ \phi_2^\Gamma \sim \arg(\Gamma_{12}).$

   $\rightarrow$ CPV when $\phi_2^M - \phi_2^\Gamma \neq 0$

   $\rightarrow$ SM in charm: $\phi_2^M, \phi_2^\Gamma \sim O(2\text{mrad})$
   Kagan & Silvestrini 2021 PRD 103.053008

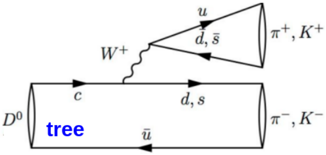


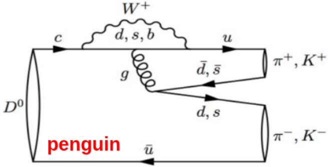


CKM Matrix and classification of decays

$$V_{\text{CKM}} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

arXiv:2405.10709v1



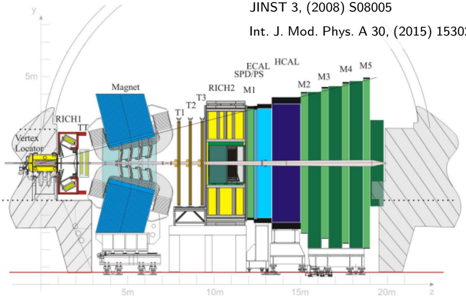


1. $\lambda \approx 0.2$ defined as sine of the Cabibbo angle.
2. Decay classification: λ^n in decay amplitudes:
   - Cabibbo favoured (CF) $\rightarrow n = 0$,
   - singly Cabibbo suppressed (SCS) $\rightarrow n = 1$,
   - doubly Cabibbo supressed (DCS) $\rightarrow n = 2$.
3. SCS decays (both tree 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 Run 1 (2011-2012) and Run 2 (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; Run2 $\to$ 6fb^{-1} @ $\sqrt{s}$ =13 TeV
- Excellent particle identification, tracking and vertexing:
  - $\Rightarrow$ K 95% eff. for 5% $\pi \to K$ mis-ID.
  - $\Rightarrow$ 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.

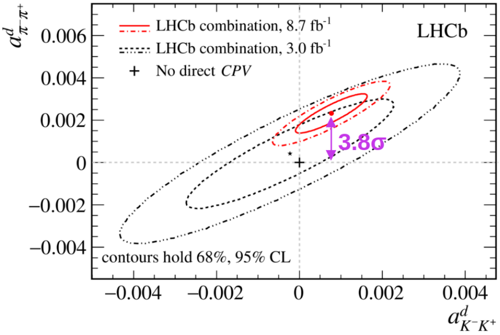
  $\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-15.4 \pm 2.9) \cdot 10^{-4}$ (5.3σ) [PRL 122.211803]

- 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]

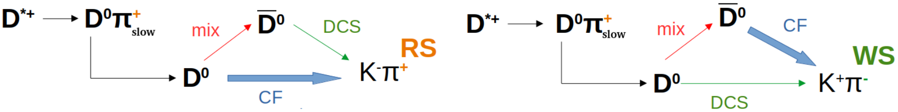
- Interpretation within the SM still debated.

[PRL 131.091802]



Measurement of CPV and mixing with $D^0 \to K\pi$ WS/RS

[arXiv:2407.18001]



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

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

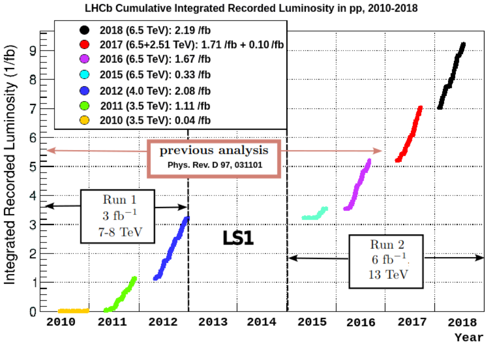
$$R^{\pm}_{K\pi}(t) \approx R_{K\pi}\,(1 \pm A_{K\pi}) + R_{K\pi}\,(1 \pm A_{K\pi})\,(c_{K\pi} \pm \Delta c_{K\pi})\left(\frac{t}{\tau_{D^0}}\right) + (c'_{K\pi} \pm \Delta c'_{K\pi})\left(\frac{t}{\tau_{D^0}}\right)^2$$

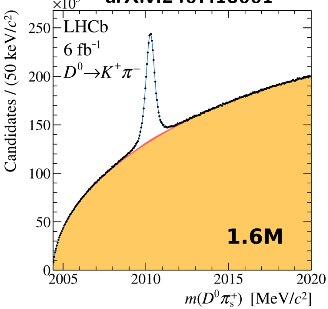
CPV observables: $A_{K\pi}$ (in decays), $\Delta c_{K\pi}$ (in interference), $\Delta c'_{K\pi}$ (in mixing).

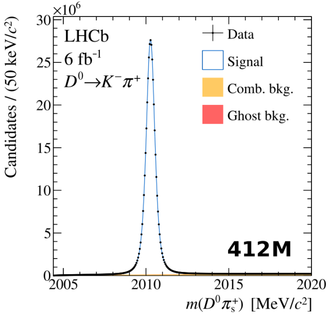
Mixing observables: $c_{K\pi}$, $c'_{K\pi}$

$R_{K\pi} \to$ DCS/CF ratio $\sim 3.4 \text{x} 10^{-3}$

Data







- Previous measurement [PRD 97.031101]
  - ⇒ Run 1 + 2015-2016 sample
  - ⇒ collected 0.7M WS + 180M RS
- Presented analysis
  - ⇒ full Run 2 sample (2015-2016 data reanalysed)
  - ⇒ collected 1.6M WS + 412M RS
- Final results
  - ⇒ full Run 1 + Run 2 sample

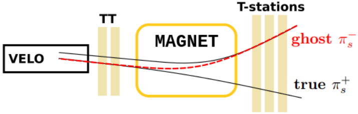
Analysis overview

- Offline Selection
- Data divided 108 bins:
  - $\rightarrow$ 18 decay-time x 3 data-taking x 2 final states
- In each bin:
  - $\rightarrow$ determine average D^0 decay-time: $\langle t \rangle, \langle t^2 \rangle$
  - $\rightarrow$ WS/RS ratio ($R^{\pm}$) $\Rightarrow$ D^* mass fit
- Correct them for systematic effects:
  - $\rightarrow$ Ratio bias
  - $\rightarrow$ Asymmetry bias
  - $\rightarrow$ D^0 decay-time bias δT
- CPV+mixing extracted from time-dependent fit

Systematic effects

◦ Ratio bias

→ Ghost bkg hits correctly identified in VELO but not in T-stations.



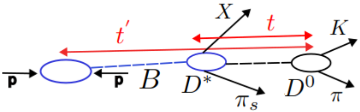
→ double mis-ID $WS \rightsquigarrow RS$: $D^0 \to K^-(\rightsquigarrow \pi^-)\pi^+(\rightsquigarrow K^+)$

◦ Instrumental asymmetry bias.

→ Differences in rec. between WS and RS may mimic CPV.

◦ D^0 decay-time bias.

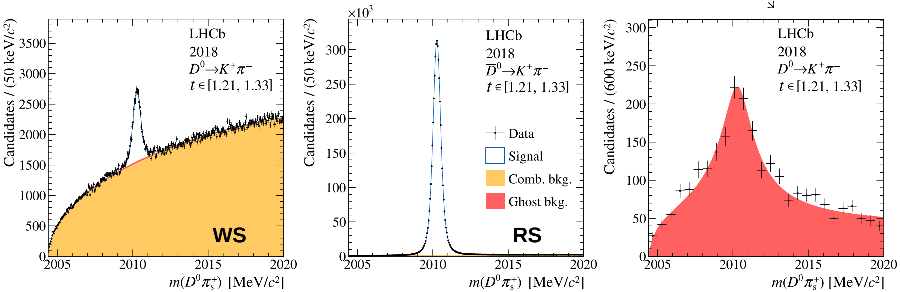
→ Contamination with secondary decays.



WS/RS ratio determination

arXiv:2407.18001

1. Simultaneous χ^2 binned fit to WS, RS and residual ghost bkg. proxy
2. Most signal and ghost bkg shape parameters are shared.



Mixing+CPV fit Model

sum over 108 bins:
× 18 decay-time t
× 3 data period y
× 2 final state f±

constraints nuisance params.

$$\chi^2 = \sum_{t,y,f} \left(\frac{\text{raw}^f_{ty} - R^f_{ty}}{\sigma(\text{raw}^f_{ty})} \right)^2 + \chi^2_{\text{nuis}}$$

$$\text{R}^{\pm}_{ty} \equiv \left[R_{K\pi}\,(1 \pm A_{K\pi}) + \sqrt{R_{K\pi}(1 \pm A_{K\pi})}(c_{K\pi} \pm \Delta c_{K\pi})\langle \boldsymbol{T} \rangle^{\pm}_{\boldsymbol{ty}} + (c'_{K\pi} \pm \Delta c'_{K\pi})\langle \boldsymbol{T}^2 \rangle^{\pm}_{\boldsymbol{ty}} \right] \times (1 \pm 2\boldsymbol{A_{ty}} - \mathbf{C}) + \mathbf{D}$$

C - bias due to WS signal candidates discarded with cut on ghosts

A_{ty} -instrumental asymmetry bias

D - bias due to cut on double mis-ID

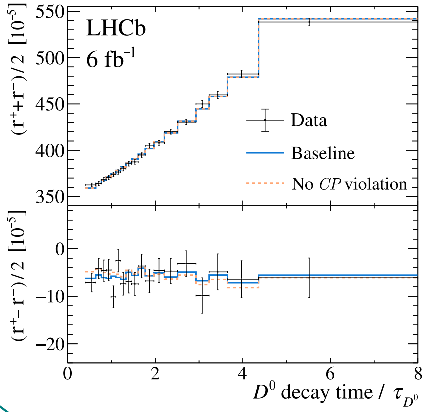
$\langle T^2 \rangle$ and $\langle T \rangle$ corrected for D^0 decay-time bias from secondary decays

Mixing+CPV fit - Results

arXiv:2407.18001

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

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

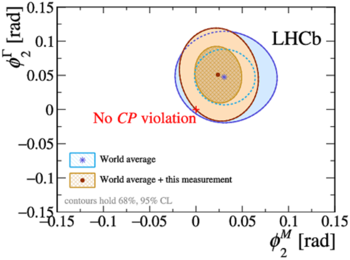


FIRST EVIDENCE OF QUADRATIC TERM IN MIXING (3.4σ)

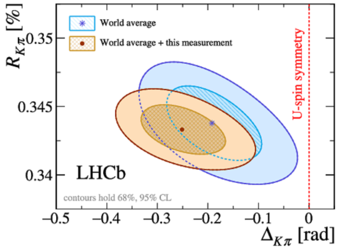
NO EVIDENCE OF CPV

Impact on the World Average

arXiv:2407.18001
parametrisation from appendix B



1. $\Delta c_{K\pi}$ mostly dependent on $x_{12} \cdot \phi_2^M$
   $\rightarrow$ 16% improvement on ϕ_2^M



2. $c_{K\pi} \approx y_{12} \cos \Delta_{K\pi} + x_{12} \sin \Delta_{K\pi}$

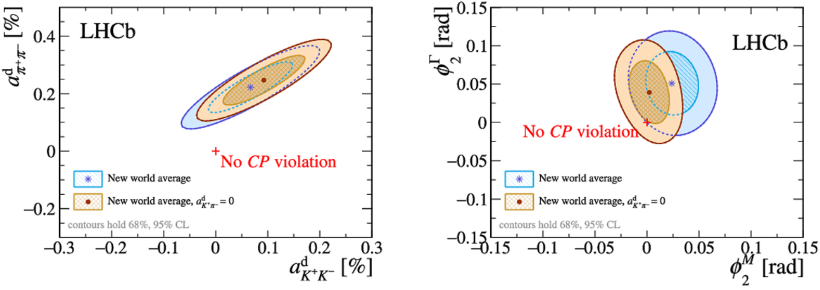
   $\rightarrow$ y_{12} precisely measured
   PRD 105.092013

   $\rightarrow$ precise determination of $\Delta_{K\pi}$
   (departure from $SU(3)_F$ at $\sim 4\sigma$)

Impact on the World Average - $a^d_{DCS} = 0$

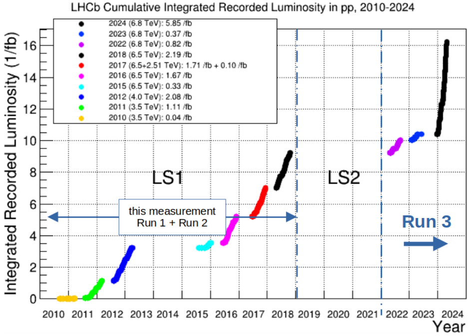
arXiv:2407.18001

parametrisation from appendix B



1. $a^d_{KK} \rightarrow$ 10% improvement wrt. [PRL 131.091802]
2. ϕ^M_2 further reduced to 13mrad
3. charm+beauty global fit, see LHCb-CONF-2024-004.

Summary and Future Prospects



1. Improved ϕ_2^M uncertainty.
2. Significant (4σ) departure of $\Delta_{K\pi}$ from zero expected in U-spin symmetry.
3. $a^d_{KK} \rightarrow$ 10% improvement wrt. [PRL 131.091802].
3. Global fit charm+beauty in LHCb-CONF-2024-004.
4. Uncertainties statistically dominated $\rightarrow$ expected improvement in Run 3.

BACKUP

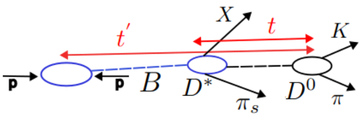
Asymmetry bias

1. Differences in rec. eff. between WS and RS may mimic CPV.

2. $D^0 \to K^+K^-$ kinematics is equalised to $D^0 \to K^+\pi^-$ to cancel instrumental asymmetries

3. $A_D(\pi_s) + A_P(D^*) = A^{raw}(KK) - \left(a^d_{KK} + \Delta Y \langle t \rangle\right)$
   $\to$ ext. input [PRL 131.091802, PRD 104.072010]

Decay-time bias



1. Poor D^* vertex resolution ($\sim$ 1 cm) $\Rightarrow$ D^* constrained in the PV
2. Contamination from secondary D^* from B decays
   $\rightarrow$ bias decay time towards higher values
   $\rightarrow$ deformed D^* mass line-shape
3. Apply cut $IP(D^0) < 60\mu m$