Mixing and CP Violation in Charm (LHCP 2023)

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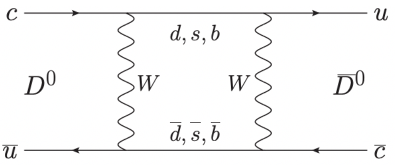
Overview

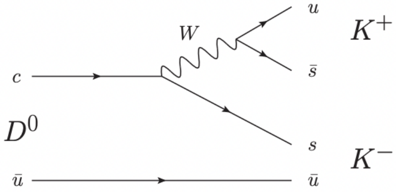
CP violation and mixing in Charm

CP violation in Charm is one of the most compelling areas of flavour physics [a] both theoretically, and experimentally.

- Mixing suppressed by the GIM mechanism.
- Penguins suppressed by off diagonal CKM elements.
- CP violation in weak decay is predicted to be small from involved CKM factors.

[a] considerable speaker bias





CP violation in decay

CP violation is a consequence of having three generations of quarks, such that the CKM

$$\begin{pmatrix} \mathbf{V}_{ud}, & \mathbf{V}_{us}, & \mathbf{V}_{ub} \\ \mathbf{V}_{cd}, & \mathbf{V}_{cs}, & \mathbf{V}_{cb} \\ \mathbf{V}_{td}, & \mathbf{V}_{ts}, & \mathbf{V}_{tb} \end{pmatrix},$$

is parameterised by three mixing angles and one CP violating phase.

CP violation can manifest in three ways. The first of these is in **decay**.

Where decays of the form $A \to f$ and $\bar{A} \to \bar{f}$ proceed at different rates.

Arises from non-zero contributions in the weak phase of the decay amplitudes.

CP violation in mixing and interference

Mixing is induced from differences between the meson mass and flavour eigenstates

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle,$$

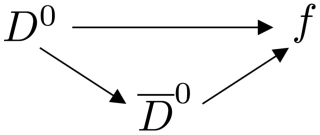
$$|p^2| + |q^2| = 1.$$

CP violation in **mixing** occurs when

$$|p| \neq |q|$$

where the weak and CP eigenstates differ. Explored through $D^0 \to K^{(*)+} l^- \bar{\nu}_l$ and other SL decays.

This final source of CP violation is **interference**.



Parameterised in terms of direct and mixing CPV parameters.

$$\phi = arg\left(\frac{q\bar{A}_f}{pA_f}\right)$$

Induces a weak phase rotation in the presence of CPV.

Measurement of the time-integrated CP asymmetry in $D^0 \to K^-K^+$ decays

Observation of CP violation in Charm (PhysRevLett.122.21180) through

$$\Delta A_{CP} = \mathcal{A}_{CP}(K^-K^+) - \mathcal{A}_{CP}(\pi^-\pi^+)$$

Precision measurement of $\mathcal{A}_{CP}(K^-K^+)$ in combination with ΔA_{CP} provide insight into U-spin symmetry breaking.

Difficult measurement requiring a detailed understanding of detector and production asymmetries.

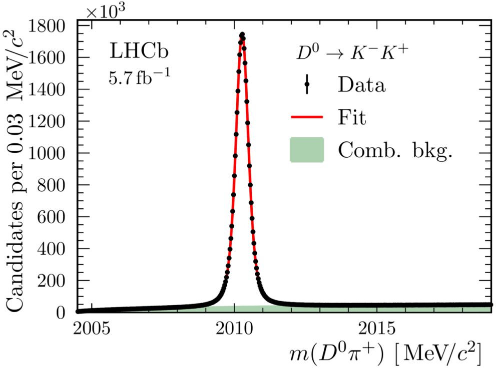


Figure: Calibrated (C_{D^+}) $D^0 \to K^-K^+$ sample (arXiv:2209.03179).

The Measurement

The raw asymmetry of the K^-K^+ system can be directly measured.

$$A(K^-K^+) = \frac{N(D^{*+} \to D^0\pi^+) - N(D^{*-} \to \bar{D}^0\pi^-)}{N(D^{*+} \to D^0\pi^+) + N(D^{*-} \to \bar{D}^0\pi^-)}$$

However, this asymmetry also contains detector asymmetries related to to the reconstruction efficiencies of the tagged pion $A_D(\pi^+_{tag})$, and to production asymmetries of $A_p(D^{*+})$ in proton-proton collision.

$$A(K^-K^+) \approx \mathcal{A}_{CP}(K^-K^+) + A_p(D^{*+}) + A_D(\pi^+_{tag})$$

Accounting for Asymmetries

These nuisance asymmetries are handled through **two** independent calibration procedures, C_{D^+} and $C_{D_s^+}$. C_{D^+} uses samples,

- $D^{+*} \to D^0(K^-\pi^+)\pi^+ : A_p(D^{*+}) + A_D(\pi^+_{tag}) + A_D(\pi^+) - A_D(K^+)$
- $D^+ \to K^-\pi^+\pi^+ : A_p(D^+) - A_D(K^+) + A_D(\pi^+_1) + A_D(\pi^+_2)$
- $D^+ \to \bar{K}^0\pi^+ : A_p(D^+) + A_D(\pi^+) + A(\bar{K}^0)$

$$C_{D^+} : \mathcal{A}_{CP}(K^-K^+) = \mathcal{A}_{CP}(K^-K^+) + [A_p(D^{*+}) - A_p(D^{*+})] + [A_D(\pi^+_{tag}) - A_D(\pi^+_{tag})] + [A_D(K^+) - A_D(K^+)] + [A_D(\pi^+_1) - A_D(\pi^+)] + [A_p(D^+) - A_p(D^+)] + [A_D(\pi^+_2) - A_D(\pi^+)] - A(\bar{K}^0) + A(\bar{K}^0)$$

$A(\bar{K}^0)$ is the asymmetry arising from the combined effect of CP violation and mixing in the neutral kaon system and the different interaction rates of K^0 and $\bar{K}^0$ with the detector material.

CP violation?

$$\mathcal{A}_{CP}(K^-K^+) = [6.8 \pm 5.4(stat) \pm 1.6(syst)] \times 10^{-4}$$

direct CPV is accessed through

$$\mathcal{A}_{CP}(f) \approx a_f^d + \frac{\langle t \rangle_f}{\tau_D} \Delta Y_f,$$

and found to be

$$a^d_{K^-K^+} = (7.7 \pm 5.7) \times 10^{-4}$$
$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4}$$

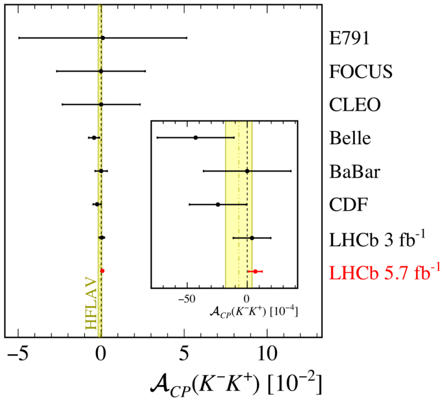


Figure: Measurements of $\mathcal{A}_{CP}(K^-K^+)$ from various experiments (arXiv:2209.03179).

Implications

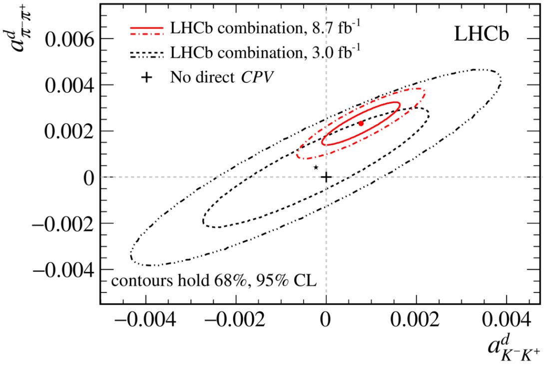


Figure: Central values and two-dimensional confidence regions in the $(a^d_{K^-K^+}, a^d_{\pi^-\pi^+})$ plane (arXiv:2209.03179).

- $\pi\pi$ inconsistent with CP symmetry $(3.8\,\sigma) \Leftarrow$ First evidence of **direct** CP violation in a specific charm decay.
- departure from U-spin symmetry of $(2.7\,\sigma) \Leftarrow a^d_{K^-K^+} + a^d_{\pi^-\pi^+} \neq 0$

Search for CP violation in $D^+_{(s)} \to K^-K^+K^+$ decays

First search for direct CP violation in

- $D^+_s \to K^-K^+K^+$ CS (Cabibbo Suppressed) decays.
- $D^+ \to K^-K^+K^+$DCS (Doubly Cabibbo Suppressed) decays.

- **NEW** model-independent method.
- 0.97 (D^+_s) and 1.27 (D^+) million candidates.
- CPV **forbidden** in DCS decays.

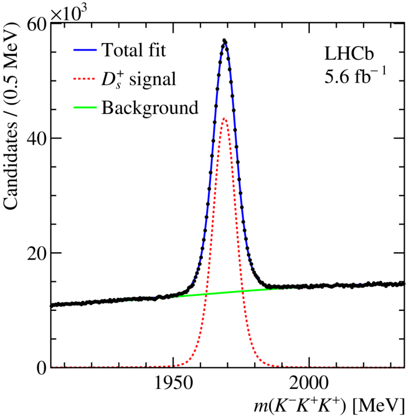


Figure: Invariant-mass distribution for $D^+_s \to K^-K^+K^+$ (arXiv:2303.04062)

Dalitz plot construction

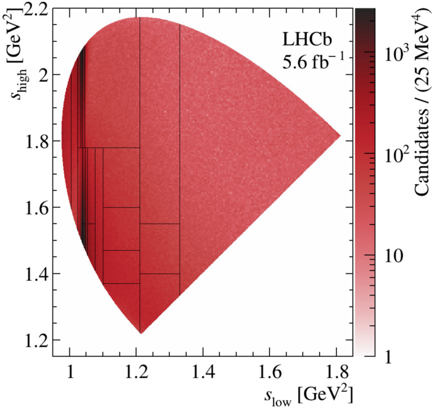


Figure: Dalitz plot distribution of $D_s^+ \to K^- K^+ K^+$ (arXiv:2303.04062)

- The Dalitz space is defined in terms of S^{KK}_{high} and S^{KK}_{low}.
- Intermediate structures $D_s^+ \to \phi(1020)K^+$.
- Binned such that the number of signal candidates are approximately equal.

Binned model-independent technique

Signal candidates in each bin are extracted from invariant mass fits (an extension of the Miranda technique), removing background contributions to local CP asymmetries.

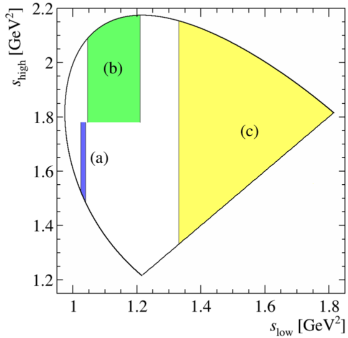


Figure: Dalitz plot bins of $D_s^+ \to K^-K^+K^+$ (arXiv:2303.04062)

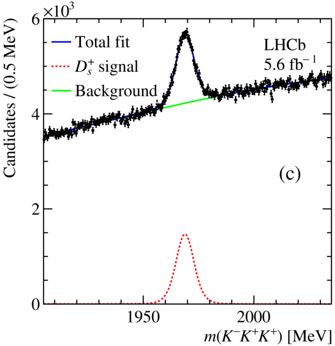


Figure: Mass distribution of $D_s^+ \to K^-K^+K^+$ extracted from bin (c) (arXiv:2303.04062)

CP violation?

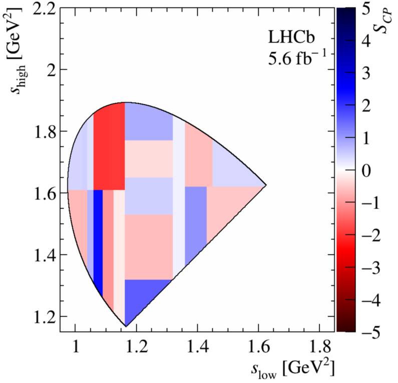


Figure: Local S_{CP} $D^+ \to K^- K^+ K^+$ (arXiv:2303.04062)

No evidence for direct CP violation.
With respect to the null-hypothesis of no CP violation

- D_s^+ p-value = 13.3%.
- D^+ p-value = 31.6%.

Energy Test of CP Violation in $D^0 \to \pi^+\pi^-\pi^0$

- $D^0 \to \pi^+\pi^-\pi^0$ is comparable to $D^0 \to \pi^+\pi^-$.
- Uses a test statistic 'T' to compute local asymmetries.

- CS decay.
- Sensitive to interference between tree and penguin diagrams.
- Run 1 analysis returned p-value of **2.6%** (j.physletb.2014.11.043).
- 3-body phase space can enrich local CPV effects.

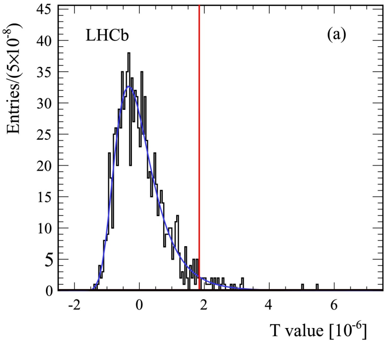
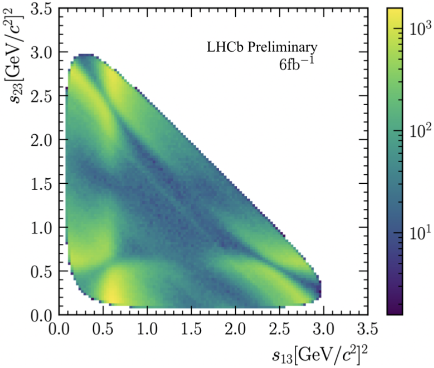
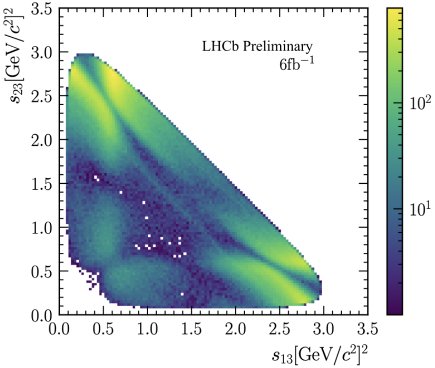


Figure: Distribution of T-values obtained by running the energy test over the final $D^0 \to \pi^+\pi^-\pi^0$ signal sample (j.physletb.2014.11.043).

π^0 samples





PRELIMINARY

Figure: **IN PREPARATION (LHCb-PAPER-2023-005):** Dalitz plots for the background-subtracted signal samples for the resolved (left) and merged (right) π^0.

The Energy Test

The energy test (PhysRevD.84.054015) computes a T-value over all $D^0 - D^0$ pairs (n) , all $\bar{D}^0 - \bar{D}^0$ pairs ($\bar{n}$) and between samples $D^0 - \bar{D}^0$.

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

The function ψ_{ij} gives a weighted distance between pairs in phase space $\psi_{ij} = e^{-d_{ij}^2/2\delta^2}$

Where $d_{ij}^2 = (s_{12}^2 + s_{13}^2 + s_{23}^2)$ and δ is a tunable parameter.

Permutations of this T-value with randomised tags for the $D^0/\bar{D}^0$ define the CP-symmetry hypothesis.

Tuning

Pseudoexperiments test CP asymmetries in the range (0.1%-1.0%) to analyse the choice of δ.

- Phase differences are injected into the subleading $\rho(770)^-\pi^+$ and dominant $\rho(770)^+\pi^-$.
- Yields are matched to data.
- Generated with(and without) background contamination.

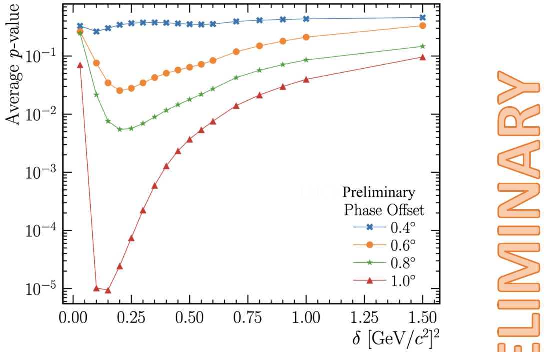


Figure: **IN PREPARATION (LHCb-PAPER-2023-005):** Average p-value as a function of the energy test distance parameter δ.

CP violation?

No evidence for CP violation in localised regions of phase space is found for the decay.

- Validated with Cabibbo favoured (CF) $D^0 \to K^- \pi^+ \pi^0$.
- P-value $= 0.62$. Consistent with **no** CPV hypothesis.
- Four times the data of the Run 1 result!

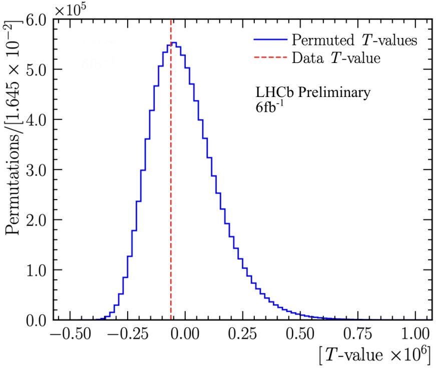
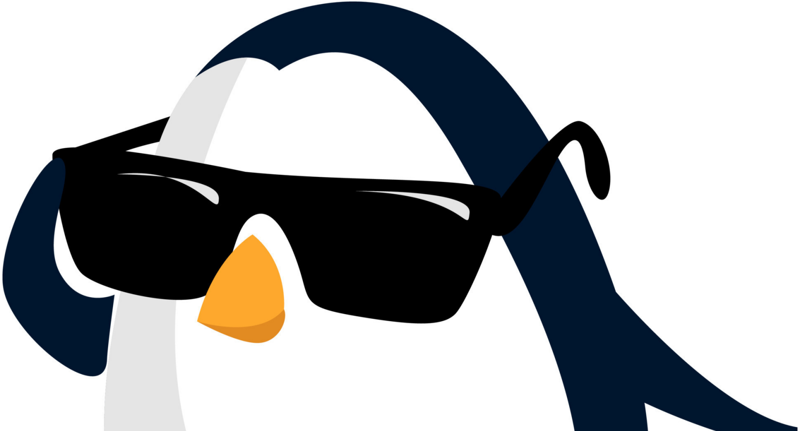


Figure: **IN PREPARATION (LHCb-PAPER-2023-005):** Distribution of T-values obtained by running the energy test over the final $D^0 \to \pi^+ \pi^- \pi^0$ signal sample.

PRELIMINARY

Summary

- **No** evidence for CP violation in $D^0 \to \pi^+\pi^-\pi^0$ (**LHCb-PAPER-2023-005)**
- **No** evidence for CP violation in $D^+_{(s)} \to K^- K^+ K^+$ (arXiv:2303.04062)
- **First** evidence of direct CP violation in $D^0 \to \pi^+\pi^-$ $(3.8\,\sigma)$ (arXiv:2209.03179)



Any Questions!