

Mixing and CPV in charm decays at LHCb

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on behalf of the LHCb collaboration

Flavor Physics and *CP* Violation (FPCP)
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Why charm is charming?

$$\text{CKM suppression} \\ \sim V_{ub}V_{cb} \left(\frac{m_b}{m_W} \right)^2 \sim 10^{-6}$$

$$\text{GIM suppression} \\ \sim \frac{m_s^2 - m_d^2}{m_W^2} \\ \text{complete cancellation in the} \\ \text{U-spin limit } (m_d=m_s)$$

(SM *asymmetries* **~0.1% or below**)

- **CP violation** (CPV) and **mixing** are suppressed in charm
 - Room for **new physics** *enhancements*

- **Predictions** are *difficult* due to low-energy strong interaction effects [[Phys.Lett. B222 \(1989\) 501](#)]



- Experimental **measurements** are *crucial*

- **LHCb** is one of the main players: $\sigma(pp \rightarrow c\bar{c} X)_{\sqrt{s}=13 \text{ TeV}} \cong 2.4 \text{ mb}$ [[JHEP 03 \(2016\) 159](#)]

- **2013**, first observation* of **D^0 mixing** in $D^0 \rightarrow K^+ \pi^-$
- **2019**, first observation of **direct CPV** in $D^0 \rightarrow h^+ h^-$

*from a single measurement

Direct CP violation measurements

- Measurement of $A_{CP}(D^0 \rightarrow K^- K^+)$ [[arXiv:2209.03179](#)]
- Search for CPV in $D_{(s)}^+ \rightarrow K^- K^+ K^+$ [[arXiv:2303.04062](#)]
- Search for CPV in $D^0 \rightarrow \pi^- \pi^+ \pi^0$ [[LHCB-PAPER-2023-005](#)] in preparation

Direct CP violation

$$|D \rightarrow f|^2 \neq |\bar{D} \rightarrow \bar{f}|^2$$

- Corresponds to

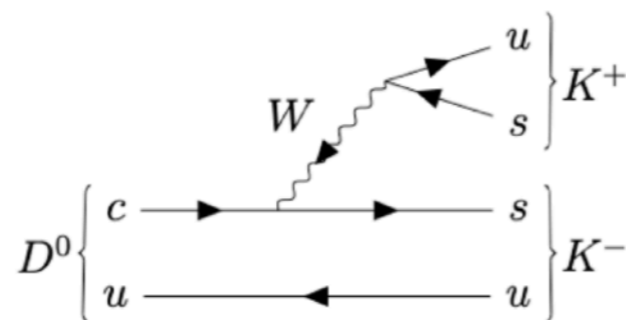
$$A_{CP} = \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2} \neq 0$$

strong phases weak phases

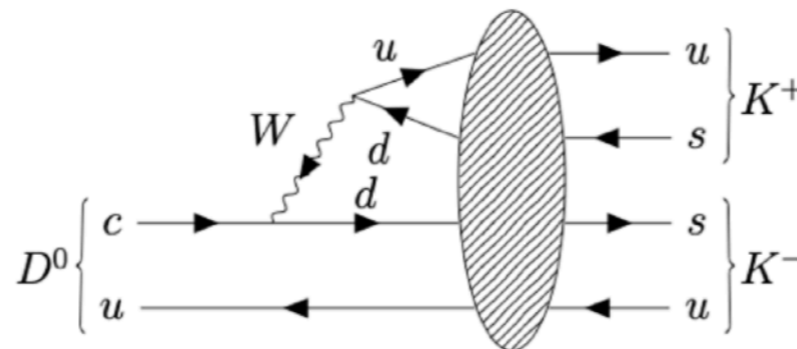
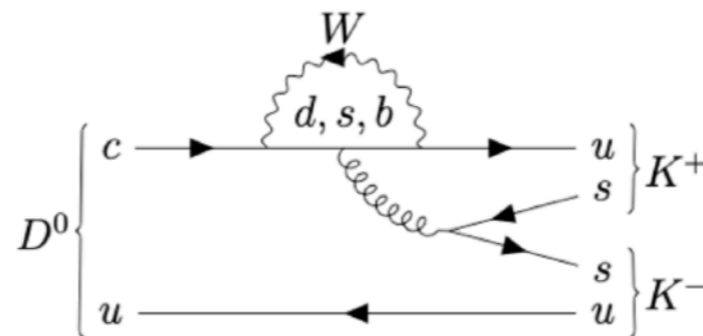
$$|A_f|^2 - |\bar{A}_{\bar{f}}|^2 = -2 \sum_{i,j} |A_i| |A_j| \sin(\delta_i - \delta_j) \sin(\phi_i - \phi_j)$$

- Most promising channels are **Cabibbo-suppressed** (CS) decays

Tree
(dominant)



Penguin
(subleading)



Rescattering
(subleading)

How can you measure A_{CP} ?

- Choose a *flavour-specific* decay such as $D^{*+} \rightarrow D^0 \pi^+$ (prompt) to determine whether the meson is a D^0 or \bar{D}^0
- The **raw asymmetry** (A) in $D^0 \rightarrow K^- K^+$ decays

$$A(D \rightarrow f) = \frac{N(D \rightarrow f) - N(\bar{D} \rightarrow \bar{f})}{N(D \rightarrow f) + N(\bar{D} \rightarrow \bar{f})}$$

includes both physics and detector effects:

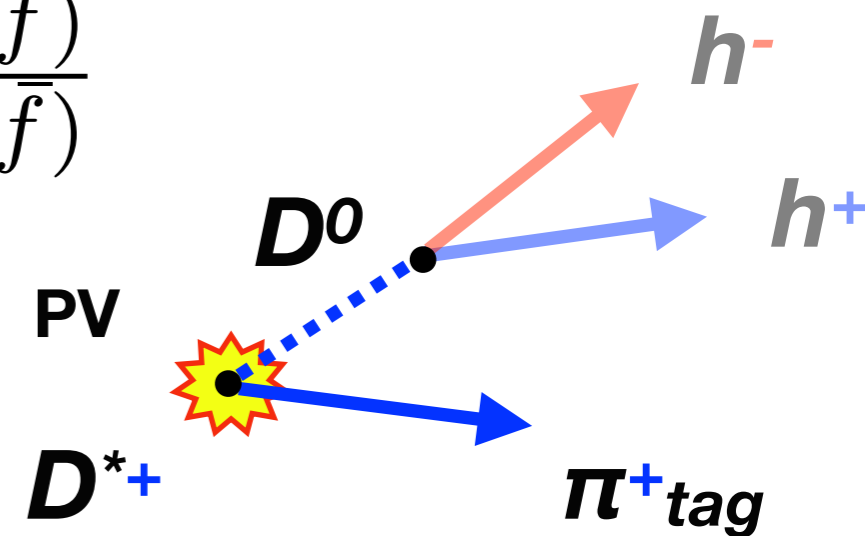
$$A = A_{CP} + A_P + A_D$$

CPV
parameter

NUISANCE ASYMMETRIES:
Production asymmetry of D^{*+}
Detection asymmetry of π^+_{tag}

$$\sigma(pp \rightarrow D^{*+} X) \neq \sigma(pp \rightarrow D^{*-} X)$$

$$\epsilon(\pi^+) \neq \epsilon(\pi^-)$$



Strategy for $A_{CP}(D^0 \rightarrow K^- K^+)$

- **Prompt** $D^0 \rightarrow K^- K^+$ collected during **Run-2**
- Two methods to *cancel* **NUISANCE** asymmetries:
 - D^+ decays, same used in **Run-1 analysis** (C_{D^+})
 - D_s^+ decays, *new!* ($C_{D_s^+}$)
- *Correct* raw asymmetry A using samples of *Cabibbo-favoured* (CF) D^0 , D^+ and $D_{(s)}^+$ decays (where CPV can be neglected):

particles with same color must have identical kinematic distributions!

$$C_{D^+}: \quad A_{CP}(D^0 \rightarrow K^- K^+) = +A(D^{*+} \rightarrow (D^0 \rightarrow K^- K^+) \pi_{soft}^+) - A(D^{*+} \rightarrow (D^0 \rightarrow K^- \pi^+) \pi_{soft}^+) \\ + A(D^+ \rightarrow K^- \pi^+ \pi^+) - [A(D^+ \rightarrow \bar{K}^0 \pi^+) - A(\bar{K}^0)]$$

$$C_{D_s^+}: \quad A_{CP}(D^0 \rightarrow K^- K^+) = +A(D^{*+} \rightarrow (D^0 \rightarrow K^- K^+) \pi_{soft}^+) - A(D^{*+} \rightarrow (D^0 \rightarrow K^- \pi^+) \pi_{soft}^+) \\ + A(D_s^+ \rightarrow \phi \pi^+) - [A(D_s^+ \rightarrow \bar{K}^0 K^+) - A(\bar{K}^0)]$$

$$\Delta A_{CP} = A_{CP}(D^0 \rightarrow K^- K^+) - A_{CP}(D^0 \rightarrow \pi^- \pi^+) = (-15.4 \pm 2.9) \times 10^{-4}$$

[Phys. Rev. Lett. 122, 211803]

Results

- The **combination** of the two approaches yields:

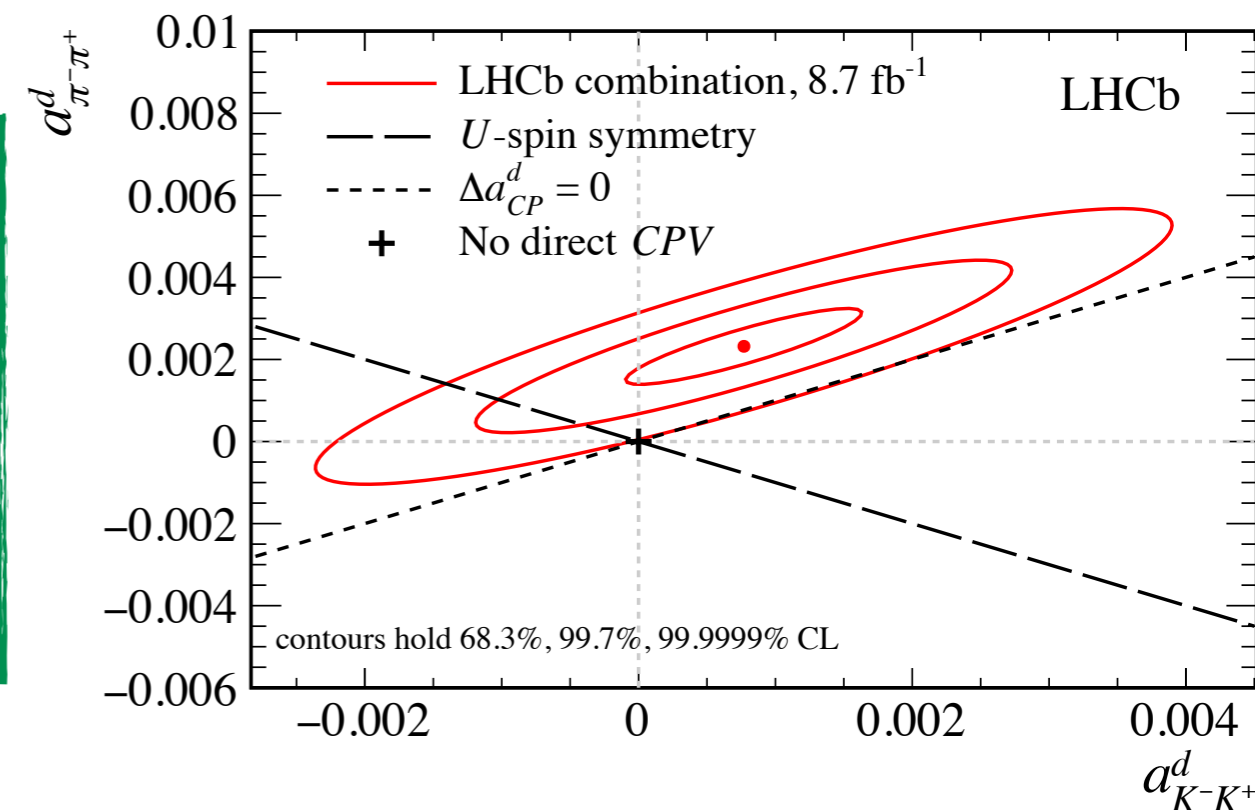
$$A_{CP}(K^- K^+) = [6.8 \pm 5.4 (\text{stat}) \pm 1.6 (\text{syst})] \times 10^{-4},$$

- Run1+Run2 measurements are combined and CP violation in $D^0 \rightarrow \pi^- \pi^+$ is extracted considering the observed CPV in ΔA_{CP}

$$a_{K^- K^+}^d = (7.7 \pm 5.7) \times 10^{-4}$$

$$a_{\pi^- \pi^+}^d = (23.2 \pm 6.1) \times 10^{-4}$$

with $\rho(a_{KK}^d, a_{\pi\pi}^d) = 88\%$



- First *evidence* for CPV in $D^0 \rightarrow \pi^- \pi^+$! $[3.8\sigma]$ [arXiv:2209.03179]

$$|A_f|^2 - |\bar{A}_{\bar{f}}|^2 = -2 \sum_{i,j} |A_i| |A_j| \sin(\delta_i - \delta_j) \sin(\phi_i - \phi_j)$$

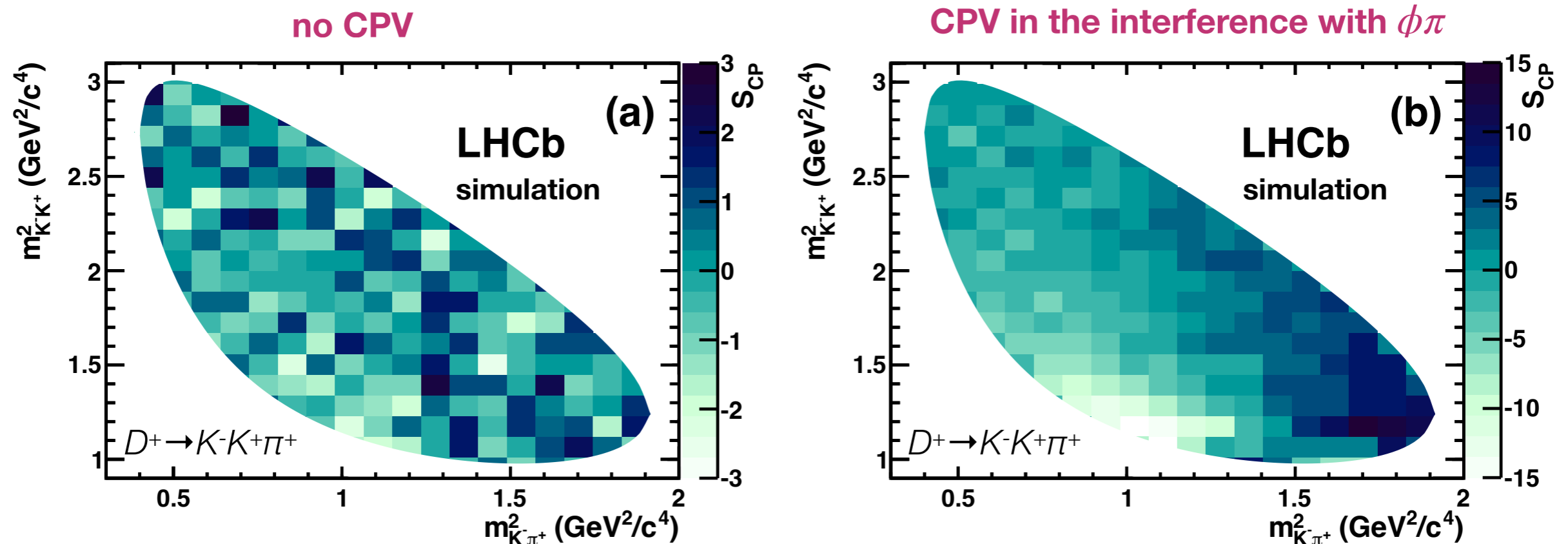
strong phases

weak phases

Search for local *CP* violation

- 3-body decays have unique features for CPV searches:
due to the *variation* of the **strong-phase** a different size of CPV can be found across the Dalitz plane

[Phys. Rev. D 84, 112008]



“local CPV estimator”

$$\mathcal{S}_{CP}^i = \frac{N^i(D_{(s)}^+) - \alpha N^i(D_{(s)}^-)}{\sqrt{\alpha(\delta_{N^i(D_{(s)}^+)}^2 + \delta_{N^i(D_{(s)}^-)}^2)}} \quad \alpha = \frac{\sum_i N^i(D_{(s)}^+)}{\sum_i N^i(D_{(s)}^-)}$$

Search for CPV in $D_{(s)}^+ \rightarrow K^- K^+ K^+$

$$\mathcal{S}_{CP}^i = \frac{N^i(D_{(s)}^+) - \alpha N^i(D_{(s)}^-)}{\sqrt{\alpha(\delta_{N^i(D_{(s)}^+)}^2 + \delta_{N^i(D_{(s)}^-)}^2)}} \quad \alpha = \frac{\sum_i N^i(D_{(s)}^+)}{\sum_i N^i(D_{(s)}^-)}$$

- Study *local* CPV in CS (D^+) and doubly-CS (D_s^+) decays using Run2 data, for the *first time*

- Strategy:
 χ^2 test of \mathcal{S}_{CP}

$$\chi^2(\mathcal{S}_{CP}) = \sum (\mathcal{S}_{CP}^i)^2 \quad \mathcal{S}_{CP}^i \sim G(0,1)$$

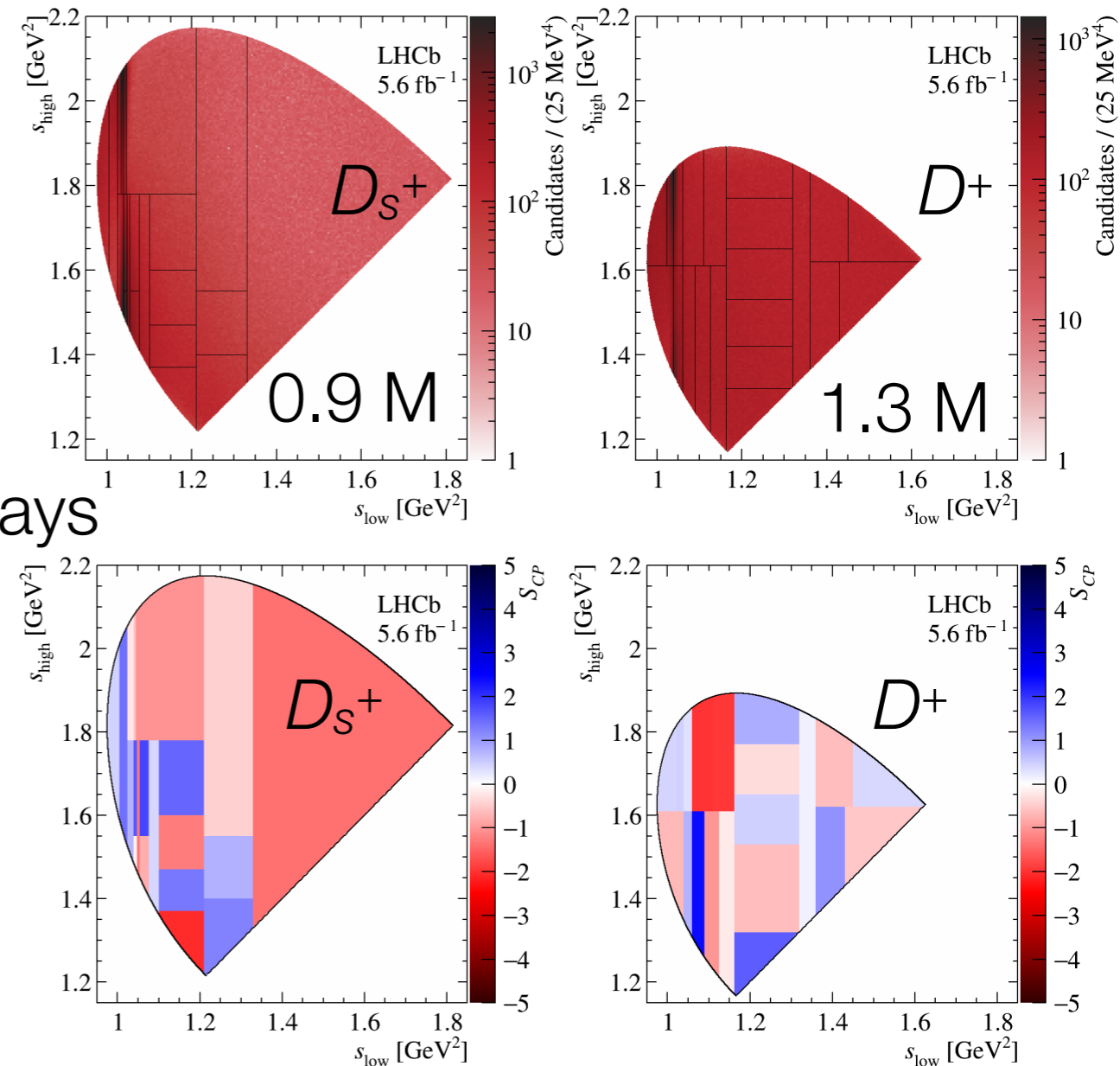
$d.o.f. = \# \text{ bins} - 1$

validated with CF $D_s^+ \rightarrow K^- K^+ \pi^+$ decays

- Results:
 $p\text{-value}(D_s^+) = 13.3\%$
 $p\text{-value}(D^+) = 31.6\%$

- No evidence of local CPV

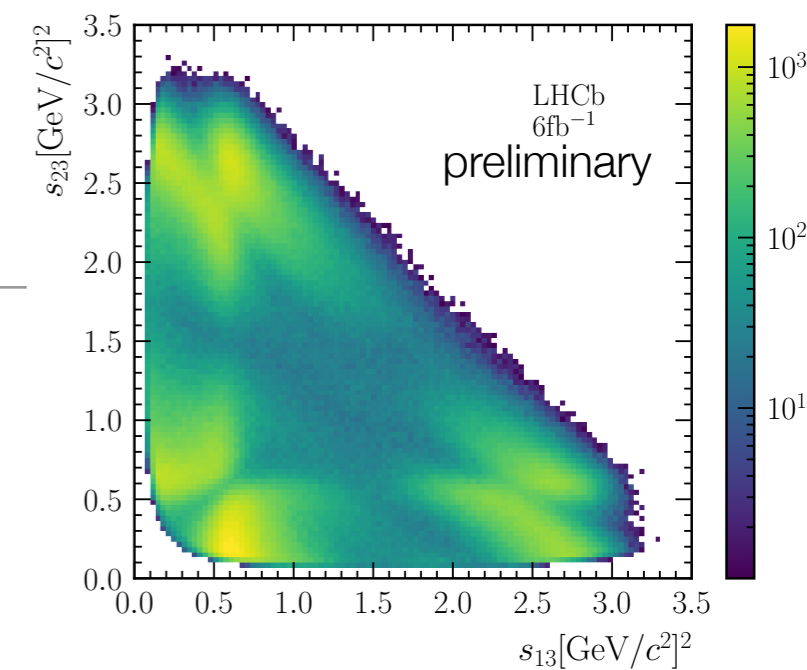
physically motivated binning scheme



[arXiv:2303.04062]

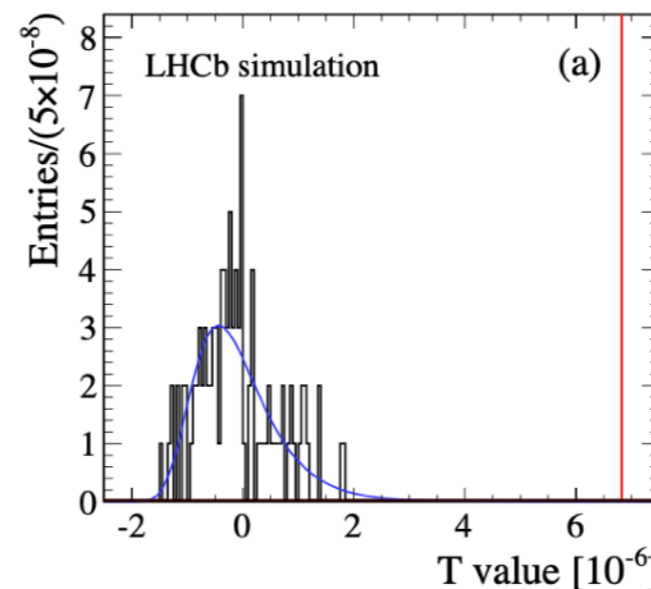
Search for CPV in $D^0 \rightarrow \pi^- \pi^+ \pi^0$

- Underlying *physics* similar to the “*CP*-violating” $D^0 \rightarrow \pi^- \pi^+$ but *enriched* with **resonances**
- Strategy: Energy test (unbinned)
 - use a test statistic ‘**T**’ sensitive both to *local* and *global* asymmetries
 - ***p-value*** by comparing the T value observed in **data** to a **distribution** of T values obtained from *permutation* samples (flavour randomly assigned)

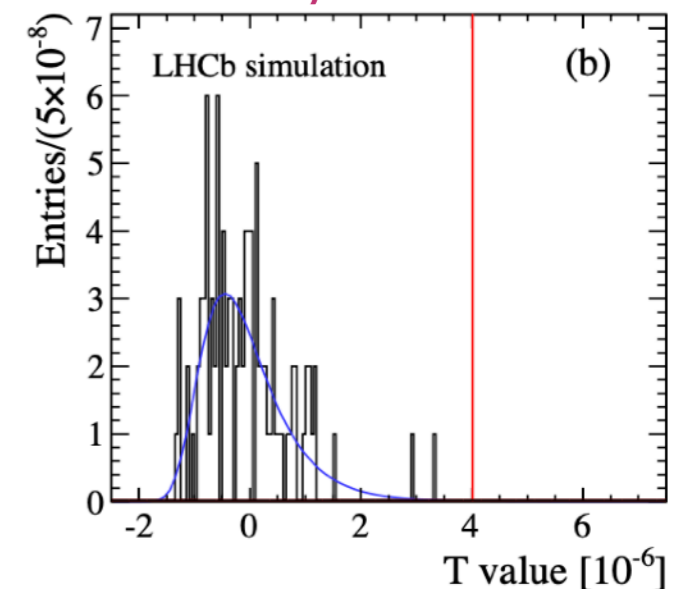


- **Run-1** analysis returned a *p-value* of 2.6%
- New results using **prompt** decays collected in **Run 2**

2% global CPV



CPV with 1° strong-phase in the ρ^+ resonance



[PhysLettB 2014 11 043]

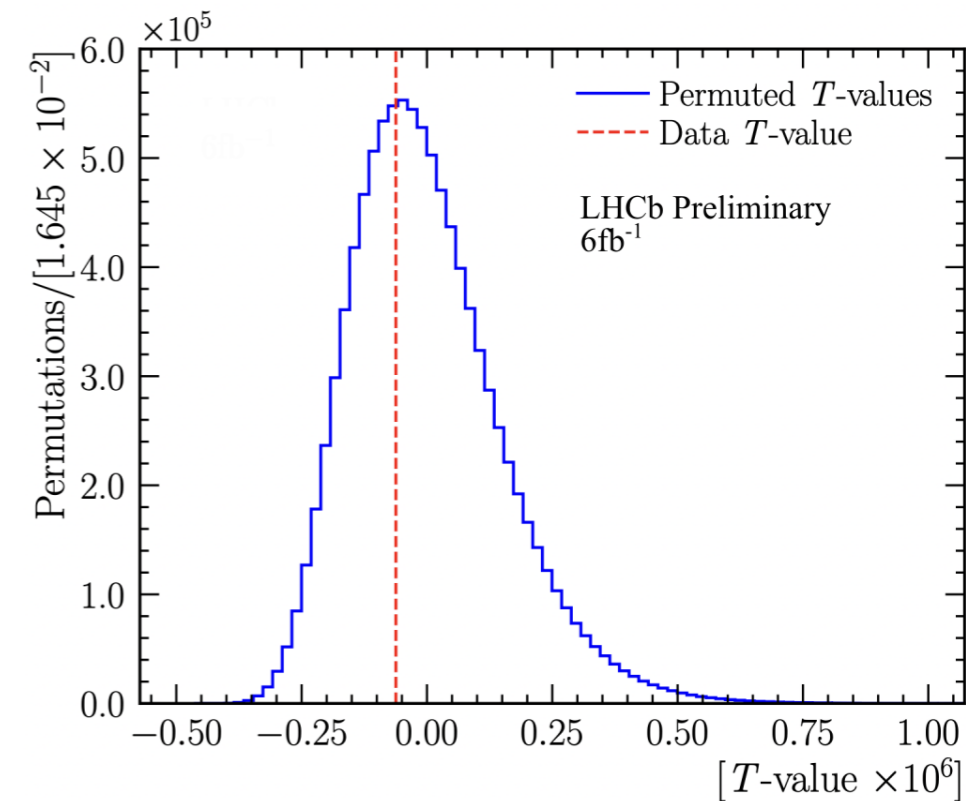
Energy test and results

- T is used to compare average *distances* d_{ij} in phase space, based on a metric function, ψ_{ij} , of pairs of events ij belonging to two samples of **opposite** flavour

$$\psi_{ij} = e^{-d_{ij}^2/2\sigma^2}$$

$$d_{ij} = |(m_{12}^{2,j} - m_{12}^{2,i}, m_{23}^{2,j} - m_{23}^{2,i}, m_{13}^{2,j} - m_{13}^{2,i})|$$

$$T = \underbrace{\sum_{i,j>i}^n \frac{\psi_{ij}}{n(n-1)} + \sum_{i,j>i}^{\bar{n}} \frac{\psi_{ij}}{\bar{n}(\bar{n}-1)}}_{\text{average distance of events with the **same** flavour (n or \bar{n})}} - \underbrace{\sum_{i,j}^{n,\bar{n}} \frac{\psi_{ij}}{n\bar{n}}}_{\text{average distance of events with the **opposite** flavour}}$$



- Method applied to the **2.7M** collected signal candidates and validated with CF $D^0 \rightarrow K \pi^+ \pi^0$ decays
- Results: p -value = 62% no evidence for CPV in this decay mode

Conclusions

- Millions of “rare” (CS) decays have been reconstructed by LHCb in Run-2 allowing high-precision CPV searches
- A precision of **6×10^{-4}** has been obtained in **$A_{CP}(D^0 \rightarrow K^- K^+)$** combining D^+ and D_s^+ decays to cancel nuisance asymmetries
- From combination with ΔA_{CP} , **first evidence** for *direct CP* violation in **$D^0 \rightarrow \pi^- \pi^+$** decays
- Statistics tests are powerful tools to *localise* CPV in **3-body** decays
- **No evidence** for CPV found with statistic tests in **$D_{(s)}^+ \rightarrow K^- K^+ K^+$** and **$D^0 \rightarrow \pi^- \pi^+ \pi^0$**
- **Run-3** data-taking has started, *early* results will come soon





Thanks!

Back-up slides →

$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

Mixing of neutral mesons

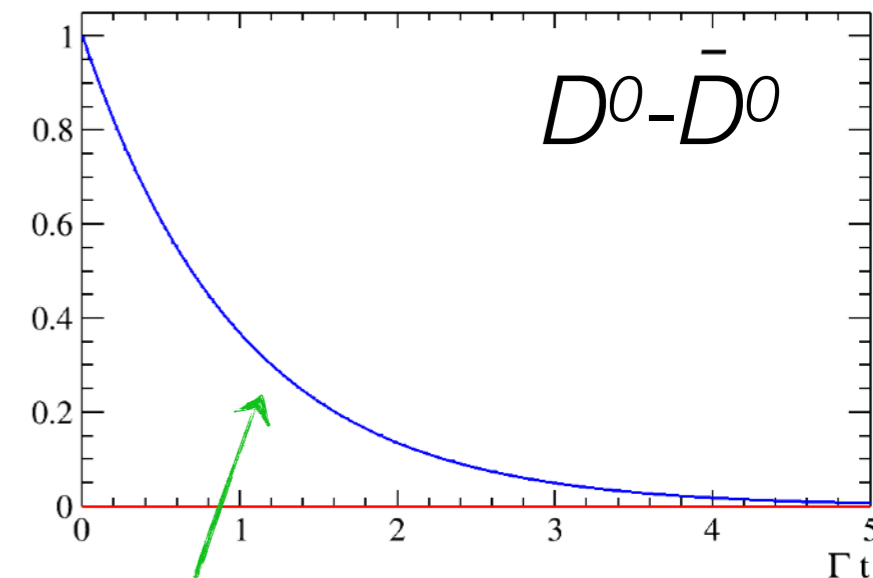
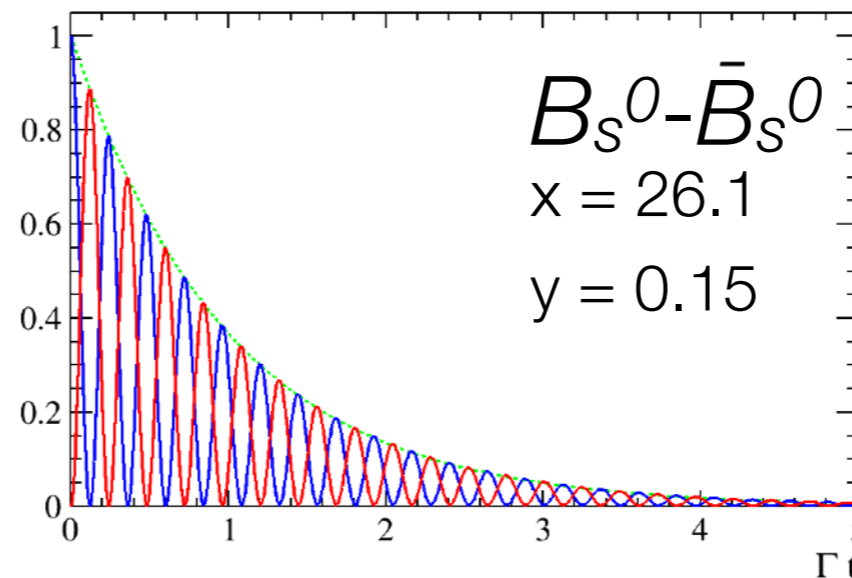
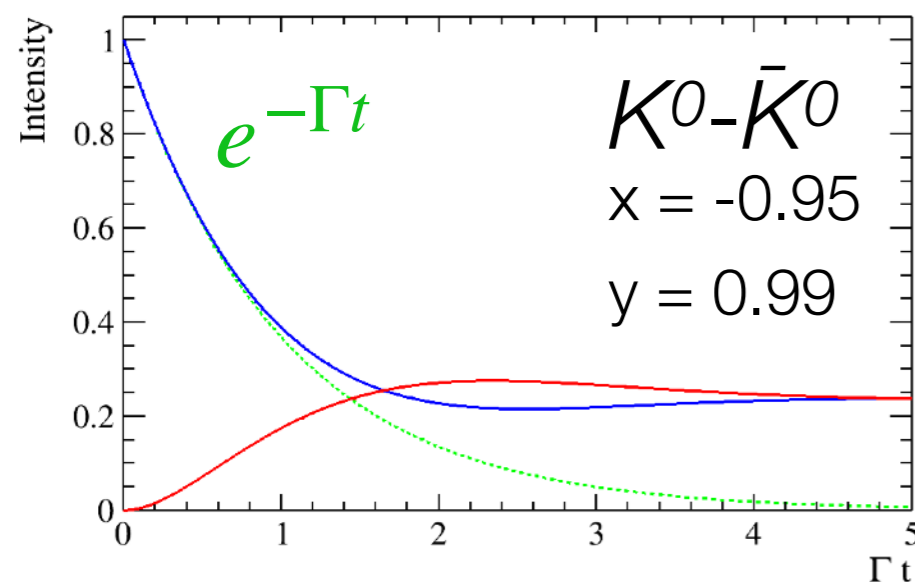
- Mass eigenstates are not flavour eigenstates:

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

- This causes $D^0 \leftrightarrow \bar{D}^0$ transitions described by

$$x = \frac{m_1 - m_2}{\Gamma}$$

$$y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$



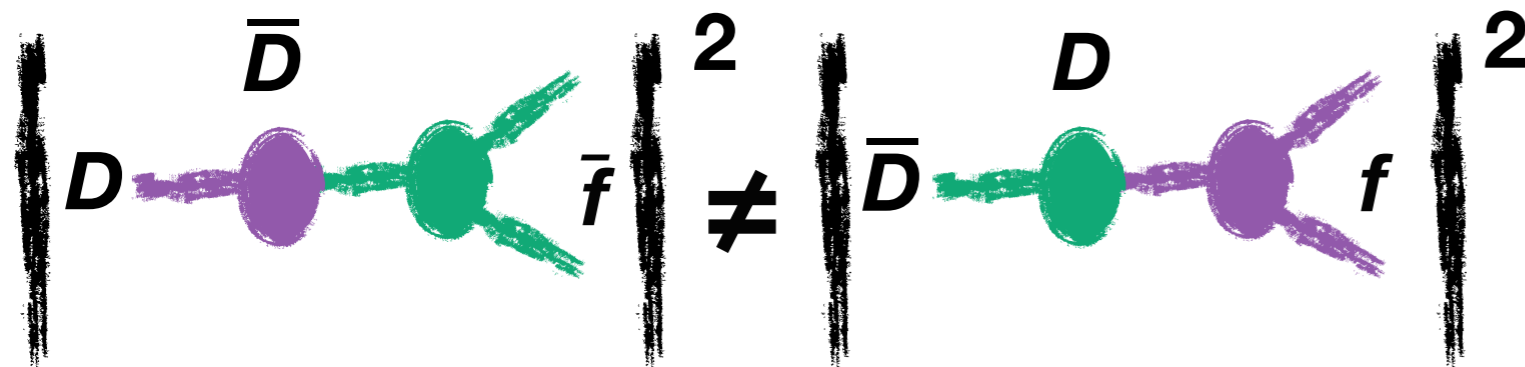
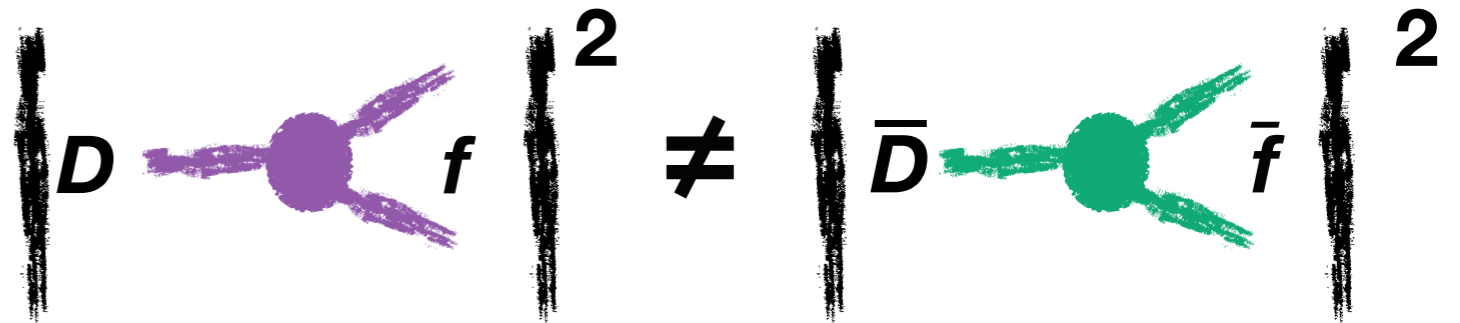
Tiny mixing in charm!

$$|\langle P^0(0) | P^0(t) \rangle|^2 \propto e^{-\Gamma t} [\cosh(y\Gamma t) + \cos(x\Gamma t)]$$

$$|\langle P^0(0) | \bar{P}^0(t) \rangle|^2 \propto e^{-\Gamma t} [\cosh(y\Gamma t) - \cos(x\Gamma t)]$$

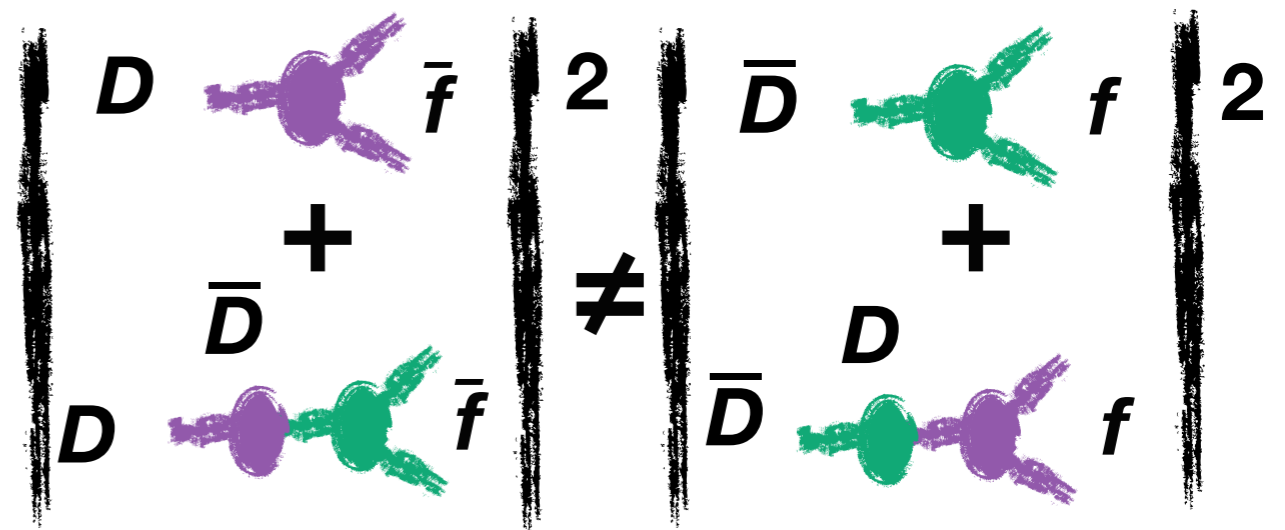
CP violation

- CPV in the **decay** occurs if $|A_f|^2 \neq |\bar{A}_{\bar{f}}|^2$



- CPV in **mixing** occurs if $|q/p| \neq 1$

- Indirect CPV in **interference** between *mixing* and *decay* occurs if $\phi_f \equiv \arg(q\bar{A}_{\bar{f}}/pA_f) \neq 0$



Conclusions

- **Run 1:**
 - observation of D^0 mixing
- **Run 2:**
 - observation of $x > 0$
 - observation of CP violation

- **Run 3: ?**

Sample (\mathcal{L})	Tag	$\sigma(\Delta A_{CP})$ [%]	$\sigma(A_{CP}(hh))$ [%]
Run 1–2 (9 fb^{-1})	Prompt	0.03 ✓	0.07 ✓
Run 1–3 (23 fb^{-1})	Prompt	0.013	0.03
Run 1–4 (50 fb^{-1})	Prompt	0.007	0.015
Run 1–5 (300 fb^{-1})	Prompt	0.003	0.007

Sample (lumi \mathcal{L})	Tag	Yield	$\sigma(x)$	$\sigma(y)$	$\sigma(q/p)$	$\sigma(\phi)$
Run 1–2 (9 fb^{-1})	SL ✓	10M	0.07%	0.05%	0.07	4.6°
	Prompt ✓	56M	0.05%	0.05%	0.04	1.8°
Run 1–3 (23 fb^{-1})	SL	33M	0.020%	0.020%	0.026	2.5°
	Prompt	200M	0.020%	0.020%	0.017	0.77°
Run 1–4 (50 fb^{-1})	SL	78M	0.012%	0.010%	0.024	1.7°
	Prompt	520M	0.012%	0.013%	0.011	0.48°
Run 1–5 (300 fb^{-1})	SL	490M	0.009%	0.008%	0.009	0.69°
	Prompt	3500M	0.005%	0.005%	0.004	0.18°

- Era of increasing precisions in charm measurements.

are we ready?



lots of work to keep under control
sources of systematic uncertainties...