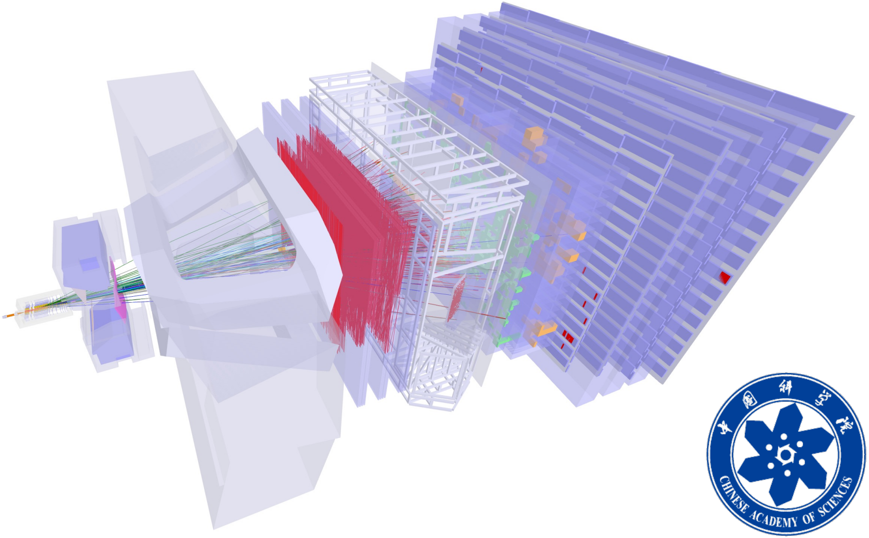
CP violation in charm hadrons @ LHCb



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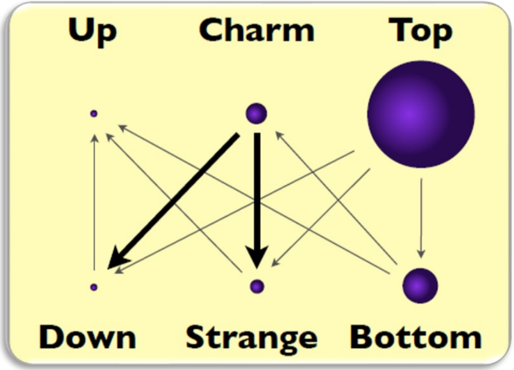
28 June 2025

CP violation in charm sector

- Charm is the only weak up-type quark decay from a bound system
  - The only up-type sector that could search for CP violation
- CP violation expected to be small in charm sector within SM
  - Imaginary part of V_{cd} very small
  - May enhance through new process and new particles
    – clean probe to NP
- CP violation in charm observed in two-body ΔA_{CP} by LHCb



$$V_{CKM} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda - iA^2\lambda^5\eta & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\hat{\rho}-i\hat{\eta}) & -A\lambda^2 - iA\lambda^4\eta & 1 \end{pmatrix}$$

Asymmetries & techniques

	global CPV	Localised in phase space
Decay-time integrated	A_{CP}, ΔA_{CP}, ……	Dalitz plot, binned χ^2, energy test, ……
Decay-time dependent	y_{CP}, A_{Γ}, ……	$D^0 \to K_S hh$ ……

Asymmetries & techniques

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CP violation in decay

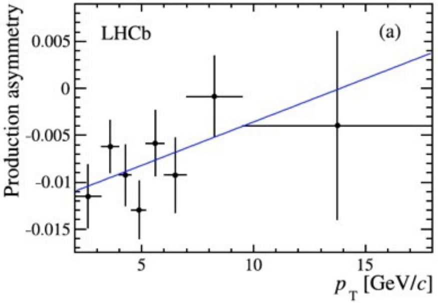
- CP violation in decays requires interference of several amplitudes
  - Can search through Singly Cabibbo suppressed decays
- Divide amplitudes into leading and sub-leading parts:
  - $A(D \to f) = C(1 + re^{i(\delta+\phi)})$
  - $A(\overline{D} \to f) = C(1 + re^{i(\delta-\phi)})$
- r is the ratio of sub-leading over leading amplitude
- CP violation requires difference in strong (δ) and weak phase (ϕ):
  - $A_{CP} = [\Gamma(D \to f) - \Gamma(\overline{D} \to f)]/[\Gamma(D \to f) + \Gamma(\overline{D} \to f)]$
    $\propto 2\, r \sin(\delta) \sin(\phi)$

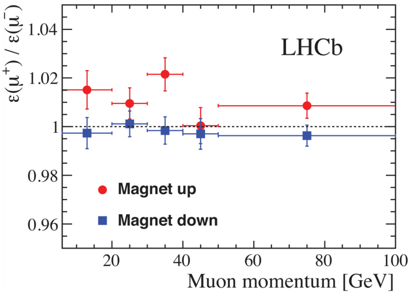
Measured asymmetries

- What we can measure:
  - $A_{raw}(\mathrm{D} \to f) = \frac{[N(\bar{D}\to f)-N(D\to f)]}{[N(\bar{D}\to f)+N(D\to f)]}$
- What we want:
  - $A_{CP}(\mathrm{D} \to f) = A_{raw}(\mathrm{D} \to f) - A_{prod}(\mathrm{D}) - A_{det}(f) - A_{det}(tag)$
- Need to constrain
  - Production asymmetry
  - Detection asymmetry
- General Idea
  - Use similar Cabibbo-allowed process as control mode
  - $A_{CP}^{ref}(\mathrm{D} \to f) \approx 0$

Nuisance asymmetries

- Production and detection asymmetries can be momentum dependent
- Need to ensure kinematic overlap to guarantee cancellation from control mode
  - Split measurement in sufficiently small kinematic bins
  - Use re-weighting techniques to equalise distributions
  - All methods have some cost in statistical precision





$\mathbf{A_{CP}}$

- Take $D^0 \to K^- K^+$ A_{CP} analysis as example
- Full decay chain $D^{*+} \to D^0(\to K^- K^+)\pi_s^+$
- $A_{raw}(i \to f) = \frac{N(i\to f)-N(\bar{i}\to \bar{f})}{N(i\to f)+N(\bar{i}\to \bar{f})}$
- $A_{CP}(D \to K^- K^+) = A_{raw}(D \to K^- K^+) - A_{prod}(D) - A_{det}(\pi_s^+)$
- Use control modes to cancel production and detection asymmetries
  - $D^{*+} \to D^0(\to K^- K^+)\pi_s^+$
  - $D^{*+} \to D^0(\to K^- \pi^+)\pi_s^+$
  - $D^+ \to K^- \pi^+ \pi^+$
  - $D^+ \to \bar{K}^0 \pi^+$
  - $\bar{K}^0$ detection asymmetry known

$$
\begin{aligned}
&A_{\mathrm{CP}}(D^0 \to K^- K^+) \\
&= A_{\mathrm{raw}}(D^0 \to K^- K^+) - A_{raw}(D^0 \to K^- \pi^+) \\
&+ A_{raw}(D^+ \to K^- \pi^+ \pi^+) - A_{raw}(D^+ \to \bar{K}^0 \pi^+) \\
&+ A_{\mathrm{det}}(\bar{K}^0)
\end{aligned}
$$

Summary of LHCb results

Table 1: Summary of LHCb direct CP violation searches in two-body charm decays.

Decay channel	Data sample	A_{CP}
$D^+ \to \phi\pi^+$ [1]	$1\,\text{fb}^{-1}$	$(-0.04 \pm 0.14 \pm 0.14)\%$
$D_s^+ \to K_S^0\pi^+$ [1]	$1\,\text{fb}^{-1}$	$(0.61 \pm 0.83 \pm 0.14)\%$
$D^0 \to K^-K^+$ [2]	$3\,\text{fb}^{-1}$	$(-0.06 \pm 0.15 \pm 0.10)\%$
$D^\pm \to K_S^0K^\pm$ [3]	$3\,\text{fb}^{-1}$	$(0.03 \pm 0.17 \pm 0.14)\%$
$D_s^\pm \to K_S^0\pi^\pm$ [3]	$3\,\text{fb}^{-1}$	$(0.38 \pm 0.46 \pm 0.17)\%$
$D^0 \to K_S^0K_S^0$ [4]	$3\,\text{fb}^{-1}$	$(-0.029 \pm 0.052 \pm 0.022)\%$
$D^0 \to K^-K^+$ [2]	$3\,\text{fb}^{-1}$	$(0.14 \pm 0.15 \pm 0.10)\%$
$D^\pm \to \eta'\pi^\pm$ [5]	$3\,\text{fb}^{-1}$	$(-0.61 \pm 0.72 \pm 0.53 \pm 0.12)\%$
$D_s^\pm \to \eta'\pi^\pm$ [5]	$3\,\text{fb}^{-1}$	$(-0.82 \pm 0.36 \pm 0.22 \pm 0.27)\%$
$D^0 \to K_S^0K_S^0$ [6]	$2\,\text{fb}^{-1}$	$(4.3 \pm 3.4 \pm 1.0)\%$
$D^0 \to K_S^0K_S^0$ [7]	$6\,\text{fb}^{-1}$	$(-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$
$D^+ \to \eta\pi^+$ [8]	$6\,\text{fb}^{-1}$	$(0.34 \pm 0.66 \pm 0.16 \pm 0.05)\%$
$D_s^+ \to \eta'\pi^+$ [8]	$6\,\text{fb}^{-1}$	$(0.32 \pm 0.51 \pm 0.12)\%$
$D^+ \to \eta\pi^+$ [8]	$6\,\text{fb}^{-1}$	$(0.49 \pm 0.18 \pm 0.06 \pm 0.05)\%$
$D_s^+ \to \eta'\pi^+$ [8]	$6\,\text{fb}^{-1}$	$(0.01 \pm 0.12 \pm 0.08)\%$
$D^+ \to \pi^+\pi^0$ [9]	$9\,\text{fb}^{-1}$	$(-1.3 \pm 0.9 \pm 0.6)\%$
$D^+ \to K^+\pi^0$ [9]	$9\,\text{fb}^{-1}$	$(-3.2 \pm 4.7 \pm 2.1)\%$
$D^+ \to \pi^+\eta$ [9]	$6\,\text{fb}^{-1}$	$(-0.2 \pm 0.8 \pm 0.4)\%$
$D^+ \to K^+\eta$ [9]	$6\,\text{fb}^{-1}$	$(-6 \pm 10 \pm 4)\%$
$D_s^+ \to K^+\pi^0$ [9]	$9\,\text{fb}^{-1}$	$(-0.8 \pm 3.9 \pm 1.2)\%$
$D_s^+ \to \pi^+\eta$ [9]	$6\,\text{fb}^{-1}$	$(0.8 \pm 0.7 \pm 0.5)\%$
$D_s^+ \to K^+\eta$ [9]	$6\,\text{fb}^{-1}$	$(0.9 \pm 3.7 \pm 1.1)\%$
$D^0 \to K^-K^+$ [10]	$5.7\,\text{fb}^{-1}$	$(0.068 \pm 0.054 \pm 0.016)\%$

[1] JHEP 06 (2013) 112
[2] Phys. Lett. B767 (2017) 177
[3] JHEP 10 (2014) 025
[4] JHEP 10 (2015) 055
[5] Phys. Lett. B771 (2017) 21
[6] JHEP 11 (2018) 048
[7] Phys. Rev. D104 (2021) L031102
[8] JHEP 04 (2023) 081
[9] JHEP 06 (2021) 019
[10] Phys. Rev. Lett. 131 (2023) 091802

ΔA_{CP}

- $A_{CP}(KK) = A_{raw}(KK) - A_{prod}(D) - A_{det}(\pi_s^+)$
- $A_{CP}(\pi\pi) = A_{raw}(\pi\pi) - A_{prod}(D) - A_{det}(\pi_s^+)$
- ΔA_{CP} is the difference between these two A_{CP}
- Advantage 1:
    - Cancel production and detection asymmetries
    - $A_{CP}(KK) - A_{CP}(\pi\pi) \approx A_{raw}(KK) - A_{raw}(\pi\pi)$
- Advantage 2:
    - $A_{CP}(KK)$ and $A_{CP}(\pi\pi)$ has similar amplitude but opposite sign
    - $A_{CP}(KK) - A_{CP}(\pi\pi) \approx 2|A_{CP}(KK)| \approx 2|A_{CP}(\pi\pi)|$
- The discovery of CP violation in charm sector in 2019 uses ΔA_{CP}

Summary of LHCb results

Table 2: Summary of the $\Delta \mathcal{A}_{CP}$ results from the LHCb two-body D^0 decay measurements in the charm sector.

Data sample	$\Delta \mathcal{A}_{CP}$ $(\times 10^{-3})$
$0.62\,\text{fb}^{-1}$, D^* tag [11]	$-8.2 \pm 4.1 \pm 0.6$
$1.0\,\text{fb}^{-1}$, B tag [12]	$4.9 \pm 3.0 \pm 1.4$
$3.0\,\text{fb}^{-1}$, B tag [13]	$1.4 \pm 1.6 \pm 0.8$
$3.0\,\text{fb}^{-1}$, D^* tag [14]	$-1.0 \pm 0.8 \pm 0.3$
$5.9\,\text{fb}^{-1}$, B or D^* tag [15]	-1.54 ± 0.29

CP violation found!

[11] Phys. Rev. Lett. 108 (2012) 111602
[12] Phys. Lett. B723 (2013) 33
[13] JHEP 07 (2014) 041
[14] Phys. Rev. Lett. 116 (2016) 191601
[15] Phys. Rev. Lett. 122 (2019) 211803

Asymmetries & techniques

	global CPV	Localised in phase space
Decay-time integrated	A_{CP}, ΔA_{CP}, ……	Dalitz plot, binned χ^2, energy test, ……
Decay-time dependent	y_{CP}, A_{Γ}, ……	$D^0 \to K_S hh$ ……

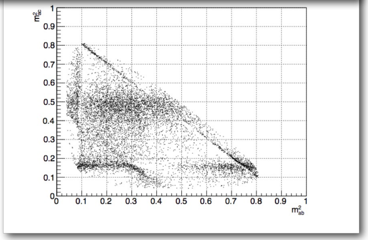
Two-body decays vs. Multi-body decays

- Two-body decays：
- pros： Large statistics
- cons： Asymmetry represented by a single number
  Need to deal with production/detection asymmetry
- Muilt-body decays：
- pros： Can analyse in Dalitz plot
  Rich phase space structure
  Can study CPV in resonances
  Local asymmetry may be larger than global asymmetry
- cons： Relatively small statistics / lower efficiencies
  Need higher dimensions for four- and even more-body decays

On Dalitz plot

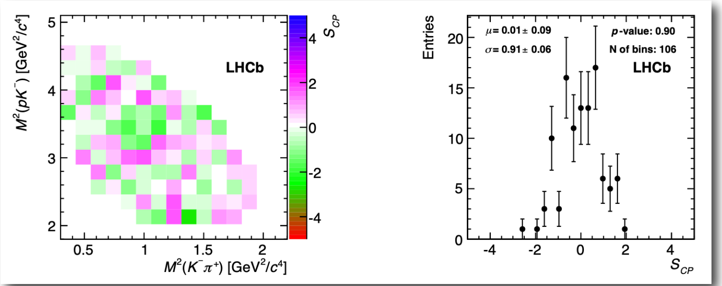
- Many ways to reach multi-body final states through intermediate resonances
- Resonances interfere and can carry different strong phases
  - Superb playground for CP violation
- Look for local asymmetries
  - Model-dependent:
    - Fit all contributions to phase-space and look for differences in fit parameters
  - Model-independent:
    - Look for asymmetries in regions of phase space by “counting”

Daughters	J^P	Mass	Width	Fit Fraction
a, b	0^+	0.3	0.025	6%
a, b	2^+	0.6	0.05	2%
a, c	1^-	0.4	0.04	18%
a, c	0^+	0.7	0.1	43%
b, c	1^-	0.35	0.01	10%
b, c	0^+	0.75	0.02	17%
a, b, c	non-resonant			1%



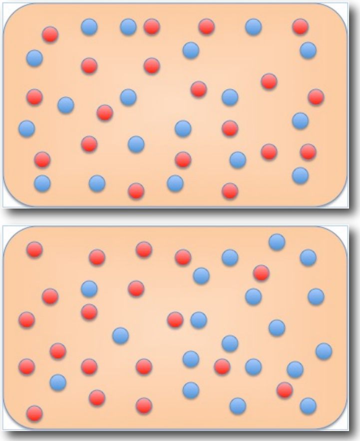
Binned χ^2 method

- Simplest and most used method in CPV searches in multi-body decays
- Divide phase space (usually Dalitz plot) into bins, calculate S_{CP}^i in each bin
- $S_{CP}^i = \frac{N^i(X) - \alpha N^i(\overline{X})}{\sqrt{N^i(X) - \alpha^2 N^i(\overline{X})}}$
- α is global asymmetry $\alpha = \frac{N_{tot}(X)}{\overline{N}_{tot}(\overline{X})}$, compare S_{CP}^i and normal distribution



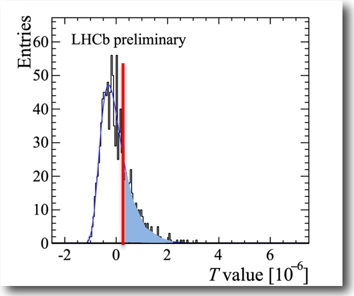
Energy test method

- Compare two distributions statistically
- Idea comes from the calculation of electric potential energy
- +q and −q equally distributed, electric potential energy = 0
- +q and −q distributions different, electric potential energy > 0
- System → phase space
  +q /−q → opposite flavoured decays
- Form test statistics T
- $T = \frac{1}{n(n-1)} \Sigma_{i,j>i}^{n} \psi(d_{ij}) + \frac{1}{\bar{n}(\bar{n}-1)} \Sigma_{i,j>i}^{\bar{n}} \psi(d_{ij}) - \frac{1}{n\bar{n}} \Sigma_{i,j}^{n,\bar{n}} \psi(d_{ij})$

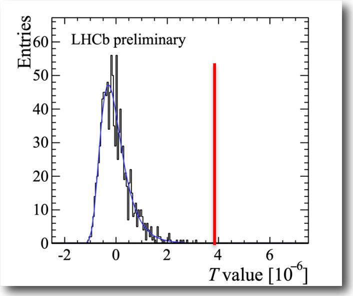


Energy test mothod

- Compare T-value from tested sample (T_0) with T-values from no-CPV samples
- No-CPV sample from permutation of data: randomly assign flavour tags
- p-value: fraction of permutation T-values above T_0



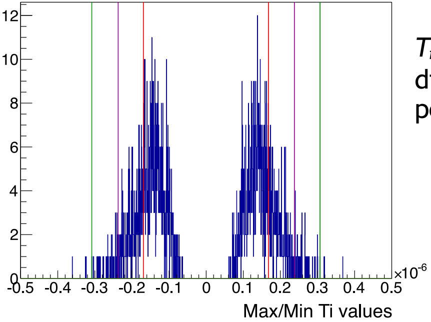
高p值——无CPV



小p值——有CPV

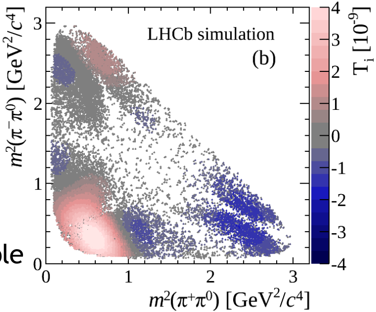
Energy test – Visualization

- Contribution of each event to total T -value: T_i
- Use T_i^{max} and T_i^{min} distributions from permutations to set significance levels
- Plot T_i values in terms of these significance levels → Show regions in Dalitz plot which contribute the most



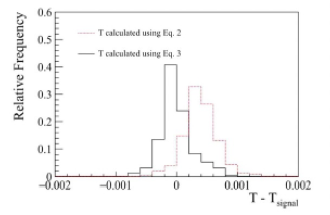
T_i^{max} and T_i^{min} distributions from permutations

Visualisation of CP asymmetric MC sample



Energy test method – bkg control

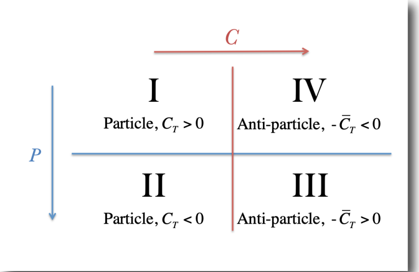
- Use extra bkg sample to cancel bkg impact on signal
- Bkg distribution comes from sideband
- Unbiased distribution after correction in simulation test



$$T = \frac{1}{2w(w-1)}\left(\sum_i^n\sum_{j\neq i}^n\psi_{ij} - \frac{2b}{b_s}\sum_i^n\sum_j^{b_s}\psi_{ij} + \frac{b(b+1)}{b_s(b_s-1)}\sum_i^{b_s}\sum_{j\neq i}^{b_s}\psi_{ij}\right)$$
$$+ \frac{1}{2\bar{w}(\bar{w}-1)}\left(\sum_i^{\bar{n}}\sum_{j\neq i}^{\bar{n}}\psi_{ij} - \frac{2\bar{b}}{\bar{b}_s}\sum_i^{\bar{n}}\sum_j^{\bar{b}_s}\psi_{ij} + \frac{\bar{b}(\bar{b}+1)}{\bar{b}_s(\bar{b}_s-1)}\sum_i^{\bar{b}_s}\sum_{j\neq i}^{\bar{b}_s}\psi_{ij}\right)$$
$$- \frac{1}{w\bar{w}}\left(\sum_i^n\sum_j^{\bar{n}}\psi_{ij} - \frac{\bar{b}}{\bar{b}_s}\sum_i^n\sum_j^{\bar{b}_s}\psi_{ij} - \frac{b}{b_s}\sum_i^{b_s}\sum_j^{\bar{n}}\psi_{ij} + \frac{b\bar{b}}{b_s\bar{b}_s}\sum_i^{b_s}\sum_j^{\bar{b}_s}\psi_{ij}\right),$$

Three-body decays and Four-body decays

- Multibody pseudo-scalar decays, Independent Variables: 3n-7
- Three-body decays → 2 independent variables → Dalitz plot analysis
- Four-body decays → 5 independent variables → No preferred choice (unlike 3-body Dalitz plot): mass combinations, helicity angles, triple product
- Binned method: limited statistics in each bin
- Four-body decays: Can test P-even and P-odd contributions to CP violation separately using sign of Triple p product
- $C_T = \vec{p}_3 \cdot (\vec{p}_1 \times \vec{p}_2)$, where $CP(C_T) = -C(C_T) = -\overline{C}_T$



- P-even: I+II vs. III+IV
- P-odd: I+IV vs. II+III

Summary of LHCb results

Table 3: Summary of LHCb direct CP violation searches in phase space of charm decays.

Decay channel	Data sample	Method
$D^+ \to K^-K^+\pi^+$ [16]	$35\,\mathrm{pb}^{-1}$	binned χ^2
$D^0 \to K^-K^+\pi^-\pi^+$ [17]	$1.0\,\mathrm{fb}^{-1}$, D^* tag	binned χ^2
$D^0 \to \pi^-\pi^+\pi^-\pi^+$ [17]	$1.0\,\mathrm{fb}^{-1}$, D^* tag	binned χ^2
$D^+ \to \pi^-\pi^+\pi^+$ [18]	$1.0\,\mathrm{fb}^{-1}$	binned χ^2
$D^0 \to K^-K^+\pi^-\pi^+$ [19]	$3.0\,\mathrm{fb}^{-1}$, B tag	binned χ^2
$D^0 \to \pi^-\pi^+\pi^0$ [20]	$2.0\,\mathrm{fb}^{-1}$, D^* tag	energy test
$D^0 \to \pi^-\pi^+\pi^-\pi^+$ [21]	$3.0\,\mathrm{fb}^{-1}$, D^* tag	energy test
$\Lambda_c^+ \to ph^-h^+$ [22]	$3.0\,\mathrm{fb}^{-1}$	$\Delta\mathcal{A}_{CP}$
$D^0 \to K^-K^+\pi^-\pi^+$ [23]	$3.0\,\mathrm{fb}^{-1}$, B tag	amplitude analysis
$\Xi_c^+ \to pK^-\pi^+$ [24]	$3.0\,\mathrm{fb}^{-1}$	binned χ^2
$D^0 \to K_S^0K^\pm\pi^\mp$ [25]	$5.4\,\mathrm{fb}^{-1}$, D^* tag	energy test
$D^0 \to \pi^-\pi^+\pi^0$ [26]	$7.7\,\mathrm{fb}^{-1}$, D^* tag	energy test
$D_{(s)}^+ \to K^-K^+K^+$ [27]	$5.6\,\mathrm{fb}^{-1}$, D^* tag	binned χ^2
$D^+ \to K^-K^+\pi^+$ [28]	$5.4\,\mathrm{fb}^{-1}$, D^* tag	binned χ^2
$\Lambda_c^+ \to p\mu^+\mu^-$ [29]	$5.4\,\mathrm{fb}^{-1}$	$\mathcal{A}_{CP}$

No CP violation found in the phase space yet

[16] Phys. Rev. D84 (2011) 112008
[17] Phys. Lett. B726 (2013) 623
[18] Phys. Lett. B728 (2014) 585
[19] JHEP 10 (2014) 005
[20] Phys. Lett. B740 (2015) 158
[21] Phys. Lett. B769 (2017) 345
[22] JHEP 03 (2018) 182
[23] JHEP 02 (2019) 126
[24] Eur. Phys. J. C80 (2020) 986
[25] JHEP 03 (2024) 107
[26] Phys. Rev. Lett. 133 (2024) 101803
[27] JHEP 07 (2023) 067
[28] Phys. Rev. Lett. 133 (2024) 251801
[29] Phys. Rev. D111 (2025) L091102

Asymmetries & techniques

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Decay-time integrated	A_{CP}, ΔA_{CP}, ……	Dalitz plot, binned χ^2, energy test, ……
Decay-time dependent	y_{CP}, A_{Γ}, ……	$D^0 \to K_S hh$ ……

$\boldsymbol{y_{CP}}$

- Due to the existence of mixing, the decay widths of D^0 decays to CP eigenstates (KK or $\pi\pi$) Γ_{CP+} and to other final states (i.e. CF decay $K\pi$) Γ can be different
- Define $y_{CP} = \Gamma_{CP+}/\Gamma - 1$

$$y_{CP} \approx \frac{1}{2}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) y\cos\phi - \frac{1}{2}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x\sin\phi$$

- is related to x, y, $|q/p|$, ϕ, and if no CP violation, $y_{CP} = y$
- Experimental measures: $y_{CP} = \frac{2\tau(D^0\to f_{CF})}{\tau(\overline{D}^0\to f_{CP})+\tau(D^0\to f_{CP})} - 1$
- $f_{CF} = K\pi$ final states, $f_{CP} = KK$ or $\pi\pi$ final states

A_Γ

- The lifetime asymmetry of D^0 and $\overline{D}^0$ decays to CP eigenstates (KK or $\pi\pi$)
- $A_\Gamma = -A_{CP}^{indirect}$, and satisfy

$$A_\Gamma \approx \frac{1}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y \cos\phi - \frac{1}{2}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x \sin\phi$$

- Experimental measures: $A_\Gamma = \frac{\tau(\overline{D}^0 \to f_{CP}) - \tau(D^0 \to f_{CP})}{\tau(\overline{D}^0 \to f_{CP}) + \tau(D^0 \to f_{CP})}$

- So far no experimental evidence of CP violation in mixing found in y_{CP} and A_Γ measurements

Summary of LHCb results

Table 4: Summary of LHCb y_{CP} and A_Γ measurements.

Data sample	Final state(s)	y_{CP} (%)	A_Γ ($\times 10^{-3}$)
$29\,\text{pb}^{-1}$, D^* tag [30]	K^+K^-	$0.55 \pm 0.63 \pm 0.41$	$-5.9 \pm 5.9 \pm 2.1$
$1.0\,\text{fb}^{-1}$, D^* tag [31]	$\pi^+\pi^-$	-	$0.33 \pm 1.06 \pm 0.14$
$1.0\,\text{fb}^{-1}$, D^* tag [31]	K^+K^-	-	$-0.35 \pm 0.62 \pm 0.12$
$3.0\,\text{fb}^{-1}$, B tag [32]	$\pi^+\pi^-$	-	$-0.92 \pm 2.6^{+0.25}_{-0.33}$
$3.0\,\text{fb}^{-1}$, B tag [32]	K^+K^-	-	$-1.34 \pm 0.77^{+0.26}_{-0.34}$
$3.0\,\text{fb}^{-1}$, B tag [32]	$\pi^+\pi^-$ & K^+K^-	-	-1.25 ± 0.73
$3.0\,\text{fb}^{-1}$, B tag [33]	$\pi^+\pi^-$ & K^+K^-	$0.57 \pm 0.13 \pm 0.09$	-
$3.0\,\text{fb}^{-1}$, D^* tag [34]	$\pi^+\pi^-$	-	$0.46 \pm 0, 58 \pm 0.12$
$3.0\,\text{fb}^{-1}$, D^* tag [34]	K^+K^-	-	$-0.30 \pm 0.32 \pm 0.10$
$3.0\,\text{fb}^{-1}$, D^* tag [34]	$\pi^+\pi^-$ & K^+K^-	-	$-0.13 \pm 2.0 \pm 0.7$
$5.4\,\text{fb}^{-1}$, B tag [35]	$\pi^+\pi^-$	-	$0.22 \pm 0.70 \pm 0.08$
$5.4\,\text{fb}^{-1}$, B tag [35]	K^+K^-	-	$-0.43 \pm 0.36 \pm 0.05$
$6\,\text{fb}^{-1}$, D^* tag [36]	$\pi^+\pi^-$	-	$0.4 \pm 0.28 \pm 0.04$
$6\,\text{fb}^{-1}$, D^* tag [36]	K^+K^-	-	$0.23 \pm 0.15 \pm 0.03$
$8.4\,\text{fb}^{-1}$, D^* or B tag [36]	$\pi^+\pi^-$	-	$0.36 \pm 0.24 \pm 0.04$
$8.4\,\text{fb}^{-1}$, D^* or B tag [36]	K^+K^-	-	$0.03 \pm 0.13 \pm 0.03$
$8.4\,\text{fb}^{-1}$, D^* or B tag [36]	$\pi^+\pi^-$ & K^+K^-	-	$0.10 \pm 0.11 \pm 0.03$
$6\,\text{fb}^{-1}$, D^* tag [37]	$\pi^+\pi^-$	$0.657 \pm 0.053 \pm 0.016$ [1]	-
$6\,\text{fb}^{-1}$, D^* tag [37]	K^+K^-	$0.708 \pm 0.030 \pm 0.014$ [2]	-
$6\,\text{fb}^{-1}$, D^* tag [37]	$\pi^+\pi^-$ & K^+K^-	$0.696 \pm 0.026 \pm 0.013$ [3]	-

1. $y_{CP}^{\pi\pi} - y_{CP}^{K\pi}$ is measured in this analysis.
2. $y_{CP}^{KK} - y_{CP}^{K\pi}$ is measured in this analysis.
3. $y_{CP} - y_{CP}^{K\pi}$ is measured in this analysis.

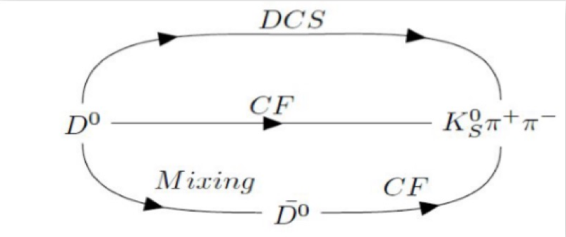
[30] JHEP 04 (2012) 129
[31] Phys. Rev. Lett. 112 (2014) 041801
[32] JHEP 04 (2015) 043
[33] Phys. Rev. Lett. 122 (2019) 011802
[34] Phys. Rev. Lett. 118 (2017) 261803
[35] Phys. Rev. D101 (2020) 012005
[36] Phys. Rev. D104 (2021) 072010
[37] Phys. Rev. D105 (2022) 092013

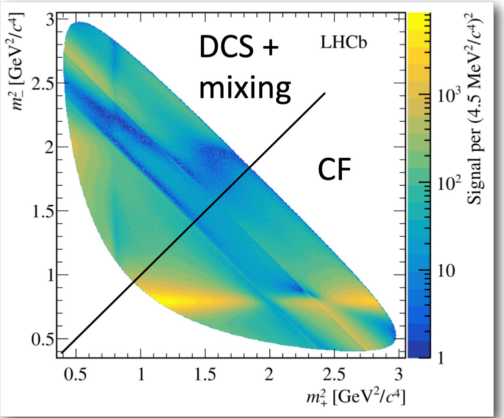
Asymmetries & techniques

	global CPV	Localised in phase space
Decay-time integrated	A_{CP}, ΔA_{CP}, ……	Dalitz plot, binned χ^2, energy test, ……
Decay-time dependent	y_{CP}, A_Γ, ……	$D^0 \to K_S hh$ ……

Mixing parameters measurements using $D^0 \to K_S\pi\pi$

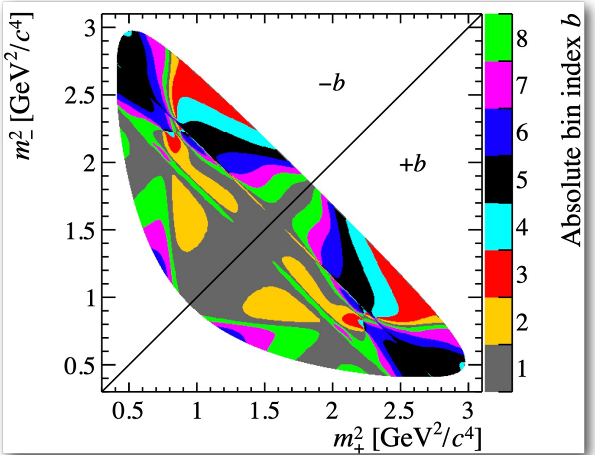
- 'Golden channel' for mixing parameter measurements
  - Many interfering amplitudes in the phase space
  - CF and DCS decays to same phase space
- 'bin-flip' method
  - Oscillation mainly contribute to the upper region in the Dalitz plot
  - Ratio between upper and bottom parts as function of time sensitive to mixing





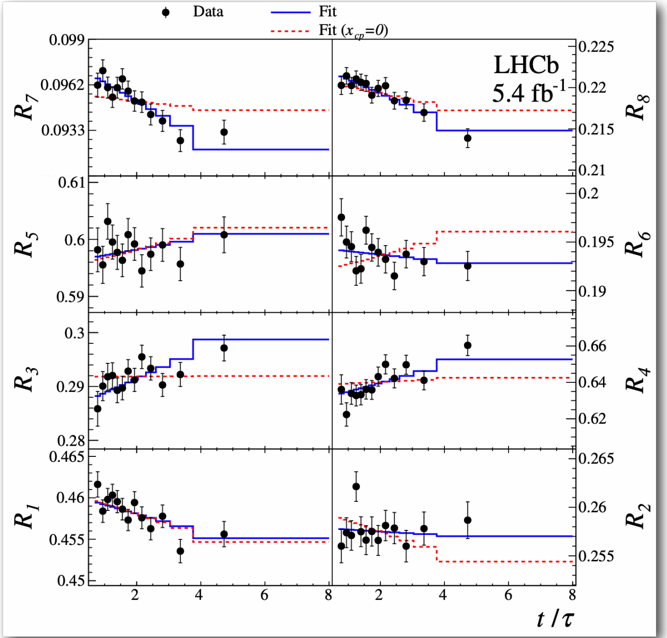
Mixing parameters measurements using $D^0 \to K_S\pi\pi$

- Bins: Strong phase measured by CLEO or BESIII
  - Reduce cancellation of different strong phase to the result
- Fit to the time dependent ratios, extract x and y from the fit function
- y > 0: lifetime of CP-even eigenstate is shorter lived than CP-odd
- x > 0: mass splitting



Mixing parameters measurements using $D^0 \to K_S\pi\pi$

- Fit results:
- $x = \left(3.98^{+0.56}_{-0.54}\right)\times10^{-3}$
- $y = \left(4.6^{+1.5}_{-1.4}\right)\times10^{-3}$
- First observation of non-zero x with significance $> 7\sigma$
  - non-zero difference between two D^0 mass eigenstates
- No CP violation found



Summary of LHCb results

Table 5: Summary of the charm mixing parameters measured by LHCb using $D^0 \to K^0_S \pi^+ \pi^-$ decays.

Data sample	CP-averaged parameters x $(\times 10^{-3})$	y $(\times 10^{-3})$
$1.0\,\text{fb}^{-1}$, D^* tag [38]	$-8.6 \pm 5.3 \pm 1.7$	$0.3 \pm 4.6 \pm 1.3$
$3.0\,\text{fb}^{-1}$, B tag [39]	$2.7 \pm 1.6 \pm 0.4$	$7.4 \pm 3.6 \pm 1.1$
$5.4\,\text{fb}^{-1}$, D^* tag [40]	$3.97 \pm 0.46 \pm 0.29$	$4.59 \pm 1.20 \pm 0.85$

Data sample	CP-violating parameters Δx $(\times 10^{-3})$	Δy $(\times 10^{-3})$
$3.0\,\text{fb}^{-1}$, B tag [39]	$-0.53 \pm 0.70 \pm 0.22$	$0.6 \pm 1.6 \pm 0.3$
$5.4\,\text{fb}^{-1}$, D^* tag [40]	$-0.27 \pm 0.18 \pm 0.01$	$0.20 \pm 0.36 \pm 0.13$

First non-zero x!

[38] JHEP 04 (2016) 033
[39] Phys. Rev. Lett. 122 (2019) 231802
[40] Phys. Rev. Lett. 127 (2021) 111801

Conclusions and prospects

- CP violation in charm sector is a rich field of study
- Essential to precisely test the SM and constraint/guide New Physics models
- LHCb has a leading role for CP violation searches
- 2024 sample size comparable to the sum of Run 1&2
- More results will come!