DISCRETE 2026

CP violation and mixing in the charm sector at LHCb

10th Symposium on Prospects in the Physics of Discrete Symmetries

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SCUOLA NORMALE SUPERIORE

INFN
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Quantum oscillations

Phenomenological parametrization

$$\boldsymbol{H} = \boldsymbol{M} - \frac{i}{2}\boldsymbol{\Gamma}$$

$$\boldsymbol{M} \equiv (\boldsymbol{H} + \boldsymbol{H}^\dagger)/2 \text{ and } \boldsymbol{\Gamma} \equiv i(\boldsymbol{H} - \boldsymbol{H}^\dagger)$$

$\boldsymbol{M}$ (dispersive) and $\boldsymbol{\Gamma}$(absorptive) are 2×2 hermitian matrices

$|M^0\rangle$ and $|\overline{M}^0\rangle$ basis

Normalized eigenstates of $\boldsymbol{H}$

$$|M_1\rangle \equiv p\,|M^0\rangle + q\,|\overline{M}^0\rangle$$
$$|M_2\rangle \equiv p\,|M^0\rangle - q\,|\overline{M}^0\rangle$$

Schrödinger equation

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

Diagonalization condition

$$\left(\frac{q}{p}\right)^2 = \frac{H_{21}}{H_{12}} = \frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}.$$

$\Longrightarrow$

Time evolution

$$|M_{1,2}(t)\rangle = e^{-i\omega_{1,2}t}\,|M_{1,2}(0)\rangle$$
$$\omega_{1,2} \equiv M_{1,2} - \frac{i}{2}\Gamma_{1,2}$$

CPV in mixing

$$\left|\frac{q}{p}\right| \neq 1$$

If $\boldsymbol{CP}$ is violated (*CPT* symmetry assumed) 5 physics observables : $M = \dfrac{M_1 + M_2}{2}$, $\Gamma = \dfrac{\Gamma_1 + \Gamma_2}{2}$, $x = \dfrac{M_2 - M_1}{\Gamma}$, $y = \dfrac{\Gamma_2 - \Gamma_1}{2\Gamma}$, and $\left|\dfrac{q}{p}\right|$.

Note that $\phi = \arg(q/p)$ is not a physics observable. A phase convention is needed to solve the ambiguity in the definition of $|M_1\rangle$ and $|M_2\rangle$, usually one assumes $y > 0$. Necessary also to solve another ambiguity due to the relative sign between phases of p and q. This depends on the convention of $\boldsymbol{CP}$ transformation of M^0 and $\overline{M}^0$ mesons.

Quantum oscillations

Theoretical parametrization

$$M = \frac{M_1 + M_2}{2} = M_{11} = M_{22}$$
$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2} = \Gamma_{11} = \Gamma_{22}$$

An alternative parametrization which is **convention-independent** and quantifies directly the magnitudes and the phase dfference between the dispersive and absorptive transition amplitudes is used. In particular, the theoretical mixing parameters and the mixing phase are defined as

$$x_{12} \equiv \frac{2|M_{12}|}{\Gamma}, \qquad y_{12} \equiv \frac{|\Gamma_{12}|}{\Gamma}, \qquad \phi_{12} \equiv \arg\left(\frac{M_{12}}{\Gamma_{12}}\right)$$

They are all observable quantities. While x_{12} and y_{12} are CP-even observables, ϕ_{12} is a CP-odd weak phase.

The theoretical and phenomenological mixing parameters are related as

$$\begin{aligned} x^2 - y^2 &= x_{12}^2 - y_{12}^2, \\ xy &= x_{12} y_{12} \cos\phi_{12}, \\ \left|\frac{q}{p}\right|^{\pm 2} (x^2 + y^2) &= x_{12}^2 + y_{12}^2 \pm 2 x_{12} y_{12} \sin\phi_{12}, \end{aligned}$$

$$\left|\frac{q}{p}\right| \approx 1 \quad \text{experimentally} \quad \Longrightarrow$$

$$x_{12} \approx |x| \text{ and } y_{12} \approx |y|$$

$$\left|\frac{q}{p}\right| - 1 \approx \frac{x_{12} y_{12}}{x_{12}^2 + y_{12}^2} \sin\phi_{12}$$

Up to quadratic correction in $\sin\phi_{12}$

Phenomenological vs Theoretical

- They are fully equivalent, and choosing one or the other is mostly a matter of personal taste.
- For mixing, the observable parameters are always three:

$$|y|,\ \frac{x}{y},\ \left|\frac{q}{p}\right| \qquad \text{vs} \qquad x_{12},\ y_{12},\ \phi_{12}$$

$$\lambda_f^{\Gamma} = \frac{\Gamma_{12}}{|\Gamma_{12}|}\frac{A_f}{\bar{A}_f}$$

$$\lambda_f^{M} = \frac{M_{12}}{|M_{12}|}\frac{A_f}{\bar{A}_f}$$

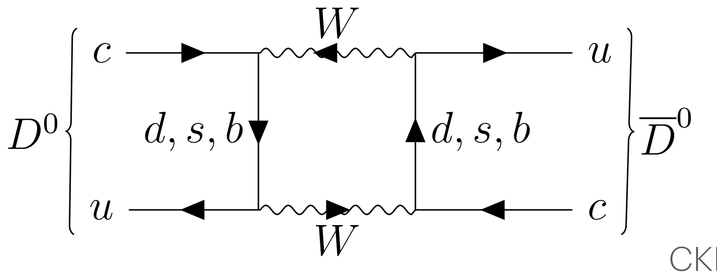
- On the contrary $\phi^M \equiv \arg(M_{12})$ and $\phi^\Gamma \equiv \arg(\Gamma_{12})$, and $\arg(q/p)$ are neither quark- nor meson-rephasing invariant and thus they are not observable. Please note that $\phi^M - \phi^\Gamma = \phi_{12}$ is observable.
- $\phi_f^M \equiv \arg(\lambda_f^M)$ and $\phi_f^\Gamma \equiv \arg(\lambda_f^\Gamma)$ instead are observable because the phase conventions cancel out in the multiplication of M_{12} (or Γ_{12}) with the decay amplitudes, as it happens for $\phi_{\lambda_f} = \arg(q\bar{A}_f/pA_f)$.
- **Final state dependence currently neglected because of still large experimental uncertainties.**
- **Note: if CP is conserved $\phi^M = \phi^\Gamma = -\arg(q/p)$ (and of course $\phi_{12} = 0$ and $|q/p| = 1$).**

Charm Mixing

Phenomenology

Complementary to K and B mesons. FCNC are extremely suppressed

GIM mechanism broken by the beauty-quark mass (instead of top)



$$\propto \left(\frac{m_{d,s,b}}{m_W}\right)^2$$

CKM suppression of b-quark contribution

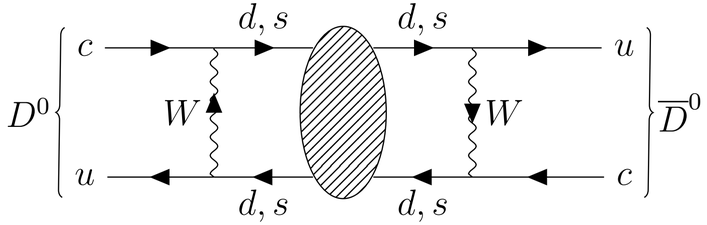
mixing — short distance

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

d s b

u c t

$$\lambda = \sin\theta_{\mathrm{C}} \approx 0.23$$



mixing — long distance

The 3rd quark generation nearly decouples from the first two, while the contributions from d and s quarks cancel out in the limit of U-spin symmetry ($m_d = m_s$)

$x_{12} \simeq |x| = 0.4\,\%$ (off-shell), $y_{12} \simeq |y| \approx 0.6\,\%$ (on-shell)

Long-distance QCD dominates: off-shell contributions to x_{12}, on-shell contributions to y_{12}. **Theory predictions are very challenging**.

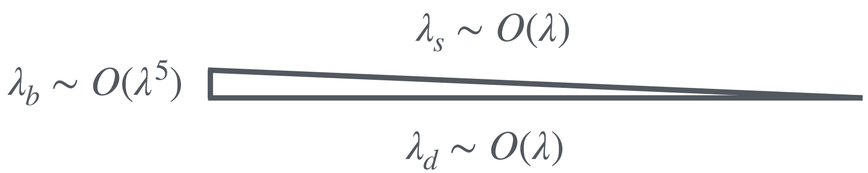
Kagan and Silvestrini, PRD 103, 053008 (2021)

CP Violation in Charm Sector

Mixing and Interference

Only transitions of a quark to lighter quarks involved in charm meson decays, mixing and relevant amplitudes are therefore described, to an excellent approximation, by the physics of the first two generations only.

$$\lambda_q = V_{cq}^* V_{uq} \quad (q \in d, s, b)$$



$$V_{cd}^* V_{ud} + V_{cs}^* V_{us} + V_{cb}^* V_{ub} = 0$$

SM expectations are naively of the order of

$$\mathrm{Im}\left(\frac{\lambda_b}{\lambda}\right) = \mathrm{Im}\left(\frac{V_{ub}V_{cb}^*}{V_{us}V_{cs}^*}\right) \approx \lambda^4 A^2 \eta \approx 6 \times 10^{-4}$$

In terms of CKM elements Γ_{12}^{SM} and M_{12}^{SM} can be decomposed in their U-spin transitions ($\Delta U = 0,1,2$, with $\Delta U_3 = 0$). The dominant are those with $\Delta U = 2$, therefore one can derive the SM phases:

$$\phi_2^M \equiv \arg\left[\frac{M_{12}}{\frac{1}{4}(\lambda_s - \lambda_d)^2 M_2}\right] \qquad \phi_2^\Gamma \equiv \arg\left[\frac{\Gamma_{12}}{\frac{1}{4}(\lambda_s - \lambda_d)^2 \Gamma_2}\right]$$

The phase ϕ_2^M is expected to be of the same order of ϕ_2^Γ.

CP Violation in Charm Sector

Mixing and Interference

- Dispersive and absorptive phases, ϕ_2^Γ and ϕ_2^M are estimated to be of the order of 2 mrad [Kagan&Silvestrini PRD 103, 053008 (2021)].
- An upper bound of 5 mrad has been argued for ϕ_2^Γ by the same authors.
- **Enhancements by up to one of order of magnitude cannot be excluded** [Bigi&Paul, JHEP06(2011)089],[Bobrowski et al. JHEP03(2010)009],[Li et al. PLB(2020)135802]
- **Current experimental limits are less precise by a large factor** (almost by one order of magnitude), as the mixing phases are measured to be $\phi_2^M = (4^{+11}_{-10})$ mrad and $\phi_2^\Gamma = (19^{+24}_{-23})$ mrad (*).
- Mixing phases can be observed only because contributions from final state f under consideration, which are **neglected at the current experimental precision**.

(*) from LHCb-PAPER-2026-058 [in preparation]. See next slides.

CP Violation in Charm Sector

In the decay (or direct)

$$A(D^0 \to h^+h^-) \equiv \lambda_s T_{h^+h^-} + \lambda_b P_{h^+h^-}$$

$$\lambda_i \equiv V_{ci}^* V_{ui} \qquad \delta_{h^+h^-} \equiv \arg\left(\frac{P_{h^+h^-}}{T_{h^+h^-}}\right)$$

$$a^d_{h^+h^-} = \mp 2\,\mathrm{Im}\left(\frac{\lambda_b}{\lambda_s}\right)\left|\frac{P_{h^+h^-}}{T_{h^+h^-}}\right|\sin\delta_{h^+h^-}$$

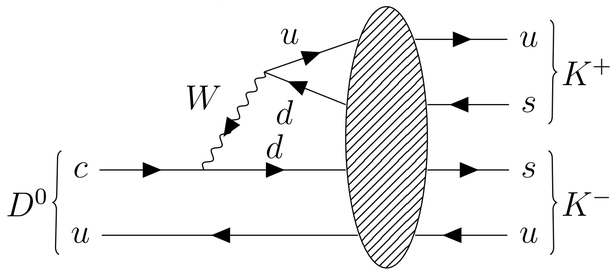
$$\simeq 1.3 \times 10^{-3}$$

Accessible primarily in singly Cabibbo-suppressed (SCS) decays.
Cabibbo-favoured (CF) and doubly Cabibbo-suppressed (DCS) very small: no QCD penguin/chromomagnetic dipole operators.

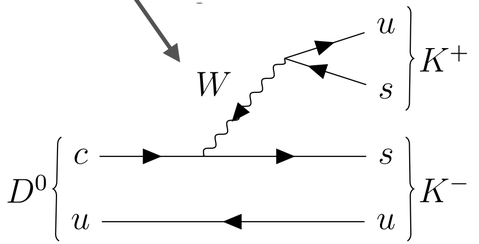
$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda - iA\lambda^5\eta & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

d s b

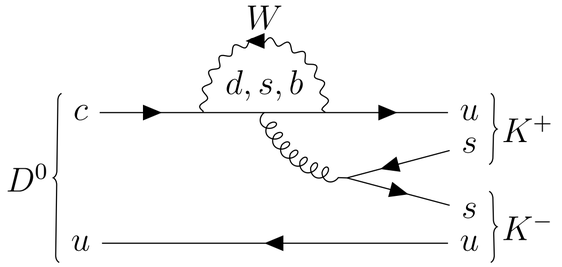
u c t



Penguin contraction
(tree + rescattering e.g. $D^0 \to \pi^+\pi^- \to K^+K^-$)
CPV from tiny nonunitarity of 2×2 CKM submatrix could enhance CPV up to 10^{-3}. Contributes also to BFs.



Tree, colour-suppressed tree, exchange...



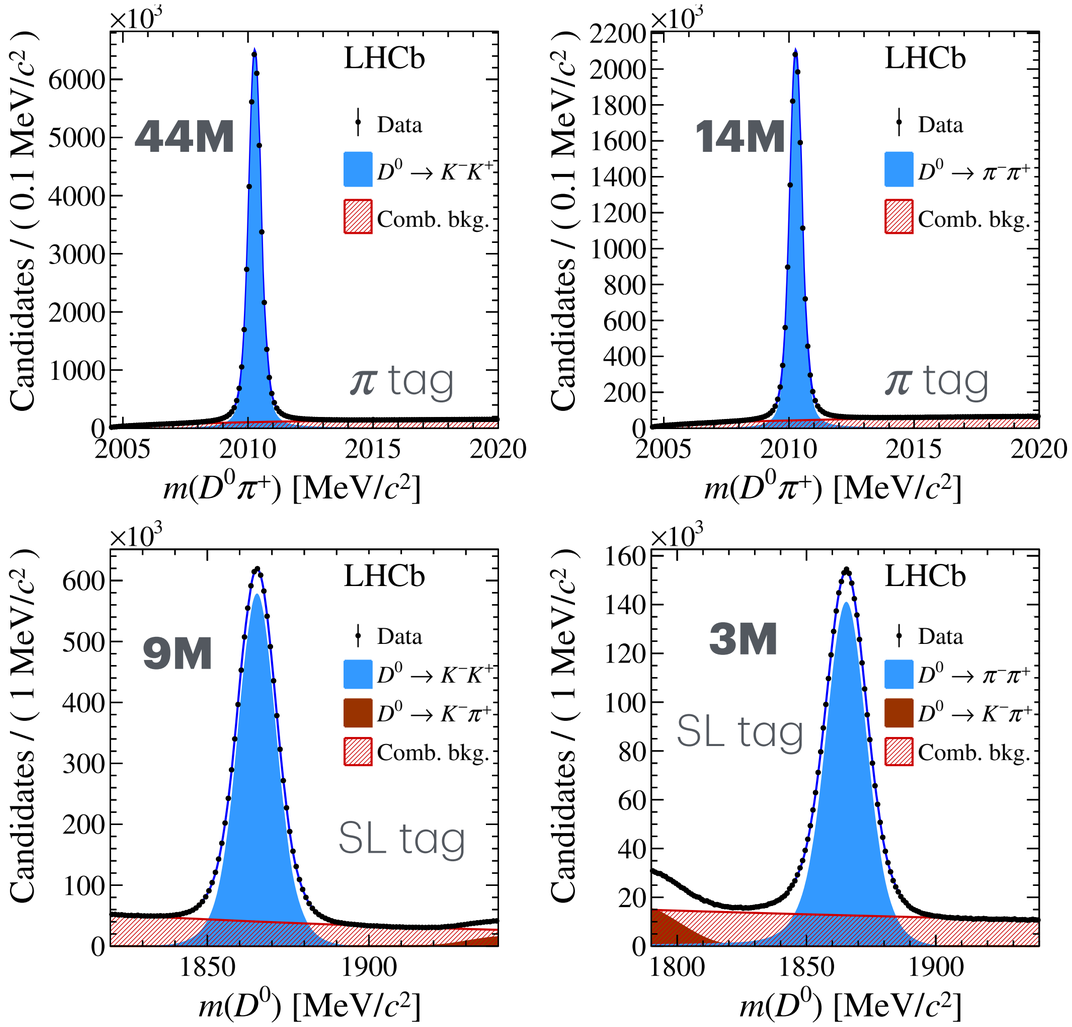
QCD penguin
(CKM and α_s suppression wrt tree amplitudes→negligible)

The golden observable $\Delta A_{CP}(D^0 \to h^+h^-)$

- LHCb Run 2, 2015-2018, 6 fb^{-1}
- Nuisance asymmetries cancel out in the difference.
- First observation ever of CP violation in the charm sector. A clear manifestation of CPV in the decay.

$$\Delta A_{CP} = A_{\text{raw}}(K^+K^-) - A_{\text{raw}}(\pi^+\pi^-)$$
$$= (-1.54 \pm 0.29) \times 10^{-3} \quad (5.3\sigma)$$
$$\approx a^d_{KK} - a^d_{\pi\pi}$$

- Very robust and efficient cancelation mechanism. Uncertainty driven by the size of the of $D^0 \to \pi^+\pi^-$.



Individual CP asymmetries ($D^0 \to h^+h^-$)

The challenge of measuring $a^d_{K^+K^-}$ and $a^d_{\pi^+\pi^-}$

Measure raw asymmetries from multiple decay modes:

$$A(K^-\pi^+) \approx A_{\rm P}(D^{*+}) - A_{\rm D}(K^+) + A_{\rm D}(\pi^+) + A_{\rm D}(\pi^+_{\rm tag}),$$
$$A(K^-\pi^+\pi^+) \approx A_{\rm P}(D^+) - A_{\rm D}(K^+) + A_{\rm D}(\pi^+_1) + A_{\rm D}(\pi^+_2),$$
$$A(\bar{K}^0\pi^+) \approx A_{\rm P}(D^+) + A(\bar{K}^0) + A_{\rm D}(\pi^+),$$
$$A(\phi\pi^+) \approx A_{\rm P}(D^+_s) + A_{\rm D}(\pi^+),$$
$$A(\bar{K}^0K^+) \approx A_{\rm P}(D^+_s) + A(\bar{K}^0) + A_{\rm D}(K^+).$$

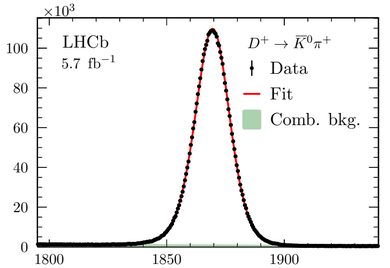
Two different chains with D^+ and D^+_s CF/DCS modes:

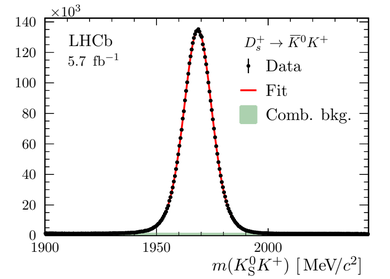
$$\mathrm{C}_{D^+}: \mathcal{A}_{CP}(K^-K^+) = A(K^-K^+) - A(K^-\pi^+) + A(K^-\pi^+\pi^+) - A(\bar{K}^0\pi^+) + A(\bar{K}^0),$$
$$\mathrm{C}_{D^+_s}: \mathcal{A}_{CP}(K^-K^+) = A(K^-K^+) - A(K^-\pi^+) + A(\phi\pi^+) - A(\bar{K}^0K^+) + A(\bar{K}^0).$$

Uncertainties dominated by the size of independent calibration decay modes. Results can be combined.

TABLE I. Signal yields and statistical reduction factors arising from the kinematic weighting of the sample for the various decay modes and both calibration procedures.

	Signal yield [10^6]		Reduction factor	
Decay mode	C_{D^+}	$\mathrm{C}_{D^+_s}$	C_{D^+}	$\mathrm{C}_{D^+_s}$
$D^0 \to K^-K^+$	37	37	0.72	0.76
$D^0 \to K^-\pi^+$	58	56	0.33	0.76
$D^+ \to K^-\pi^+\pi^+$	188	···	0.23	···
$D^+ \to \bar{K}^0\pi^+$	6	···	0.25	···
$D^+_s \to \phi\pi^+$	···	43	···	0.55
$D^+_s \to \bar{K}^0K^+$	···	5	···	0.70





$$\mathrm{C}_{D^+}: \mathcal{A}_{CP}(K^-K^+) = [13.6 \pm 8.8(\mathrm{stat}) \pm 1.6(\mathrm{syst})] \times 10^{-4},$$
$$\mathrm{C}_{D^+_s}: \mathcal{A}_{CP}(K^-K^+) = [2.8 \pm 6.7(\mathrm{stat}) \pm 2.0(\mathrm{syst})] \times 10^{-4},$$

[with a total correlation of 6%]

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

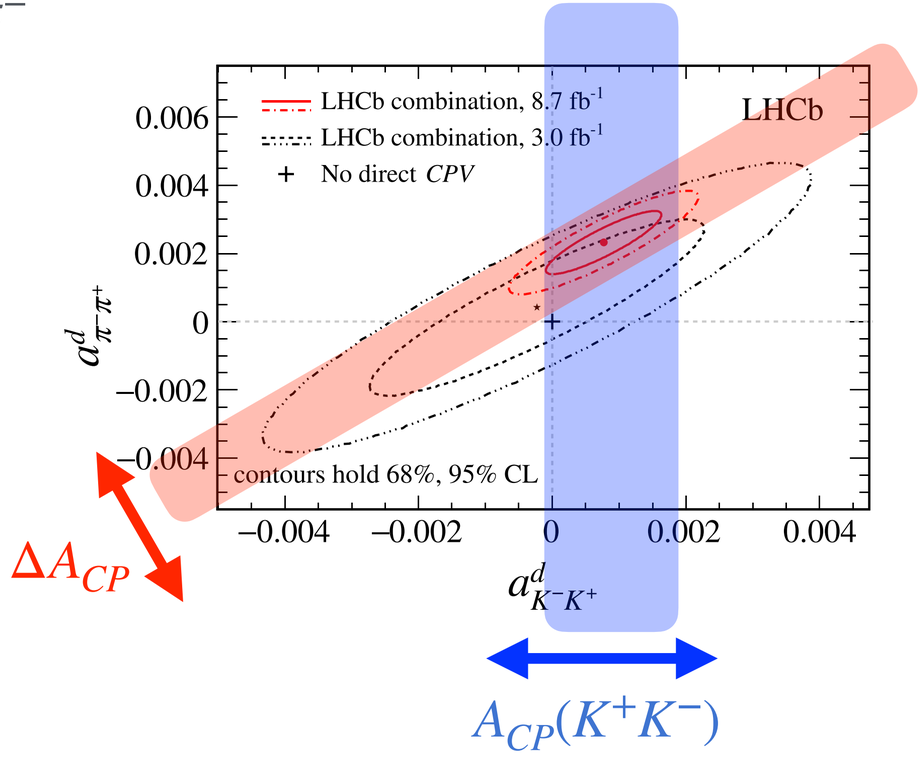
Individual CP asymmetries ($D^0 \to h^+h^-$)

The challenge of measuring $a^d_{K^+K^-}$ and $a^d_{\pi^+\pi^-}$

$$A_{CP}(f,t) \approx a^d_{h^+h^-} + \Delta Y_{h^+h^-} \cdot \frac{t}{\tau_{D^0}}$$

By combining with ΔA_{CP} and $\Delta Y_{h^+h^-}$ to measure direct CP asymmetry in both decays

$$a^d_{K^+K^-} = (7.7 \pm 5.7) \times 10^{-4}$$
$$a^d_{\pi^+\pi^-} = (23.2 \pm 6.1) \times 10^{-4} \quad (3.8\sigma)$$
$$\left[\rho(a^d_{K^+K^-}, a^d_{\pi^+\pi^-}) = 88\,\%\right]$$



$\Delta Y_{h^+h^-}$ from LHCb, PRD 104(2021)072010

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$$A(D^0 \to h^+h^-) \equiv \lambda_s T_{h^+h^-} + \lambda_b P_{h^+h^-}$$

$$\lambda_i \equiv V^*_{ci}V_{ui} \quad \delta_{h^+h^-} \equiv \arg\left(\frac{P_{h^+h^-}}{T_{h^+h^-}}\right)$$

$$a^d_{h^+h^-} = \mp\, 2\,\mathrm{Im}\left(\frac{\lambda_b}{\lambda_s}\right) \left|\frac{P_{h^+h^-}}{T_{h^+h^-}}\right| \sin\delta_{h^+h^-}$$

$\simeq 1.3 \times 10^{-3}$

It must be of order of unity. NP or SM? Very important to access |P/T| and strong phase difference.

$\Delta Y_{h^+h^-}$ from LHCb, PRD 104(2021)072010

LHCb, PRL131(2023)091802

Individual CP asymmetries ($D^0 \to h^+h^-$)

The challenge of measuring $a^d_{K^+K^-}$ and $a^d_{\pi^+\pi^-}$

$$A_{CP}(f,t) \approx a^d_{h^+h^-} + \Delta Y_{h^+h^-} \cdot \frac{t}{\tau_{D^0}}$$

By combining with ΔA_{CP} and ΔY to measure direct CP asymmetry in both decays

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$$\lambda_i \equiv V^*_{ci}V_{ui} \qquad \delta_{h^+h^-} \equiv \arg\left(\frac{P_{h^+h^-}}{T_{h^+h^-}}\right)$$

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$\simeq 1.3 \times 10^{-3}$

It must be of order of unity. NP or SM? Very important to access |P/T| and strong phase difference.

Final precision given by $D^+_{(s)} \to K^0_S h^+$ decays.

→ Long-lived K^0 meson has a limited acceptance in LHCb $\Longrightarrow$ different trigger selections mainly based on single track

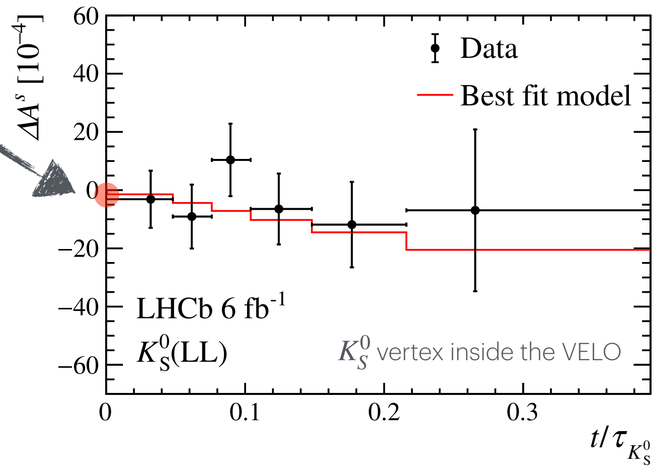
→ Kaon regeneration in the LHCb detector and CPV in kaon mixing explicitly accounted for [CERN-THESIS-2014-274].
More recently, interference between CF and DCS decay amplitudes has also been included, as it is no longer negligible at the current precision [LHCb, JHEP10(2026)256].

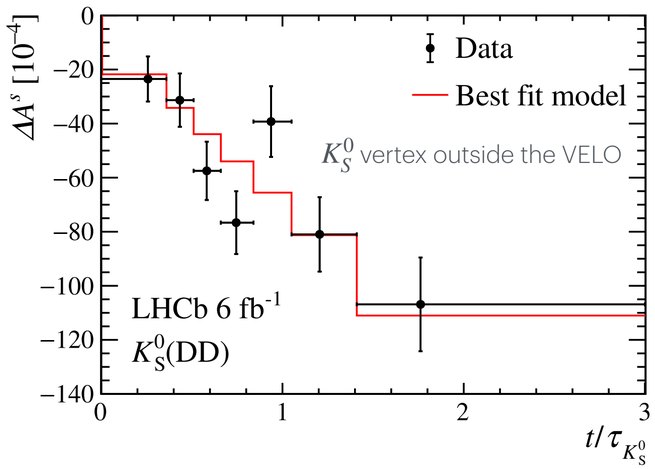
CP in the decay: $D^+ \to \phi\pi^+$

Kaon regeneration and CPV in kaon mixing

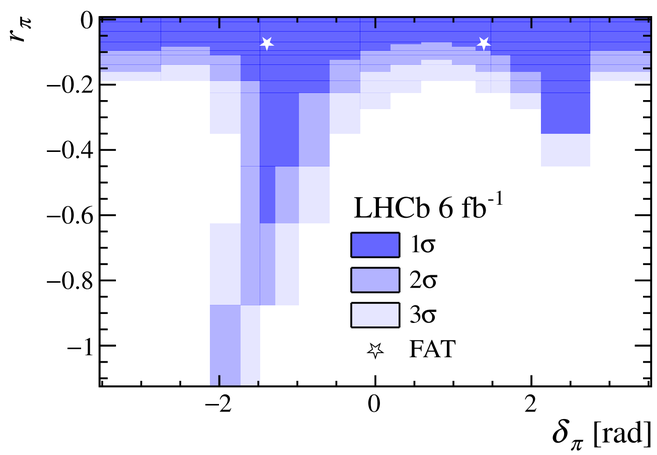
- Use $D^+ \to K^0_S\pi^+$ decays as calibration → $\Delta A^s = A^s_{\rm raw}(D^+ \to K^0_S\pi^+) - A^s_{\rm raw}(D^+ \to \phi\pi^+)$
- **Precise modeling of neutral kaon asymmetry** [CPV in kaon system, kaon regeneration, CF-DCS interference]
- Time-dependent measurement → $\Delta A^s = A^s(K^0) - a^d_{\phi\pi^+}$, where s labels the K^0 decay-time bin

$$a^d_{\phi\pi^+} = (0.1 \pm 4.9\,(\text{stat}) \pm 2.4\,(\text{syst})) \times 10^{-4}$$





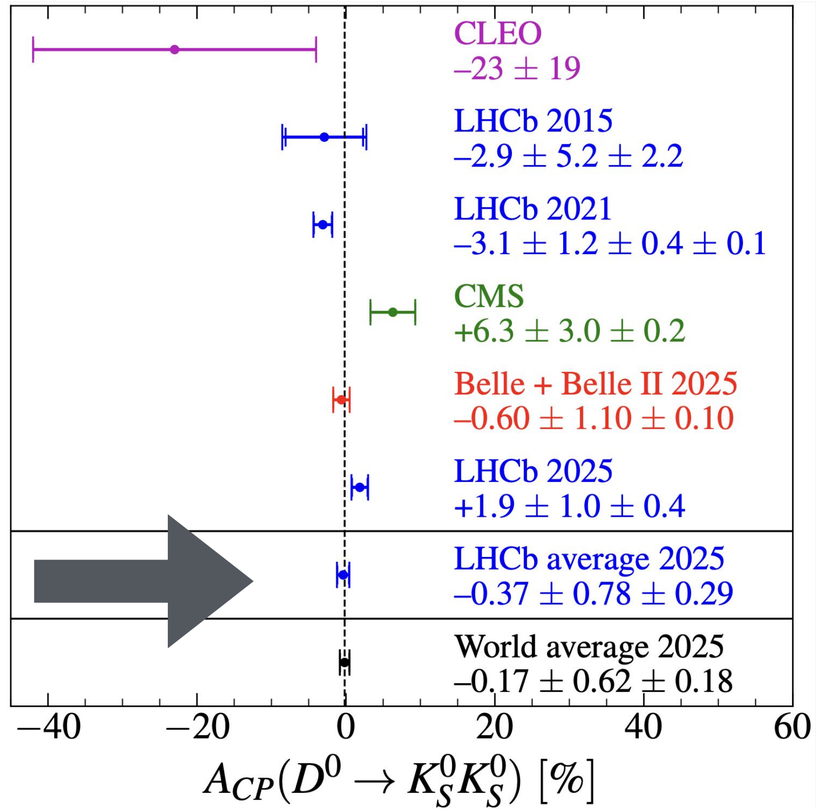
$$r_\pi\, e^{i(\delta_\pi+\varphi)} \equiv \frac{\mathcal{A}(D^+ \to K^0\pi^+)}{\mathcal{A}(D^+ \to \overline{K}^0\pi^+)}$$



CP in the decay: $D^0 \to K^0_S K^0_S$

A special role

- First LHCb measurement with 2024 data, 6.2 fb^{-1}.
- Confirmed x3 efficiency gain wrt LHCb Run 2 at analysis level.
- Excellent candidate for charm CPV confirmation.
  - Penguin diagram suppressed due to CKM.
  - Tree diagram vanishes in the SU(3) limit.
  - Complementarity with $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$.
- The upper end of theoretical predictions is $\approx 1\,\%$ (*).
- **An accuracy of $\approx 3 \times 10^{-3}$ might be no longer a dream with the entire dataset from LHCb Run 3**.
- Note that both LHCb and CMS use $D^0 \to K^0_S \pi^+\pi^-$ as calibration.



(*) Nierste&Schacht, PRD92(2015)054036

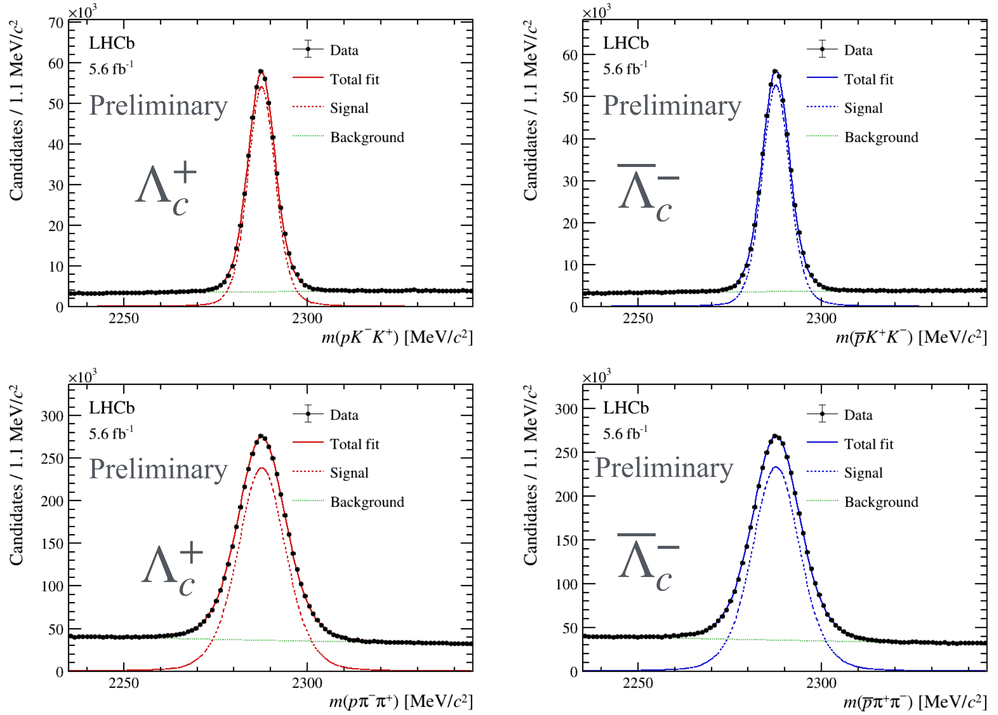
LHCb-PAPER-2026-051
in preparation

CP in the decay: $\Lambda_c^+ \to p h^+ h^-$

Extending the search to baryons

For more details please refer to
F. Zenesini talk a the LHCb IW workshop

- **Complementary search for direct CPV** in baryon sector using SCS decays, to search for other CP-violating signals.
- **Exploit a similar, but more complex, strategy** based on $\Delta A_{CP}(D^0)$ to cancel nuisance charge asymmetries.
- Theoretical prediction even more challenging.
- Previous measurement is statistically limited (Run 1) with produced Λ_c^+ from SL Λ_b decays [JHEP03(2018)182]
- Employ 2016-2018 data (5.6 fb^{-1}). **Precision improves by a factor of 7 relative to Run 1 reaching per-mille precision**.



1.7M

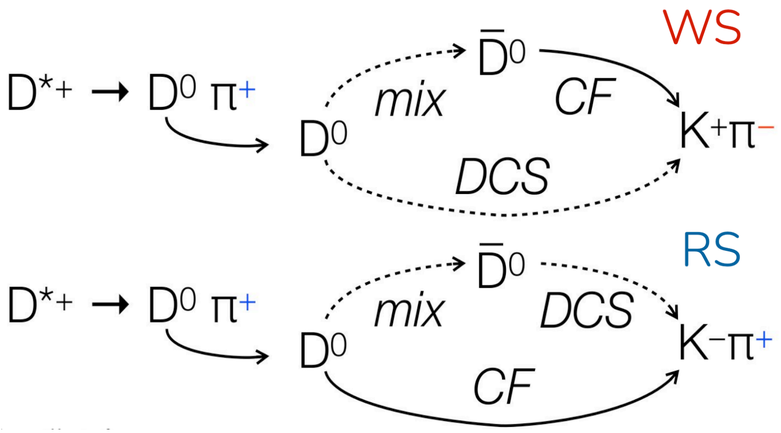
14M

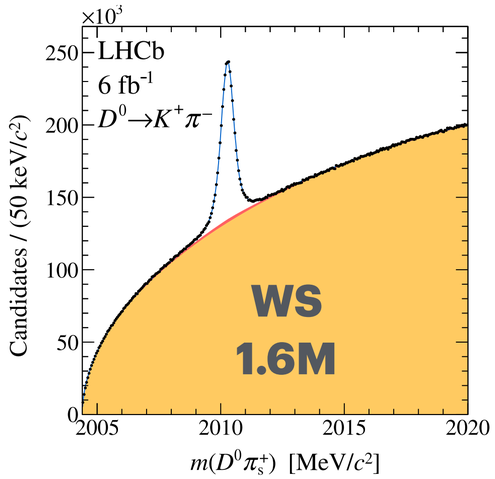
$$a^d_{pK^+K^-} - a^d_{p\pi^+\pi^-} \approx A_{\text{raw}}(\Lambda_c^+ \to pK^+K^-) - A_{\text{raw}}(\Lambda_c^+ \to p\pi^+\pi^-) = (-0.13 \pm 0.14 \pm 0.05)\,\%$$

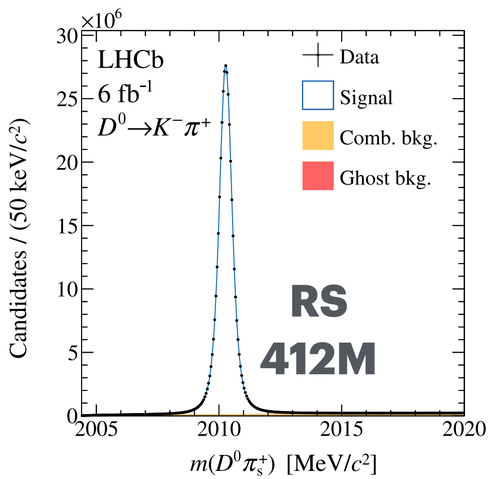
LHCb, PRD111(2025)012001
LHCb, JHEP03(2025)149

Mixing and CPV with $D^0 \to K\pi$

Right-Sign and Wrong-Sign $D^0 \to K\pi$ decays







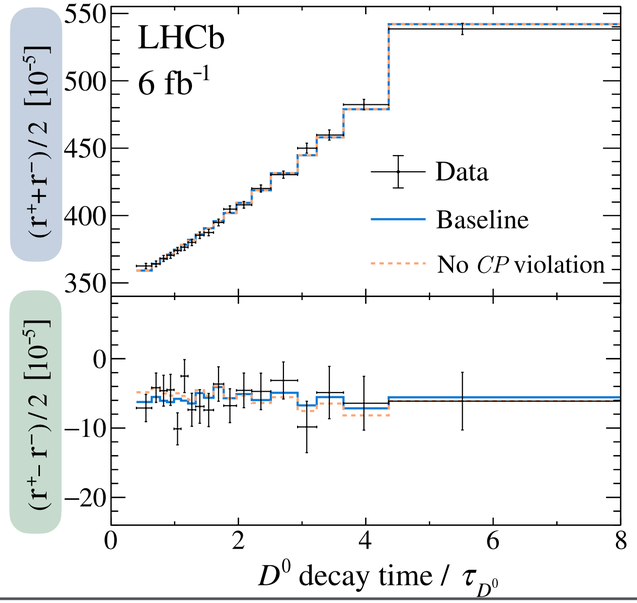
Time-dependence of the WS-to-RS yield ratios

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

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

Mixing → $\dfrac{R^+_{K\pi} + R^-_{K\pi}}{2}$

CP Violation → $\dfrac{R^+_{K\pi} - R^-_{K\pi}}{2}$



LHCb, PRD111(2025)012001
LHCb, JHEP03(2025)149

Mixing and CPV with $D^0 \to K\pi$

Mixing observables (mostly probing $y_{12}\cos\Delta_{K\pi}$)

$$\frac{R^+_{K\pi}+R^-_{K\pi}}{2} = R_{K\pi}\left(1+\frac{c_{K\pi}}{\sqrt{R_{K\pi}}}t+\frac{c'_{K\pi}}{R_{K\pi}}t^2\right) \approx \frac{x_{12}^2+y_{12}^2}{4}$$

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

Parameters		Correlations [%]				
		$c_{K\pi}$	$c'_{K\pi}$	$A_{K\pi}$	$\Delta c_{K\pi}$	$\Delta c'_{K\pi}$
$R_{K\pi}$	$(343.1 \pm 2.0)\times 10^{-5}$	−92.4	80.0	0.9	−0.8	0.1
$c_{K\pi}$	$(51.4 \pm 3.5)\times 10^{-4}$		−94.1	−1.4	1.4	−0.7
$c'_{K\pi}$	$(13.1 \pm 3.7)\times 10^{-6}$			0.7	−0.7	0.1
$A_{K\pi}$	$(-7.1 \pm 6.0)\times 10^{-3}$				−91.5	79.4
$\Delta c_{K\pi}$	$(3.0 \pm 3.6)\times 10^{-4}$					−94.1
$\Delta c'_{K\pi}$	$(-1.9 \pm 3.8)\times 10^{-6}$					

CP violation observables: all compatible with no CPV

$$\frac{R^+_{K\pi}-R^-_{K\pi}}{2} = R_{K\pi}\left(A_{K\pi}+\frac{\Delta c_{K\pi}}{\sqrt{R_{K\pi}}}t+\frac{\Delta c'_{K\pi}}{R_{K\pi}}t^2\right) \approx \left(\phi_2^M-\phi_2^\Gamma\right)\frac{x_{12}y_{12}}{2}$$

$$\approx a^d_{K^+\pi^-}$$ direct

$$\approx \phi_2^M x_{12}$$ interference

mixing

DCS/CF magnitude ratio

$R_{K\pi} \approx 3.4\times 10^{-3}$

Strong phase diff. (BESIII+CLEOc+LHCb)

$\Delta_{K\pi} = \left(-12.9^{+2.4}_{-2.3}\right)^\circ$

$\Delta_{K\pi} = -\delta_{K\pi}(\text{HFLAV}) = \pi - \delta^D_{K\pi}$

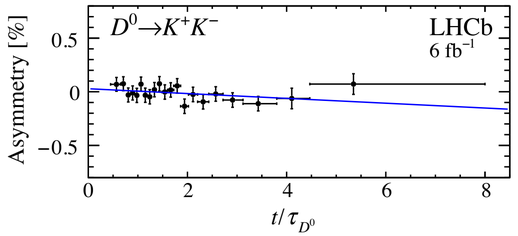
LHCb, PRD 104(2021)072010
LHCb, PRD 105(2022)092013

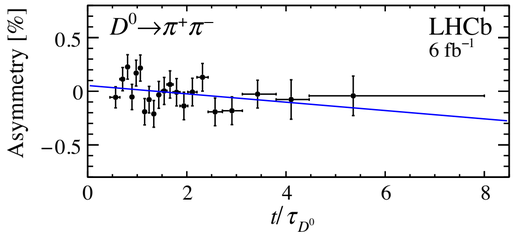
ΔY and y_{CP} in $D^0 \to h^+h^-$

Time-dependent measurement

$$A_{CP}(f,t) \approx a_f^d + \Delta Y_f \frac{t}{\tau_{D^0}},$$

$$\phi_f^M \equiv \phi_2^M + \delta\phi_f$$
$$\delta\phi_f = -a_f^d \cot\delta_f$$





$$\Delta Y_f \approx (-x_{12}\sin\phi_f^M + y_{12}a_f^d) \approx -x_{12}\sin\phi_2^M + y_{12}a_f^d\left(1 + \frac{x_{12}}{y_{12}}\cot\delta_f\right)$$

Less than 10^{-5} by using experimental info on $a^d_{\pi^+\pi^-}$ and $a^d_{K^+K^-}$.

Can enhance the dependence on the final state, even though the phase δ_f is expected to be of $O(1)$ due to large rescattering at the charm mass scale.

$$\Delta Y_{K^+K^-} = (-0.3 \pm 1.3 \pm 0.3) \times 10^{-4}$$
$$\Delta Y_{\pi^+\pi^-} = (-3.6 \pm 2.4 \pm 0.4) \times 10^{-4}$$
$$\Delta Y = (-1.0 \pm 1.1 \pm 0.3) \times 10^{-4}$$

$$\frac{\Gamma(D^0(t)\to f) + \Gamma(\bar{D}^0(t)\to f)}{\Gamma(D^0(t)\to K^-\pi^+) + \Gamma(\bar{D}^0(t)\to K^+\pi^-)} \propto 1 + (y_{CP}^f - y_{CP}^{K\pi})\frac{t}{\tau_{D^0}}$$

$$y_{CP}^f = y_{12}\cos\phi_f^\Gamma,$$

$$y_{CP}^{K\pi} \approx -0.4 \times 10^{-3}$$

$$y_{CP} - y_{CP}^{K\pi} = (6.96 \pm 0.26 \pm 0.13) \times 10^{-3}$$

Current experimental accuracy probes y_{12} parameter $\Longrightarrow$ strong phase difference $\Delta_{K\pi}$ in DCS/CF $D \to K\pi$ decays

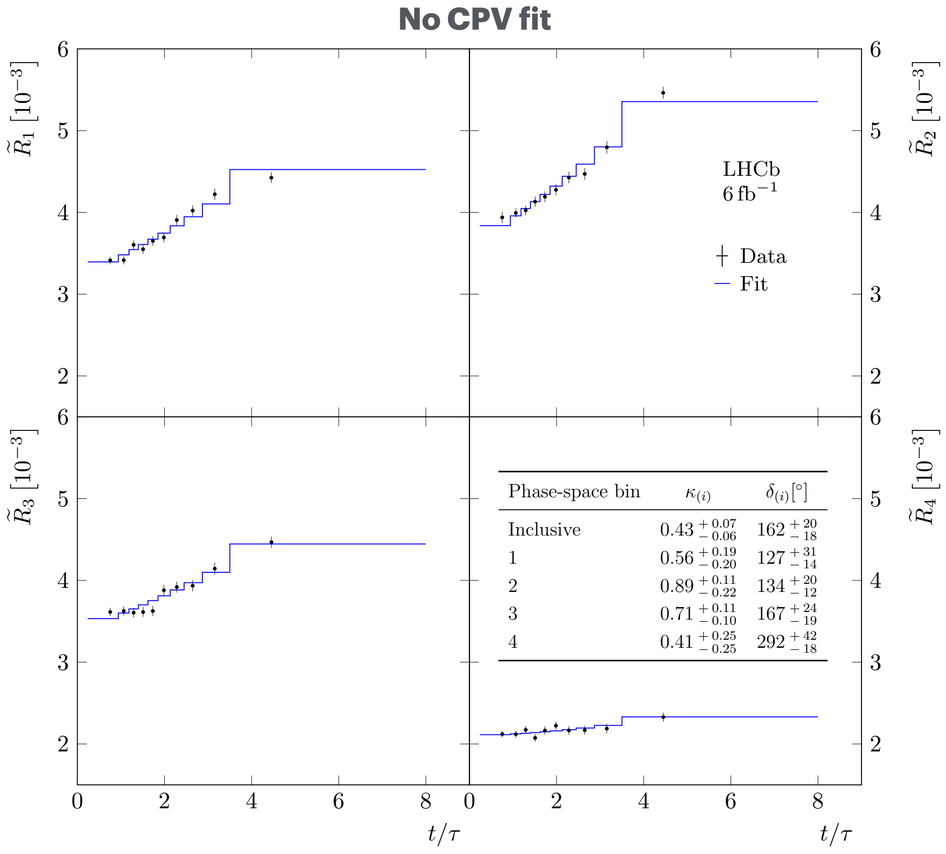
Mixing and CPV with $D^0 \to K\pi\pi\pi$

- Similar analysis approach of $D^0 \to K\pi$ decays by studying the WS-to-RS ratio as a function of decay time. **442k (128M) WS(RS) sig. yields**.
- Time-dependence (index j) measured in **4 phase-space bins (index i)**

$$R^+_{ij} \equiv \frac{\Gamma[D^0 \to K^+\pi^-\pi^+\pi^-]}{\Gamma[\overline{D}^0 \to K^+\pi^-\pi^+\pi^-]} \approx r^+_i - r^+_i(\kappa y'^+)_i \left\langle \frac{t_{ij}}{\tau} \right\rangle + \frac{(x^{+2} + y^{+2})}{4} \left\langle \frac{t_{ij}}{\tau}^2 \right\rangle,$$

$$R^-_{ij} \equiv \frac{\Gamma[\overline{D}^0 \to K^-\pi^+\pi^-\pi^+]}{\Gamma[D^0 \to K^-\pi^+\pi^-\pi^+]} \approx r^-_i - r^-_i(\kappa y'^-)_i \left\langle \frac{t_{ij}}{\tau} \right\rangle + \frac{(x^{-2} + y^{-2})}{4} \left\langle \frac{t_{ij}}{\tau}^2 \right\rangle,$$

- Hadronic parameters, k_i and $\delta_{i'}$ taken from CLEO-c, BESIII (and LHCb).
- CP-violating parameters: $\Delta x = (x^+ - x^-)/2$, $\Delta y = (y^+ - y^-)/2$
- Access to $x \simeq x_{12}\cos\phi_2^M, \quad y \simeq y_{12}\sin\phi_2^\Gamma,$
$\Delta x \simeq -y_{12}\sin\phi_2^\Gamma, \ \Delta y \simeq x_{12}\sin\phi_2^M.$



$$x = \left(0.89\ ^{+0.11}_{-0.17}\right)\% \qquad \Delta x = \left(-0.03\ ^{+0.04}_{-0.05}\right)\%$$

$$y = \left(0.08\ ^{+0.31}_{-0.27}\right)\% \qquad \Delta y = \left(0.03\ ^{+0.06}_{-0.05}\right)\%$$

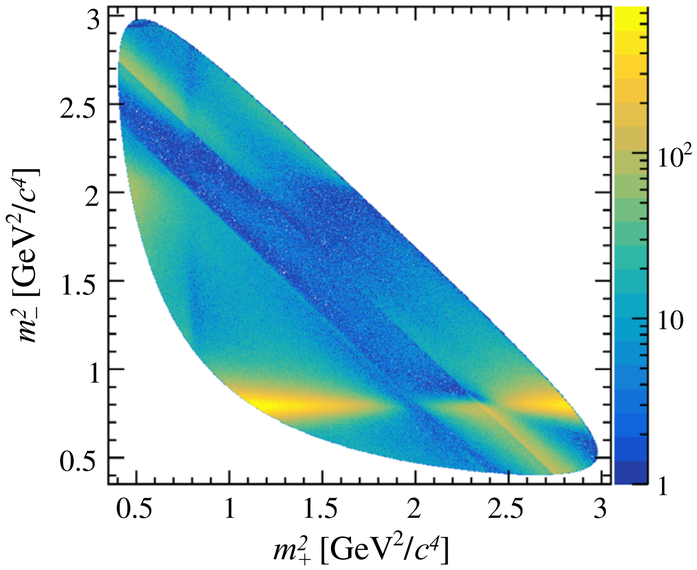
LHCb, PRL (2021)127.111801
LHCb, PRD108(2023) 052005

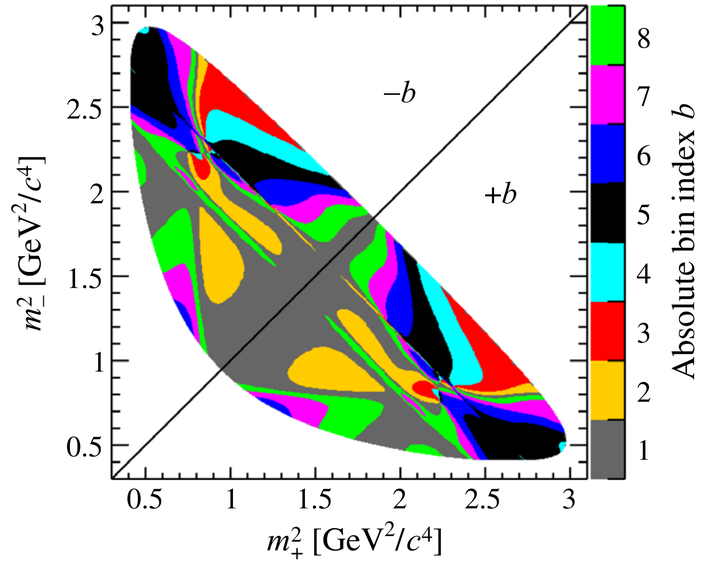
$D^0 \to K^0_s \pi^+ \pi^-$

The golden mode

- Phenomenology very rich. Probe Mixing and CPV with different sensitivity to physic observables depending on the DP position. Multiple interfering intermediate amplitudes (CF and DCS).
- Model-independent (bin-flip) using strong-phase differences in bins of Dalitz plot from Charm Factories (BES-III, CLEO-c)
- Particularly sensitive to $x = (M_2 - M_1)/2\Gamma$. **First observation in 2021!!!**

$$x_{CP} \approx x_{12} \approx x = (4.01 \pm 0.45 \pm 0.20) \times 10^{-3} \quad (7.5\sigma)$$
$$y_{CP} \approx y_{12} \approx y = (5.51 \pm 1.16 \pm 0.59) \times 10^{-3}$$
$$\Delta x \approx -\, y_{12} \sin\phi_2^{\Gamma} = (-0.29 \pm 0.18 \pm 0.01) \times 10^{-3}$$
$$\Delta y \approx +\, x_{12} \sin\phi_2^{M} = (+0.31 \pm 0.35 \pm 0.13) \times 10^{-3}$$





$$m^2_{\pm} \equiv \begin{cases} m^2(K^0_S\pi^{\pm}) & \text{for } D^0 \to K^0_S\pi^+\pi^- \text{decays} \\ m^2(K^0_S\pi^{\mp}) & \text{for } \bar{D}^0 \to K^0_S\pi^+\pi^- \text{decays} \end{cases}$$

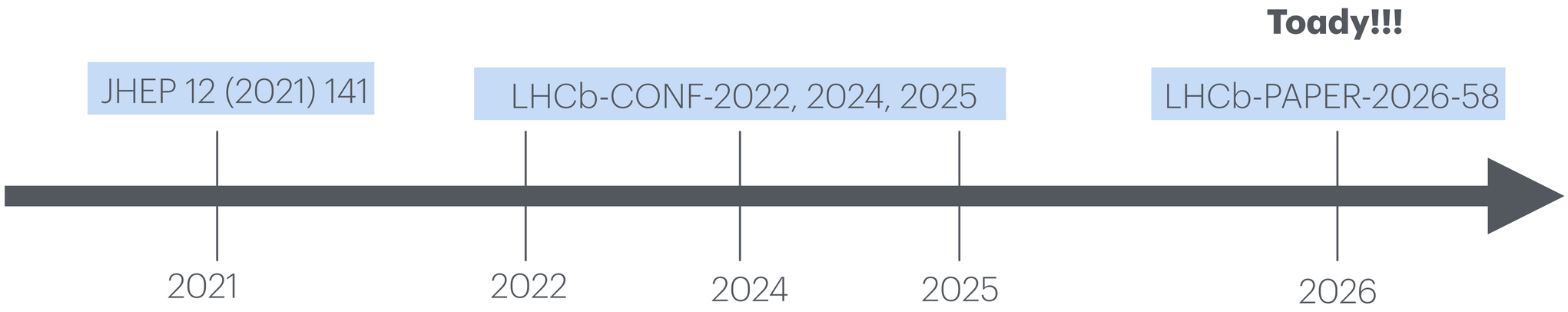
LHCb-PAPER-2026-058
in preparation

Putting it all together

CKM angle γ and charm mixing

For more details please refer to I. Celestino and S. Zhang at the LHCb IW workshop

- Simultaneous combination of all LHCb measurements sensitive to the CKM angle γ and charm observables.
- Stringent and complementary tests of the CKM framework and of the charm and beauty sectors.
- CKM angle γ measured in B decays into D mesons.
- γ and charm observables share a dependence on the same hadronic parameters—obtained from external inputs—which can therefore be constrained through a global fit.

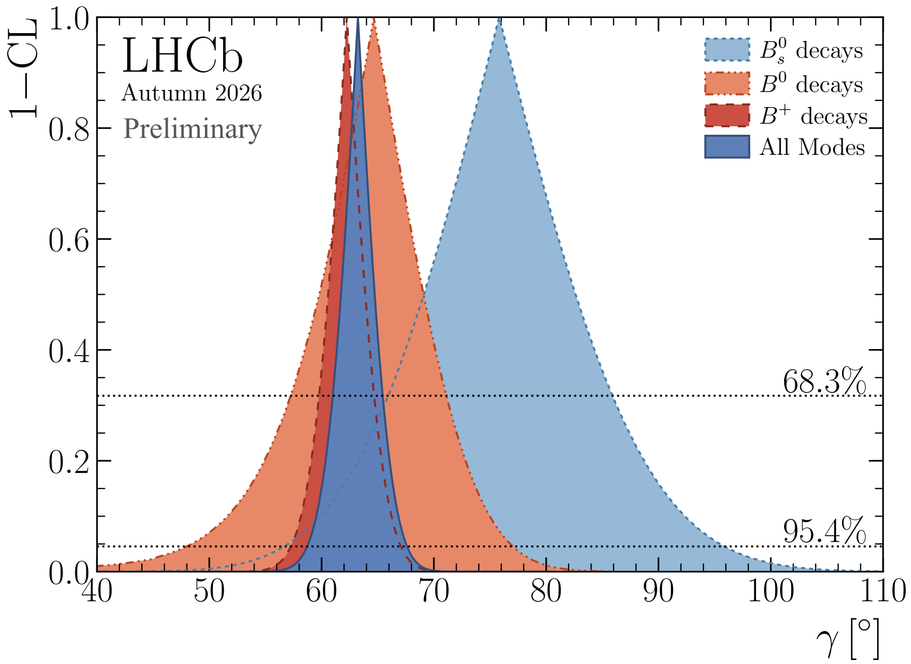


What changed since 2025

LHCb-PAPER-2026-058
in preparation

For more details on γ
see T. Mombächer's talk

- New LHCb input [negligible impact on charm parameters]
  - Recent determination of γ using $B^{\pm} \to D^0(\to K^0_S\pi^+\pi^-)h^{\pm}$ decays with 2024 data [LHCb coll., JHEP 08 (2026)037]
- Update of hadronic inputs from BESIII
  - $D^0 \to K^0_S\pi^+\pi^-$: [BESIII, JHEP 06 (2025) 086]
  - $D^+ \to K^{\mp}\pi^{\pm}\pi^+\pi^+$: [BESIII, JHEP 08 (2026) 038]
- New charm fit strategy
  - Both theoretical and phenomenological parameterizations
  - First unbiased determination of $a^d_{h^+h^-}$ by allowing final-state dependence of $\Delta Y_{h^+h^-}$



$$\gamma = \left(63.2^{+2.3}_{-2.2}\right)^{\circ}$$

$\gamma = \left(62.8 \pm 2.6\right)^{\circ}$, LHCb-CONF-2025-003,
$\gamma = \left(65.4^{+3.8}_{-4.2}\right)^{\circ}$, LHCb, JHEP 12 (2021) 141

LHCb-PAPER-2026-058
in preparation

Combination results

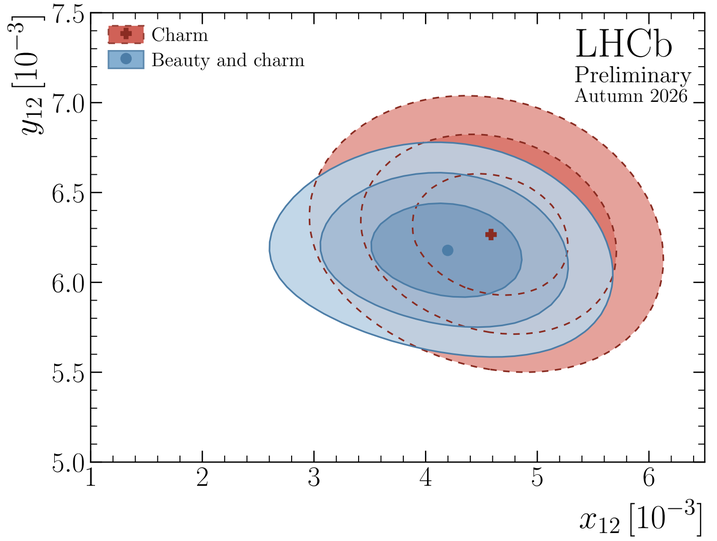
Mixing and CPV parameters

$$x_{12} = \left(4.2^{+0.4}_{-0.5}\right) \times 10^{-3}$$
$$y_{12} = \left(6.18^{+0.17}_{-0.18}\right) \times 10^{-3}$$

LHCb-CONF-2025-003

$$x = (3.91 \pm 0.42) \times 10^{-3}$$
$$y = (6.25 \pm 0.20) \times 10^{-3}$$

Relative uncertainty of 11% and 3% achieved for x_{12} and y_{12}, respectively.
Value of x_{12} is slightly larger, mostly owing to new BESIII inputs in $D^0 \to K^0_S\pi^+\pi^-$



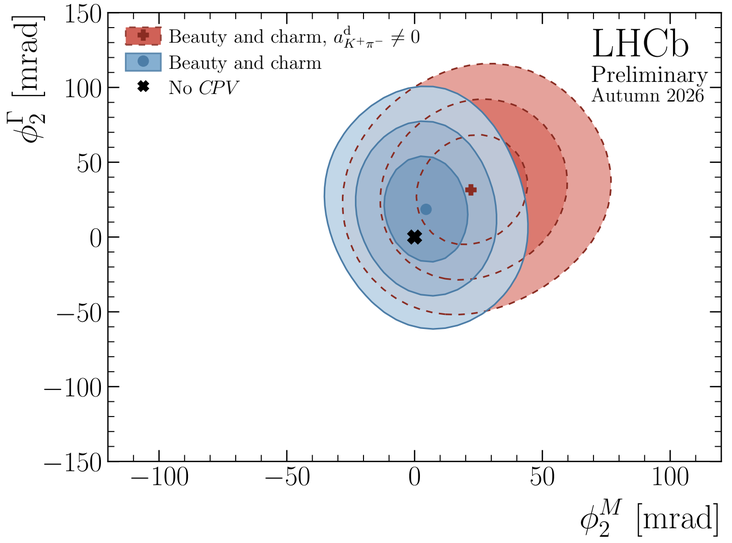
$$\phi_2^M = \left(4^{+11}_{-10}\right) \text{ mrad}$$
$$\phi_2^\Gamma = \left(19^{+23}_{-24}\right) \text{ mrad}$$

[compatible with CP symmetry]

$$|q/p| - 1 = -0.007^{+0.013}_{-0.012}$$
$$\phi_2 = (-14 \pm 16) \text{ mrad}$$

LHCb-CONF-2025-003

$$|q/p| - 1 = -0.010^{+0.012}_{-0.011}$$
$$\phi_2 = (-20.9 \pm 15.7) \text{ mrad}$$



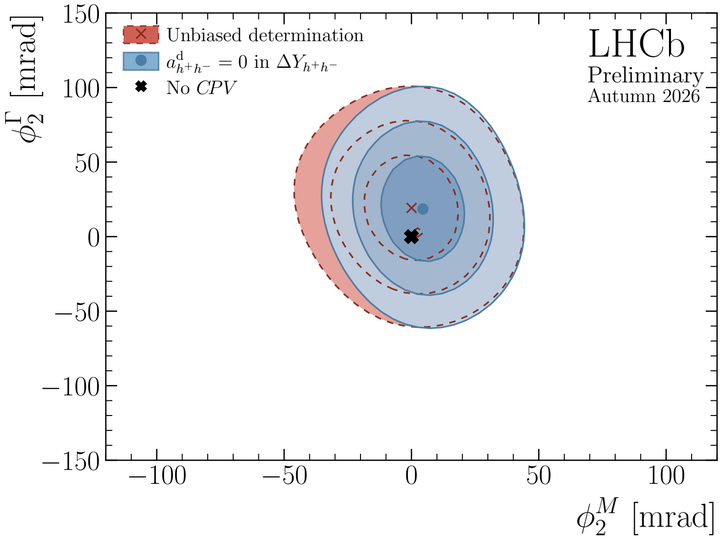
Relaxing the assumption $a^d_{K^+\pi^-} = 0$ significantly degrades the sensitivity to ϕ_2^M

Combination results

$a^d_{h^+h^-}$ and final-state dependence of $\Delta Y_{h^+h^-}$

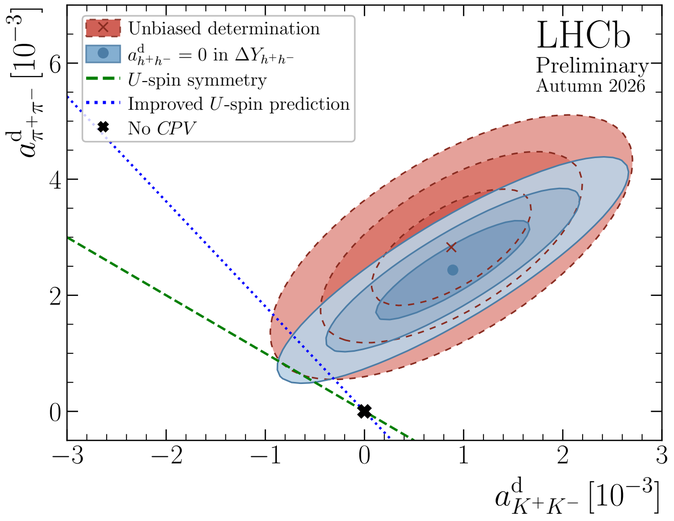
$$A_{CP}(f,t) \approx a^d_{h^+h^-} + \Delta Y_{h^+h^-} \cdot \frac{t}{\tau_{D^0}}$$

$$\Delta Y_{h^+h^-} \approx -x_{12} \sin\phi_2^M + y_{12} a^d_{h^+h^-} \left(1 + \frac{x_{12}}{y_{12}} \cot\delta_{h^+h^-}\right)$$



In the baseline combination, the second term is neglected ($a^d_{h^+h^-} = 0$)

$$a^d_{K^+K^-} = (9 \pm 5) \times 10^{-4}$$
$$a^d_{\pi^+\pi^-} = (24 \pm 6) \times 10^{-4}$$



Alternative unbiased determination allowing for final-state dependence.

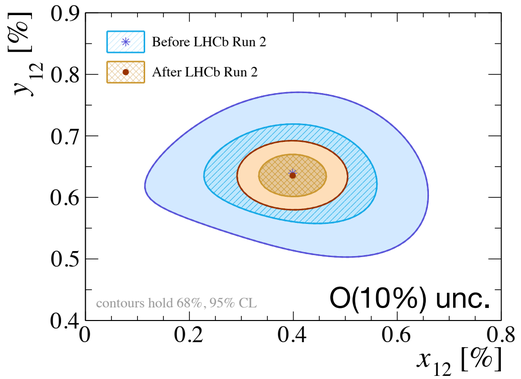
$\Delta Y_{h^+h^-}$ no longer contributes to the determination of first term.

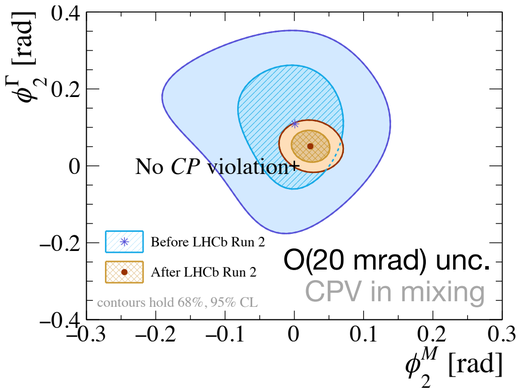
$a^d_{K^+K^-} = (9 \pm 5) \times 10^{-4}$ and $a^d_{\pi^+\pi^-} = (28 \pm 7) \times 10^{-4}$.

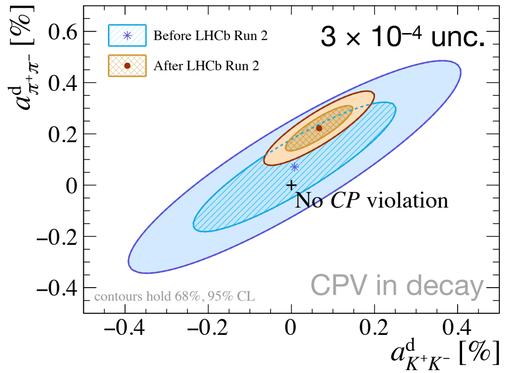
Conclusions

- After 50 years, Charm is still a very “young” and “attractive” field with many open questions and is moving fast.
- The last decade has been astonishing, and the field entered a previously unexplored precision regime. **However still plenty of room for unexpected things with x10 signal yields in Run 3**.
- **Theory input is essential for the success of current and future experiments.**
- **LHCb will remain a leading player in charm physics, even including the era of future facilities (>2041)**.

CHARM-Fitter,
Pajero&MJM JHEP03(2022)162



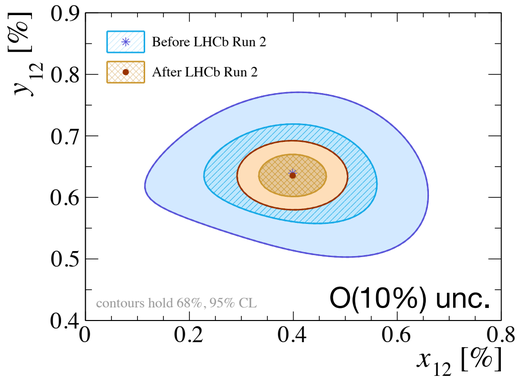


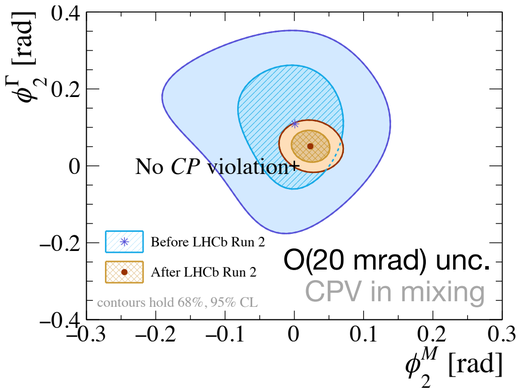


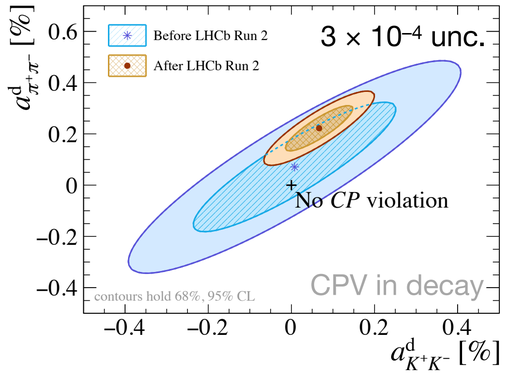
Conclusions

- After 50 years, Charm is still a very “young” and “attractive” field with many open questions and is moving fast.
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CHARM-Fitter,
Pajero&MJM JHEP03(2022)162







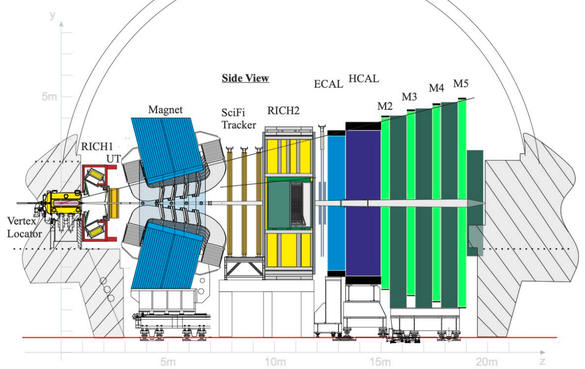
Thank you

Backup

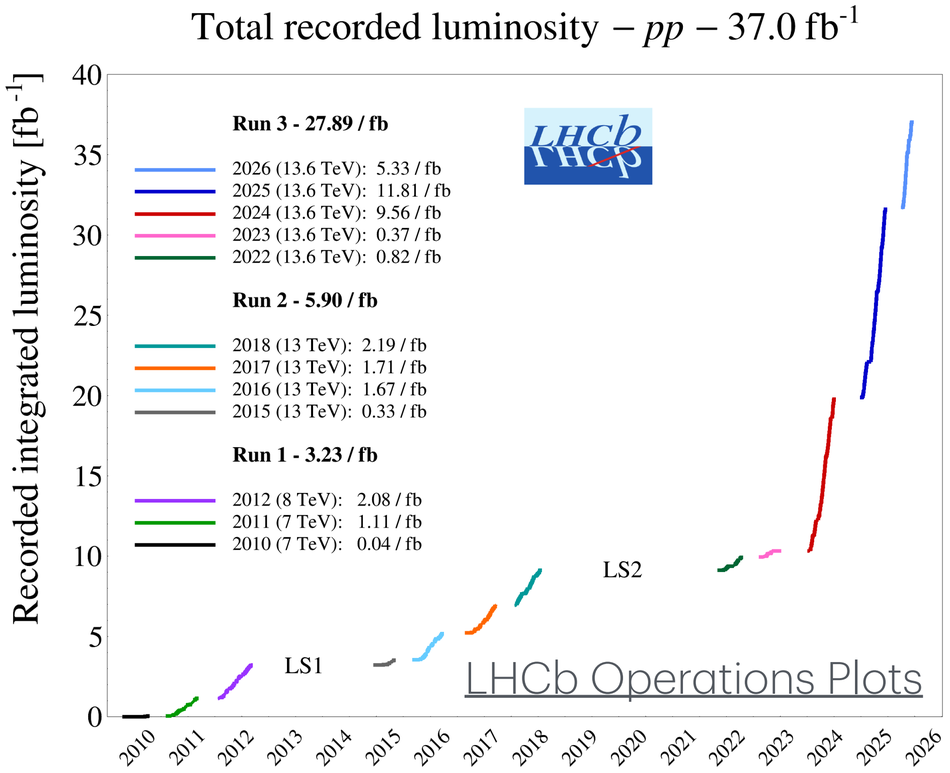
Experimental environment

LHCb and LHCb Upgrade I

LHCb, JINST19(2024)P05065



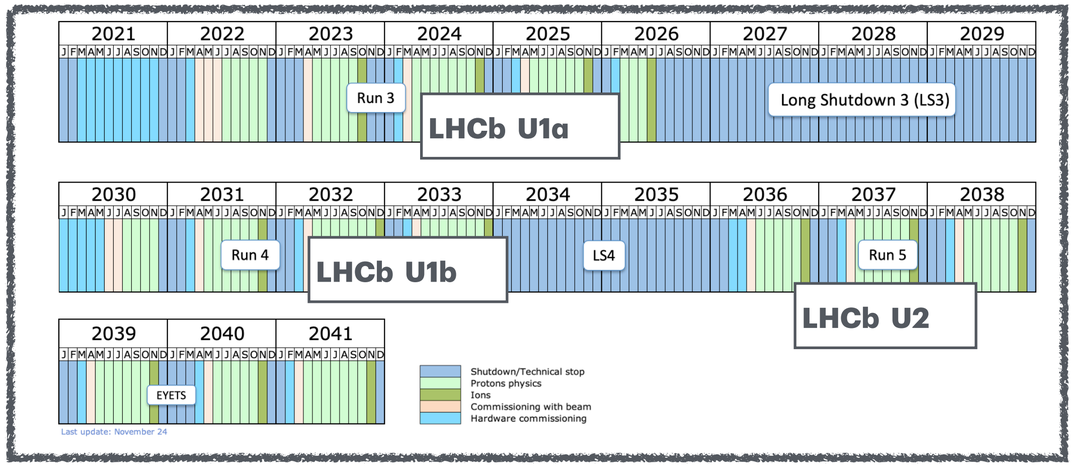
- LHCb underwent a major upgrade during LS2
  - Operating in Run 3 at $\mathscr{L}_{\text{inst}} = 2 \times 10^{33}\,\text{cm}^{-2}\text{s}^{-1}$, five times LHCb luminosity in Run 2 (and five times the pile-up!)
  - **All sub-detectors can now be read out at 30 MHz**.
  - A far more powerful DAQ system and High Level Trigger, capable of reconstructing pp collisions in real time at the full 30 MHz input rate.
- Essentially a new detector, matching—and in some areas surpassing—the performance achieved during Run 2.
- **Successful operation in 2024-2026, recording total of 27 fb-1.**
- Most of the results presented today still based on Run 2 data.
- New Run 3 results (with up to 10 times larger signal yields) are coming soon!

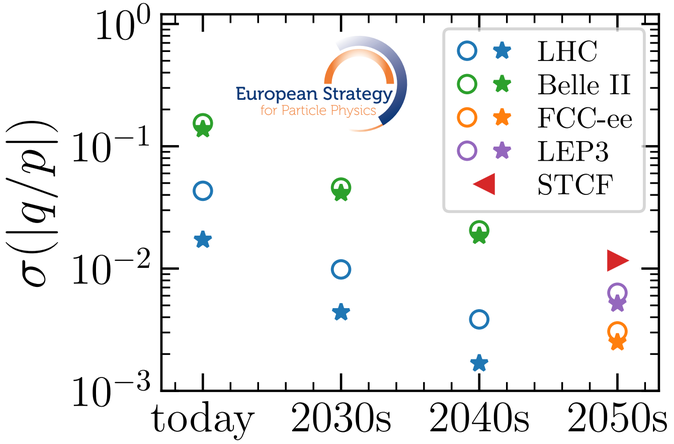


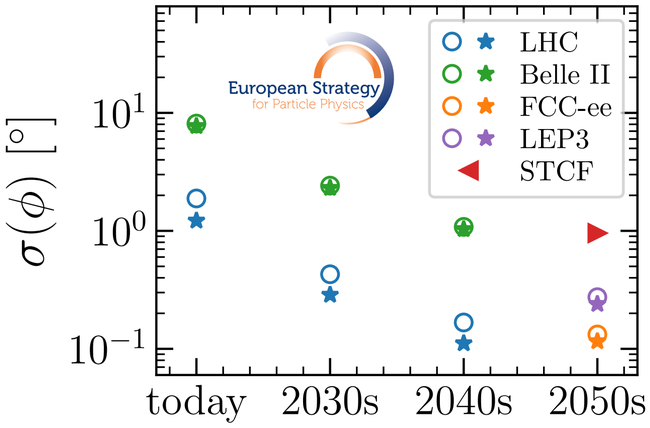
Future perspectives

- LHCb Upgrade I (Run3) ended by June 2026. Already collected 27 fb^{-1} during 2024-2026 of good data.
  - For hadronic channels efficiency/fb^{-1} improved by at least a factor of 2 wrt Run2.
- LHCb will collect data after LS3 during Run4, and during Run5 with an Upgraded detector (Phase 2) with a goal of 300 fb-1.
- With a similar time scale Belle II (and its upgrades) aims at collecting 50 ab^{-1} of data.
- **LHCb best player in charm physics, even in the era of future facilities**.

LHC schedule (today)



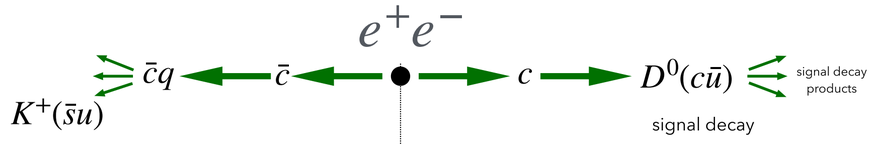




Physics Briefing Book — Input for the 2026 update of the European Strategy for Particle Physics [2511.03883]

How we measure CP asymmetries

- D^0 flavour cannot be inferred from the final state if this is shared by D^0 and $\overline{D}^0$. Rely on production.
  - Strong decay $D^{*+}(2010) \to D^0\pi^+$
  - Semi-leptonic decay. i.e. $B^+ \to \overline{D}^0\ell^+\nu_\ell$
  - Charm Flavor Tagger at B-Factories [PRD 107, 112010 (2023)]
  - Quantum-correlated production in $e^+e^- \to \psi(3770) \to D\overline{D}$ (**allow measurement of strong phases**).



$$A_{\text{raw}}(f) = \frac{N(D \to f) - N(\overline{D} \to \bar{f})}{N(D \to f) + N(\overline{D} \to \bar{f})} \approx A_{CP}(f) + A_{\text{det}}(f) + A_{\text{prod}}(D)$$

a_f^d + small time-dependent contribution (for D^0)

Detection asymmetry of π^+ tag and final-state (if not self-conjugate)

production asymmetry

Removed by difference with raw asym. of one or more control samples CF decays (assuming CPV=0), often include K_S^0 limiting sensitivity ($D^+ \to K_S^0\pi^+$, $D_s^+ \to K_S^0K^+$, ...). Use also CS decays for which CPV is known with better precision.

LHCb-PAPER-2026-058
in preparation

Combination results

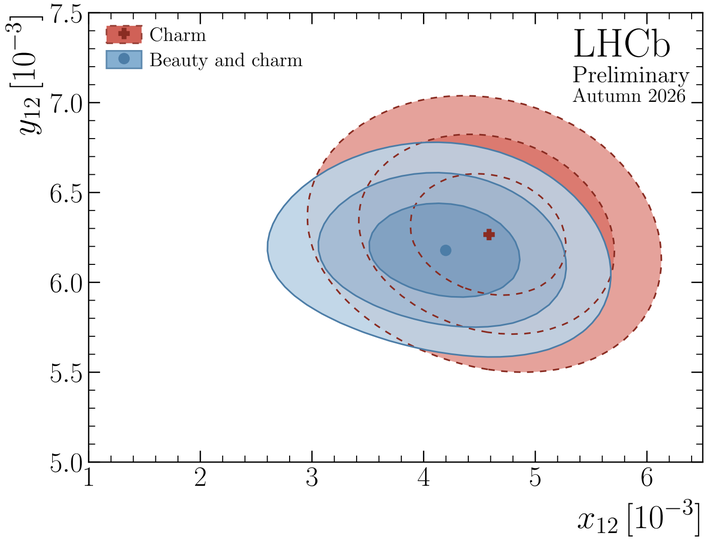
Mixing parameters

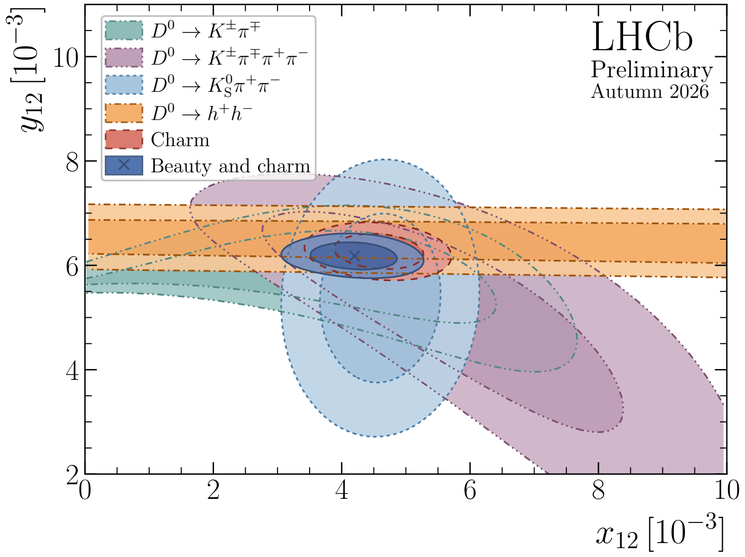
$$x_{12} = \left(4.2^{+0.4}_{-0.5}\right) \times 10^{-3}$$
$$y_{12} = \left(6.18^{+0.17}_{-0.18}\right) \times 10^{-3}$$

LHCb-CONF-2025-003

$x = (3.91 \pm 0.42) \times 10^{-3}$

$y = (6.25 \pm 0.20) \times 10^{-3}$





Relative uncertainty of 11% and 3% achieved for x_{12} and y_{12}, respectively.

Value of x_{12} is slightly larger, mostly owing to new BESIII inputs in $D^0 \to K^0_S\pi^+\pi^-$

Including the beauty inputs significantly improves the precision on y_{12} with respect to the charm-only combination, since they contribute to constraining the $D \to K^+\pi^-$ and $D \to K^\mp\pi^\pm\pi^+\pi^+$ hadronic parameters, **demonstrating the advantage of this approach.**

Combination results

CP violation parameters

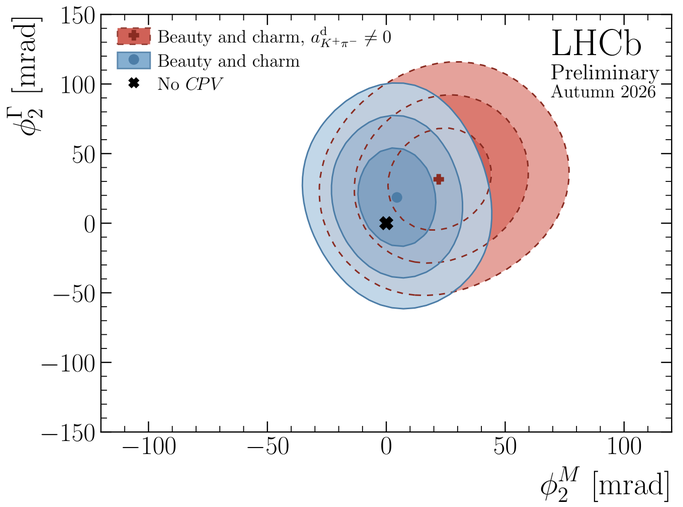
$$\phi_2^M = \left(4^{+11}_{-10}\right)\,\text{mrad}$$
$$\phi_2^\Gamma = \left(19^{+23}_{-24}\right)\,\text{mrad}$$

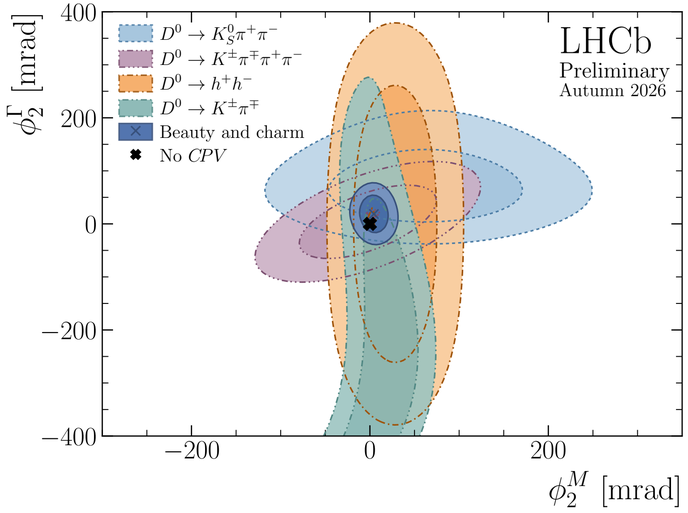
(compatible with CP symmetry)

$$|q/p| - 1 = -0.007^{+0.013}_{-0.012}$$
$$\phi_2 = (-14 \pm 16)\,\text{mrad}$$

LHCb-CONF-2025-003

$$|q/p| - 1 = -0.010^{+0.012}_{-0.011}$$
$$\phi_2 = (-20.9 \pm 15.7)\,\text{mrad}$$





Relaxing the assumption $a^d_{K^+\pi^-} = 0$ significantly degrades the sensitivity to ϕ_2^M, due to the correlation between $A_{K\pi}$ and $\Delta c_{K\pi}$ parameters in the $D \to K\pi$ WS/RS time-dependent measurement.

Available estimates for ϕ_2^Γ and ϕ_2^M lie in the range $[1-5]\,\text{mrad}$, but enhancements up to one of order of magnitude cannot be excluded.

Mixing and CPV with $D^0 \to K\pi$

LHCb-PAPER-2026-058
in preparation

Nuisance asymmetries removal

Physics observable

$$R^{\pm}_{K\pi}(t) \approx R_{K\pi}(1 \pm A_{K\pi}) + \sqrt{R_{K\pi}(1 \pm A_{K\pi})}(c_{K\pi} \pm \Delta c_{K\pi})t + (c'_{K\pi} \pm \Delta c'_{K\pi})t^2$$

Experimental observable includes instrumental asymmetries, A^I_i, in each decay-time bin i (production and π tag asymmetries)

$$\tilde{R}^{\pm}_i = R^{\pm}_i(1 \pm 2A^{\mathrm{I}}_i),$$

Correct using raw asymmetry of $D^{*+} \to D^0(\to K^+K^-)\pi^+$

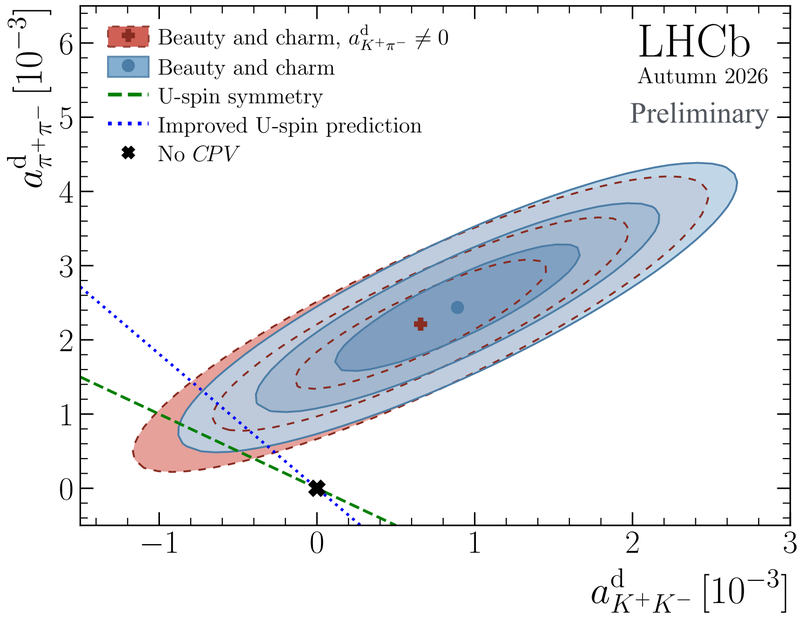
$$A^I_i = A_{\mathrm{raw}}(KK)_i - (a^d_{K^+K^-} + \Delta Y_{K^+K^-} \cdot \langle t_i \rangle)$$

$$\tilde{A}_{K\pi} \approx A_{K\pi} - 2a^d_{K^+K^-} \approx a^d_{K^+\pi^-} - 2a^d_{K^+K^-}$$

$$\Delta\tilde{c}_{K\pi} \approx \Delta c_{K\pi} - c_{K\pi}\, a^d_{K^+K^-} - 2\sqrt{R_{k\pi}}\,\Delta Y_{K^+K^-}$$

$$\Delta\tilde{c}'_{K\pi} \approx \Delta c'_{K\pi} - 2c'_{K\pi}a^d_{K^+K^-} - 2\sqrt{R_{K\pi}}\,c_{K\pi}\,\Delta Y_{K^+K^-}$$

- Sensitive to $a^d_{K^+K^-}$ if assuming no CPV in DCS decays ($a^d_{K^+\pi^-} = 0$).
- Probe a CP-violating observable free from any assumption.
- It could become competitive with improved precision on $\Delta c_{K\pi} \approx \phi_2^M x_{12}$.



$$a^d_{K^+K^-} = (9 \pm 5) \times 10^{-4}$$
$$a^d_{\pi^+\pi^-} = (24 \pm 6) \times 10^{-4}$$

$$a^d_{K^+K^-} = (7 \pm 5) \times 10^{-4}$$
$$a^d_{\pi^+\pi^-} = (22 \pm 6) \times 10^{-4}$$

U-spin

Constraint on $a^d_{K^+K^-}$ and $a^d_{\pi^+\pi^-}$

$$A(D^0 \to h^+h^-) \equiv \lambda_s T_{h^+h^-} + \lambda_b P_{h^+h^-}$$

$$\lambda_i \equiv V_{ci}^* V_{ui} \quad \delta_{h^+h^-} \equiv \arg\left(\frac{P_{h^+h^-}}{T_{h^+h^-}}\right)$$

$$a^d_{h^+h^-} = \mp 2\,\mathrm{Im}\left(\frac{\lambda_b}{\lambda_s}\right)\left|\frac{P_{h^+h^-}}{T_{h^+h^-}}\right|\sin\delta_{h^+h^-}$$

$$\simeq 1.3 \times 10^{-3}$$

U-spin symmetry

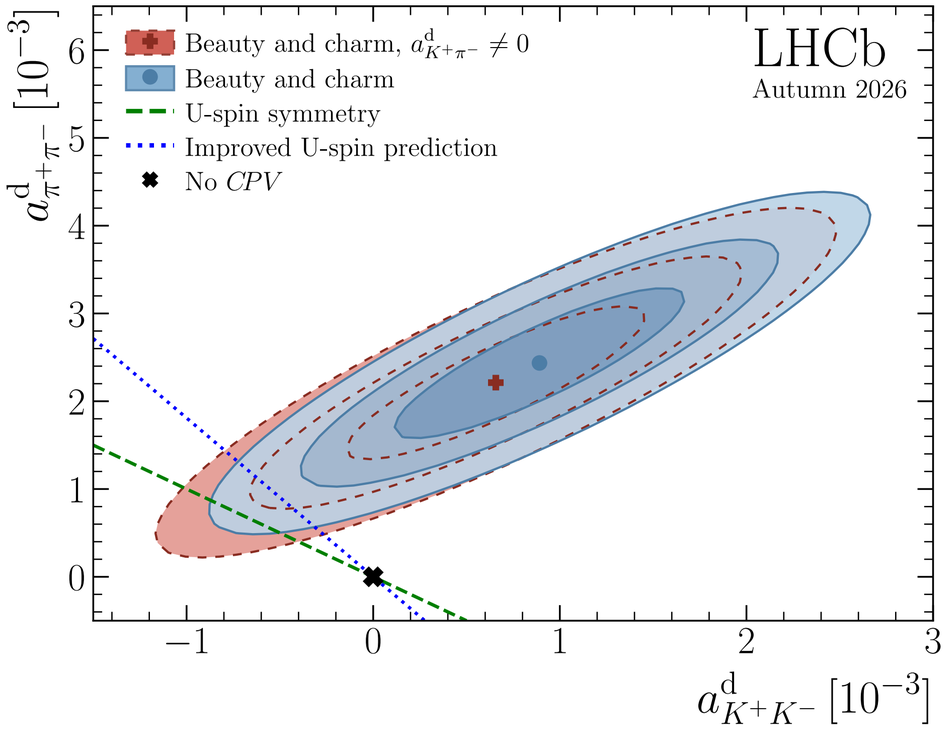
$$\frac{a^d_{K^+K^-}}{a^d_{\pi^+\pi^-}} = -1$$

Improved U-spin prediction

$$(1.81 \pm 0.02)$$

$$\frac{a^d_{K^+K^-}}{a^d_{\pi^+\pi^-}}\left|\frac{T_{K^+K^-}}{T_{\pi^+\pi^-}}\right| = -1$$

[This relation still relies on the assumption $\sin\delta_{K^+K^-} = \sin\delta_{\pi^+\pi^-}$]



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Strong-phase difference

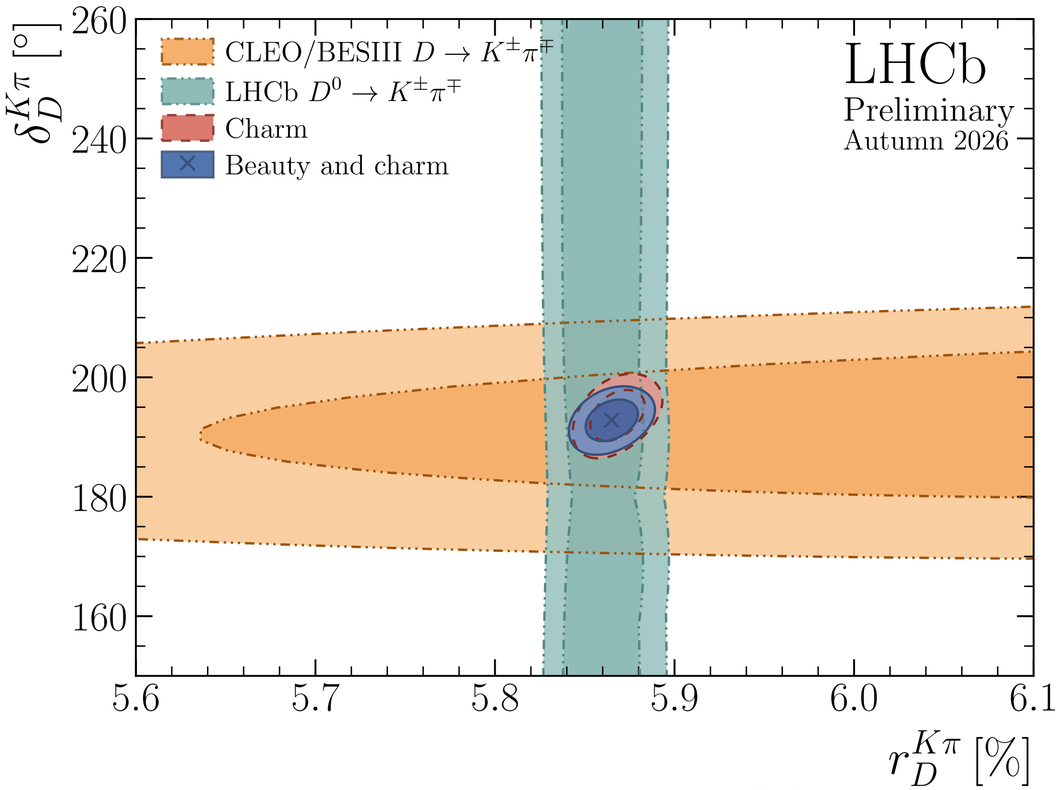
$D^0 \to K\pi$ DCS/CF

$$R_{K\pi} \equiv (r_D^{K\pi})^2 \equiv \frac{1}{2}\left(\left|\frac{A(D^0 \to K^+\pi^-)}{A(D^0 \to K^-\pi^+)}\right|^2 + \left|\frac{A(\overline{D}^0 \to K^-\pi^+)}{A(\overline{D}^0 \to K^+\pi^-)}\right|^2\right)$$

$$\phi_2^M + \delta_D^{K\pi} \equiv \arg\left(M_{12}\frac{A(D^0 \to K^-\pi^+)}{A(\overline{D}^0 \to K^-\pi^+)}\right)$$

$$\phi_2^M - \delta_D^{K\pi} \equiv \arg\left(M_{12}\frac{A(D^0 \to K^+\pi^-)}{A(\overline{D}^0 \to K^+\pi^-)}\right)$$

$$\Delta_{K\pi} = -\delta_{K\pi}(\text{HFLAV}) = \pi - \delta^D_{K\pi}$$



BESIII, Phys. Rev. D 112, (2025) 072006 (7.13 fb^{-1})

$$\delta^D_{K\pi} = \left(192^{+11.0+1.9}_{-12.4-2.4}\right)^\circ$$

$$\delta^D_{k\pi} = (192.9^{+2.3}_{-2.4})^\circ$$

LHCb, PRL (2021)127.111801
LHCb, PRD108(2023) 052005

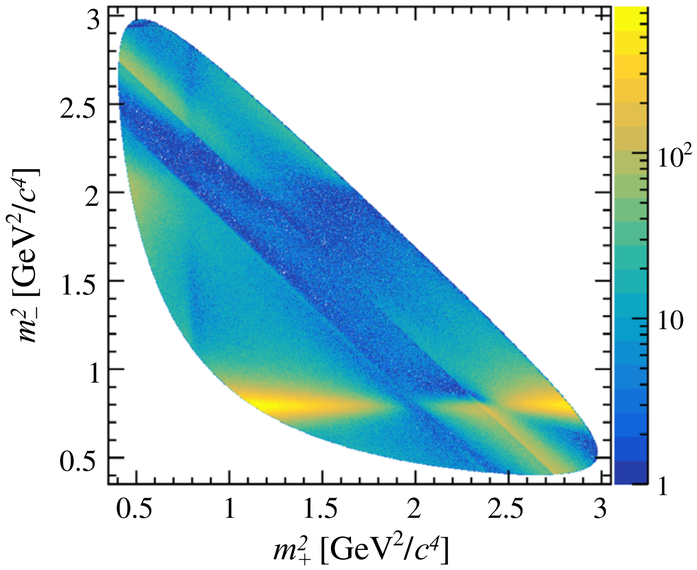
$D^0 \to K^0_s \pi^+ \pi^-$

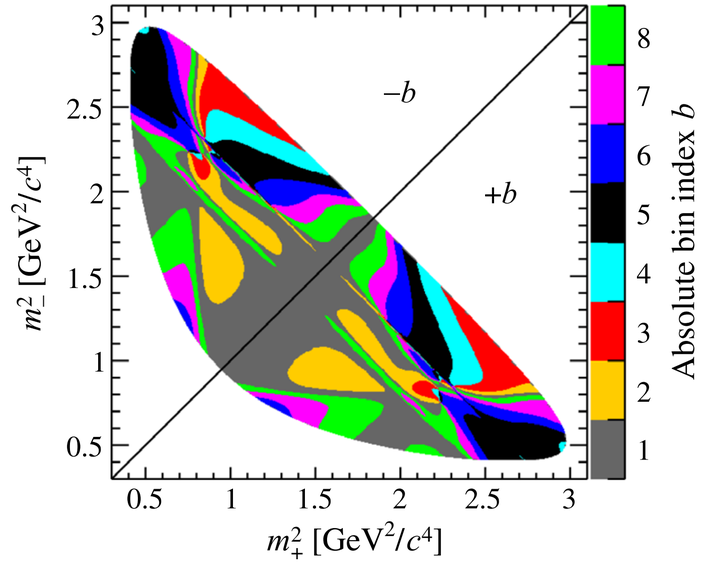
The golden mode

- Phenomenology very rich. Probe Mixing and CPV with different sensitivity to physic observables depending on the DP position. Multiple interfering intermediate amplitudes (CF and DCS).
- Two **time-dependent** approaches:
  - Model dependent (full time-dependent amplitude analysis).
  - Model-independent (bin-flip) using strong-phase differences in bins of Dalitz plot from Charm Factories (BES-III, CLEO-c)
- Particularly sensitive to $x = (M_2 - M_1)/2\Gamma$. **First observation in 2021!!!**

$$x_{CP} \approx x_{12} \approx x = (4.01 \pm 0.45 \pm 0.20) \times 10^{-3} \quad (7.5\sigma)$$
$$y_{CP} \approx y_{12} \approx y = (5.51 \pm 1.16 \pm 0.59) \times 10^{-3}$$
$$\Delta x \approx -\, y_{12} \sin\phi_2^{\Gamma} = (-0.29 \pm 0.18 \pm 0.01) \times 10^{-3}$$
$$\Delta y \approx +\, x_{12} \sin\phi_2^{M} = (+0.31 \pm 0.35 \pm 0.13) \times 10^{-3}$$

$$m^2_{\pm} \equiv \begin{cases} m^2(K^0_S\pi^{\pm}) & \text{for } D^0 \to K^0_S\pi^+\pi^- \text{decays} \\ m^2(K^0_S\pi^{\mp}) & \text{for } \bar{D}^0 \to K^0_S\pi^+\pi^- \text{decays} \end{cases}$$



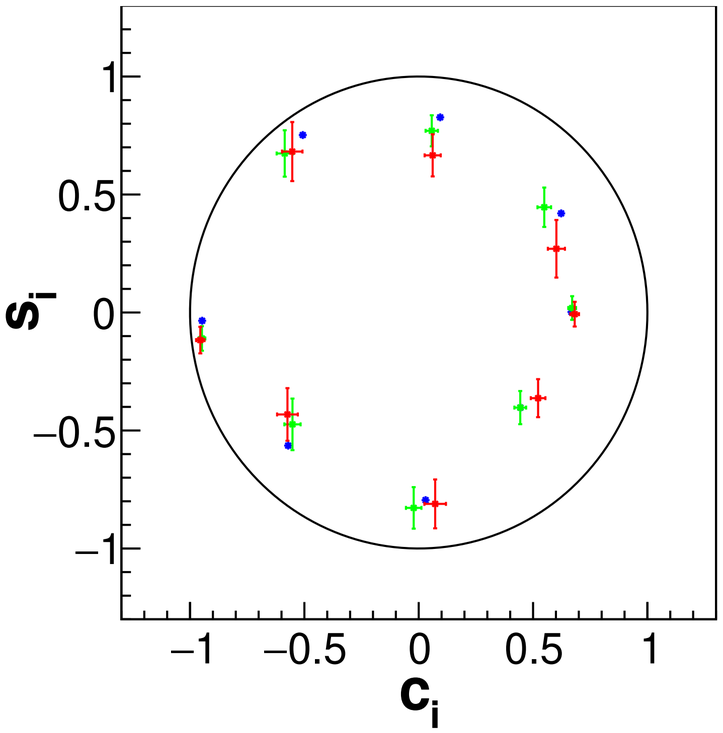


$D^0 \to K^0_s \pi^+ \pi^-$

Hadronic inputs to bin-flip analysis

- Strong-phase parameters (c_b, s_b) in the 8 Dalitz-plot bins, measured by BESIII (in general by e+e- charm factories by using QC)
- Previous determination [BESIII, JHEP02(2021)169, 9fb^{-1}]
  - use both $D^0 \to K^0_S \pi^+ \pi^-$ and $D^0 \to K^0_L \pi^+ \pi^-$
  - Ratio $A_{\rm DCS}/A_{\rm CF}$ related to the intermediate resonance amplitudes in K^0_S and K^0_L DP.
  - BESIII can access even neutral resonances: by measuring U-spin breaking parameter $\to A_{\rm DCS}/A_{\rm CF} \equiv \tan^2\theta_C \cdot \hat{\rho}$ $\to$ constraint $|\hat{\rho}| = 1 \pm 0.5$
- New determination [BESIII, JHEP06(2025)086, 7.93 fb^{-1}]
  - (c_b, s_b) also measured with no constraints on U-spin breaking
- Very recent determination [BESIII, 2610.13101, 20.3 fb^{-1}]
  - More precise and reliable. Not yet used.

BESIII, JHEP06(2025)086



Amplitude model

U-spin breaking constraints

No U-spin breaking constraints

$D^0 \to K^0_s \pi^+ \pi^-$

Hadronic input to bin-flip analysis

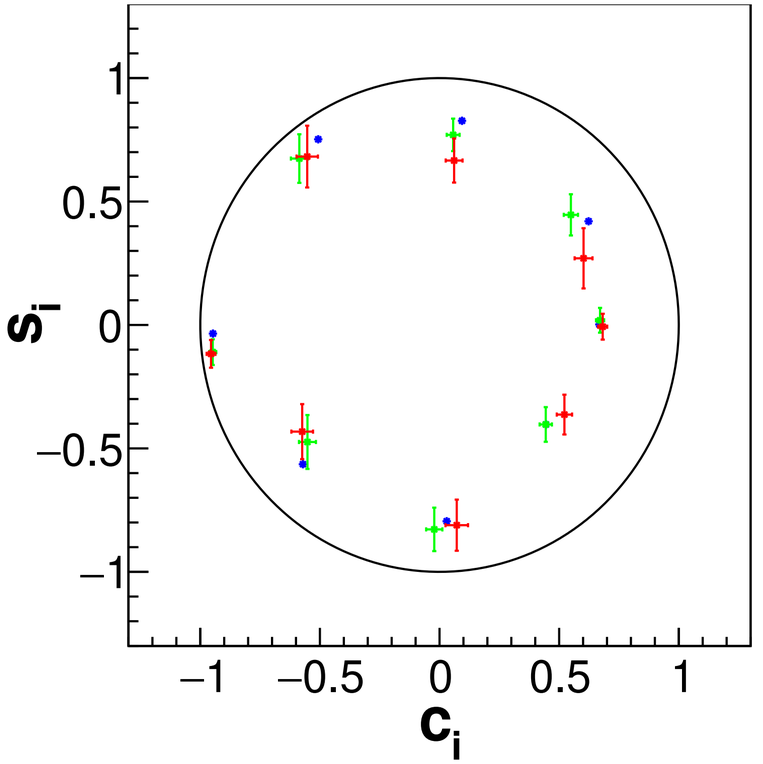
Table 6: (Left) Results of the bin-flip measurements of $D^0 \to K^0_S \pi^+ \pi^-$ decays using Run 2 data [32, 48], updated to use the determination of the hadronic parameters without U-spin constraints by the BESIII collaboration in Table 4 of Ref. [134], and (right) the corresponding correlation matrix.

Observable	Value $[10^{-3}]$
x_{CP}	4.903 ± 0.661
y_{CP}	5.123 ± 1.184
Δx	-0.329 ± 0.220
Δy	0.282 ± 0.347

	x_{CP}	y_{CP}	Δx	Δy
x_{CP}	1	0.042	−0.083	−0.007
y_{CP}		1	−0.004	−0.072
Δx			1	0.012
Δy				1

LHCb-PAPER-2026-058, in preparation

BESIII, JHEP06(2025)086



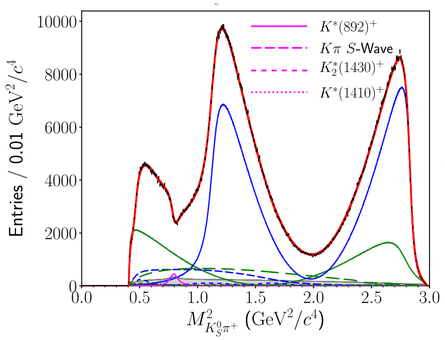
Amplitude model

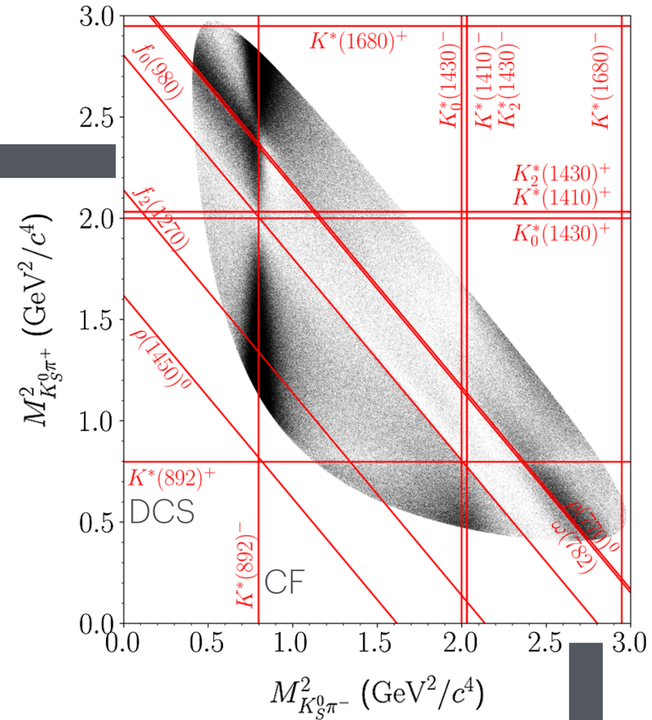
U-spin breaking constraints

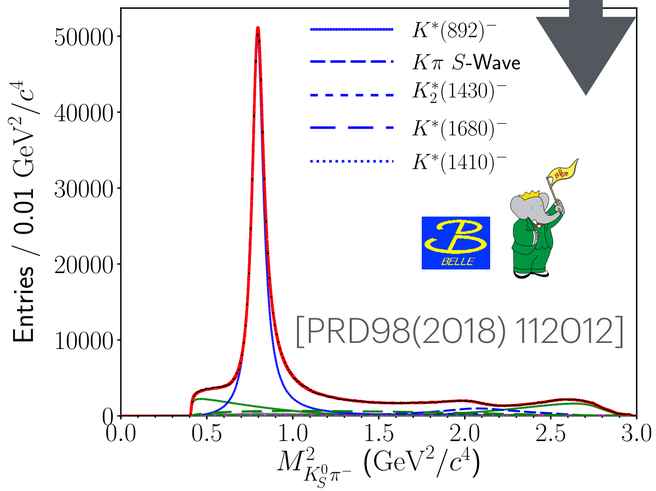
No U-spin breaking constraints

$D^0 \to K^0_s \pi^+ \pi^-$

The golden mode



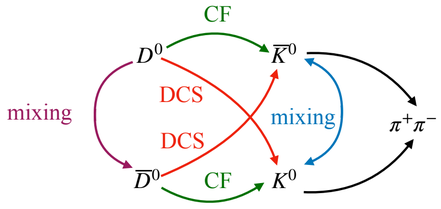




- Model-idependent approach very powerful, particularly in hadronic environment, but **it also has a rich and important amplitude structure**.
  - Mixing and CPV from B-Factories — Belle PRD 89(2014) 091103(R), BaBar PRL105(2010)081803 — Hoping for BelleII updates soon.
  - More challenging at LHCb, but feasible.
- **More sensitive to mixing and CPV than bin-flip**.
- **Becoming more and more important as a calibration channel.**
  For instance for time-integrated $A_{CP}(D^0 \to K^+K^-), A_{CP}(D^0 \to K^0_S K^0_S)$.
- Particularly relevant for future measurements. Key role of mixing and CPV in neutral kaon system and regeneration effect in matter.

$D^0 \to K^0_S \pi^+ \pi^-$

Approaching extreme precision



$$|\psi_K(0)\rangle \propto \mathcal{A}(D^0 \to \overline{K}^0\pi^+\pi^-)|\overline{K}^0\rangle + \mathcal{A}(D^0 \to K^0\pi^+\pi^-)|K^0\rangle$$
$$\equiv \mathcal{A}^{tot}_{CF}|\overline{K}^0\rangle + \mathcal{A}^{tot}_{DCS}e^{i\phi_{DCS}}|K^0\rangle$$
$$\equiv \mathcal{A}^{tot}_{CF}\left[|\overline{K}^0\rangle + r_{tot}e^{i\delta_{tot}+\phi_{DCS}}|K^0\rangle\right],$$

$$|\overline{\psi}_K(0)\rangle \propto \mathcal{A}(\overline{D}^0 \to K^0\pi^+\pi^-)|K^0\rangle + \mathcal{A}(\overline{D}^0 \to \overline{K}^0\pi^+\pi^-)|\overline{K}^0\rangle$$
$$= \mathcal{A}^{tot}_{CF}|K^0\rangle + \mathcal{A}^{tot}_{DCS}e^{-i\phi_{DCS}}|\overline{K}^0\rangle$$
$$= \mathcal{A}^{tot}_{CF}\left[|\overline{K}^0\rangle + r_{tot}e^{i\delta_{tot}-\phi_{DCS}}|K^0\rangle\right].$$

- Neutral kaon time evolution essential.
- Multiple interfering processes including CF, DCS, kaon mixing (and D^0 mixing at some point) give a mixture of $K^0/\overline{K}^0$ at $t = 0$.
- Precise knowledge of the detector material is necessary..
- "Coherent forward scattering" approximation used for regeneration. [Fortschritte der Physik 21, 57-84 (1973), R. H. Good at al. PhysRev.124 (1961)1223]

No longer unknown mixture of CF/DCS ($K^0/\overline{K}^0$).
Recent results from BESIII [2610.13101, 20.3 fb^{-1}]

Table 7. Measured U-spin breaking parameters. The first and second uncertainties on phases and FFs are statistical and systematic, respectively.

Resonance	$\lvert\hat{\rho}\rvert$	$\arg(\hat{\rho})$ [rad]	$\lvert 1 - 2\hat{\rho}\tan^2\theta_C\rvert^2$
$\rho(770)$	$0.62 \pm 0.09 \pm 0.06$	$-2.73 \pm 0.16 \pm 0.27$	$1.13 \pm 0.02 \pm 0.02$
$\omega(782)$	$1.56 \pm 0.53 \pm 0.29$	$-2.78 \pm 0.25 \pm 0.16$	$1.34 \pm 0.13 \pm 0.07$
$f_2(1270)$	$3.34 \pm 0.34 \pm 0.19$	$-0.73 \pm 0.09 \pm 0.05$	$0.59 \pm 0.05 \pm 0.03$
$\rho(1450)$	$4.45 \pm 0.83 \pm 0.60$	$1.30 \pm 0.19 \pm 0.14$	$0.97 \pm 0.18 \pm 0.13$
$\pi\pi$ S-wave	$0.77 \pm 0.13 \pm 0.17$	$-1.74 \pm 0.13 \pm 0.11$	$1.04 \pm 0.02 \pm 0.02$

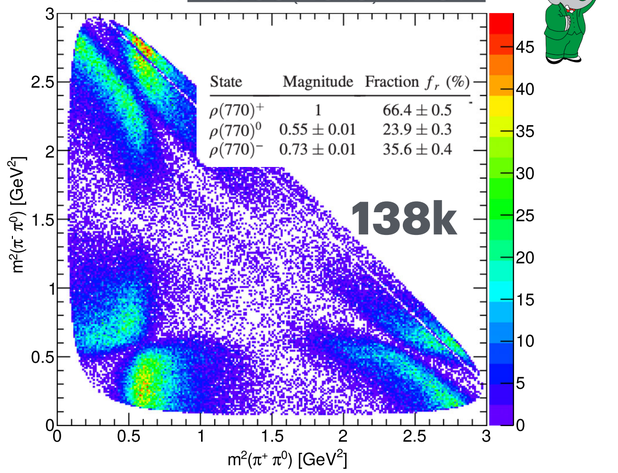
[PRD98(2018) 112012]

Group	Resonance	Amplitude	Phase (deg)	Fit fraction (%)
CF	$K^*(892)^-\pi^+$	1.720 ± 0.006	136.8 ± 0.2	59.9
	$K^*_2(1430)^-\pi^+$	1.27 ± 0.02	-44.1 ± 0.8	1.3
	$K^*(1680)^-\pi^+$	3.31 ± 0.20	-118.2 ± 3.1	0.5
	$K^*(1410)^-\pi^+$	0.29 ± 0.03	99.4 ± 5.5	0.1
	$K^*_0(1430)^-\pi^+$	2.36 ± 0.06	99.4 ± 1.7	7.0
DCS	$K^*(892)^+\pi^-$	0.164 ± 0.003	-42.2 ± 0.9	0.6
	$K^*_2(1430)^+\pi^-$	0.10 ± 0.01	-89.6 ± 7.6	< 0.1
	$K^*(1410)^+\pi^-$	0.21 ± 0.02	150.2 ± 5.3	< 0.1
	$K^*_0(1430)^+\pi^-$	0.11 ± 0.01	162.3 ± 6.6	< 0.1
Neutrals	$K^0_1\rho(770)^0$	1 (fixed)	0 (fixed)	20.4
	$K^0_1\omega(782)$	0.0388 ± 0.0005	120.7 ± 0.7	0.5
	$K^0_1 f_2(1270)$	1.43 ± 0.03	-36.3 ± 1.1	0.8
	$K^0_1\rho(1450)^0$	2.85 ± 0.10	102.1 ± 1.9	0.6
$S-$wave	β_1	8.5 ± 0.5	68.5 ± 3.4	
	β_2	12.2 ± 0.3	24.0 ± 1.4	
	β_3	29.2 ± 1.6	-0.1 ± 2.5	
	β_4	10.8 ± 0.5	-51.9 ± 2.4	
	$f^{\rm prod}_{11}$	8.0 ± 0.4	-126.0 ± 2.5	10.0
	$f^{\rm prod}_{12}$	26.3 ± 1.6	-152.3 ± 3.0	
	$f^{\rm prod}_{13}$	33.0 ± 1.8	-93.2 ± 3.1	
	$f^{\rm prod}_{14}$	26.2 ± 1.3	-121.4 ± 2.7	
	$s^{\rm prod}_0$	-0.07 (fixed)		

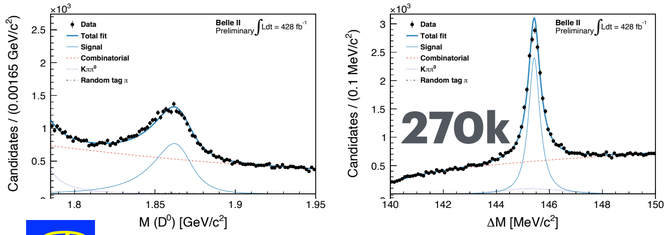
$D^0 \to \pi^+\pi^-\pi^0$

An interesting opportunity

BaBar PRD93(2016) 112014

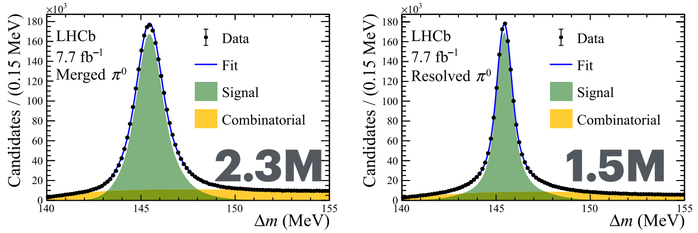


- Pseudo two-body decays have similarities with $D^0 \to \pi^+\pi^-$. Interference of two-body decays leading to a common three-body final state can be used to extract relative penguin phase arg(P/T).
  [Dery, Grossman, Schacht, Soffer JHEP05(2021)179 and references therein].



$\mathcal{A}_{CP} = (0.29 \pm 0.27 \pm 0.13)\%$

- Search for CPV based on a model-independent method (Energy Test) with LHCb Run 2 data consistent with CP conservation (p-value: 62%) [JHEP09(2023)129].
- Time- and phase-space-integrated CP asymmetry by the Belle II experiment from 2019 to 2022, 428 fb^{-1}. PRD [2510.21224].
- Time-dependent CPV measured by LHCb [PRL 133 (2024)101803] with Run1+2 data. The CP-even fraction measured using CLEO-c data is $F_+^{\pi\pi\pi^0} = 0.973 \pm 0.017$ providing almost undiluted sensitivity.



$\Delta Y = (-1.3 \pm 6.3 \pm 2.4) \times 10^{-4}$

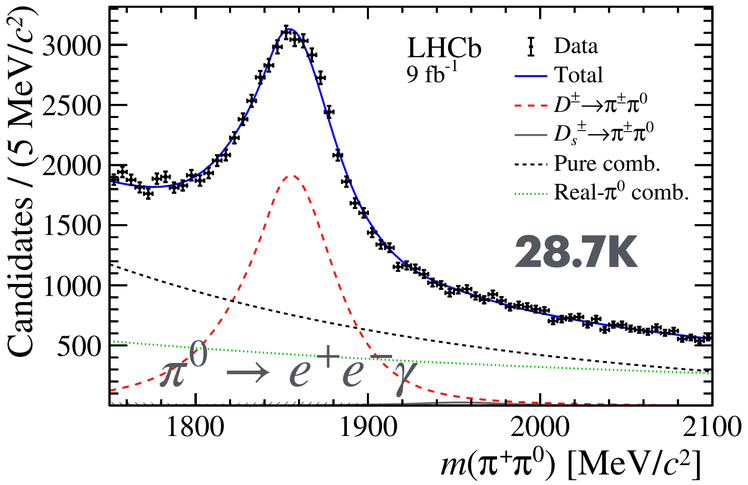
$\Delta Y_f^{\text{eff}} = (2F_+^f - 1)\Delta Y$

Two-body decays with π^0

Note that for isospin symmetry $A_{CP}^{dir}(D^+ \to \pi^+\pi^0) = 0$ in SM.

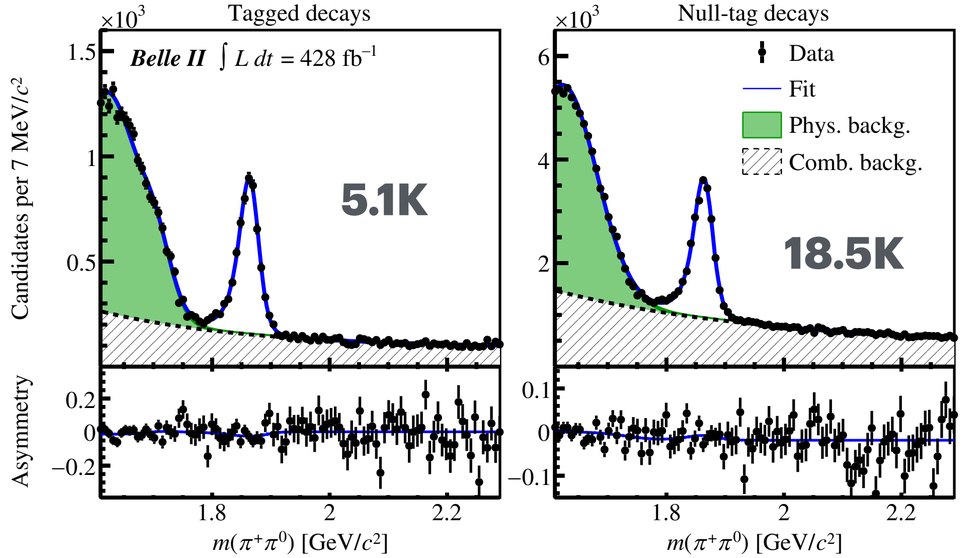
[only at B-factories]

LHCb JHEP06(2021)019



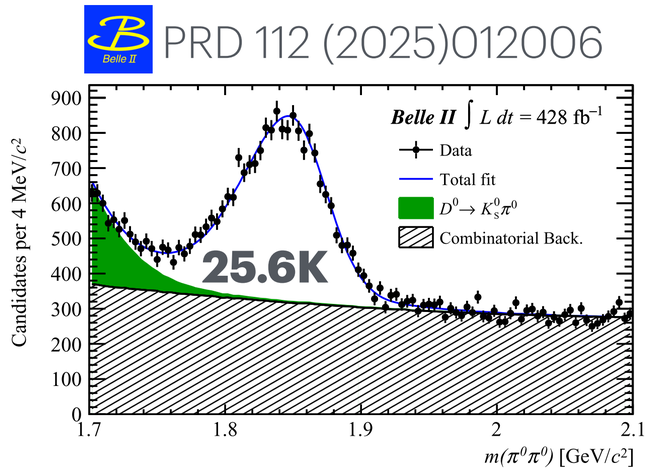
$\mathcal{A}_{CP}(D^+ \to \pi^+\pi^0) = (-1.3 \pm 0.9 \pm 0.6)\%$

Belle II PRD 112(2025) L031101



$A_{CP}(D^+ \to \pi^+\pi^0) = (-1.8 \pm 0.9 \pm 0.1)\%$

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$A_{CP}(D^0 \to \pi^0\pi^0) = (0.30 \pm 0.72 \pm 0.20)\%$

$$R = \frac{A_{CP}^{\rm dir}(D^0 \to \pi^+\pi^-)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{+-}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}} - \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)} + \frac{A_{CP}^{\rm dir}(D^0 \to \pi^0\pi^0)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{00}}\left(\frac{\mathcal{B}_{+-}}{\tau_{D^0}} - \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)} + \frac{A_{CP}^{\rm dir}(D^+ \to \pi^+\pi^0)}{1 - \frac{3}{2}\frac{\tau_{D^+}}{\mathcal{B}_{+0}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}} + \frac{\mathcal{B}_{+-}}{\tau_{D^0}}\right)}$$

$R = (1.5 \pm 2.5) \times 10^{-3}$, precision of the sum rule improved by approximately 20% with latest measurement of $A_{CP}(D^0 \to \pi^0\pi^0)$. Still limited by the precision on it.

H.-n. Li, C.-D. Lu and F.-S. Yu, PRD 86 (2012) 036012 , D. Pirtskhalava and P. Uttayarat, PLB 712 (2012) 81
F. Buccella, A. Paul and P. Santorelli, PRD99(2019)113001, B. Bhattacharya, M. Gronau and J.L. Rosner, PRD85(2012)054014.