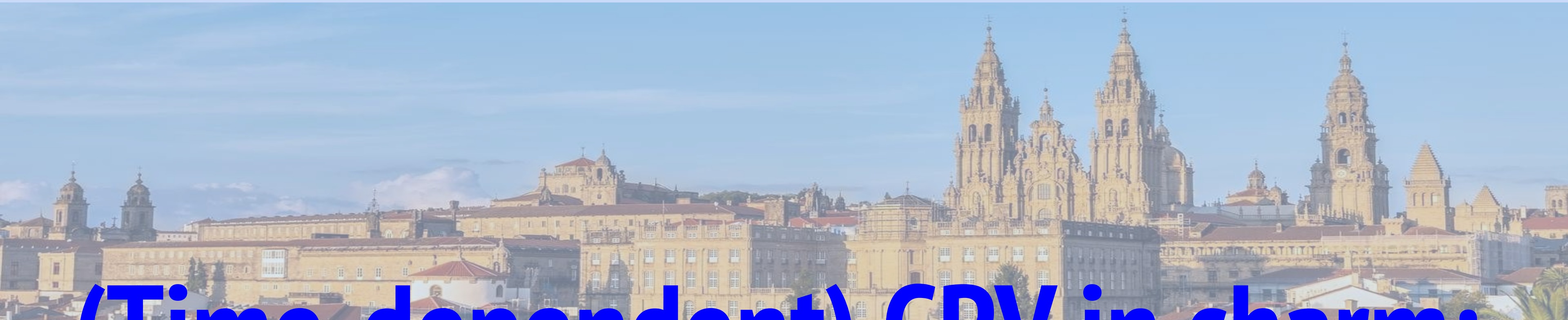


(Time-dependent) CPV in charm: experimental status

Giulia Tuci
Heidelberg University

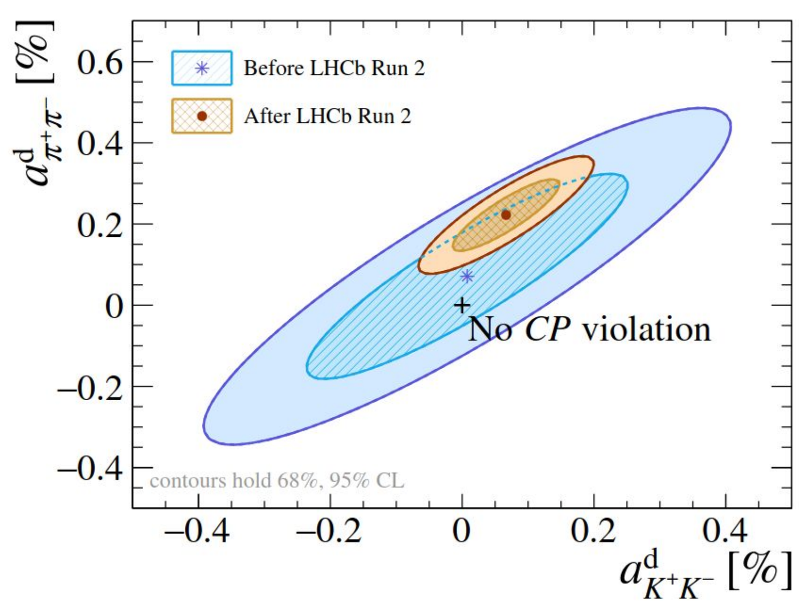
Santiago de Compostela, 17/04/2026

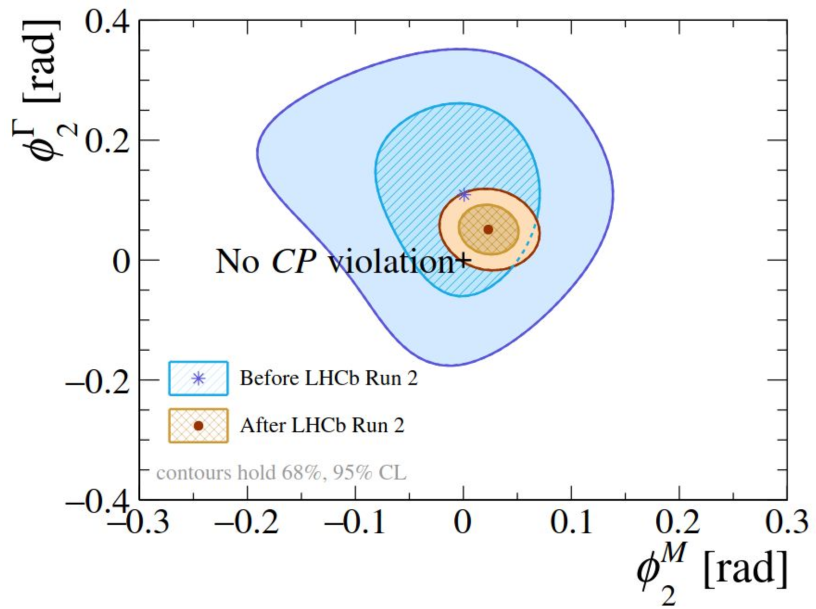
LHCb

UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

CPV in charm: state of the art

- **CPV in charm observed by LHCb in 2019** PRL122. 211803
  - $\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-15.4 \pm 2.9) \times 10^{-4}$ (5.3σ)
- Then, evidence that this is mainly coming from $D^0 \to \pi^+\pi^-$ decays
  - $a^d_{\pi\pi} = (23.2 \pm 5.2) \times 10^{-4}$ (3.8σ) PRL131.091802



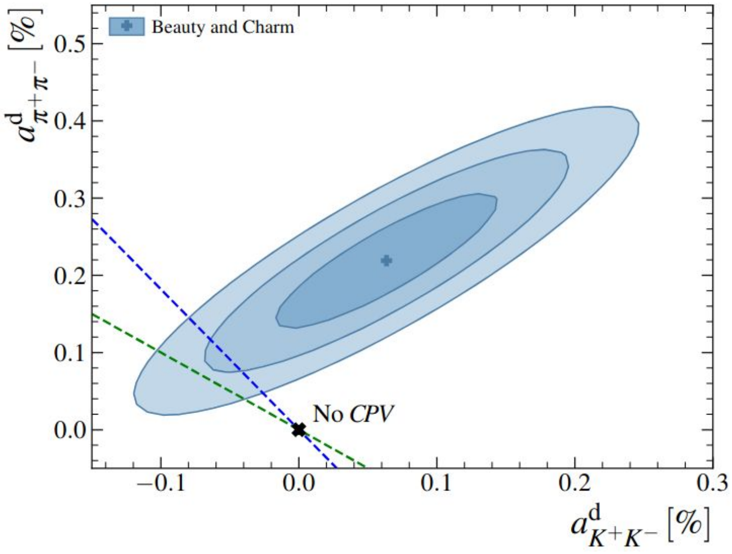


charm-fitter

CPV in charm: state of the art

- Is U-spin a good symmetry?

LHCb-CONF-2024-004



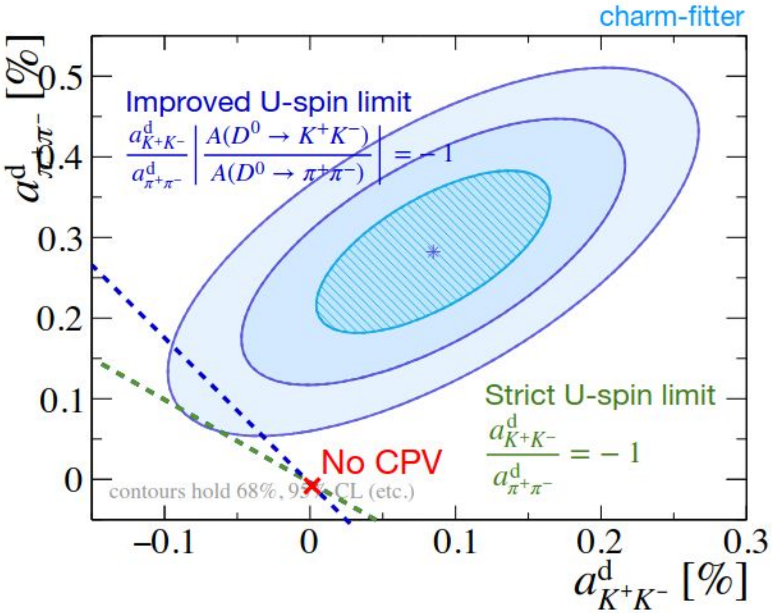
Strict U-spin limit: $\dfrac{a^{d}_{K^+K^-}}{a^{d}_{\pi^+\pi^-}} = -1$

Improved U-spin limit: $\dfrac{a^{d}_{K^+K^-}}{a^{d}_{\pi^+\pi^-}} \left| \dfrac{A(D^0 \to K^+K^-)}{A(D^0 \to \pi^+\pi^-)} \right| = -1$

- Measured CPV → $\left|\dfrac{P}{T}\right| \sin(\delta_P - \delta_T) = O(1)$
  - SM or not? Theoretical interpretation is debated
- More data → more precision → clarify physics picture

How do we determine a_d from A^{CP} measurements?

see also T.Pajero and K.Vos slides @ CKM 2026



$$a^{d}_{K^+K^-} = (\ 8.5 \pm 5.3) \times 10^{-4}$$
$$a^{d}_{\pi^+\pi^-} = (28.2 \pm 6.6) \times 10^{-4}$$

Kagan Silvestrini 2001.07207

$$x_{12} \equiv \frac{2|M_{12}|}{\Gamma}, \quad y_{12} \equiv \frac{|\Gamma_{12}|}{\Gamma}$$

$$\phi_f^M \equiv \arg\left(M_{12}\frac{A_f}{\overline{A}_f}\right) \qquad \phi_f^\Gamma \equiv \arg\left(\Gamma_{12}\frac{A_f}{\overline{A}_f}\right)$$

$$A^f_{CP}(t) \approx a^{d}_f + \Delta Y_f \frac{t}{\tau_{D^0}}$$

arg(P/T)

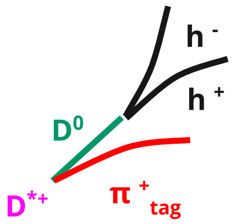
$$\Delta Y_f \approx -x_{12}\sin\phi_2^M + y_{12}a^{d}_f + x_{12}a^{d}_f\cot\delta_f$$

How can we measure time-dependent CPV in charm?

Very small mixing

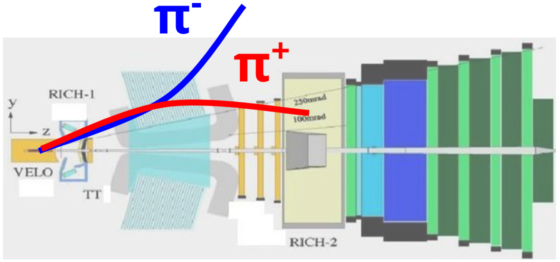
$$A_{CP}(t) = \frac{\Gamma(D^0(t)\to f) - \Gamma(\overline{D}^0(t)\to f)}{\Gamma(D^0(t)\to f) + \Gamma(\overline{D}^0(t)\to f)} \approx a^f_{\text{dir}} + \Delta Y_f \frac{t}{\tau_D}$$

$$\mathcal{A}^{raw} \equiv \frac{N_{D^0} - N_{\bar{D}^0}}{N_{D^0} + N_{\bar{D}^0}}$$



$$A_{\text{raw}}(f,t) = A_{CP}(f,t) + A_D(\pi_s^+, p(t)) + A_P(D^{*+}, p(t))$$

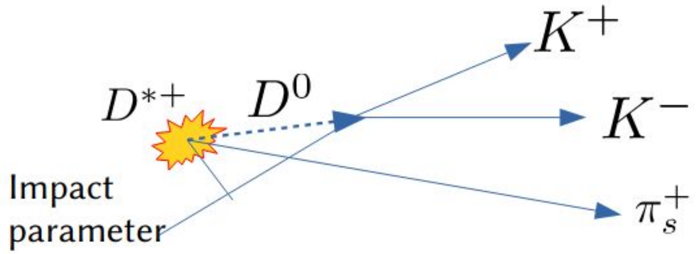
Production asymmetry: initial state pp is not CP symmetric



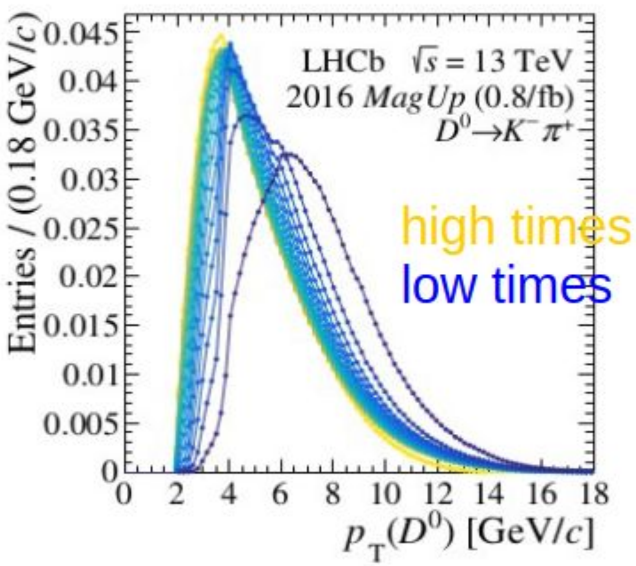
Asymmetric detector acceptance + material interaction different for particles/antiparticles

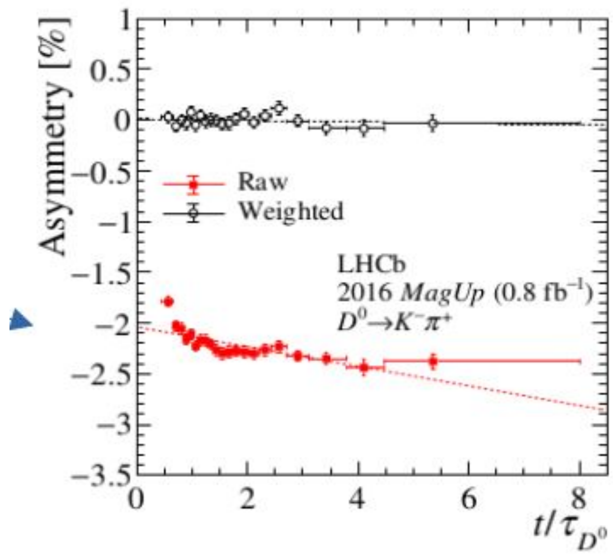
Detection asymmetries

[PRD104072010]



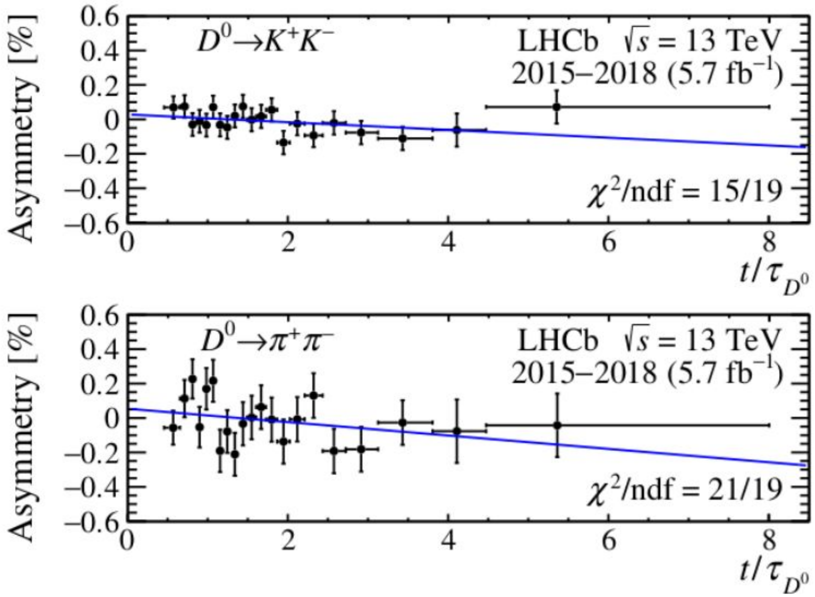
- Correlation between decay-time and momentum induced by trigger requirements
  - → fakes time-dependent CPV
- Weighting of D^0 and anti-D^0, and π^+ and π^- momentum distributions to equalise kinematics
  - Procedure validate with control mode: Cabibbo-favoured $D^0 \to K^-\pi^+$





Results

PRD104072010



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

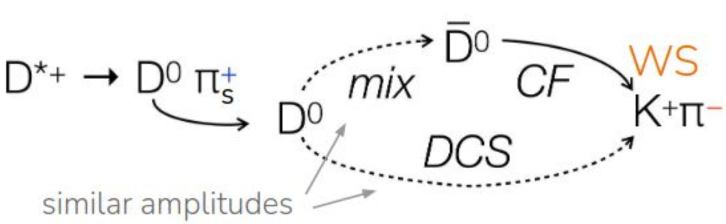
- No sign for time-dependent CPV yet
- To extract CP violating phase, precise measurement of mixing parameters is needed!

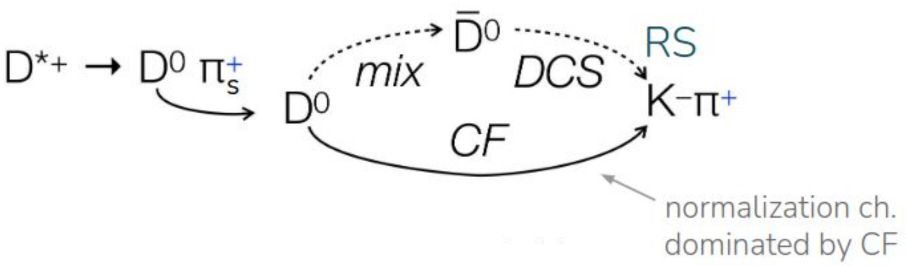
$$\Delta Y_f \approx -x_{12} \sin \phi_2^M + y_{12} a_f^{\mathrm{d}} + x_{12} a_f^{\mathrm{d}} \cot \delta_f$$

How can we measure mixing parameters?

- $D^0 \to K_S^0\pi\pi$: "golden channel" PRL122231802 , PRD111112011
- Today: will focus on more recent LHCb measurements with $D^0 \to K\pi(\pi\pi)$ decays

PRD111012001, JHEP03(2025)049, JHEP12 (2025)153





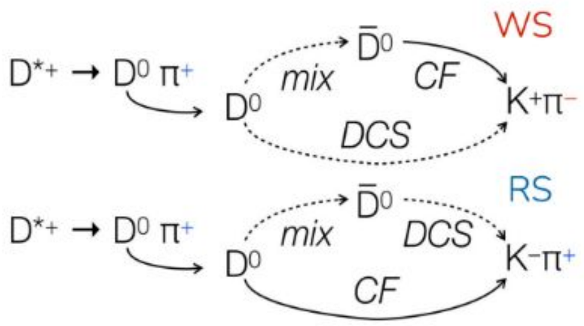
- We can access mixing and CPV parameters by measuring the ratio WS/RS as a function of the decay time

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

How can we measure mixing parameters?

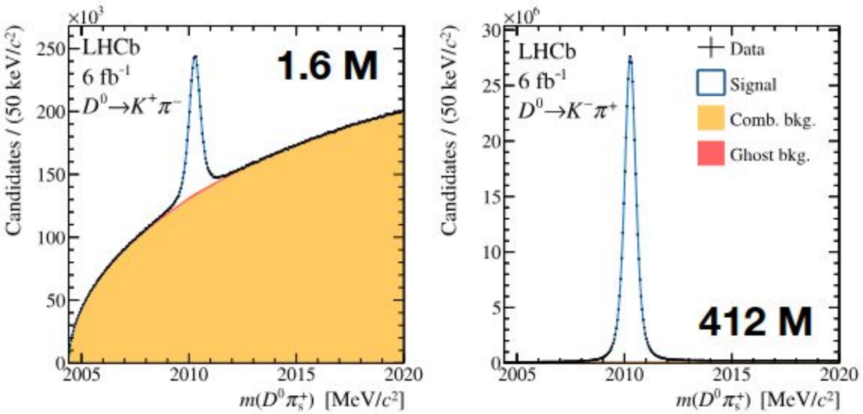
[PRD111012001](PRD111012001)

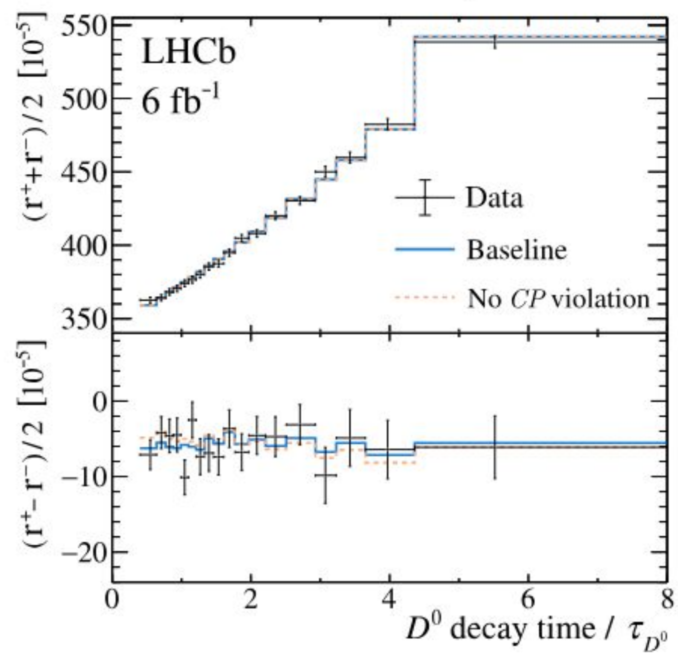
$$R(t) = \frac{\Gamma(D^0 \to K^+\pi^-)(t)}{\Gamma(D^0 \to K^-\pi^+)(t)} \approx r^2 - r\, y' \frac{t}{\tau} + \frac{x^2+y^2}{4}\left(\frac{t}{\tau}\right)^2$$



$$y' = y_{12}\cos\delta - x_{12}\sin\delta$$

$$\delta = (-191.6 \pm 2.4)^\circ$$



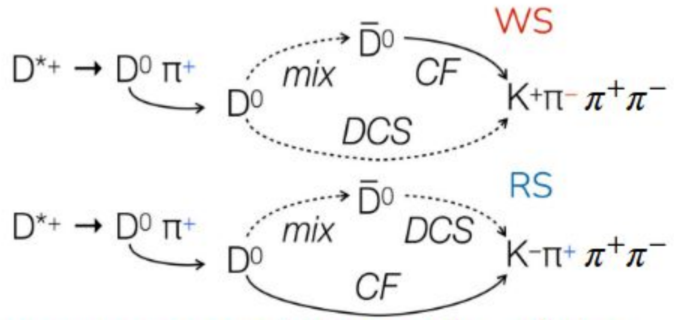


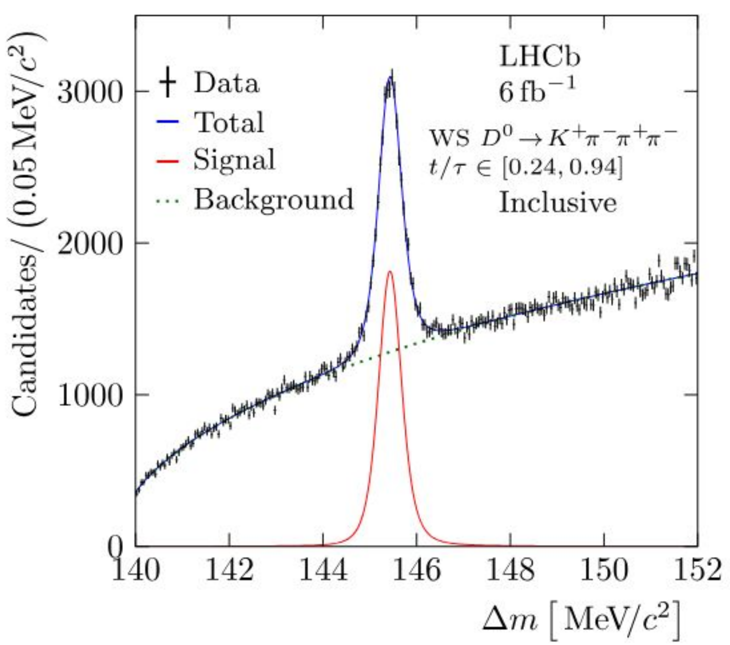
How can we measure mixing parameters?

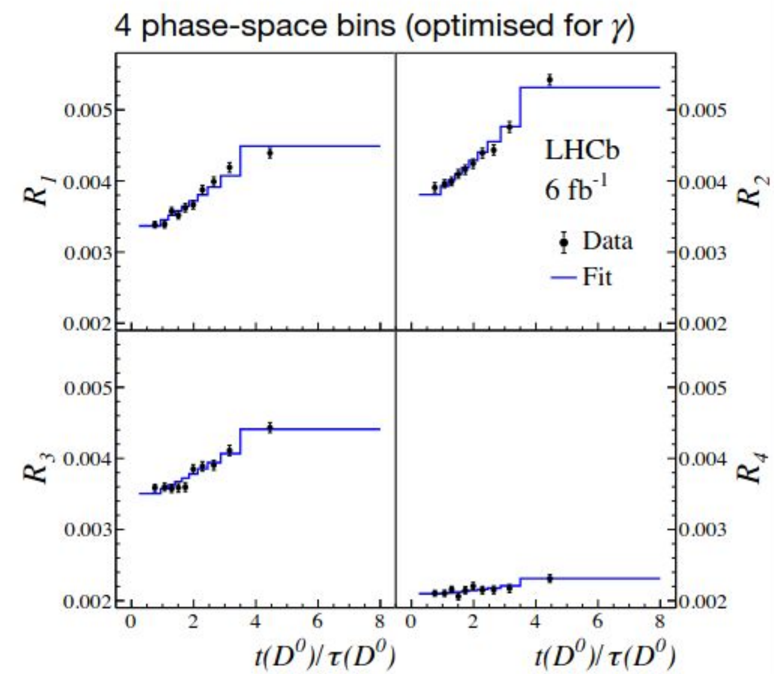
JHEP12 (2025)153

$$R(t) = \frac{\Gamma(D^0 \to K^+\pi^-\pi^+\pi^-)(t)}{\Gamma(D^0 \to K^-\pi^+\pi^-\pi^+)(t)} \approx r^2 - r\kappa y' \frac{t}{\tau} + \frac{x^2+y^2}{4}\left(\frac{t}{\tau}\right)^2$$

$$ky' = y_{12}\langle\cos\delta\rangle - x_{12}\langle\sin\delta\rangle$$

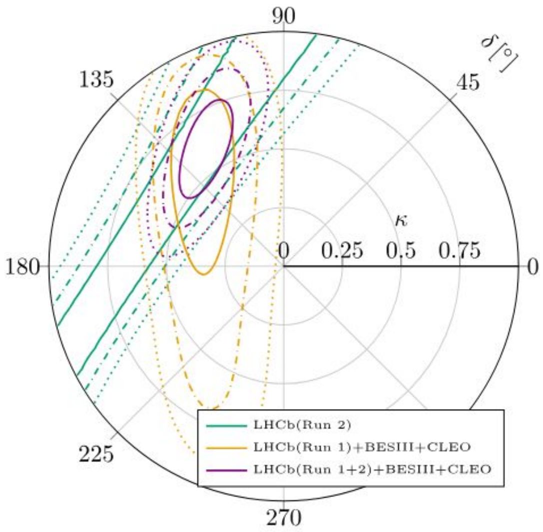


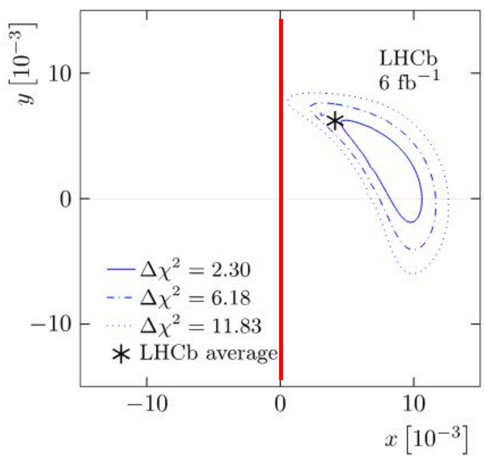


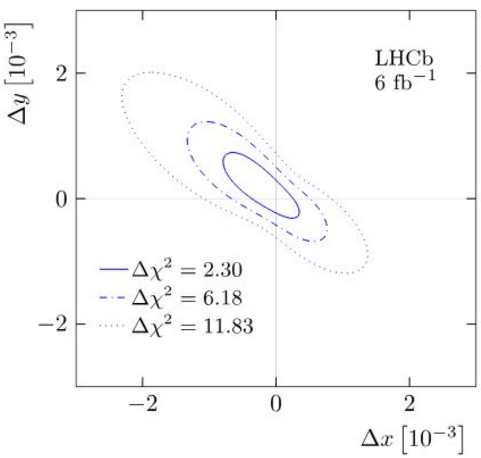


Mixing and CPV with 4-body D^0 decays

JHEP12 (2025)153



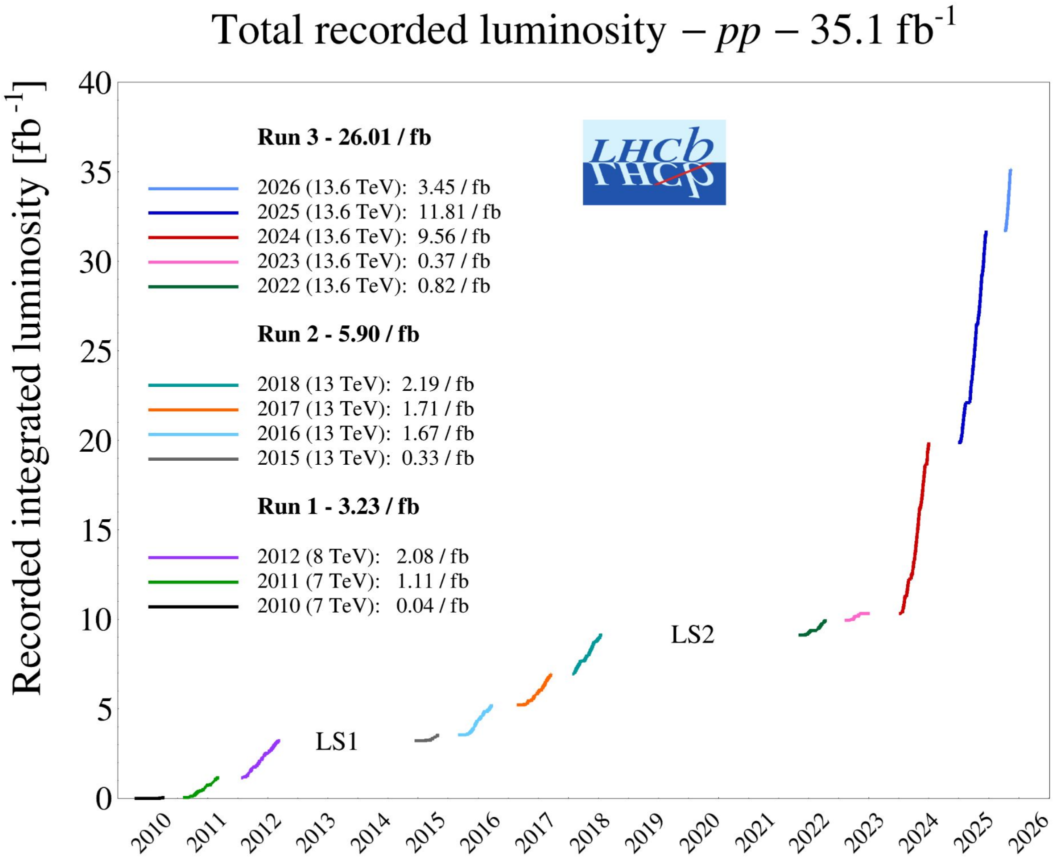




- Improve knowledge on charm hadronic parameters and charm mixing
- Second evidence of non-zero x after $D^0 \to K_S^0\pi\pi$

Future prospects with LHCb

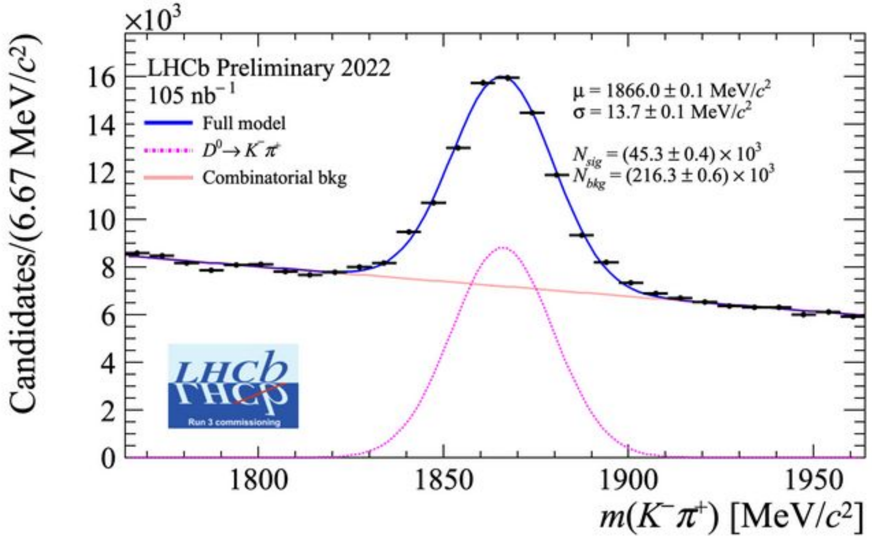
- All results presented up to now based on Run 1 + Run 2 datasets (~9fb^{-1})
- LHCb has already collected more than 26 fb^{-1} in Run 3 (data-taking still ongoing)



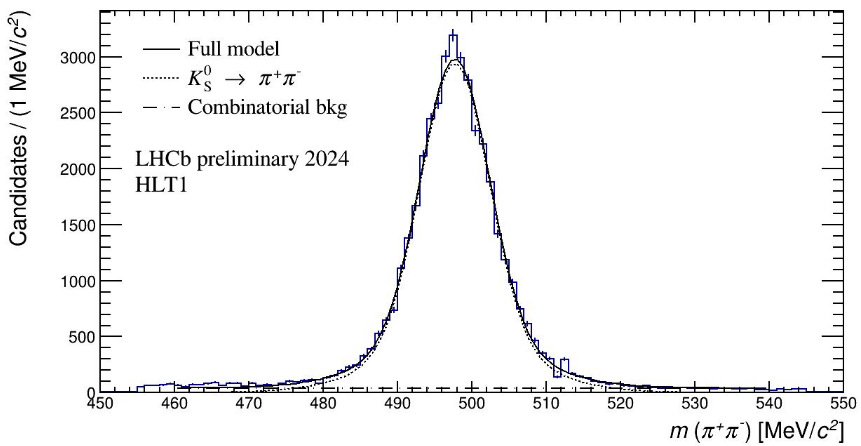
LHCb in Run 3

- Completely new detector and trigger system, with improved performance at a 5x instantaneous luminosity w.r.t Run 2
- Triggerless readout and reconstruction of events at full LHC collision rate
- Greater flexibility in design of selections
  - → room for improving trigger efficiency w.r.t. Run 2

LHCb-FIGURE-2023-009

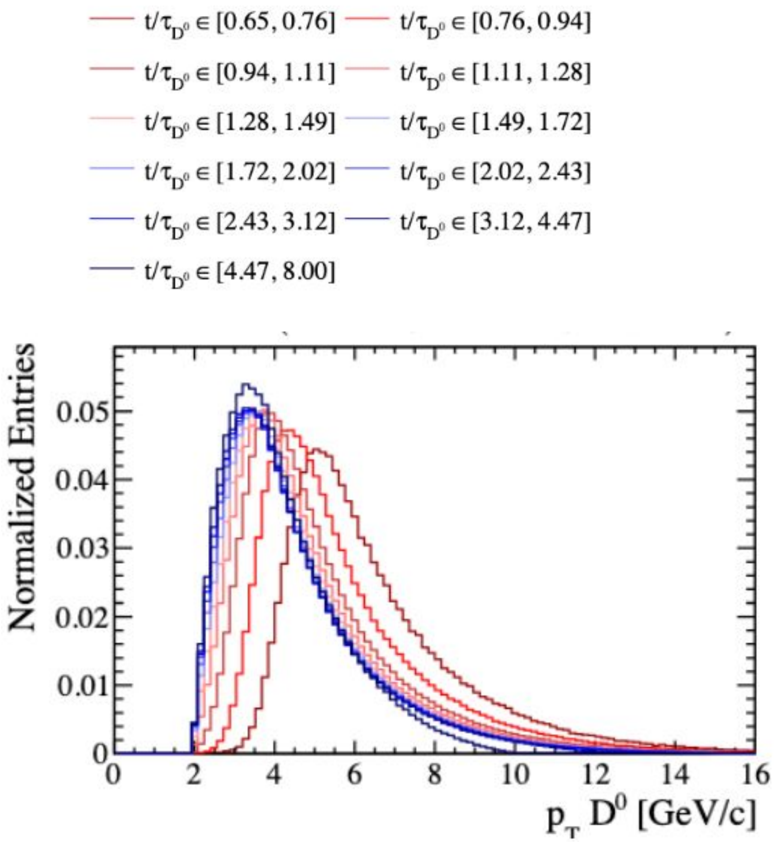


LHCb-FIGURE-2024-013



Not only more yields...

❖ Dedicated trigger selections developed to reduce correlations between decay-time and momentum → better control of systematic uncertainties

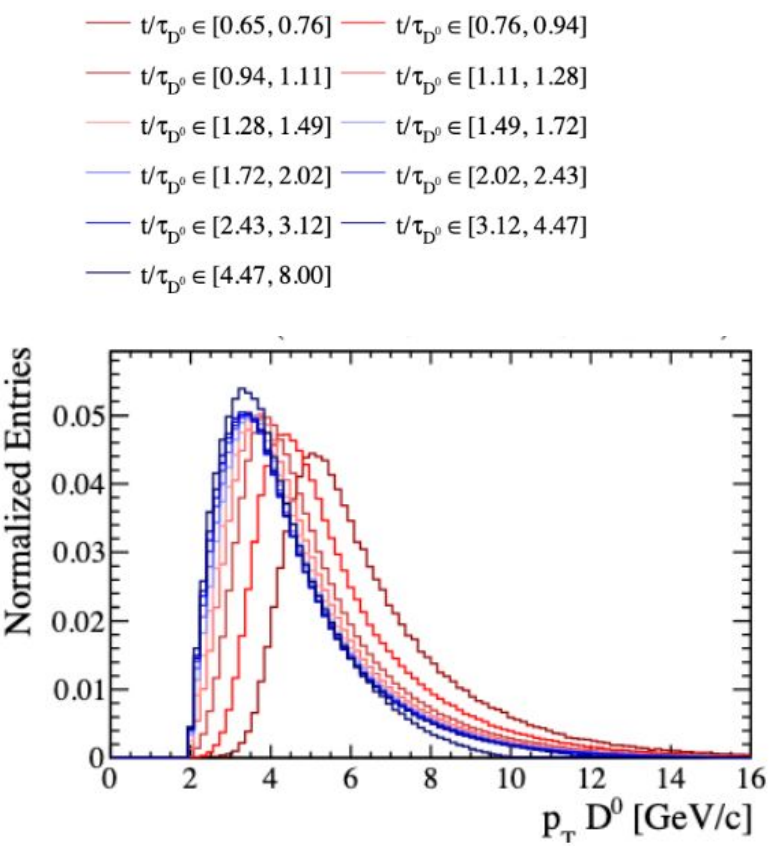


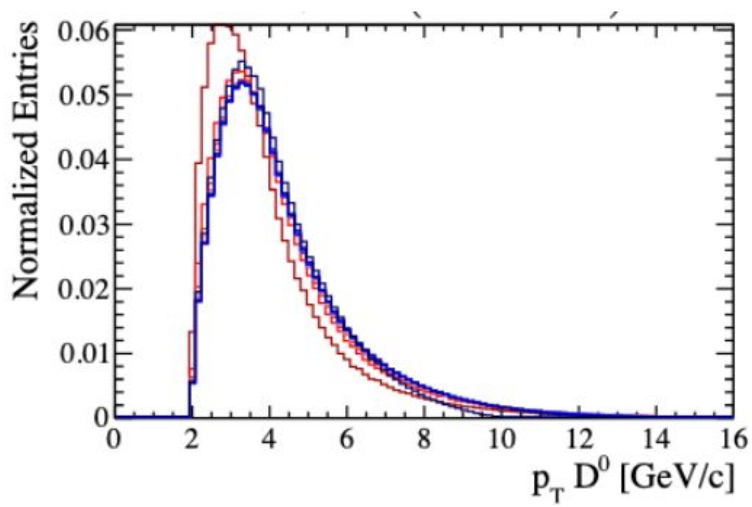
Nico Kleijne PhD Thesis

Not only more yields…

- Dedicated trigger selections developed to reduce correlations between decay-time and momentum → better control of systematic uncertainties

Nico Kleijne PhD Thesis





The $D^0 \rightarrow K_S^0 K_S^0$ decay channel

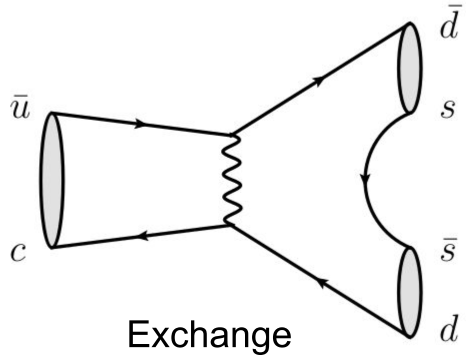
- In $D^0 \rightarrow K_S^0 K_S^0$ decay channel A_{CP} could be as large as ~1% PRD 92 (2015) 054036

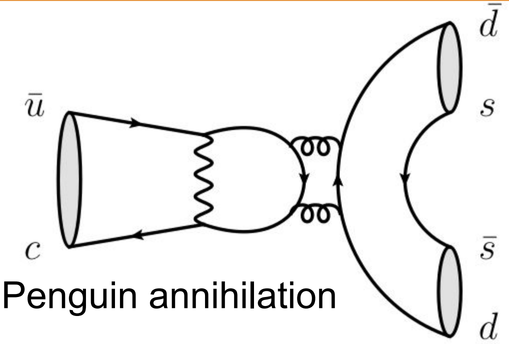
$$\frac{|\mathcal{A}|^2 - |\bar{\mathcal{A}}|^2}{|\mathcal{A}|^2 + |\bar{\mathcal{A}}|^2} = Im\frac{\lambda_b}{(\lambda_s - \lambda_d)} Im\frac{A_b}{A_{sd}}$$

$$\lambda_q \equiv V_{cq}^* V_{uq}$$

~10^{-3}

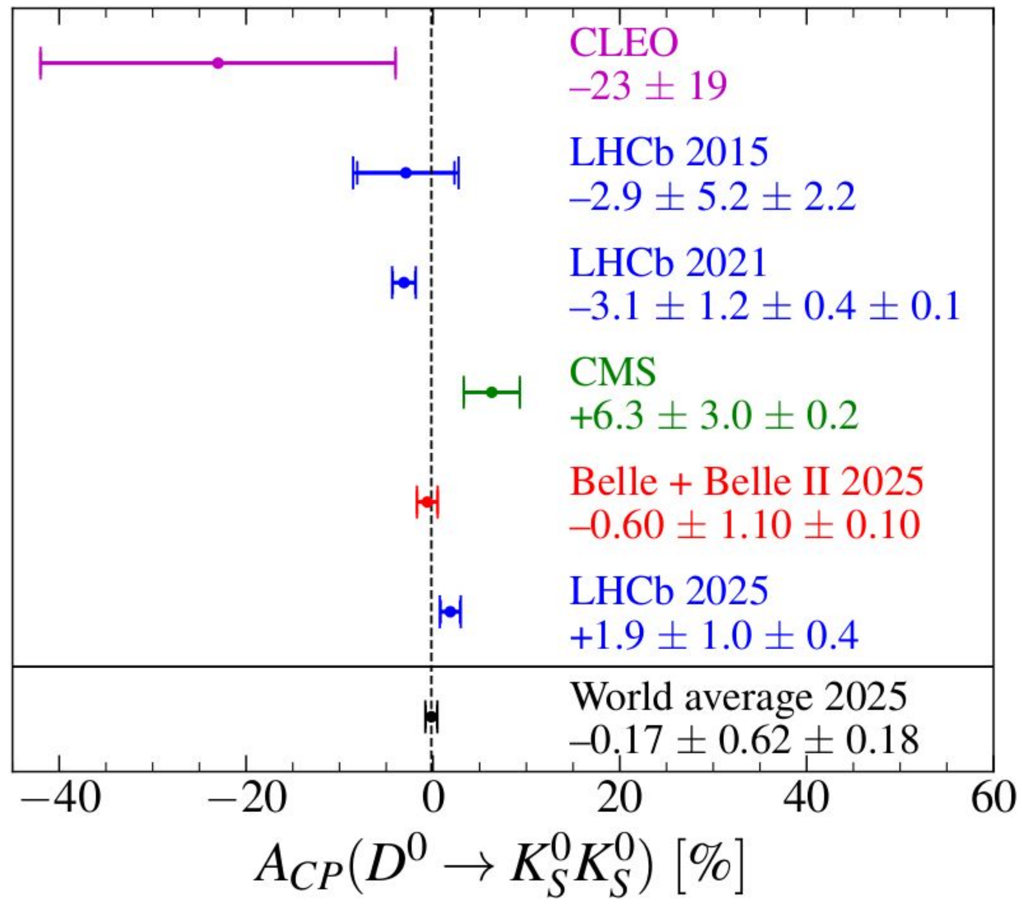
$\propto$ 1/SU(3) breaking size





- Conversely, some theory fits to data constrain the exchange contribution and predict small $A_{CP}(K_S^0 K_S^0) \simeq 0.35 \cdot A_{CP}(\pi^+\pi^-) = O(10^{-4})$ PRD 99(2019)113001

$A_{CP}(D^0 \rightarrow K_S^0 K_S^0)$



charm-fitter

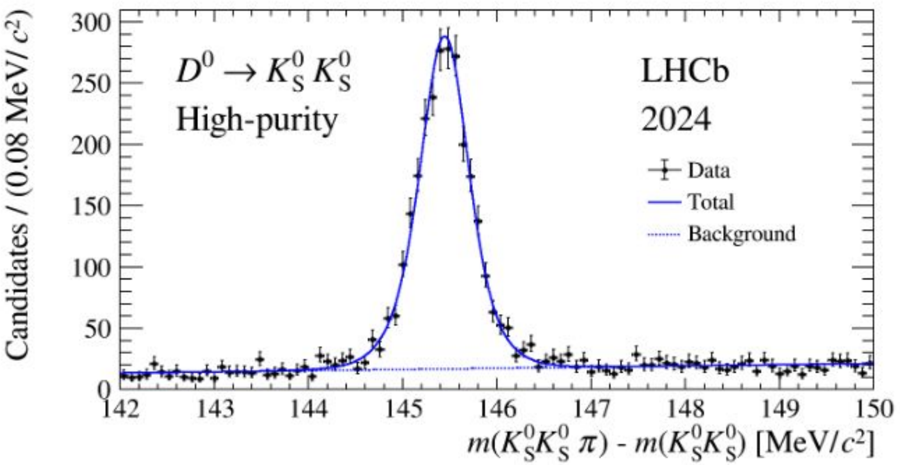
$A_{CP}(D^0 \to K_S^0 K_S^0)$

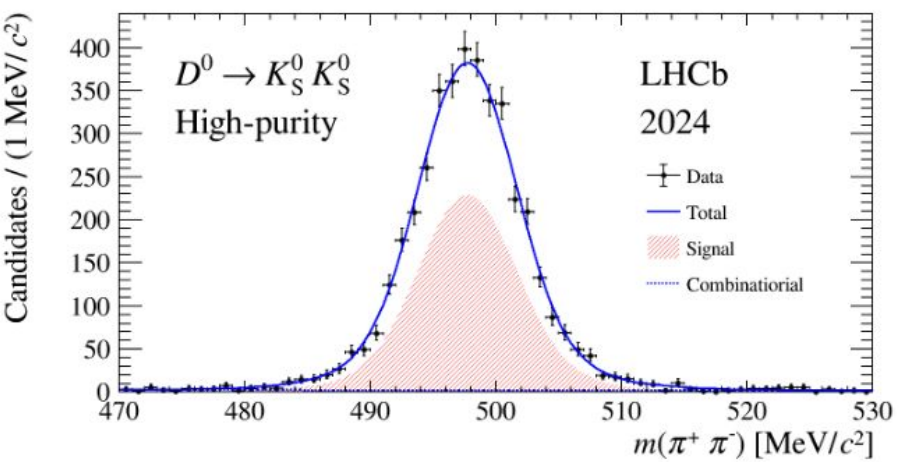
JHEP02(2026)253

❖ First LHCb result with 2024 data! Total signal yield: 15,676 ± 229

❖ → Largest existing D*-tag sample!

- ➢ LHCb Run 2 ~8000 candidates
- ➢ Belle ~4000 candidates
- ➢ Belle II ~2200 candidates
- ➢ CMS ~2000 candidates
- ➢ 19k non-D* sample collected by Belle and Belle II, but with much more background



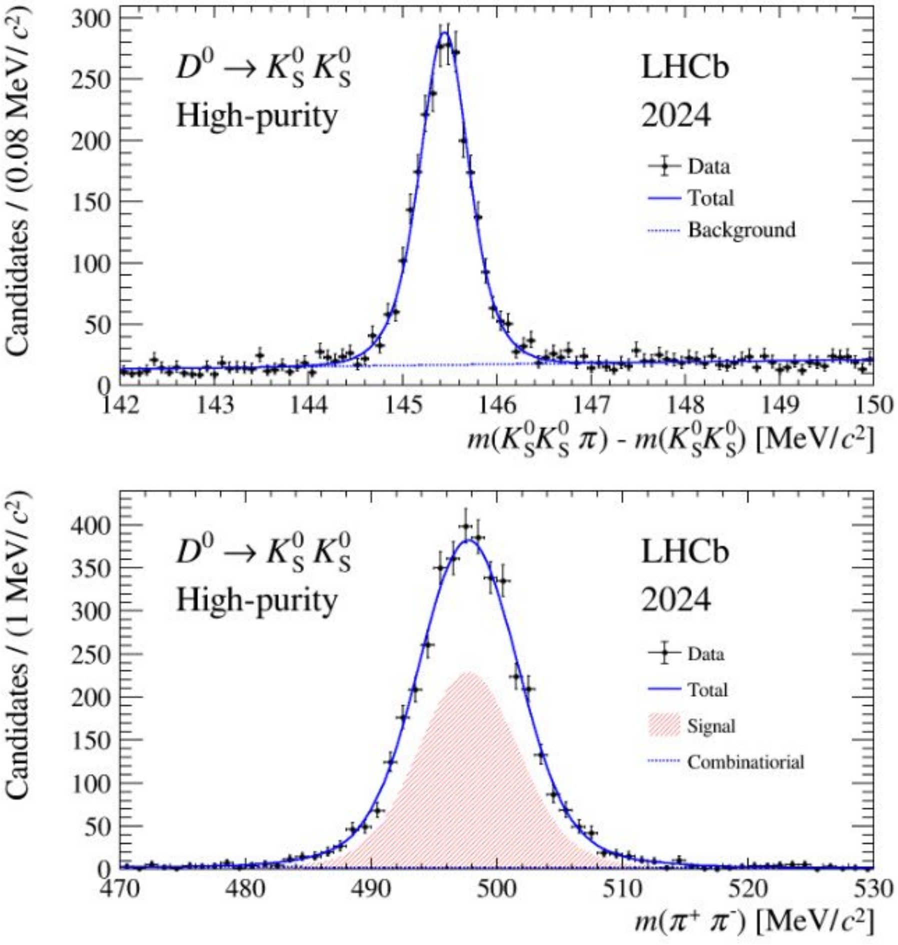


$A_{CP}(D^0 \rightarrow K_S^0 K_S^0)$

JHEP02(2026)253

- First LHCb result with 2024 data! Total signal yield: 15,676 ± 229

- LHCb Run2 : 5400 candidates ($6 fb^{-1}$) if considering only K_S^0 decaying in the VELO $\rightarrow$ **x3 efficiency gain (new trigger) with a x5 instantaneous luminosity**
  $\rightarrow$ **decays collected at rate ~15 times larger**



Conclusions

- Many new results on charm physics in the last years, but still a lot to explore
  - Hunting CPV in mixing
  - Need to clarify if the size of observed CPV in the decay is compatible or not with SM expectations
- Detectors and techniques are improving, much more data being collected → unprecedented precision can be now achieved
- Stay tuned for new results!

Backup slides

Time-dependent CPV: how to describe it?

- Two equivalent parameterizations:

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}$$

Phenomenological (PDG)

$$x = \frac{2(m_2 - m_1)}{\Gamma_1 + \Gamma_2}, \qquad y = \frac{\Gamma_2 - \Gamma_1}{\Gamma_2 + \Gamma_1},$$

$$\phi_{\lambda_f} \equiv \arg\left(-\frac{q}{p}\frac{\overline{A}_f}{A_f}\right) \qquad \left|\frac{q}{p}\right|$$

Theoretical (UTFit)

Kagan Silvestrini 2001.07207

$$x_{12} \equiv \frac{2|M_{12}|}{\Gamma}, \quad y_{12} \equiv \frac{|\Gamma_{12}|}{\Gamma}$$

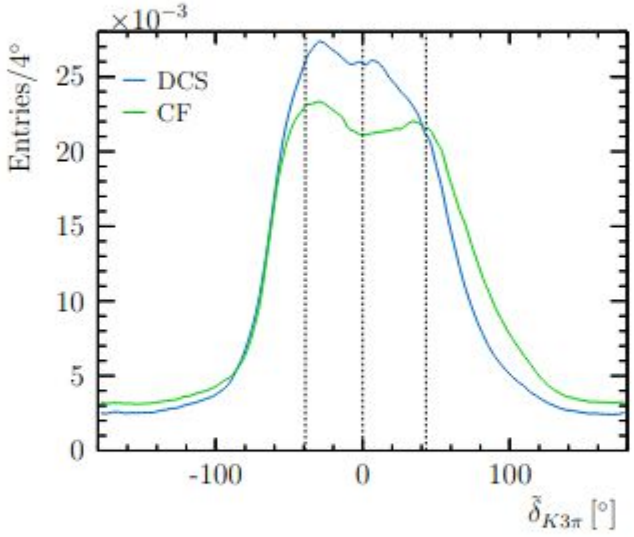
$$\phi_f^M \equiv \arg\left(M_{12}\frac{A_f}{\overline{A}_f}\right) \qquad \phi_f^\Gamma \equiv \arg\left(\Gamma_{12}\frac{A_f}{\overline{A}_f}\right)$$

Mixing and CPV in $D^0 \rightarrow K\pi\pi\pi$ @ LHCb

JHEP12 (2025)153

Phase-space bin	$r_{(i)}$ ($\times 10^{-2}$)	$\kappa_{(i)}$	$\delta_{(i)}$ ($^\circ$)
Inclusive	5.49 ± 0.02	$0.430\,^{+0.043}_{-0.039}$	$163.3\,^{+13.8}_{-14.8}$
Bin 1	5.68 ± 0.04	$0.598\,^{+0.106}_{-0.088}$	$123.8\,^{+13.3}_{-10.7}$
Bin 2	5.98 ± 0.04	$0.777\,^{+0.073}_{-0.064}$	$149.7\,^{+11.1}_{-10.8}$
Bin 3	5.82 ± 0.04	$0.663\,^{+0.091}_{-0.087}$	$196.3\,^{+8.7}_{-11.2}$
Bin 4	4.64 ± 0.05	$0.075\,^{+0.108}_{-0.049}$	$319.3\,^{+82.5}_{-58.3}$

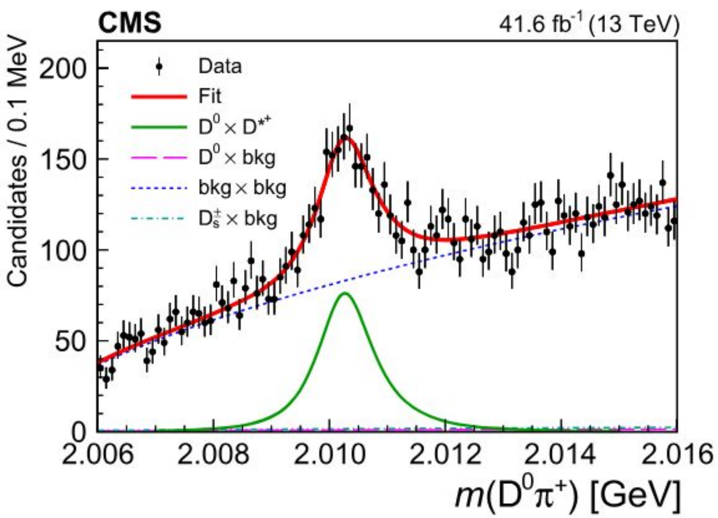
PLB 802 (2020) 135188

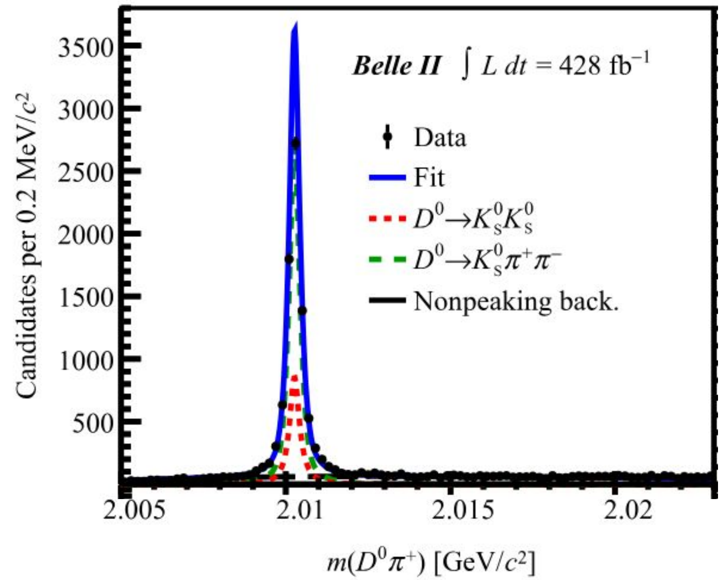


$A_{CP}(D^0 \to K_S{}^0 K_S{}^0)$

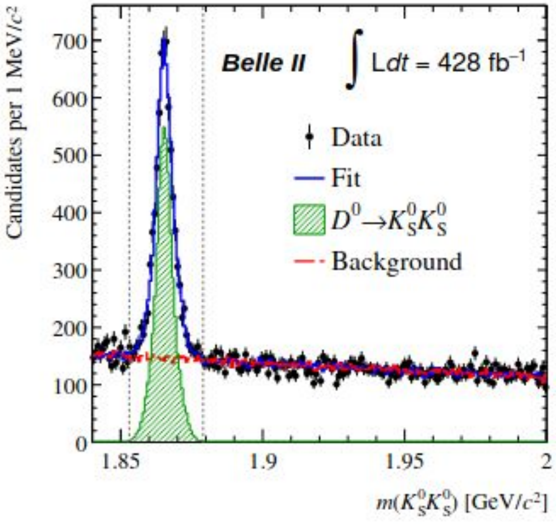
PRD 111, 012015 (2025)

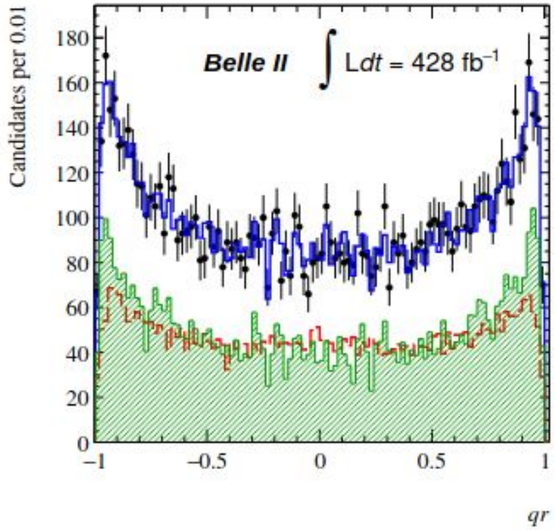
EPJC s10052-024-13244





PRD 112, 012017 (2025)

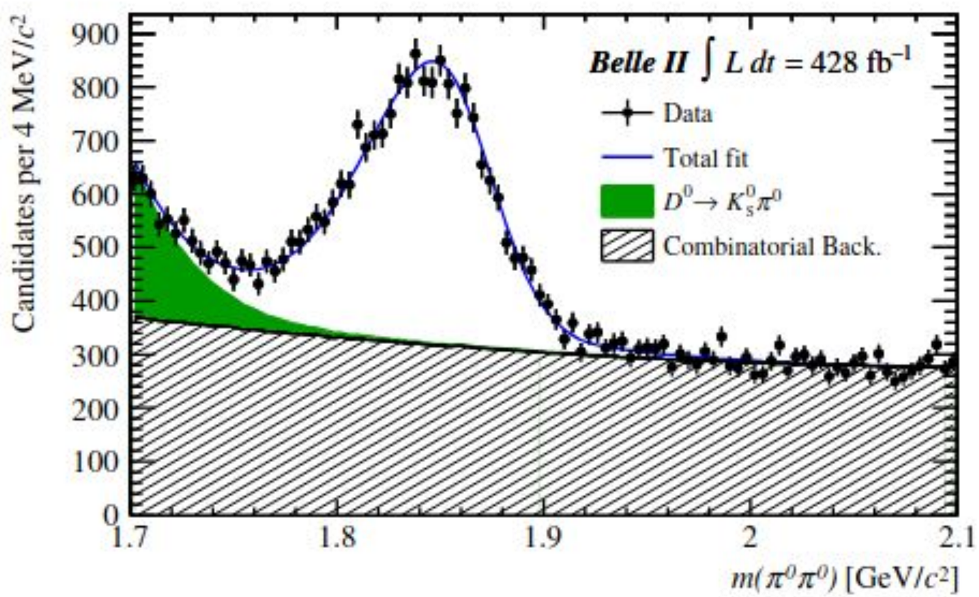




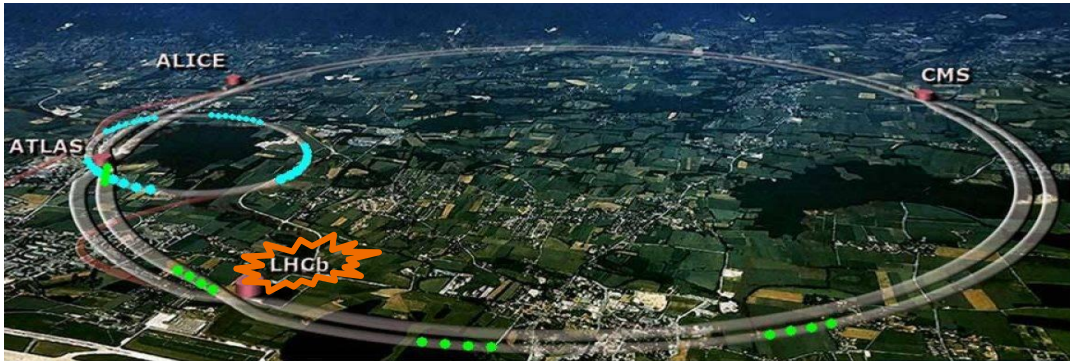
$A_{CP}(D^0 \rightarrow \pi^0\pi^0)$ @ Belle II

PRD 112, 012006 (2025)

- Isospin relation to $D^0 \rightarrow \pi^+\pi^-$ implies $A_{CP}(D^0 \rightarrow \pi^0\pi^0) \sim O(10^{-3})$ in SM
  EPJC 83, 279 (2023)
- Result at Belle II (428 fb^{-1}): ACP $(D^0 \rightarrow \pi^0\pi^0) = (+0.30 \pm 0.72 \pm 0.20)\%$
  - ➢ improved precision per luminosity w.r.t. Belle



LHC: a charm factory



- **LHCb**: forward spectrometer designed to study *b*- and *c*-hadrons
- In LHCb acceptance: JHEP 03(2016)159
  - $\sigma(pp \to c\bar{c}X) \sim 2.4$ mb ($\sqrt{s} = 13$ TeV)
  - $\sigma(pp \to b\bar{b}X) \sim 0.1$mb ($\sqrt{s} = 13$ TeV)
- Data needs to be properly saved on disk → trigger
  - ~1 billion D^0 decays collected in Run 1 + Run 2

10^6 $c\bar{c}$ pairs per second in Run 2

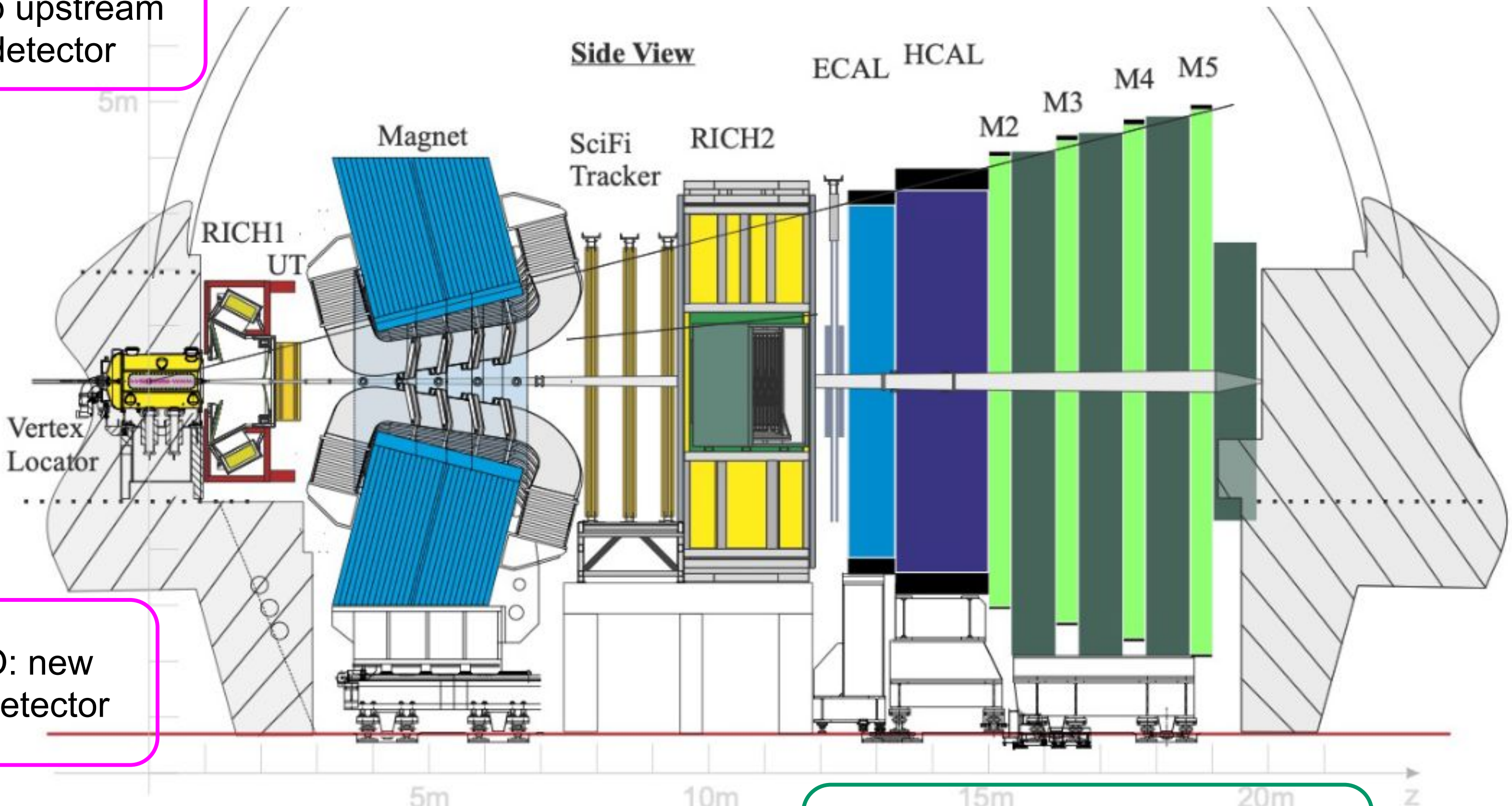
LHCb in Run 3

[JINST 19P05065]

UT: new silicon strip upstream detector

SciFi: new scintillating fibres downstream detector

RICH: new mechanics, optics, photodetectors



VELO: new pixel detector

New frontend electronics and new DAQ for all sub-detectors!