Search for time-dependent CP violation in $D^0 \to \pi^+\pi^-\pi^0$ decays

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Time-dependent CP violation in D^0 decays

- Charm hadrons: only probe of CPV in up-type quarks
  - Time-dependent CPV elusive so far [Phys. Rev. D 104, 072010 (2021), Phys. Rev. D 101, 012005 (2020)]
- Time-dependent CP asymmetry given by [Phys. Rev. D 91, 094032 (2015)]:

$$A_{CP}^{f}(t) = \frac{\Gamma_{D^0\to f}(t) - \Gamma_{\bar{D}^0\to f}(t)}{\Gamma_{D^0\to f}(t) + \Gamma_{\bar{D}^0\to f}(t)} \approx a_{\text{dir}}^{f} + \Delta Y_{f}^{(eff)} \frac{t}{\tau_{D^0}}$$

CP-even fraction

$$\Delta Y_{f}^{eff} \approx (2F_{f}^{+} - 1)\left\{ x\sin\phi - \left(\left|\frac{q}{p}\right| - 1 \right) y \right\}$$

(Neglecting direct CPV)

Usual definitions ($|D_1\rangle \approx$ CP-even):

$$|D_{1,2}\rangle = p\,|D^0\rangle \mp q\,|\bar{D}^0\rangle$$
$$x = (m_1 - m_2)/\Gamma$$
$$y = (\Gamma_1 - \Gamma_2)/2\Gamma$$
$$\phi = \arg(q/p)$$

- $D^0 \to \pi^+\pi^-\pi^0$ almost entirely CP-even ⇒ almost optimal sensitivity in PHSP integrated measurement [Phys. Lett. B 747, 9 (2015)]:

$$F^{+}_{\pi^+\pi^-\pi^0} = 0.973 \pm 0.017$$

- World average of previous measurements [Phys. Rev. D107, 052008]:

$$\left(\frac{\Delta Y_{f}^{\text{eff}}}{|2F_{f}^{+} - 1|} = \Delta Y \approx -A_{\Gamma} \right)$$

$$-\Delta Y \approx A_{\Gamma} = (0.9 \pm 1.1) \times 10^{-4}$$

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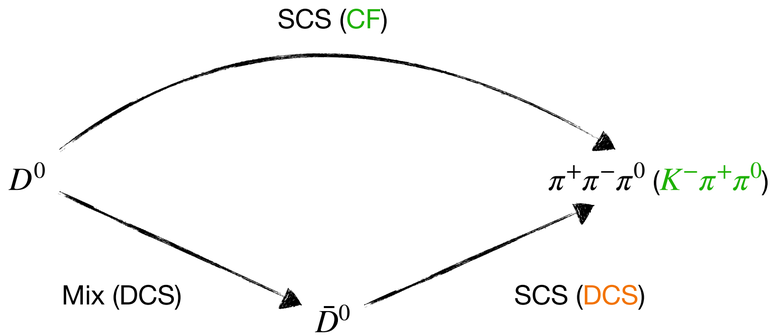
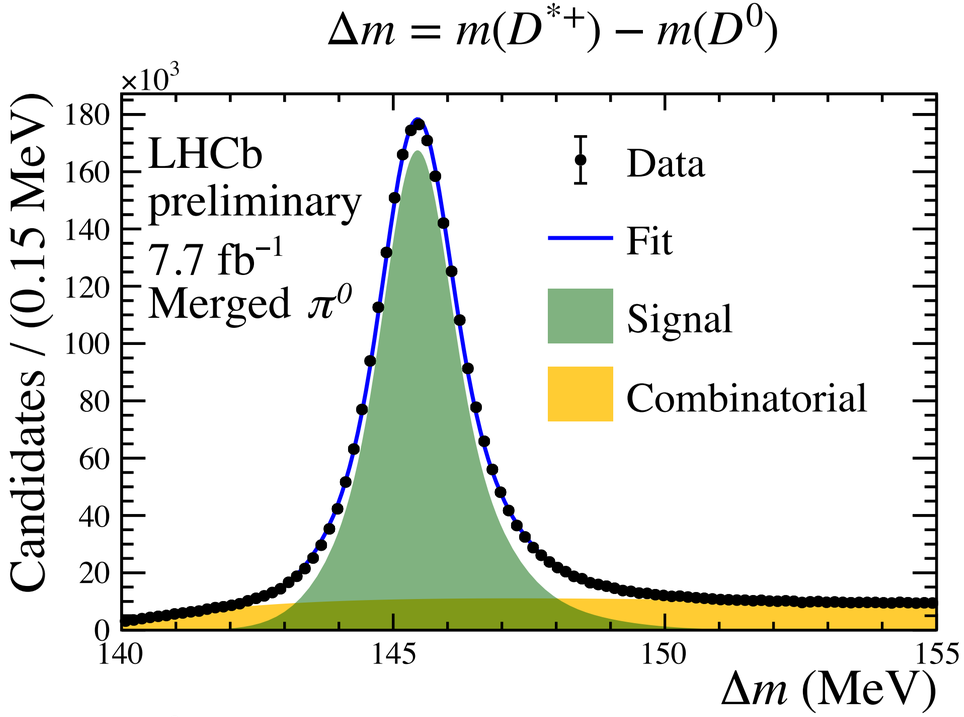
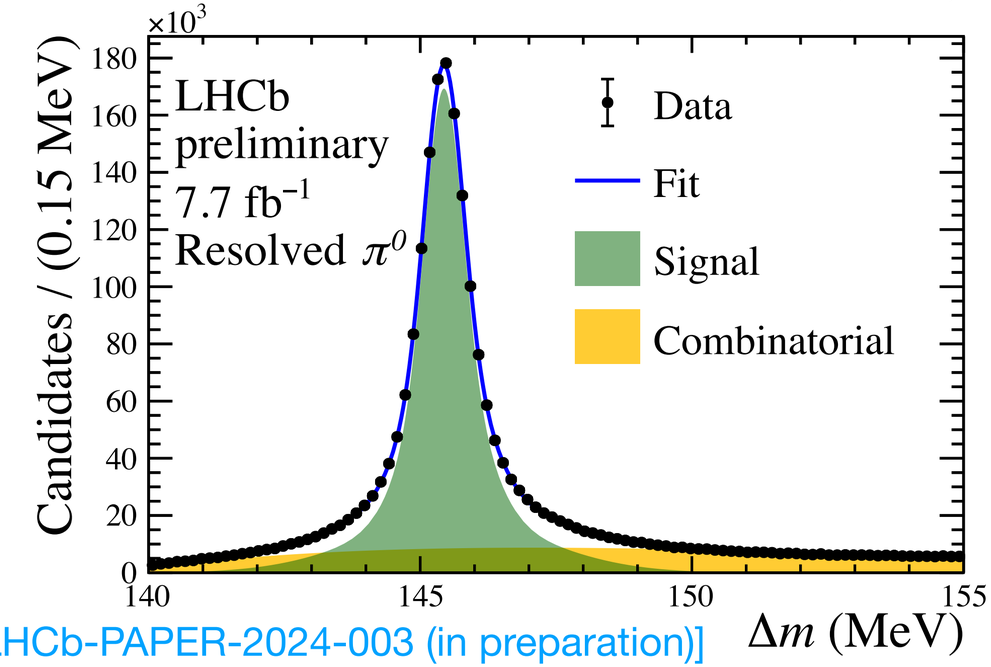
- **Control channel: CF** $D^0 \to K^-\pi^+\pi^0$
  - $|\Delta Y_{K\pi\pi}| < 2.5 \times 10^{-5}$@ 90% CL



Datasets and selections

- Dataset: $7.7\ \text{fb}^{-1}$ collected in 2012 and 2015-18 @ 8,13 TeV
- Studying prompt decays: $D^{*+} \to D^0(\to h^-\pi^+\pi^0)\,\pi^+_{\text{tag}}$ ← Tag $D^0/\bar{D}^0$ flavour at production
- **Merged** and **resolved** $\pi^0(\to\gamma\gamma)$ decays analysed separately
  - Merged: photon clusters overlap
  - Resolved: two distinct photon clusters
- Physics backgrounds removed by cut-based selection
  - D^{*+} from displaced b-hadron decay
  - $D^0 \to K^-\pi^+\pi^0$, $K^- \to \pi^-$ mis-ID
  - $D^0 \to K^0_S(\to\pi^+\pi^-)\pi^0$
- Combinatorial backgrounds suppressed by BDT
- Final yields: 2.3M merged and 1.5M resolved, ~87% purity ($\pm 2\sigma$)





[LHCb-PAPER-2024-003 (in preparation)]

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Correction of nuisance asymmetries

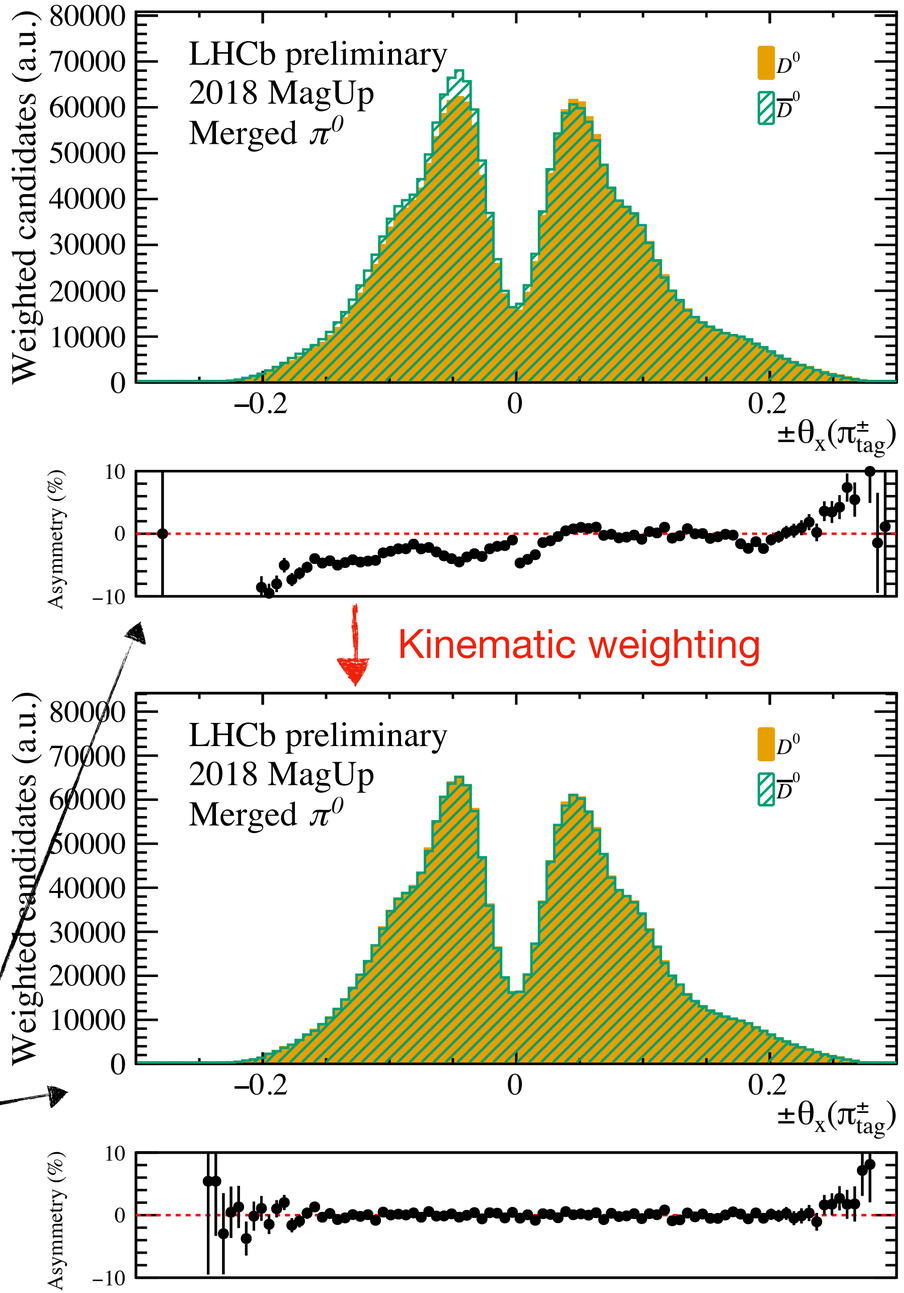
- Selection requirements induce correlations between kinematics/ decay time
  - Kinematic-dependent detection asymmetries ⇒ time-dependent nuisance asymmetry
  - Primarily affects $\pi^{\pm}_{\text{tag}}$: deflected in opposite directions, detector not perfectly symmetric
  - K^+/K^- (and π^+/π^-) asymmetries can produce $D^0/\bar{D}^0$ kinematic asymmetries
- Data-driven correction procedure
  - Weights calculated to equalise binned opposite-tag distributions:

Track curvature

$$\theta_{x/y}(\pi^{\pm}_{\text{tag}}) = \arctan\left(\frac{p_{x/y}}{p_z}\right), \quad k(\pi^{\pm}_{\text{tag}}) = \frac{1}{\sqrt{p_x^2 + p_y^2}}, \quad \eta(D^0), \quad \eta(\pi^{\pm}_{\text{tag}}), \quad \text{and } p_T(D^0)$$

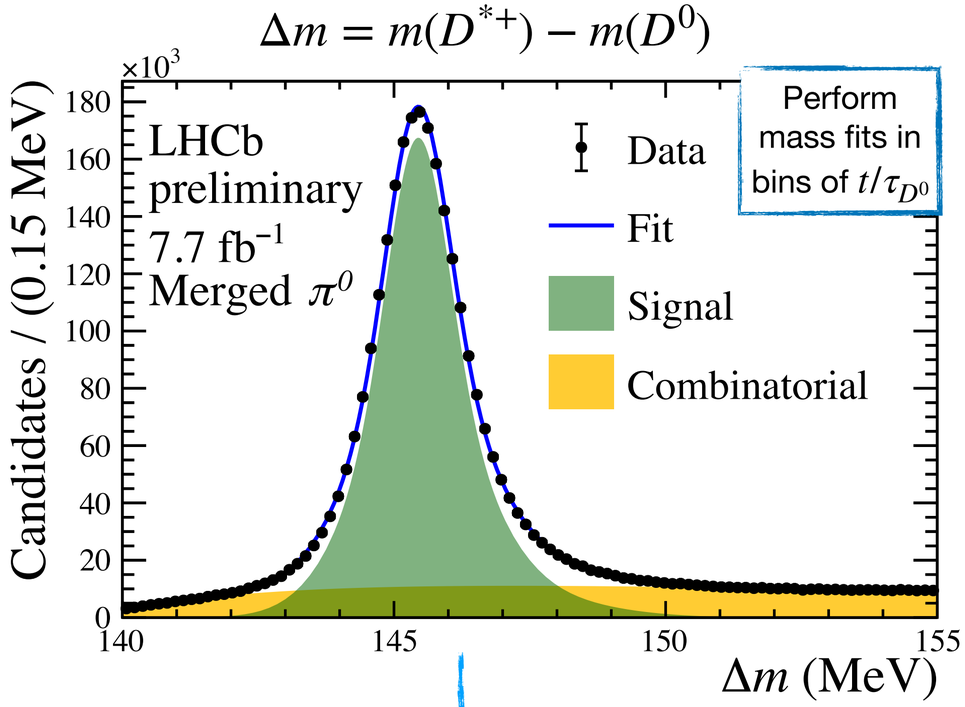
Track projection angles

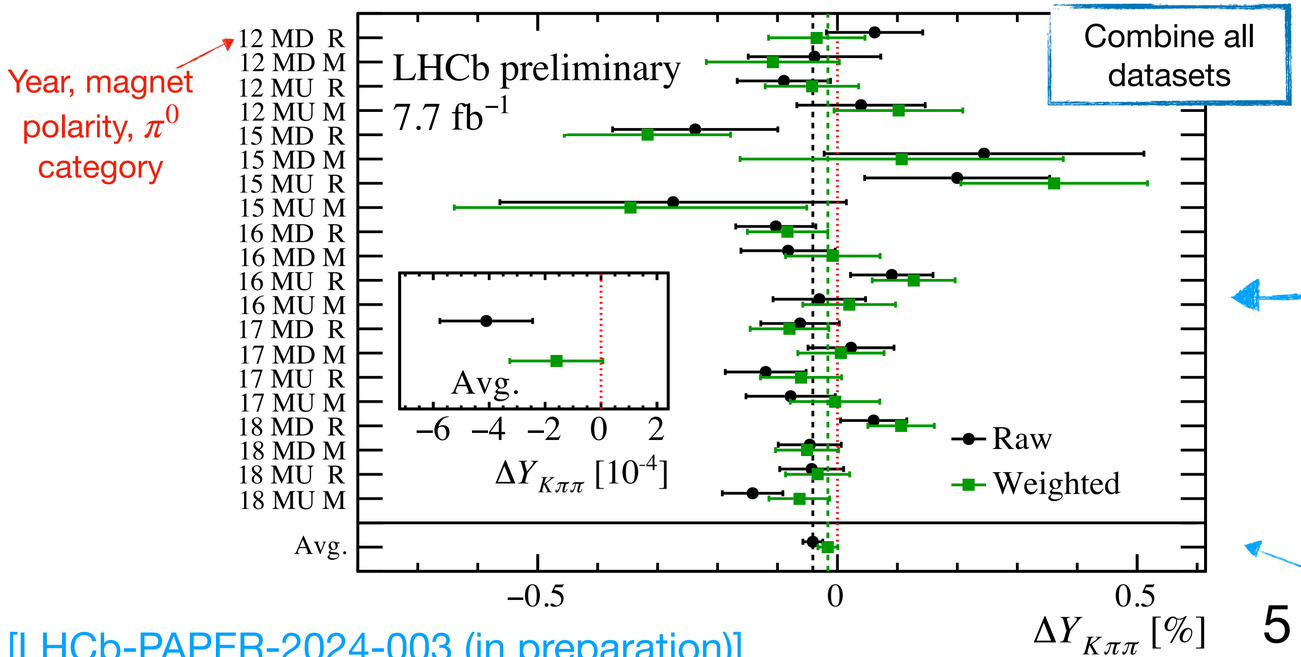
$D^0 \to K^-\pi^+\pi^0$ data

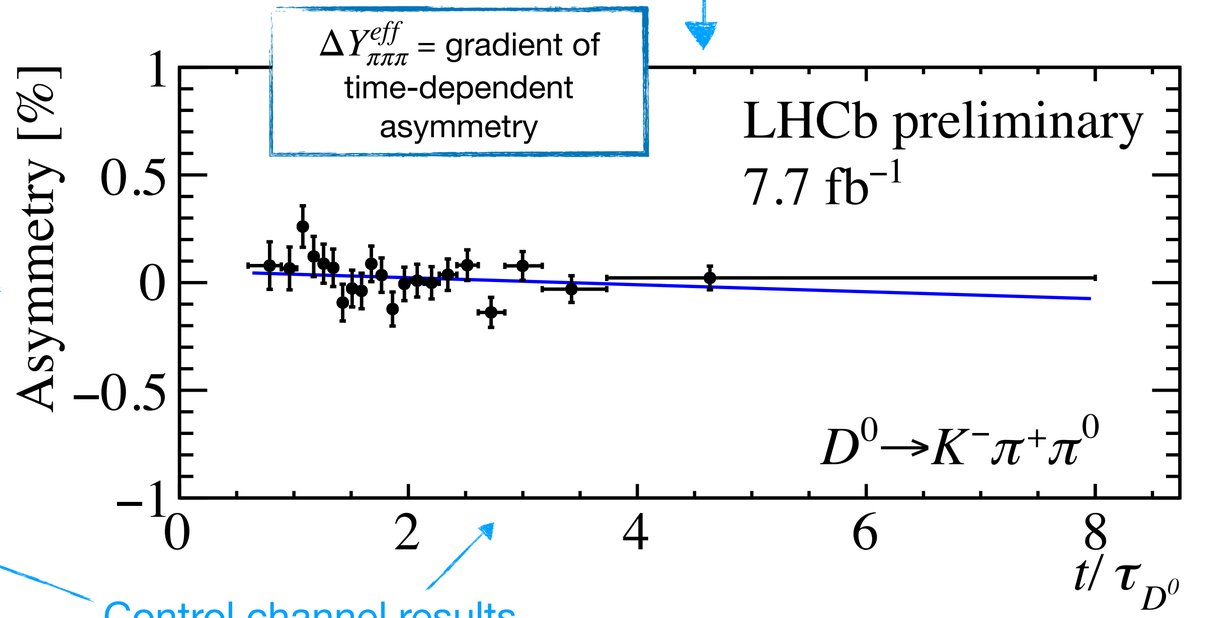


Measurement of ΔY

- Fit Δm in bins of t/τ_{D^0} to extract $A_{\mathrm{CP}}(t)$
  - Simultaneously for $D^0/\bar{D}^0$ with shared shape parameters
  - Real D^0 with random tag pion do not peak in Δm
- Linear fit to $A_{\mathrm{CP}}(t)$ to extract ΔY, per-year/polarity/π^0 category
  - Control channel: $\Delta Y_{K\pi\pi} = (-1.7 \pm 1.8\,(\mathrm{stat.}) \pm 3.5\,(\mathrm{syst.})) \times 10^{-4}$







Control channel results

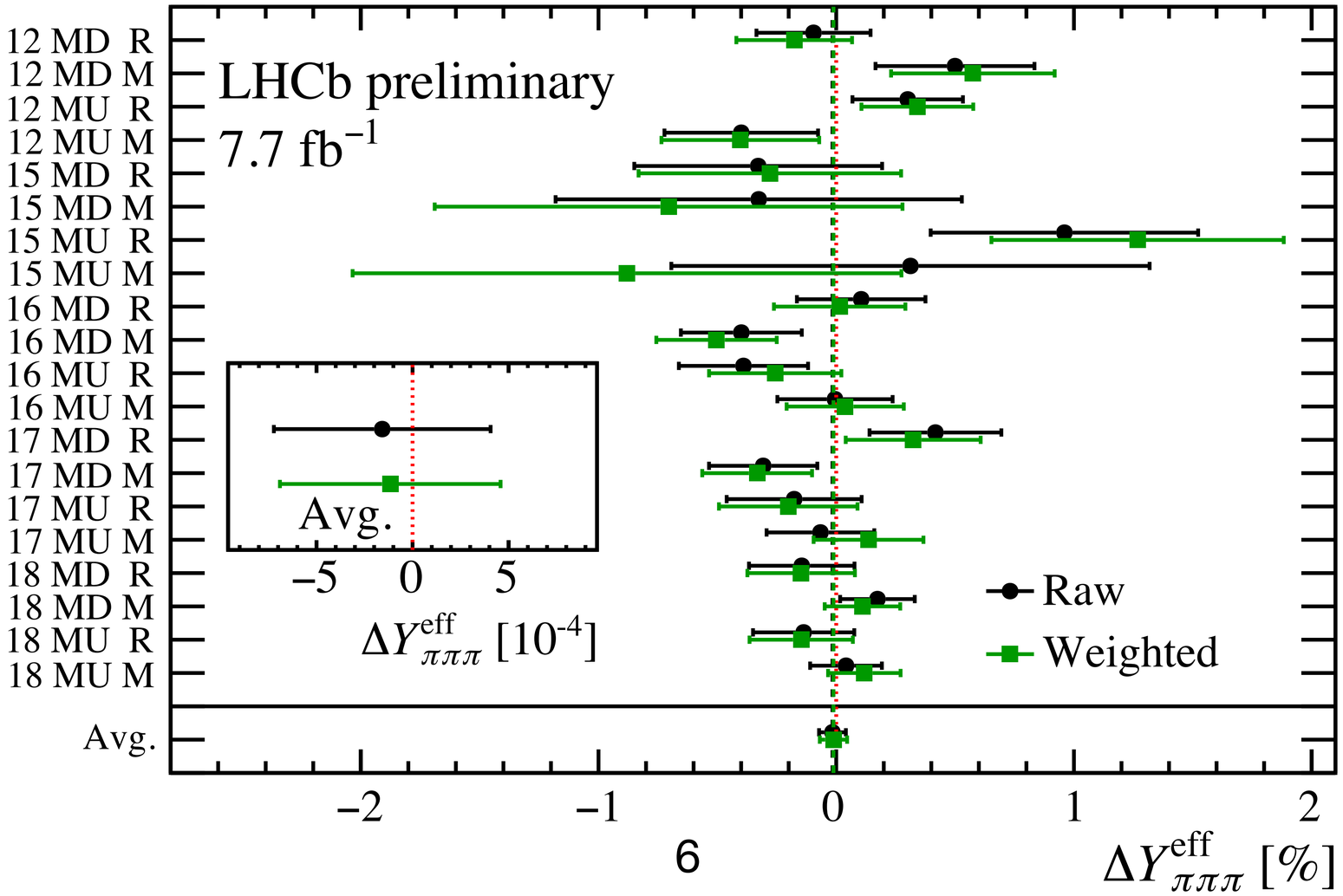
[LHCb-PAPER-2024-003 (in preparation)]

Final results

[LHCb-PAPER-2024-003 (in preparation)]

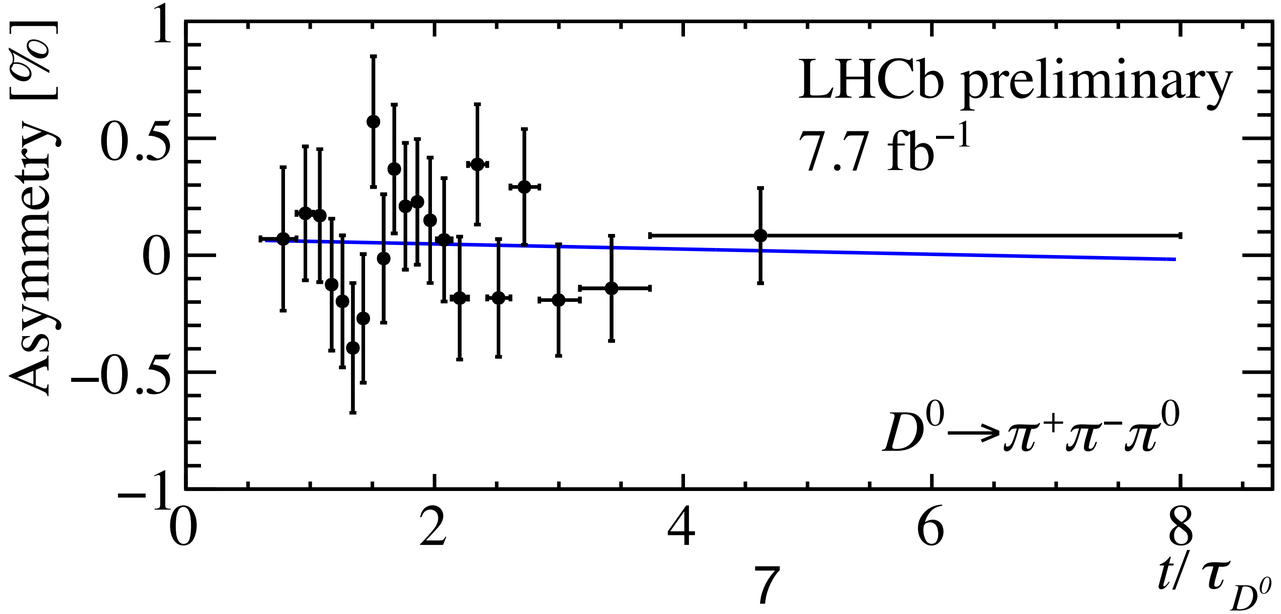
$$\Delta Y^{\text{eff}}_{\pi\pi\pi} = (-1.2 \pm 6.0\,(\text{stat.}) \pm 2.3\,(\text{syst.})) \times 10^{-4}$$

$$\Rightarrow \Delta Y = (-1.3 \pm 6.3\,(\text{stat.}) \pm 2.4\,(\text{syst.})) \times 10^{-4}$$



Conclusions

- Full Run 1 + 2 search for time-dependent CP violation with $D^0 \to \pi^+\pi^-\pi^0$ decays
  - $\Delta Y = (-1.3 \pm 6.3\,(\text{stat.}) \pm 2.4\,(\text{syst.})) \times 10^{-4}$
  - Consistent with no CP violation and compatible with world average
  - First measurement of time-dependent CPV in a D^0 decay with a neutral pion at a hadron collider*
- Not competitive with world average: proof-of-principle for future universality tests
- LHCb-PAPER-2024-003 coming soon!

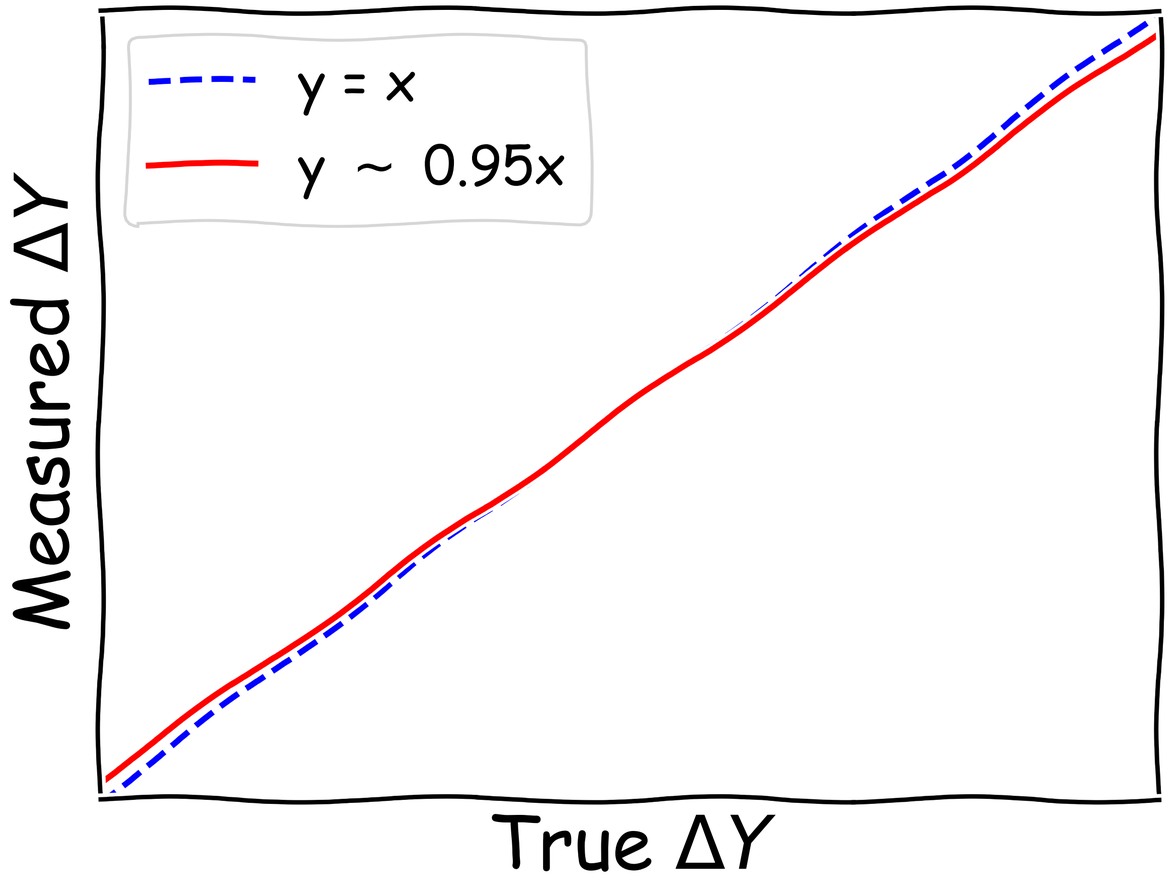


*and at all except [Phys. Rev. Lett. 97, 221803 (2006)]

Backup

Kinematic weighting dilution

- Time-dependent asymmetry + decay time/kinematic correlations ⇒ kinematic asymmetry
  - Removed by kinematic weighting ⇒ slight dilution of measured ΔY
- Studied with pseudo-experiments
  - $\sim 5\,\%$ dilution observed
  - Correction factor applied to final result



Systematic uncertainties

Kinematic-dependent $K^-\pi^+/\pi^+\pi^-$ detection asymmetries

Vary decay-time binning scheme (conservative approach)

Residual contamination from D^{*+} originating from b-hadron decays

Pseudo-experiments using alternative Δm model

Vary kinematic weighting binning scheme

Source	$\Delta Y^{\text{eff}}_{\pi\pi\pi}$ (10^{-4})	$\Delta Y_{K\pi\pi}$ (10^{-4})
Detection asymmetries	1.6	3.4
t/τ_{D^0} binning	1.0	0.14
Secondary contamination	0.84	0.84
Δm fit model	0.75	0.08
Kinematic weighting	0.22	0.22
Total	2.3	3.5

Kinematic-dependent $K^-\pi^+/\pi^+\pi^-$ detection asymmetries

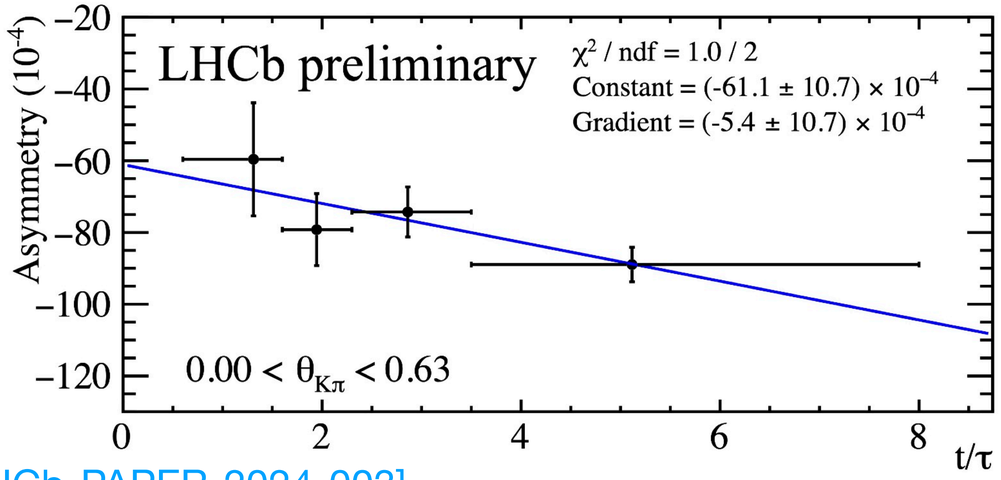
- Largest systematic from kinematic-dependent kaon/pion detection asymmetries
  - Measured using a set of calibration decays:

$$A_{\text{det}}^{\pi\pi} = A_{D_{(s)}^+\to\pi^+\pi^-\pi^+} - A_{D_{(s)}^+\to\phi(\to K^+K^-)\pi^+}$$

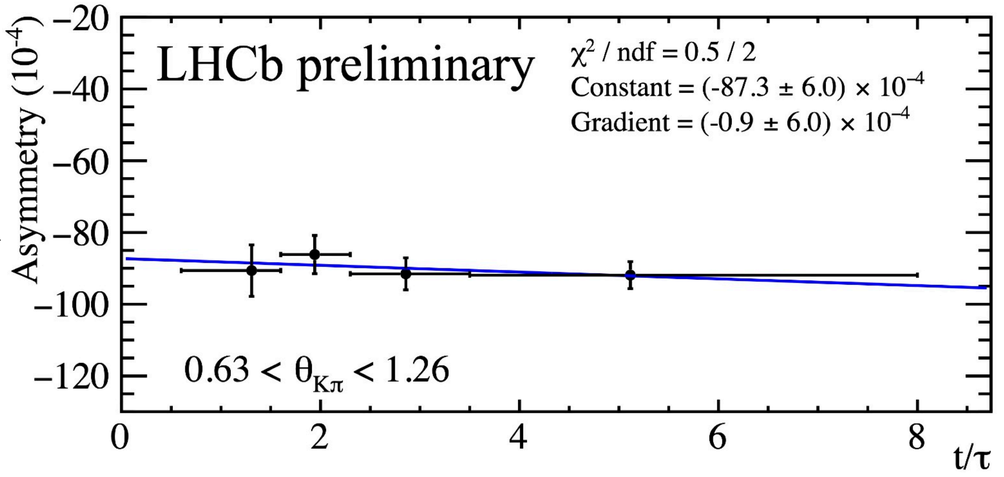
$$A_{\text{det}}^{K\pi} = A_{D^+\to K^-\pi^+\pi^+} - A_{D^+\to\phi(\to K^+K^-)\pi^+}$$

All compatible with no CP asymmetry [PDG 2022] at typical size of detection asymmetries

- Calibration decay kinematics weighted to agree with signal/control modes
- Measured (time-dependent) asymmetry maps used for a set of pseudo-experiments



Example asymmetry maps



[LHCb-PAPER-2024-003]