Charm hadrons production and decay properties

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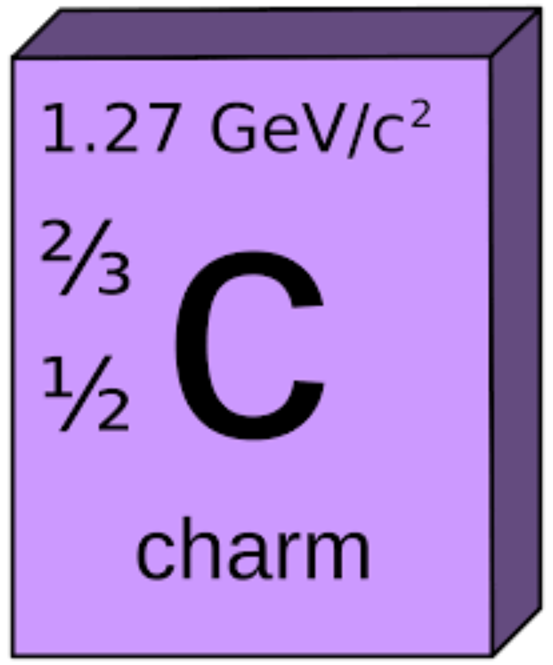


Charm Physics: Why?

- Charmed hadrons are composed of up-like quark → Complementary studies to bottom and strange hadrons
- Heavy quark with the lowest mass → Powerful probe for non-perturbative QCD effects
- Difficult theoretical predictions in charm physics due to large QCD corrections → Input from experimental side for validation of theoretical models

LHCb is the perfect environment to study charm physics thanks to the geometry of the detector

- Recent discovery of CP violation in charm decays in 2019 at LHCb [Phys. Rev. Lett. 122, 211803]
- LHCb has observed and measured properties of plenty of new state of charm hadrons

Recent Results at LHCb

From Run 2:

Measurement of the Ω_c^0 and Ξ_c^0 baryon lifetimes using hadronic b-baryon decays [2506.13334]

From Run 3:

Measurements of charmed meson and antimeson production asymmetry at $\sqrt{s} = 13.6$ TeV [2505.14494]

Other recent Run 2 results that will not be covered in this talk

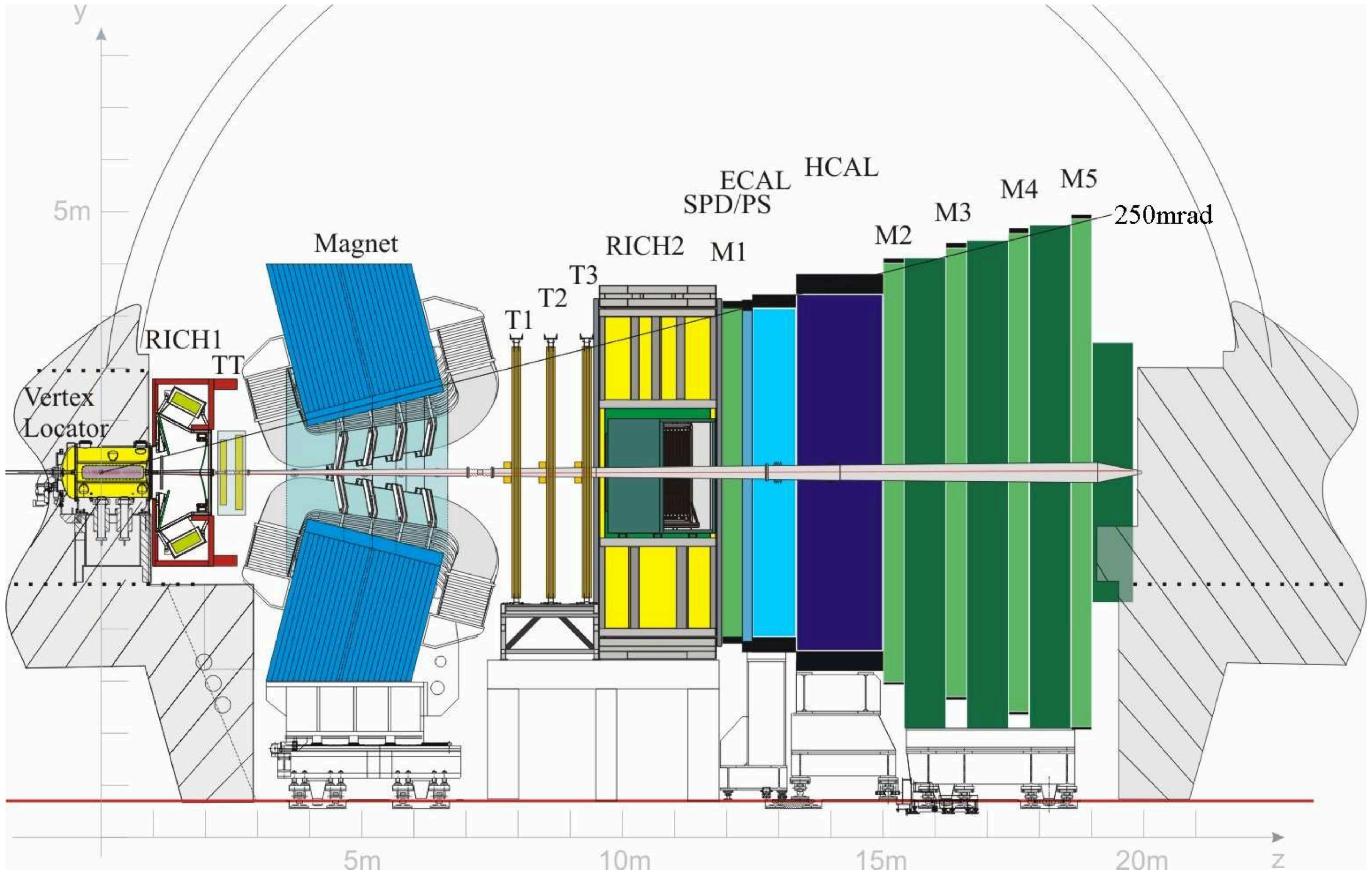
Observation of the doubly-charmed-baryon decay $\Xi_c^{++} \rightarrow \Xi_c^0\pi^+\pi^+$ [2504.05063]

Observation of a new charmed baryon decaying to $\Xi_c^+\pi^-\pi^+$ [2502.18987]

The LHCb Experiment

[2008 JINST 3 S08005]

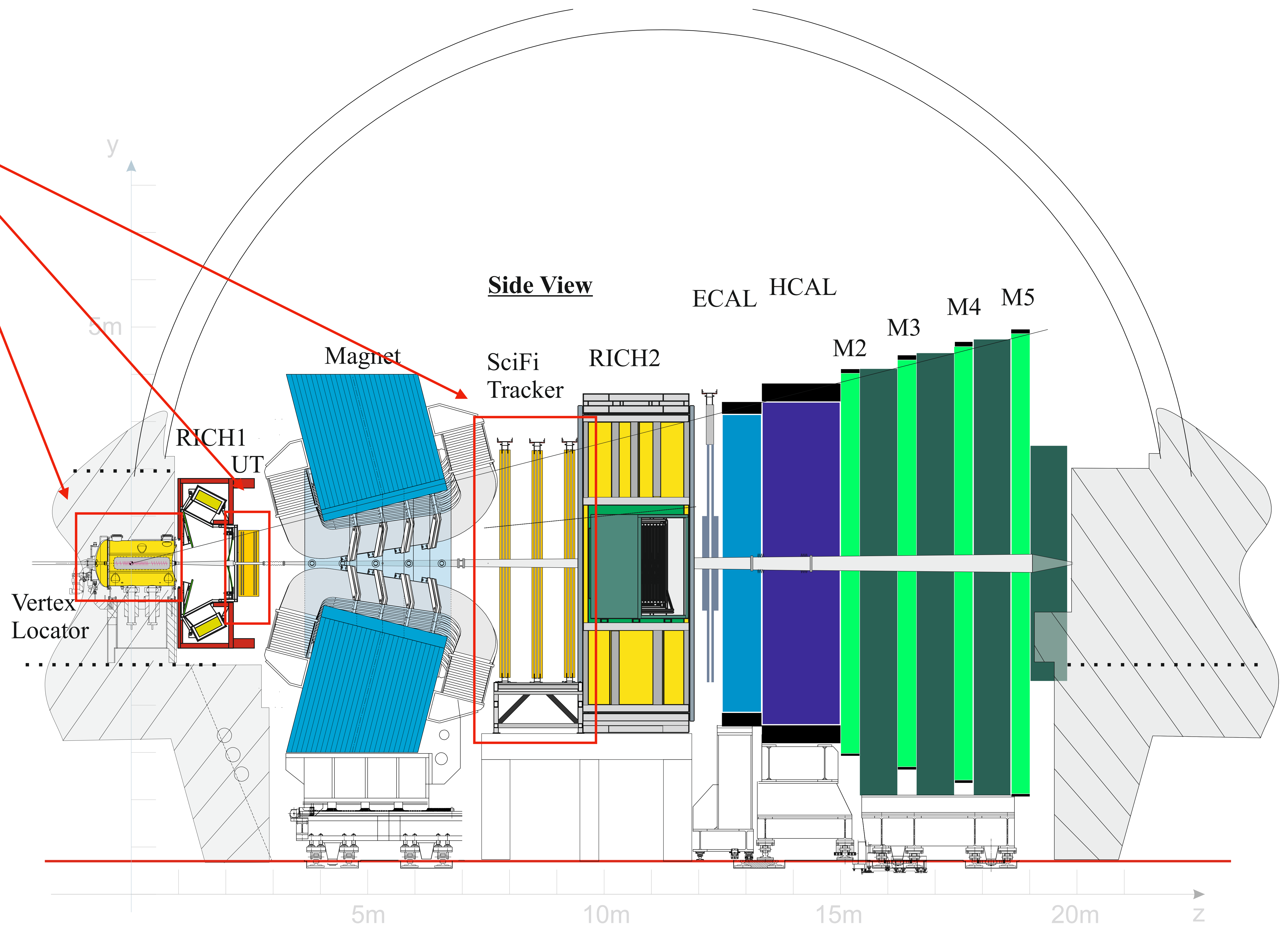
- Forward spectrometer at LHC
- $< 0.8\,\%$ momentum resolution in $[5{,}100]$ GeV/c range
- Excellent particle identification thanks to RICH detectors, calorimeters and muon chambers
- Collected data during Run 1 and 2 of LHC
- Combination of hardware and software trigger
- Focus on b-hadrons and c-hadrons physics



LHCb in Run 3

[JINST 19 (2024) P05065]

- New tracking sub-detectors (UT not present in 2022, not active in 2023)
- Upgraded RICH readout system
- Upgraded calorimeter and muon chamber electronics
- Full software trigger
- Energy of centre-of-mass $\sqrt{s} = 13.6$ TeV



Measurement of the Ω_c^0 and Ξ_c^0 baryon lifetimes using hadronic b-baryon decays

[2506.13334]

Goal of the analysis

[2506.13334]

- Measurement of charm hadrons lifetime can shed light on the theoretical framework employed to compute these quantities
- Recent measurements of the charm baryon Ω_c^0 lifetime from LHCb are in tension with previous average [Phys. Rev. Lett. 121, 092003, Science Bulletin 67 (2022)]
- Similarly, recent Ξ_c^0 lifetime estimates are in tension with previous results [Phys. Rev. D100 (2019) 032001, Science Bulletin 67 (2022)]
- These measurements provide information on the lifetime hierarchy

↓

Need to further investigate the lifetime of these baryons

Strategy of the analysis

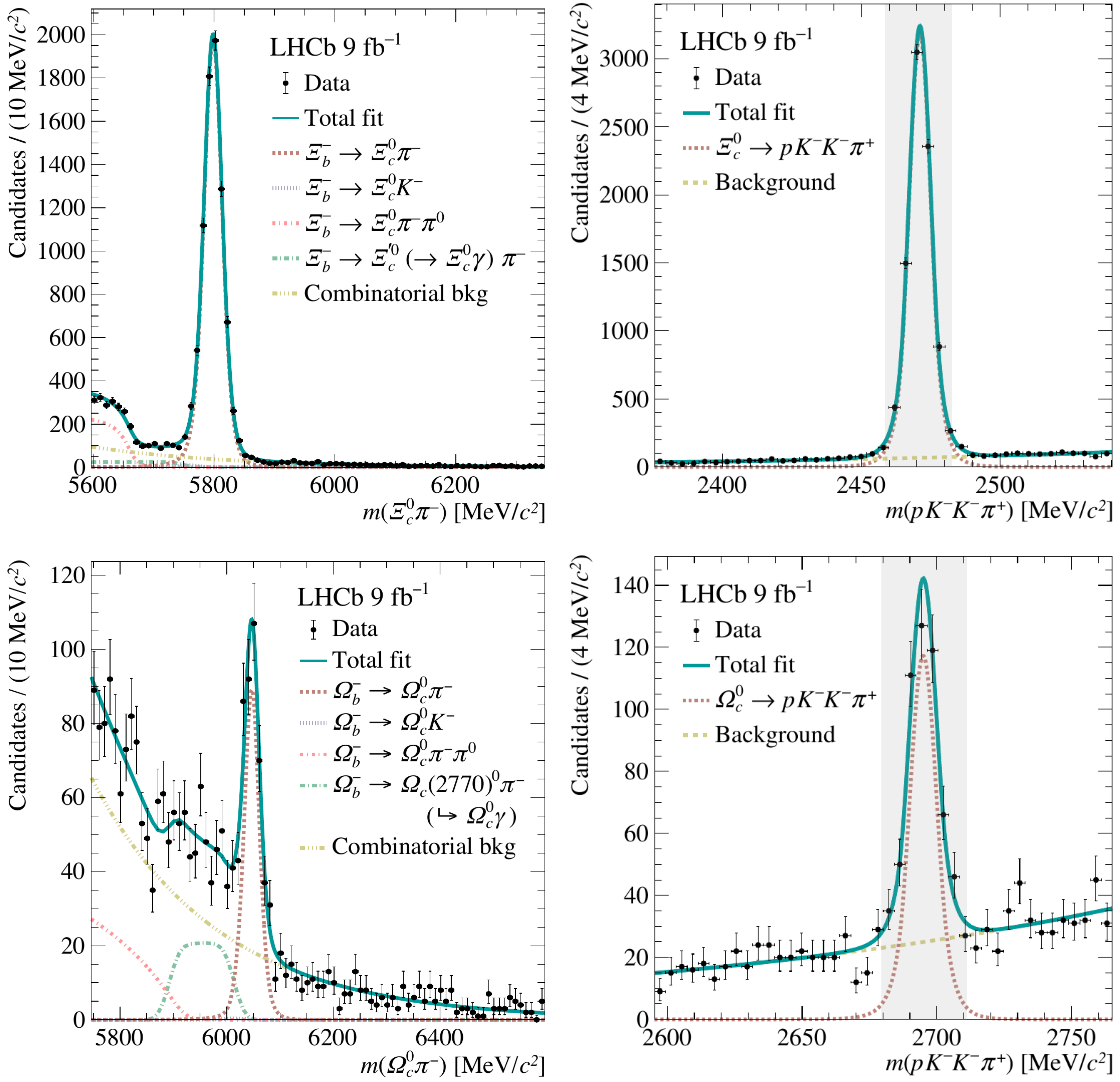
[2506.13334]

- Charm baryons produced from b-baryons i.e. $\Omega_b^- \to \Omega_c^0(\to pK^-K^-\pi^+)\pi^-$ and $\Xi_b^- \to \Xi_c^0(\to pK^-K^-\pi^+)\pi^-$
- Data collected at LHCb in pp collisions at $\sqrt{s} = 7,\ 8$ and $13\ \text{TeV}$ during 2011, 2012 and 2015-2018 with $\mathscr{L} = 9\ \text{fb}^{-1}$
- The topologically and kinematically similar $B^- \to D^0(\to K^-K^+\pi^-\pi^+)\pi^-$ decay is employed for normalization
- Data are first selected with the LHCb trigger, and then further filtered with a BDT
  - Signal proxy: simulated events, background proxy: invariant mass sideband
  - Optimal cut on the BDT variable is chosen with the figure of merit: $S_0\epsilon_s/\sqrt{S_0\epsilon_s + B}$
  - Tighter cut is applied to the normalization channel to have a purer sample
  - Training and optimization is performed independently for 2011-2012 data and 2015-2018
- After the selection, invariant mass fits are performed to separate signal and background
- The lifetime is measured with ratio between signal channel and normalization channel

Fits to the invariant mass spectra

- Unbinned maximum likelihood performed on b-baryon spectra for better discrimination to other charm baryon background
- Fits performed with Gaussian + Double Sided Crystal Ball with tail parameters fixed from simulation
- Partially reconstructed backgrounds and mis-identified backgrounds are modeled with all shape parameters fixed from simulation
- Similar fits are performed on normalization channel with two different selections on decay time to match the range of decay time in the signal sample
- Signal yield of Ω_c^0: 355 ± 26
- Signal yield of Ξ_c^0: 8260 ± 100

[2506.13334]



Lifetime measurement

[2506.13334]

- Lifetime is extracted from least-squares fit to the ratio of yields in bins of decay time
- For each bin the ratio is modeled as

Acceptance functions

Resolution functions

$$r_i \equiv \frac{\int_{t_i}^{t_{i+1}} A_{\Omega_c^0,\Xi_c^0}(t) \cdot \left(e^{-t/\tau_{\Omega_c^0,\Xi_c^0}} * R_{\Omega_c^0,\Xi_c^0}(t)\right) dt}{\int_{t_i}^{t_{i+1}} A_{D^0}(t) \cdot \left(e^{-t/\tau_{D^0}} * R_{D^0}(t)\right) dt}$$

- Decay time resolution functions are modeled as three gaussians with effective resolutions of 83 fs (Ω_c^0) and 101 fs (Ξ_c^0)
- Decay time acceptance functions are modeled as sum of second-order polynomials

Method 1

- Sample divided in bins of decay time and signal fitted with all parameters except the yield fixed from the full sample fit

Method 2

- From full sample fit, sWeights are extracted and applied in each bin of decay time

[Nucl. Instrum. Meth. A 555, 356 (2005)]

Compatible results between the two methods

Method 1 is chosen as slightly more precise

Results

[2506.13334]

- Lifetimes are measured to be

$$\tau_{\Omega_c^0} = 276.3 \pm 19.4_{(stat)} \pm 1.8_{(syst)} \pm 0.7_{\tau_{D^0}} \text{ fs}$$

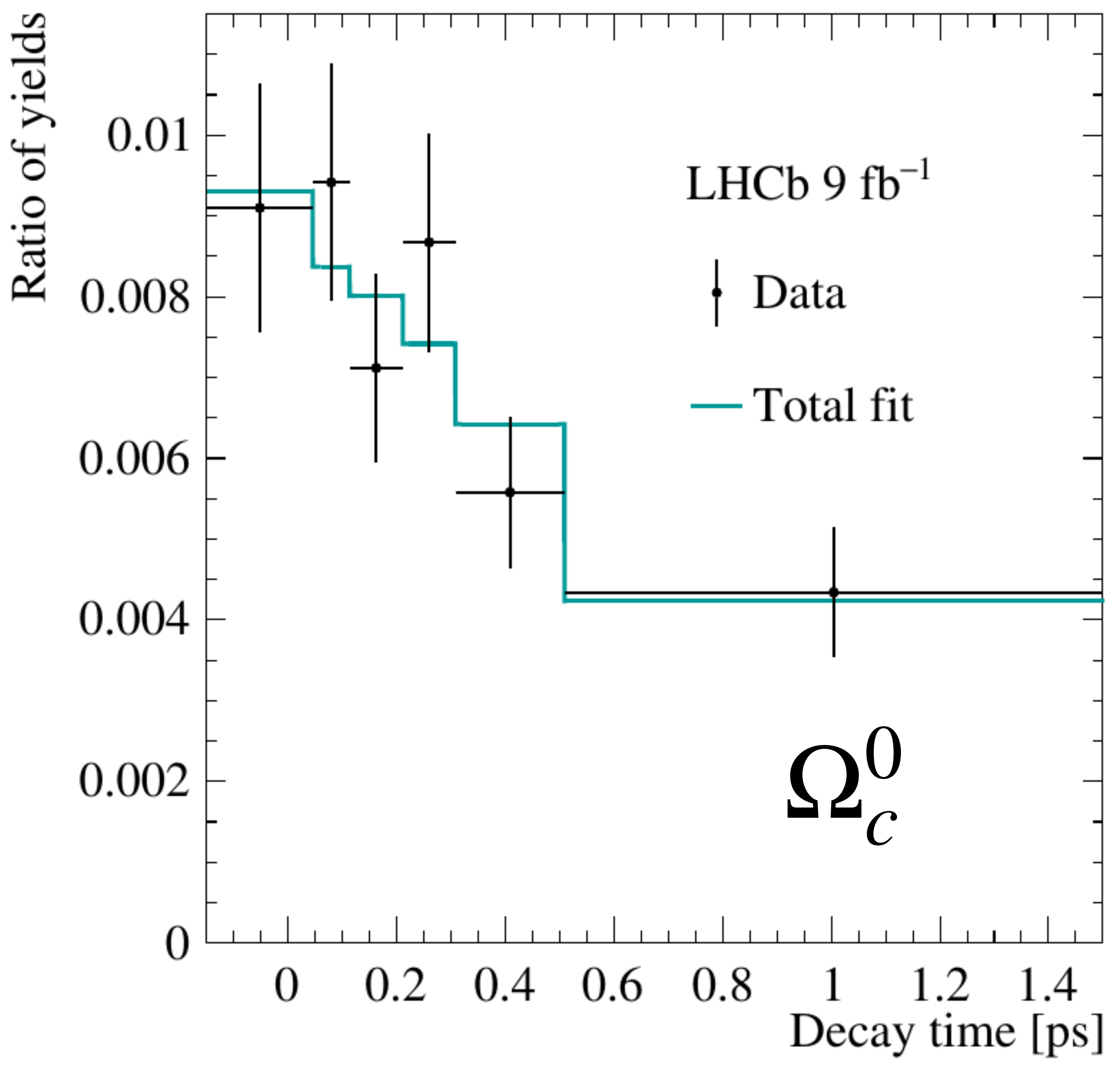
$$\tau_{\Xi_c^0} = 149.2 \pm 2.5_{(stat)} \pm 0.9_{(syst)} \pm 0.4_{\tau_{D^0}} \text{ fs}$$

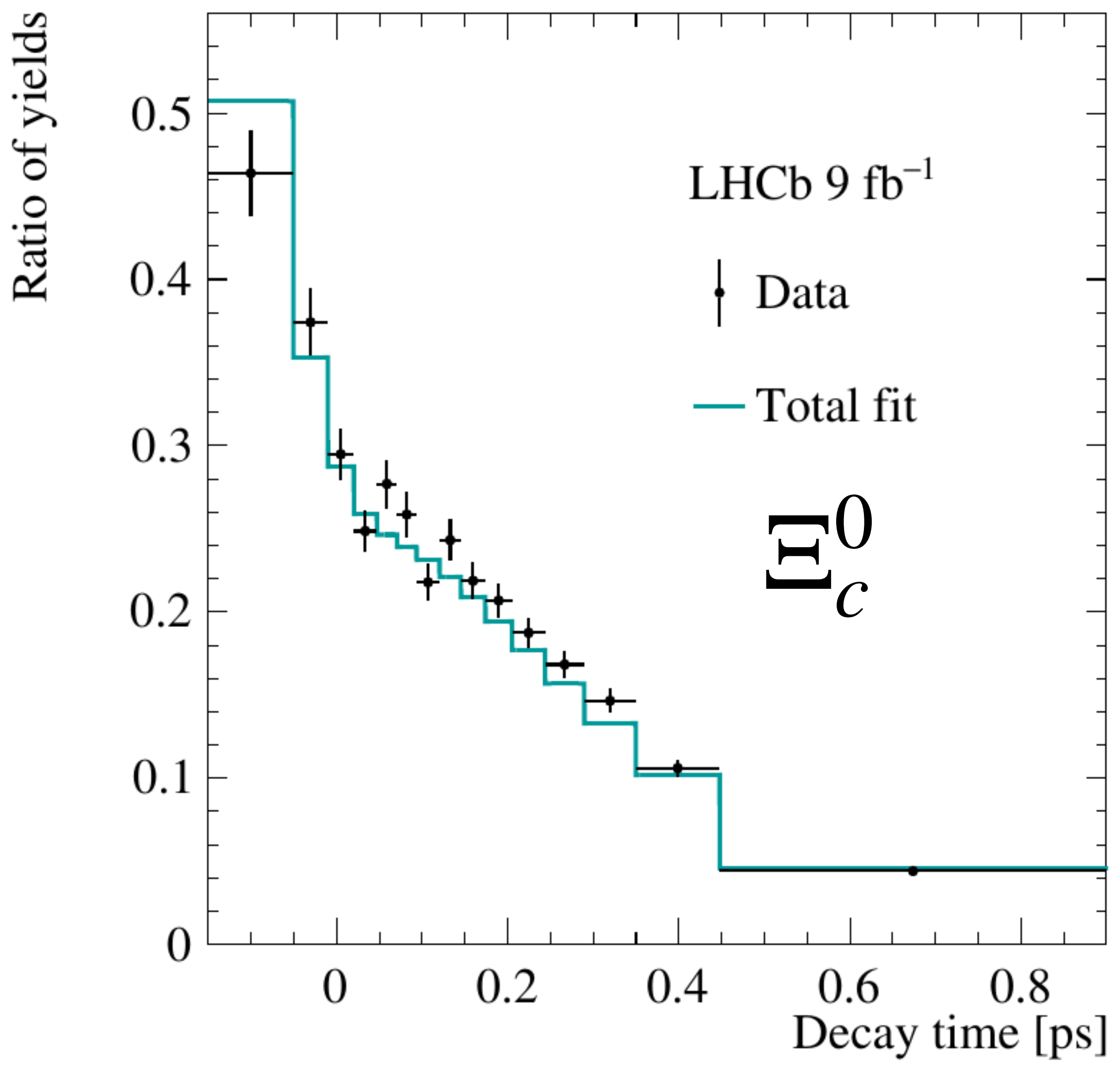
- Dominant uncertainty is the statistical one
- Consistent results with previous LHCb measurements
- Sample is statistically independent with respect to previous measurements, performed with semileptonic and prompt c-baryons
- Combining these results with previous measurements of LHCb gives

$$\tau_{\Omega_c^0} = 274.8 \pm 10.5 \text{ fs}$$

$$\tau_{\Xi_c^0} = 150.7 \pm 1.6 \text{ fs}$$

- Total combination still in tension with previous average, will be further investigated with Run 3 data



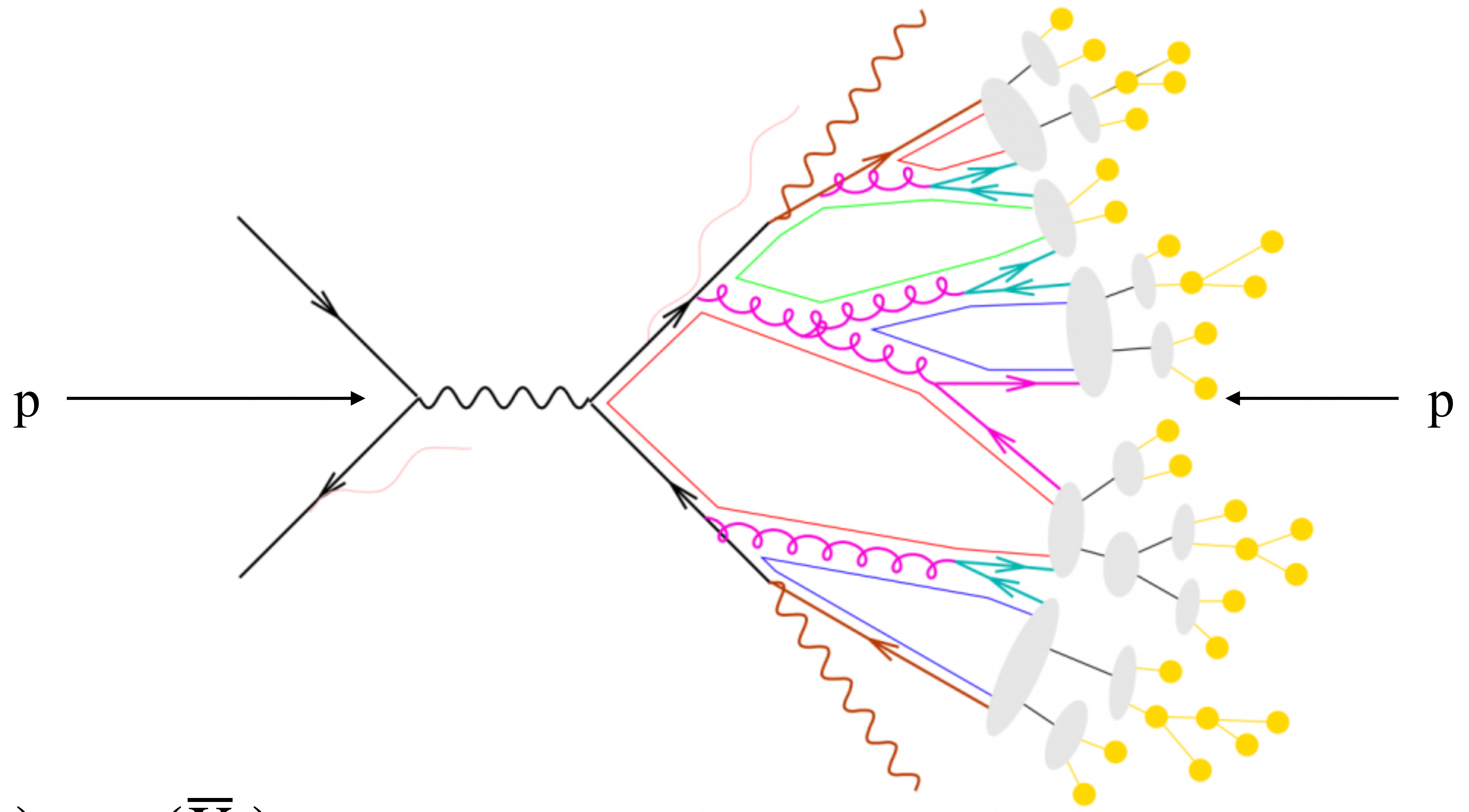


Measurements of charmed meson and antimeson production asymmetry at $\sqrt{s} = 13.6$ TeV

[2505.14494]

Charm production asymmetries

- In pp collisions $c - \bar{c}$ quark are produced in pairs at LO
- Valence quarks in colliding protons modify this symmetry during hadronisation
- Various theoretical frameworks describe this process such as Lund string model, cluster-hadronisation mode, meson-cloud model and heavy-quark recombination.
- Experimental input is needed to further understand the hadronisation process
- Charm production asymmetries are also important inputs for precise CP violation measurements at LHCb



$$A_P(X_c) = \frac{\sigma(X_c) - \sigma(\overline{X}_c)}{\sigma(X_c) + \sigma(\overline{X}_c)}$$

Goal of the analysis

[2505.14494]

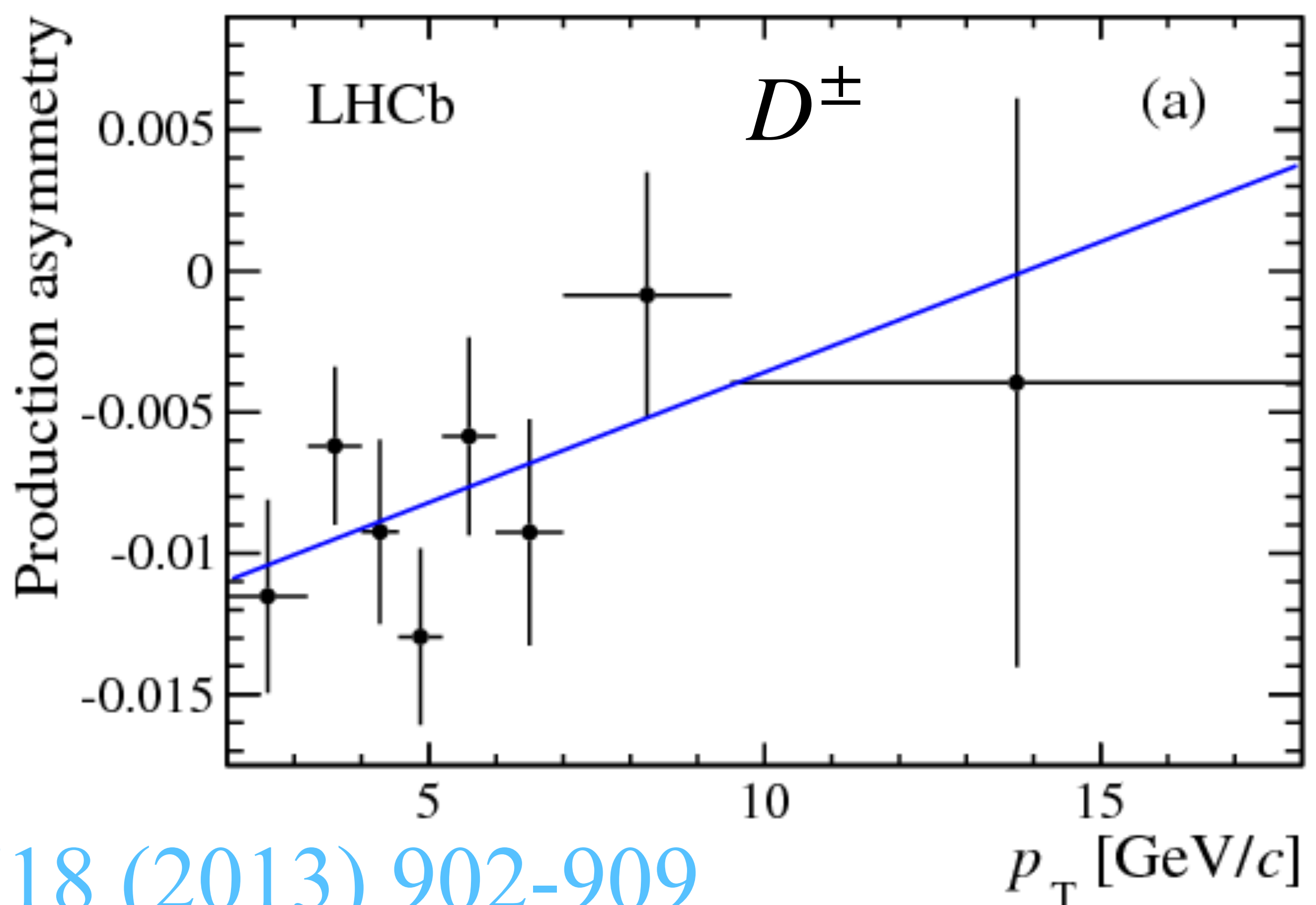
- Measure double differential production asymmetries for D^0, D^+ and D_s^+ as function of η, p_T
- Data collected in 2022 (15 pb^{-1}) and 2023 (162 pb^{-1} for D^0 and 41 pb^{-1} for $D_{(s)}^+$) with upgraded LHCb detector
- Previous measurements:
  - Run 1 measurement of $D^\pm$ production asymmetry at 7 TeV [Phys. Lett. B 718 (2013) 902-909]

$$A_P(D^+) = (-0.96 \pm 0.26_{(stat)} \pm 0.18_{(syst)})\ \%$$

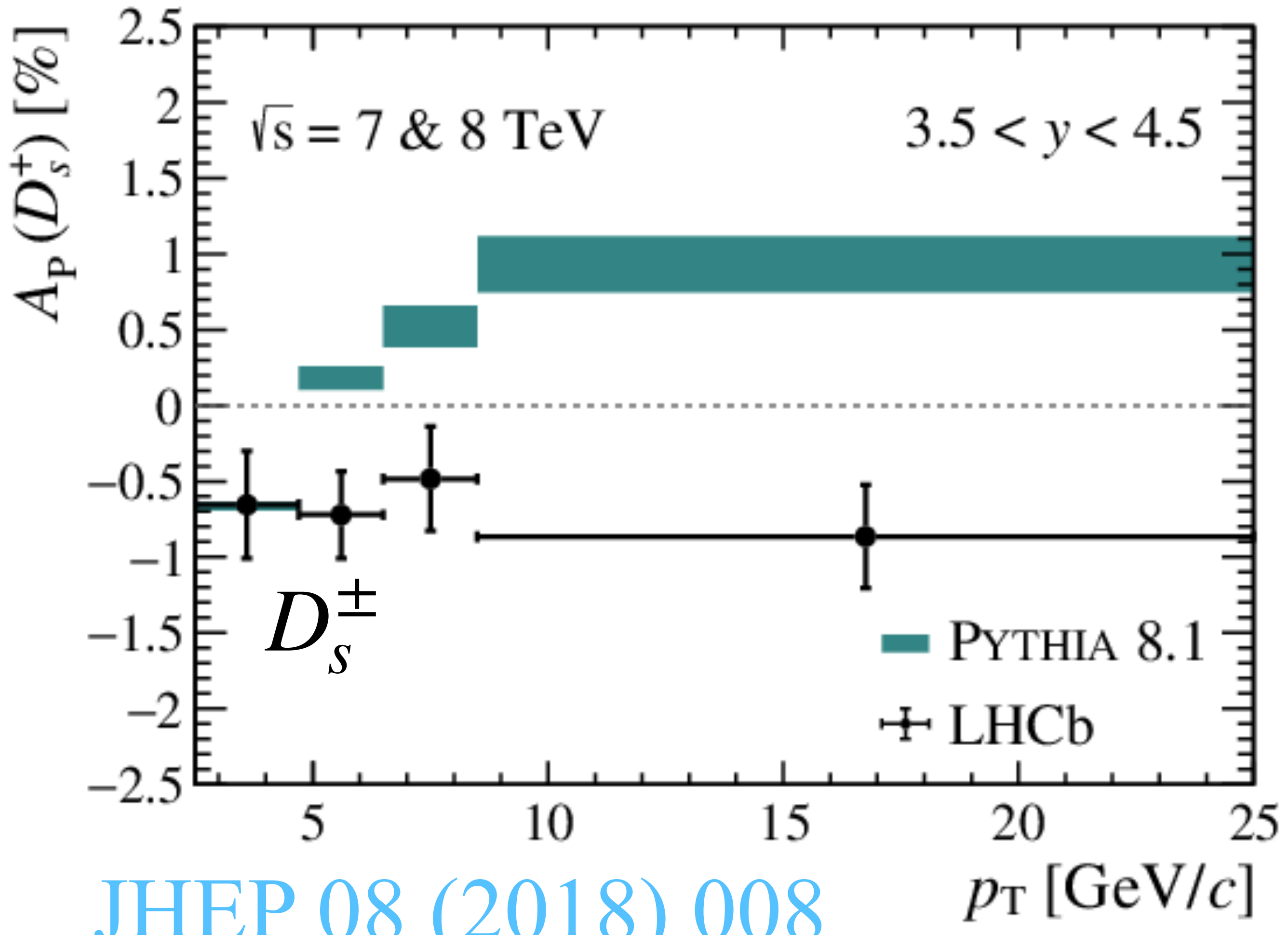
  - Run 1 measurement of the $D_s^\pm$ production asymmetry at $\sqrt{s} = 7$ and 8 TeV [JHEP 08 (2018) 008]

$$A_P(D_s^+) = (-0.52 \pm 0.13_{(stat)} \pm 0.10_{(syst)})\ \%$$

- Production asymmetry expected to depend on $\sqrt{s}, \eta, p_T$



Phys. Lett. B 718 (2013) 902-909



JHEP 08 (2018) 008

Strategy of the analysis

[2505.14494]

Raw asymmetries defined as $A_{raw} = \dfrac{N(X_c) - N(\overline{X}_c)}{N(X_c) + N(\overline{X}_c)}$ extracted from simultaneous fit to data

Production asymmetries extracted from $A_{raw}(X_c \to f) = (1 - f_{sec})A_P(X_c) + A_{det}(f) + A_{CP}(X_c \to f) + f_{sec}A_{sec}(X_c)$

$D^+_{(s)}$

- Decays of interest: $D^+_{(s)} \to \phi(1020)\pi^+$ with $\phi \to K^+K^-$
- $A_{det}(\pi)$ has contributes from PID and reconstruction asymmetry
- $A_{PID}(\pi)$ extracted from $D^{*+}(2010) \to D^0\pi^+$ with $D^0 \to K^-\pi^+$ without PID requirements
- $A_{rec}(\pi)$ extracted with tag-and-probe method with $K^0_s \to \pi^+\pi^-$
- $A_{CP}(D^+ \to \phi\pi^+)$ input from Run 2

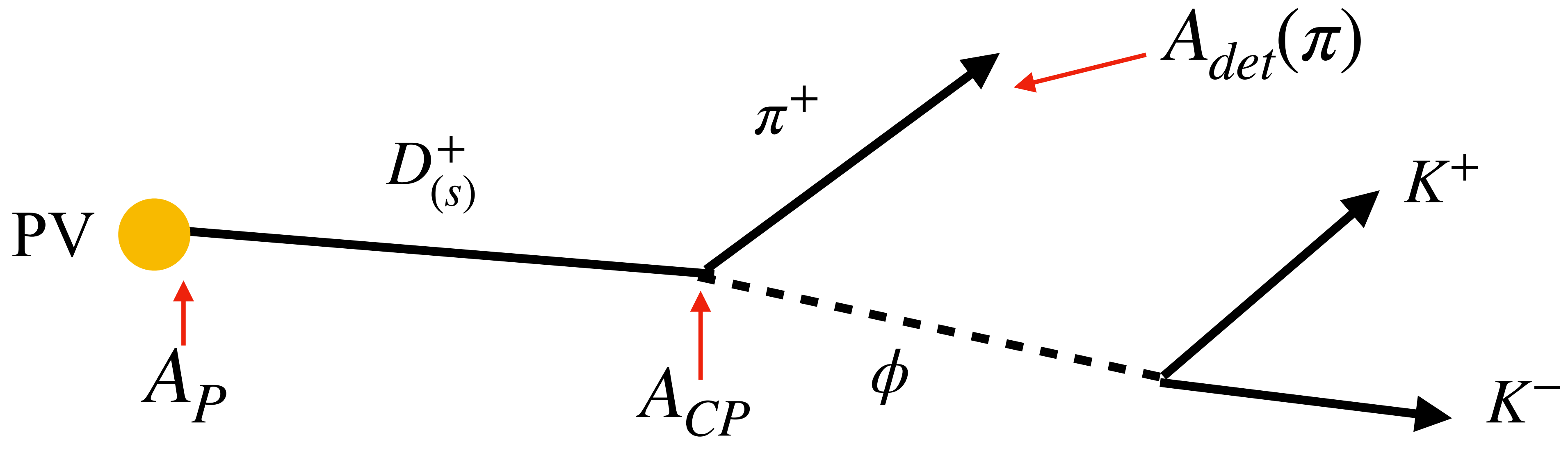
D^0

- Decay of interest: prompt $D^0 \to K^-\pi^+$
- $A_{det}(K^-\pi^+)$ extracted from $D^{*+} \to D^0\pi^+$ with $D^0 \to K^-\pi^+$ and $D^0 \to K^-K^+$ as

$$A_{det}(K\pi) = A_{raw}(D^{*+} \to D^0(\to K^-\pi^+)\pi^+) + \\ -A_{raw}(D^{*+} \to D^0(\to K^-K^+)\pi^+) + \\ +A_{CP}(D^0 \to K^-K^+)$$

- $A_{CP}(D^0 \to K^-K^+)$ input from Run 2

After the selection of data, kinematic weights are applied to ensure asymmetries cancellation



Weighting and asymmetry estimation

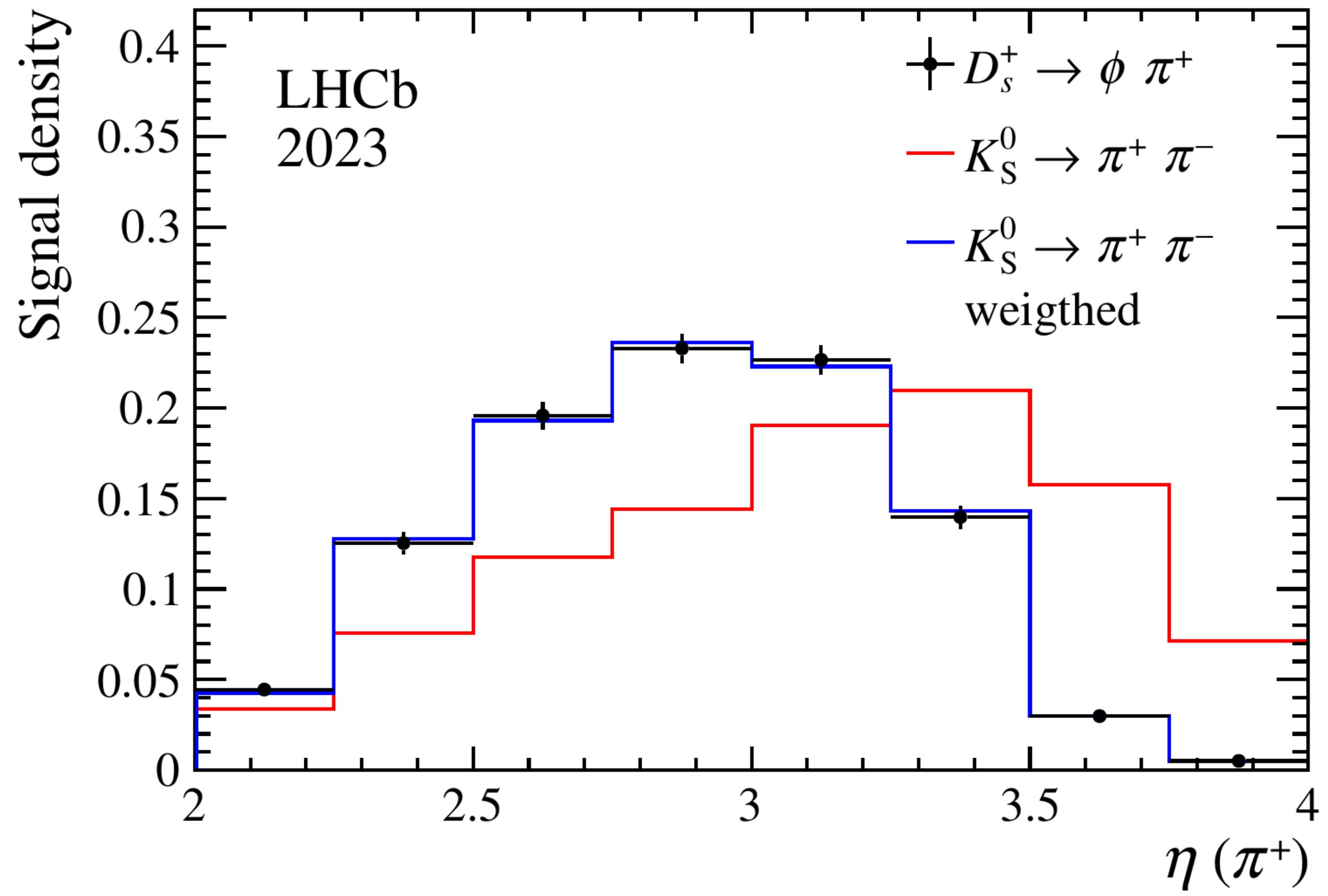
[2505.14494]

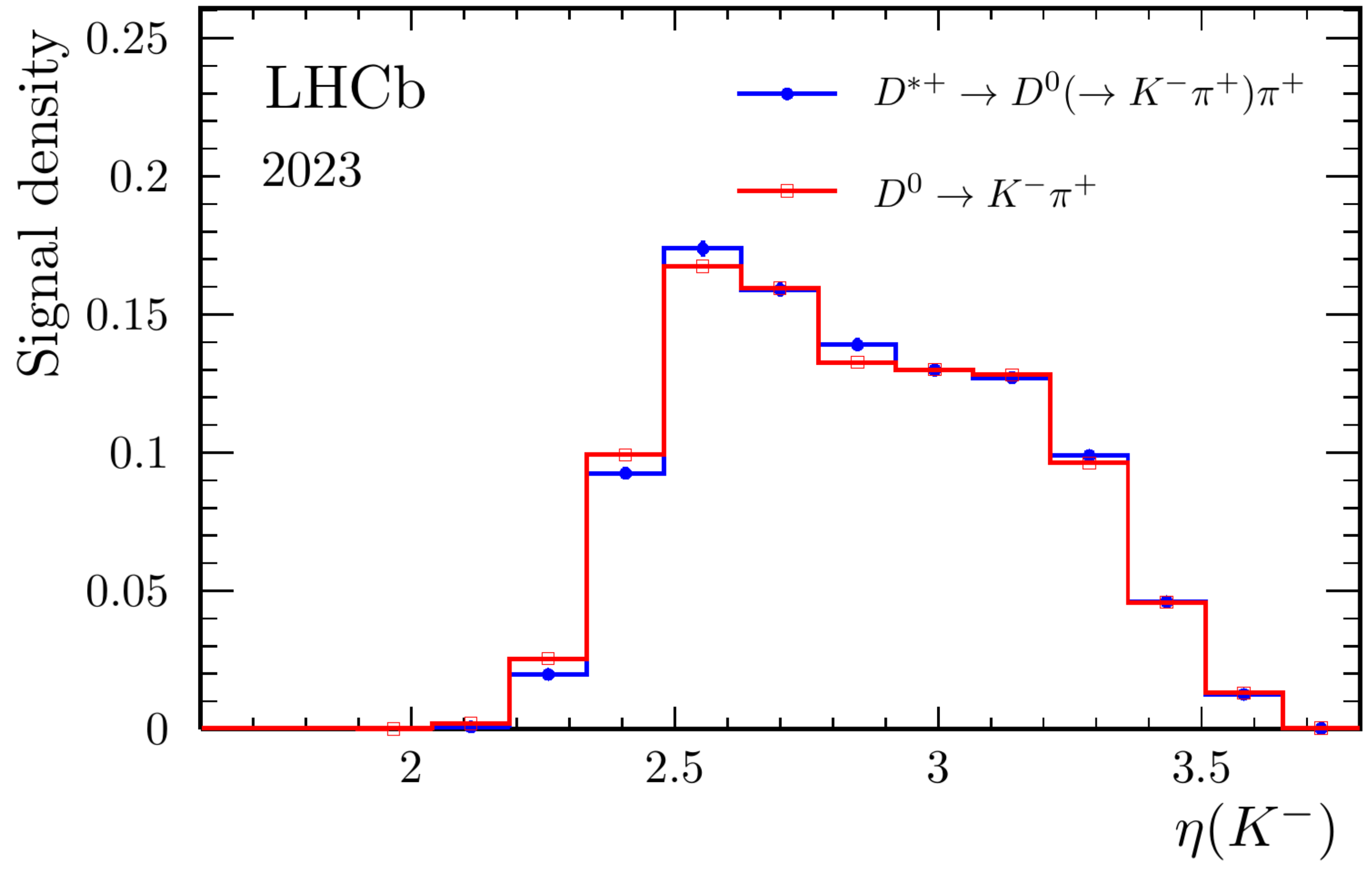
- $A_{rec}(\pi)$ depends on the kinematic of the pion
- Kinematic weights are applied to the signal candidates from $K_s^0 \to \pi\pi$ sample
- The strategy is repeated for each kinematic region of the charmed meson and for A_{PID}

$D_{(s)}^{+}$

- To extract $A_{det}(K\pi)$ all other asymmetries must cancel out
- Due to limited size of the control sample, kinematic weights are applied to the $D^0 \to K\pi$ sample

D^0



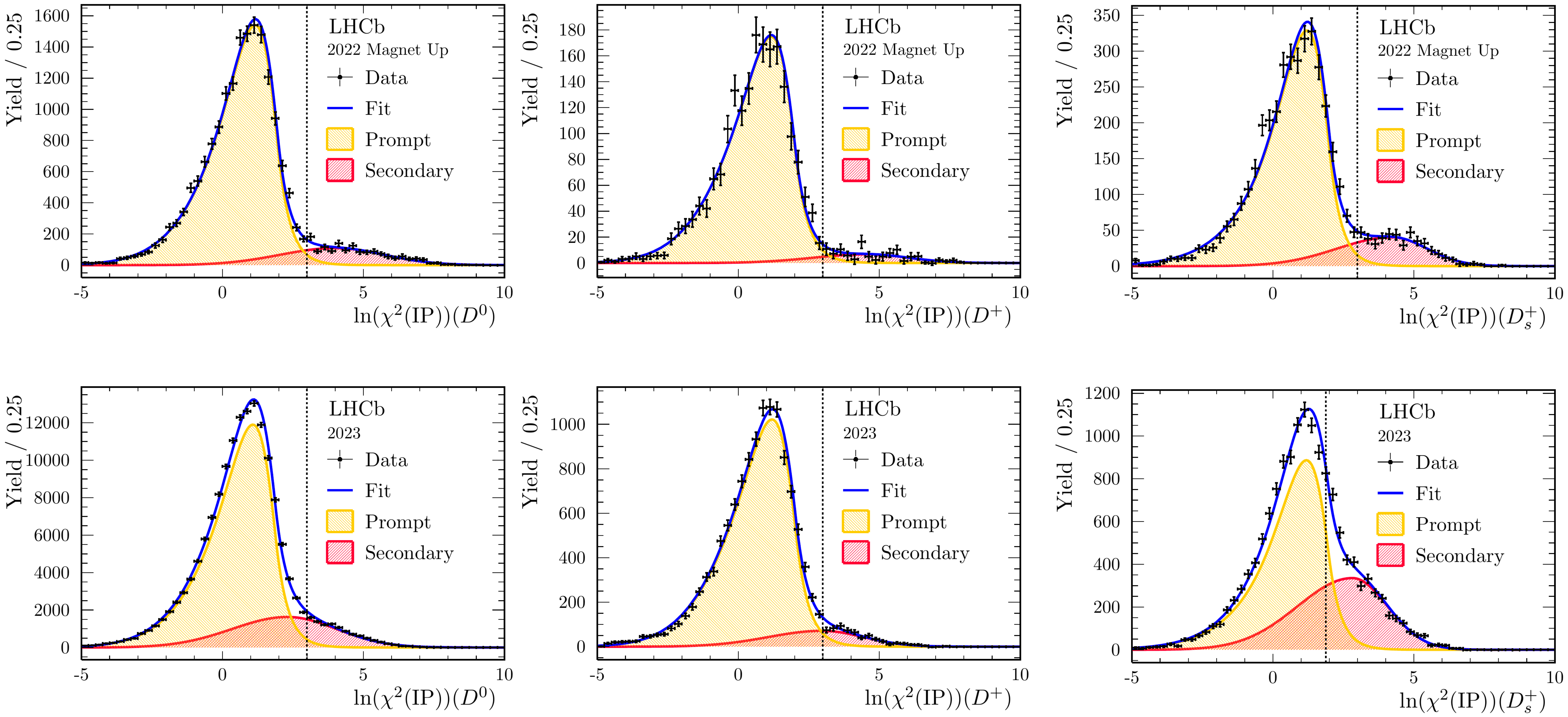


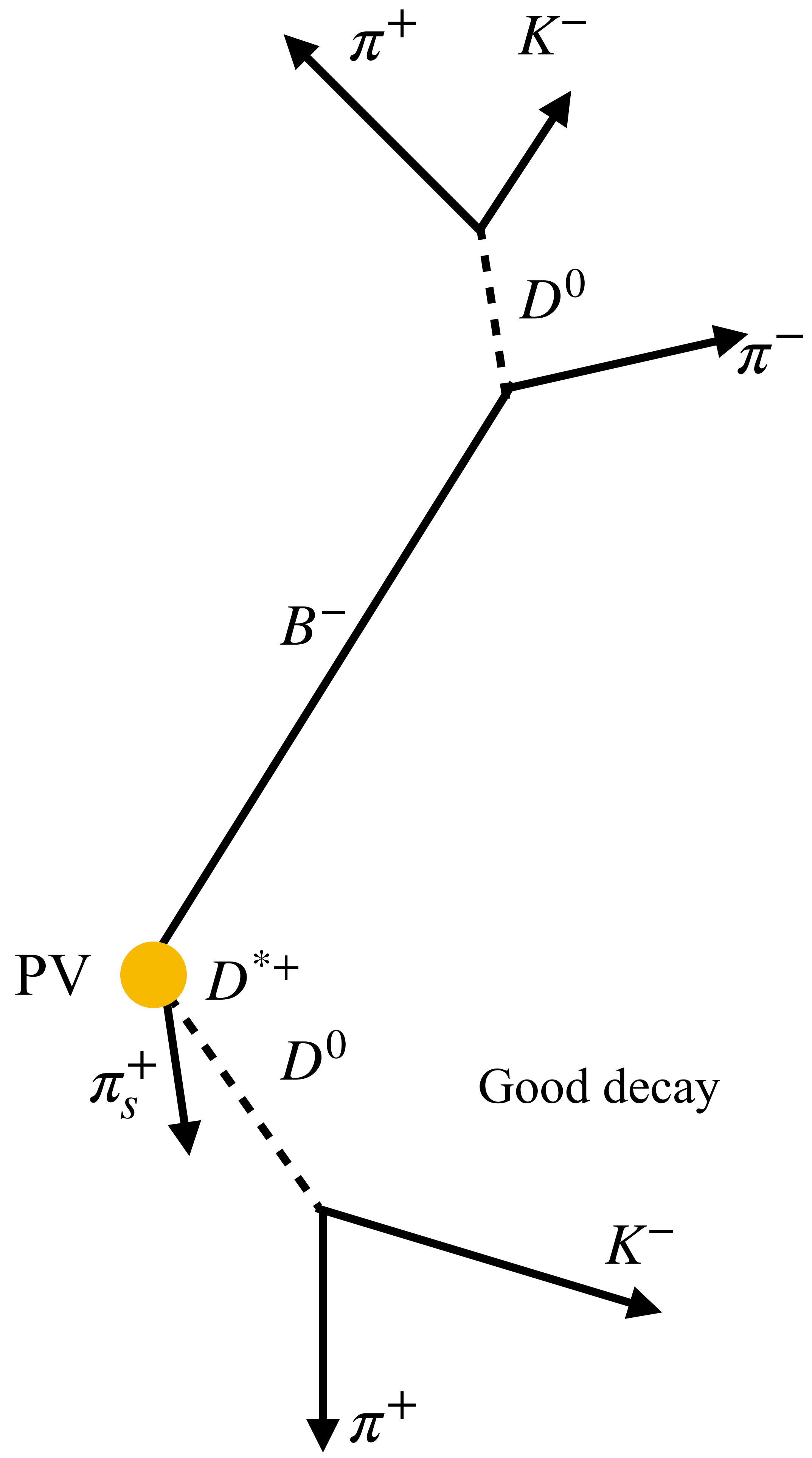
After the weighting, for each charmed meson and for each kinematic bin, asymmetries are extracted with simultaneous fits to both meson-anti meson invariant mass distributions

Secondary contributions estimate

[2505.14494]

- Correction for b-produced charm mesons: $\Delta A_{sec} = f_{sec}(A_P(X_c) - A_{sec}(X_c))$
- To extract f_{sec}, A_{sec} unbinned maximum likelihood fit on $\ln(\chi^2_{IP})$





- All ΔA_{sec} are compatible within 3 standard deviations with zero

Results

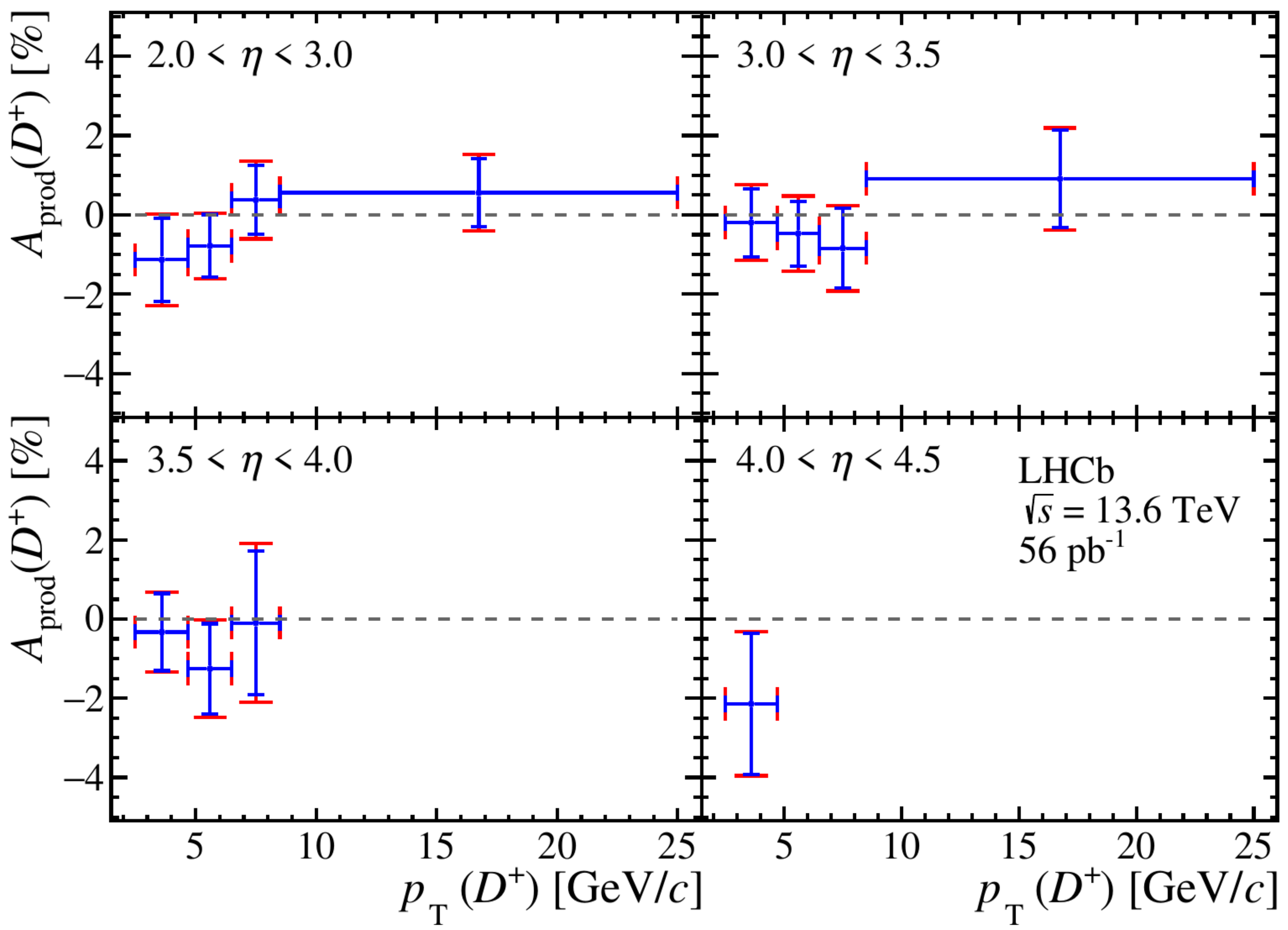
[2505.14494]

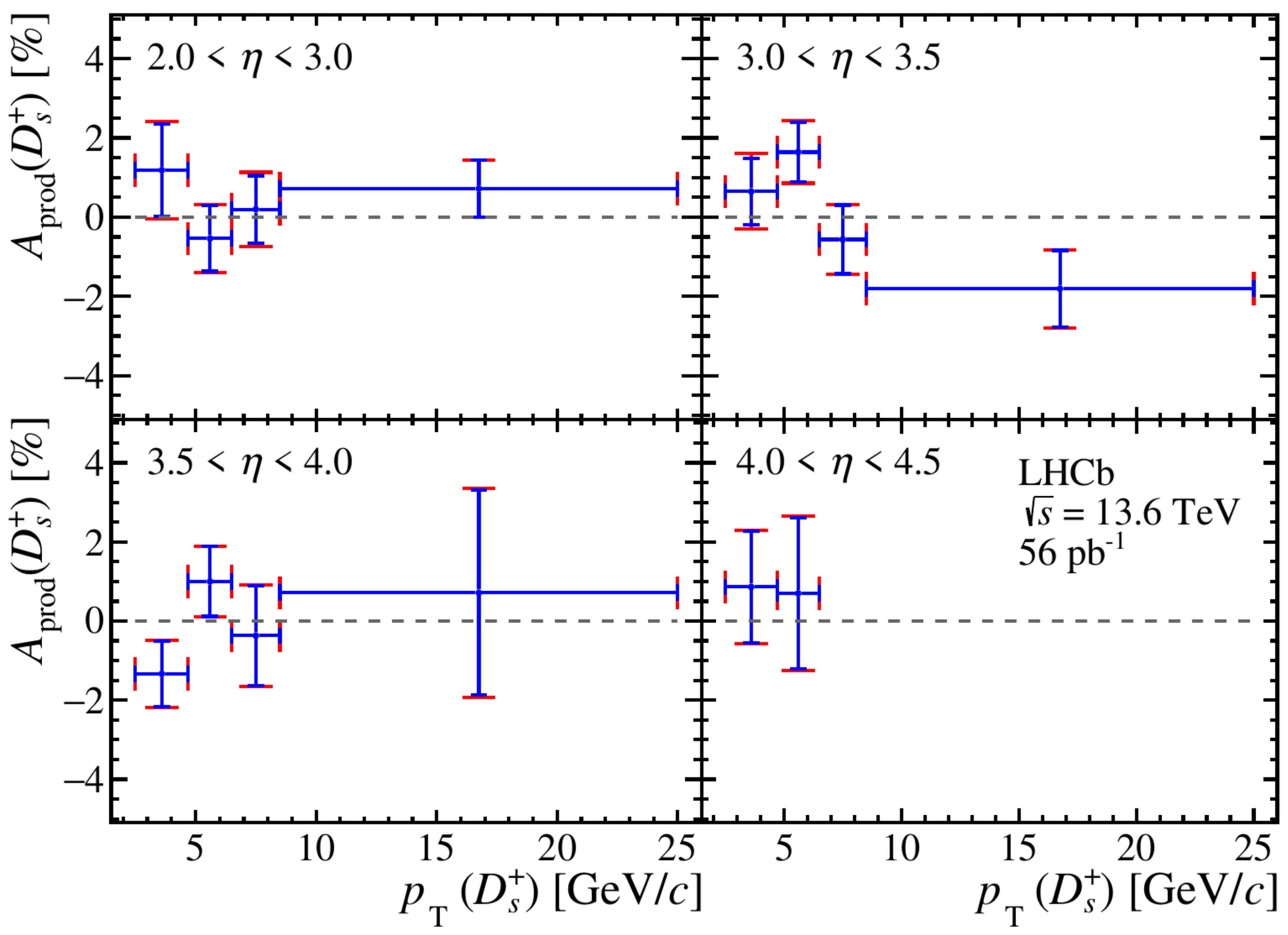
- No dependence of production asymmetry as functions of kinematics
- Integrated results over the kinematic regions compatible with symmetry:

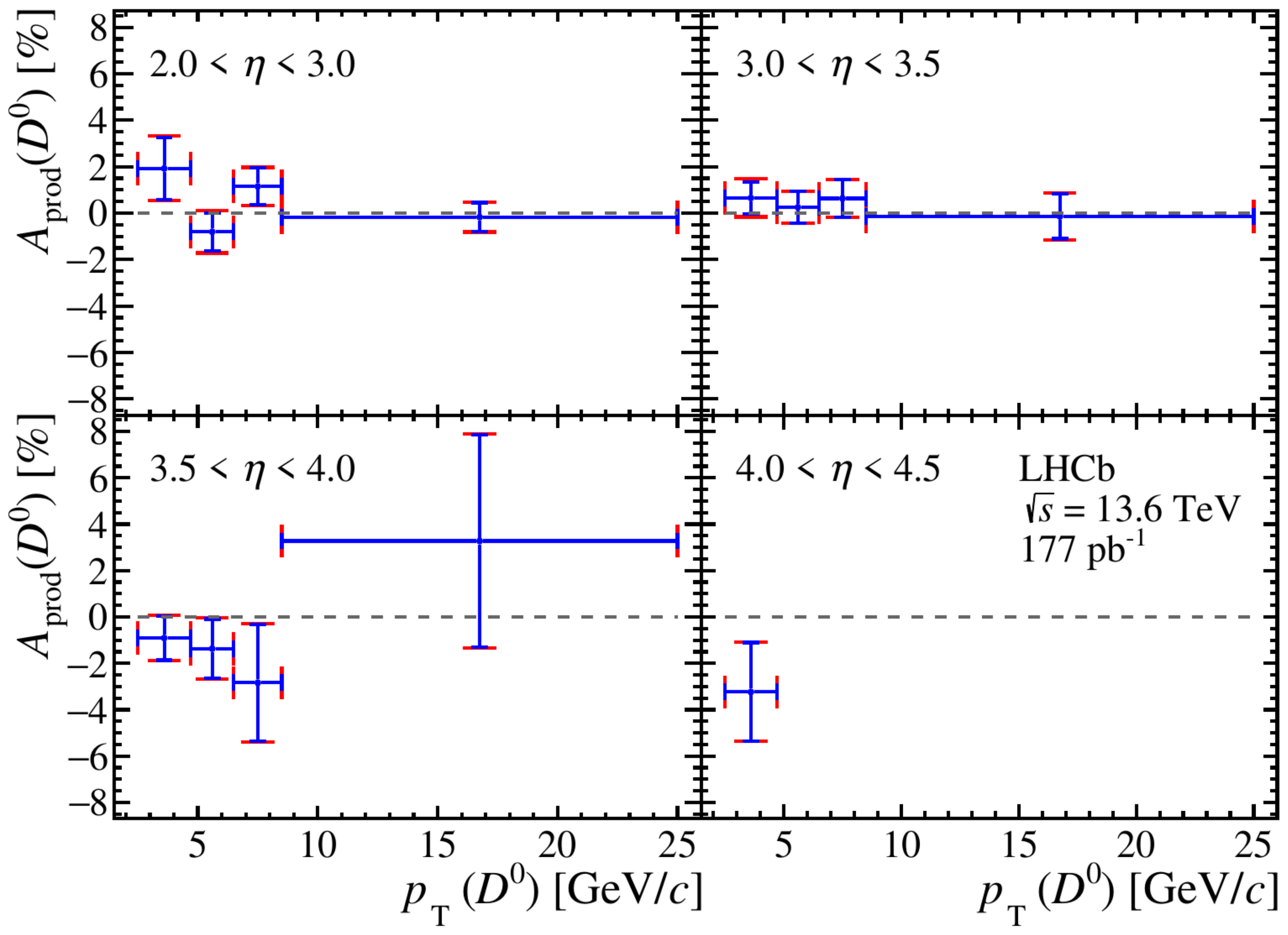
$$A_P(D^0) = (0.07 \pm 0.26_{stat} \pm 0.10_{syst})\ \%$$

$$A_P(D^+) = (-0.33 \pm 0.29_{stat} \pm 0.14_{syst})\ \%$$

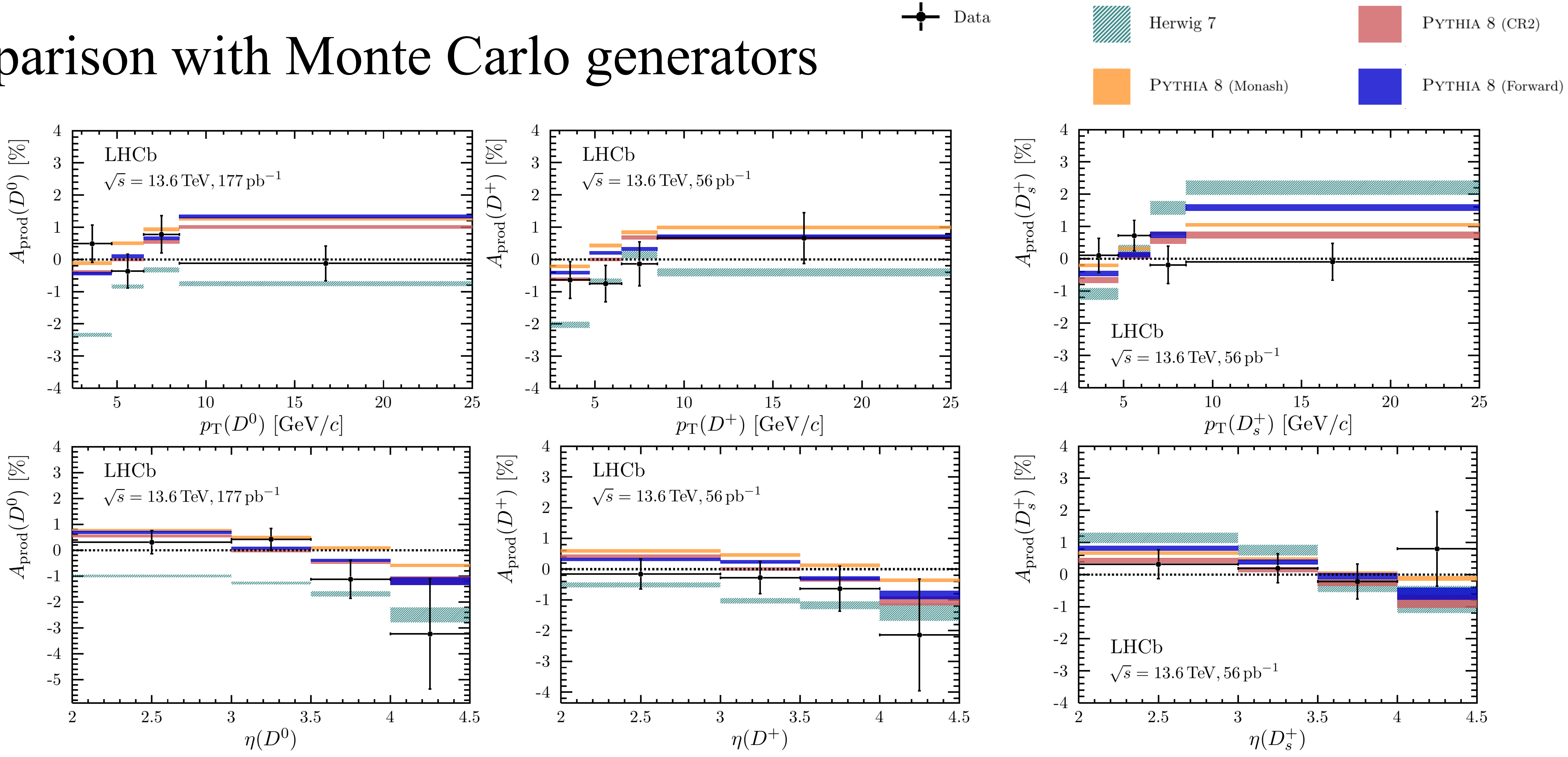
$$A_P(D_s^+) = (0.18 \pm 0.26_{stat} \pm 0.08_{syst})\ \%$$







Comparison with Monte Carlo generators



- One dimensional projections show tensions in high and low p_T regions
- PYTHIA8 with Color-Reconnection shows best agreement with experimental results

[2505.14494]

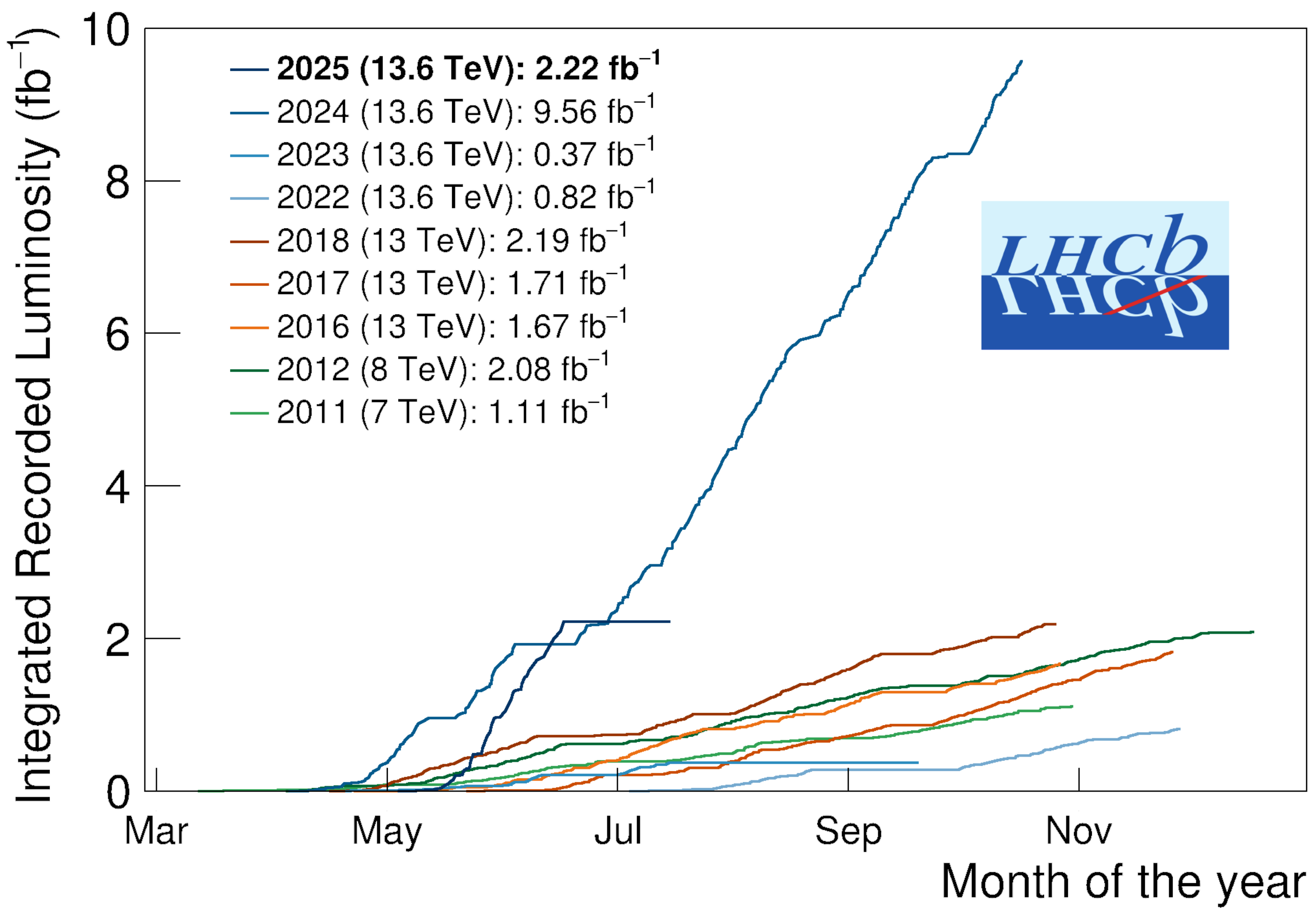
Conclusions

[2505.14494]

- Double differential measurements of D^0, D^+ and D_s^+ production asymmetries have been presented
- Measurements are compatible within statistical error with absence of production asymmetries and with Run 1 results.
- These results have similar statistical uncertainty with respect to Run 1 but with a much lower integrated luminosity, thanks to the improved efficiency of the LHCb detector in Run 3
- This is the first measurement of LHCb with early Run 3 data at a centre-of-mass energy of $\sqrt{s} = 13.6\ \text{TeV}$

Summary

- Charm physics is a unique sector to explore non-perturbative effects in QCD
- LHCb continues to explore and characterize charm hadron states
- First measurement with early Run 3 data has been presented
- However with Run 3 full dataset new precision measurement will be possible
- Collected luminosity in Run 3 is larger then Run1+2
- At the end of 2026 expected $\mathscr{L} = 23 \text{ fb}^{-1}$



Thank you for your attention!