CKM and CPV in Beauty and Charm decays at LHCb

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(*on behalf of the LHCb collaboration*)

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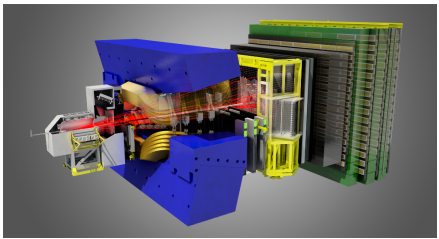
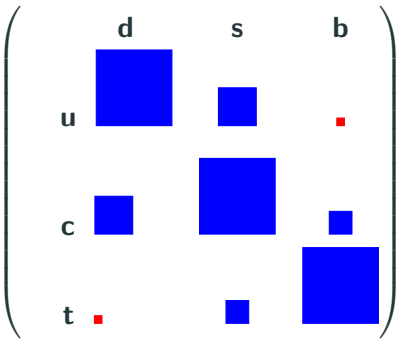
Outline

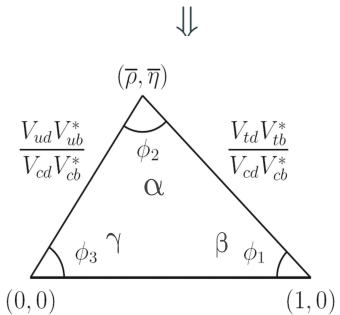
- Introduction
- Beauty decays
  - Beauty to charmonium decays
  - Baryonic decays
  - γ measurements
- Charm decays
- Conclusions & Outlook



- Interactions between the quarks described by CKM matrix

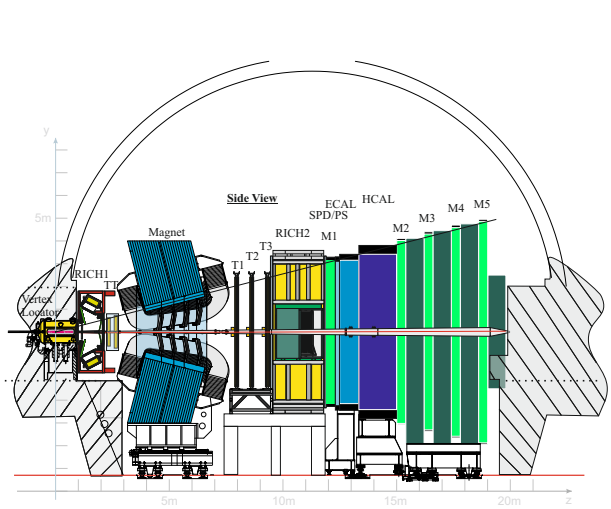


- Unitarity conditions between 1st and 3rd columns



- *CP* violation is measured as the complex phase coming in CKM elements V_{ub} and V_{td} $\Rightarrow$ SM description

LHCb experiment



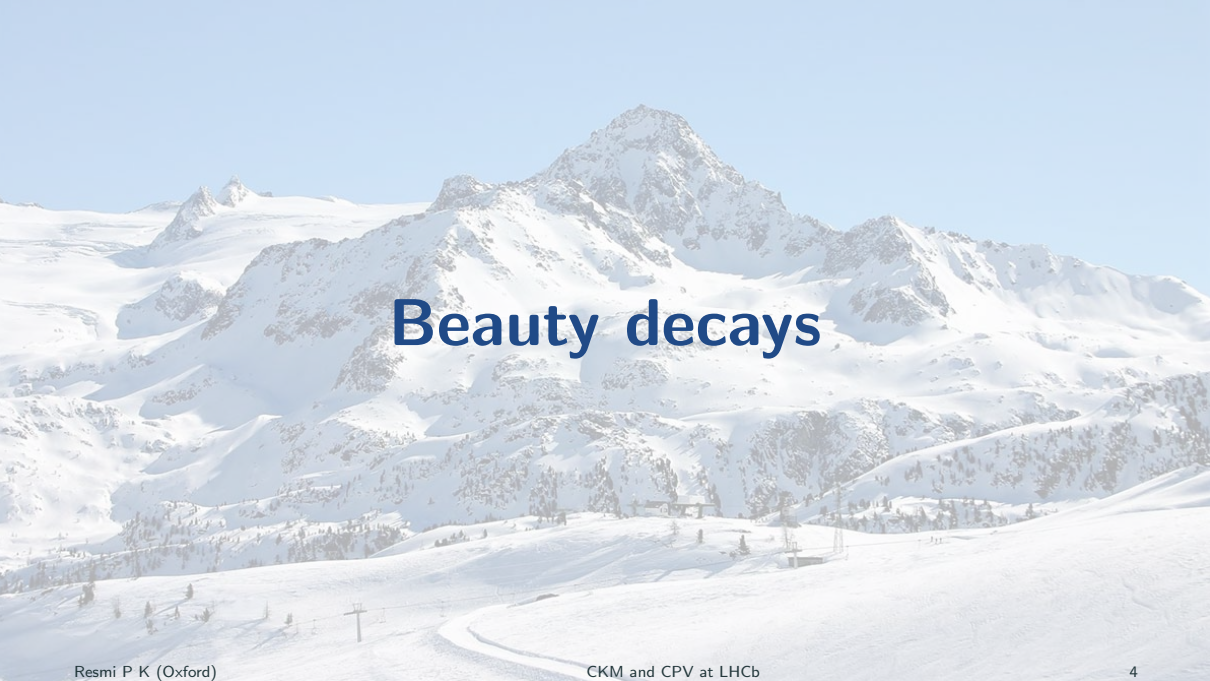
[JINST 3 (2008) S08005, Int. J. Mod. Phys. **A30**, 1530022 (2015)]

- Excellent vertex resolution ($10 - 40\ \mu m$ in xy-plane and **$50 - 300\ \mu m$ in z-axis**)

  B meson lifetime resolution $\mathcal{O}(ps)$

- Particle identification efficiencies $\sim$97% for μ, e and $\sim$3% pion misidentification, good separation between π, K, p

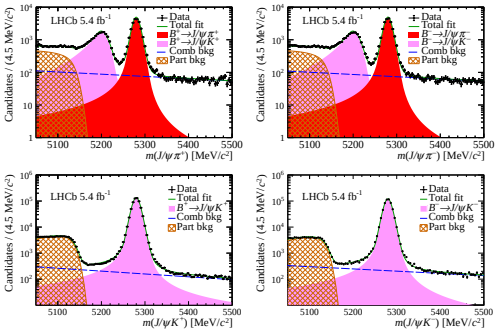
- Run 1+2: 9 fb^{-1} of pp collisions



Beauty decays

- CPV measurements in $b \to c\bar{c}X$ decays
  - $B^0 \to J/\psi K^0_S$ to measure the CKM parameter β
  - These probe indirect CPV via B meson mixing
  - Require additional constraints from direct CPV similar decays to control highly suppressed penguin contributioins from $b \to c\bar{c}s$
- First evidence for direct CPV in $B^+ \to J/\psi\pi^+$ decays PRL **134**, 101801 (2025)

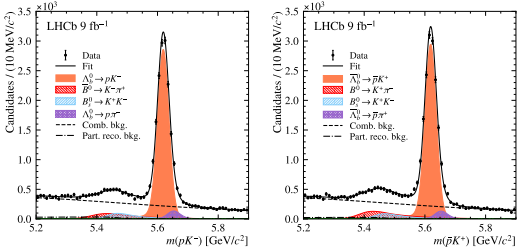
- Difference in CP asymmetries between $B^+ \to J/\psi\pi^+$ and $B^+ \to J/\psi K^+$ decays
- $\Delta A^{CP} = (1.42 \pm 0.43 \pm 0.08) \times 10^{-2}$
- Significance of 3.2σ for nonzero ΔA^{CP}



- Baryons are less explored for CPV measurements than mesons until now
- Identical quark-level transitions could point to similar CPV as in mesons

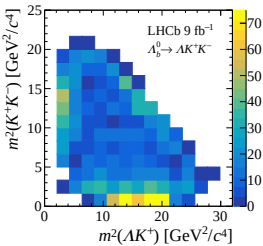
$\Lambda_b \to ph^-$ decays

- $A_{CP}^{pK^-} = (-1.1 \pm 0.7 \pm 0.4)\%$
- $A_{CP}^{p\pi^-} = (\ \ 0.2 \pm 0.8 \pm 0.4)\%$
- Most precise result in this mode arXiv:2412.13958, submitted to PRD
- Compatible with zero; no longer systematically limited



$\Lambda_b/\Xi_b \to \Lambda h^+ h'^-$ decays PRL 134, 101802 (2025)

- $\Delta A^{CP}(\Lambda_b^0 \to \Lambda K^+ K^-) = 0.083 \pm 0.023 \pm 0.016$
- Evidence of direct CPV in baryon decays (3.1σ)
- Possibly due to enhancement from $N^{*+} \to \Lambda K^+$ decays

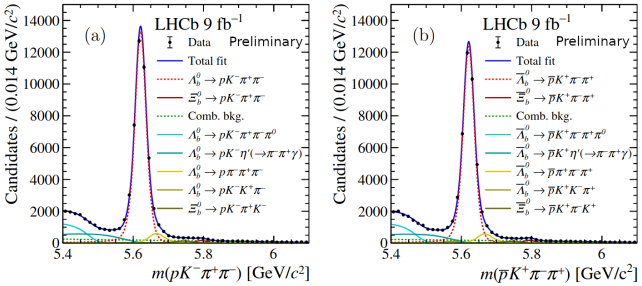


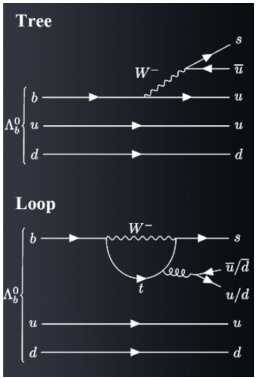
NEW!

$\Lambda_b \to pK^-\pi^+\pi^-$ decays LHCb-PAPER-2024-054, arXiv:2503.16954

$$A_{CP} \equiv \frac{\Gamma(\Lambda_b^0 \to pK^-\pi^+\pi^-) - \Gamma(\overline{\Lambda}_b^0 \to \overline{p}K^+\pi^-\pi^+)}{\Gamma(\Lambda_b^0 \to pK^-\pi^+\pi^-) + \Gamma(\overline{\Lambda}_b^0 \to \overline{p}K^+\pi^-\pi^+)}$$

- A_{CP} arises from interference between the tree- and loop-level amplitudes
- Resonant structure may create significant *CP* asymmetries which could vary across the phase space





NEW!

LHCb-PAPER-2024-054, arXiv:2503.16954

- Measured raw asymmetry includes both physics and detector effects

$$A_{\text{raw}} = A_{CP} + A_{\text{det}} + A_{\text{prod}}$$

- A_{det} due to different behaviour of particle and antiparticle while interacting with detector
- A_{prod} due to nonzero net baryon number in pp collisions
- Control channel $\Lambda_b \to \Lambda_c^+(\to pK^-\pi^+)\pi^-$ to subtract these nuisance asymmetries
- The CP asymmetry in $\boldsymbol{\Lambda_b \to pK^-\pi^+\pi^-}$ decays:

$$\boxed{A_{CP} = (2.45 \pm 0.46 \pm 0.10)\%}$$

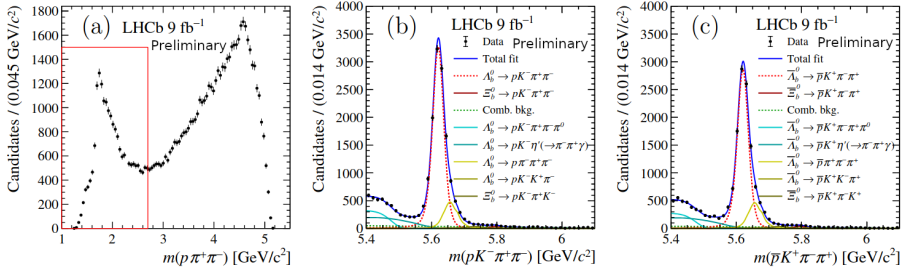
- **First observation of CPV in baryonic decays** - difference of $\mathbf{5.2\sigma}$ from zero

NEW!

- Local asymmetries of up to $\mathbf{6\sigma}$

LHCb-PAPER-2024-054, arXiv:2503.16954

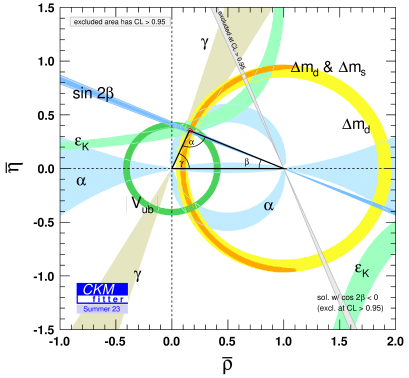
Decay topology	Mass region (GeV/c^2)	$\mathcal{A}_{CP}$
$\Lambda_b^0 \to R(pK^-)R(\pi^+\pi^-)$	$m_{pK^-} < 2.2$ $m_{\pi^+\pi^-} < 1.1$	$(5.24 \pm 1.29 \pm 0.21)\%$
$\Lambda_b^0 \to R(p\pi^-)R(K^-\pi^+)$	$m_{p\pi^-} < 1.7$ $0.8 < m_{\pi^+K^-} < 1.0$ or $1.1 < m_{\pi^+K^-} < 1.6$	$(2.73 \pm 0.82 \pm 0.14)\%$
$\Lambda_b^0 \to R(p\pi^-\pi^+)K^-$	$m_{p\pi^-\pi^+} < 2.7$	$(5.39 \pm 0.86 \pm 0.10)\%$
$\Lambda_b^0 \to R(K^-\pi^+\pi^-)p$	$m_{K^-\pi^+\pi^-} < 2.0$	$(2.01 \pm 1.16 \pm 0.30)\%$



NEW!

- After 60 years since the first observation of *CP* violation in K-meson decays, followed by several other measurements and first observations in beauty and charm, always with meson decays, this is the **first time that *CP* violation is observed in a baryon decay!**

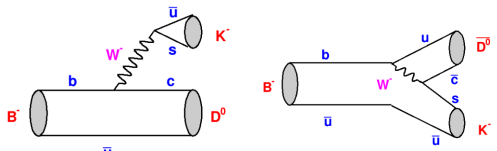
LHCb-PAPER-2024-054, arXiv:2503.16954



CKMfitter Summer 2023

- $\gamma_{\text{direct}} = \left(66.4^{+2.8}_{-3.0}\right)^\circ$ HFLAV Winter 2024
- $\gamma_{\text{indirect}} = \left(66.3^{+0.7}_{-1.9}\right)^\circ$ CKMfitter Summer 2023

- γ measured from the interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$, tree-level diagrams $\Rightarrow 10^{-7}$ theoretical uncertainty JHEP **2014**, 51 (2014)

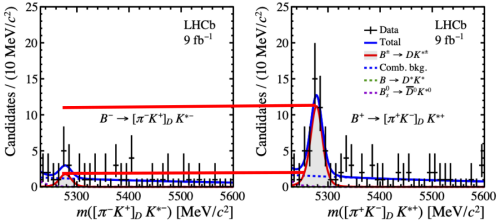


- Statistically limited due to small branching fractions of decays involved
- Exploit more decay modes

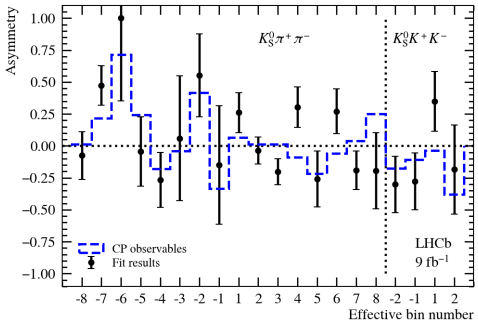
Measurement of γ with $B^{\pm} \to DK^{*\pm}$ decays

- Measurement with $D \to h^+h^-(h^+h^-)$ and $D \to K^0_S h^+h^-$ decays ($h = \pi, K$)
- High signal purity is an added advantage

JHEP **02**, 113 (2025)



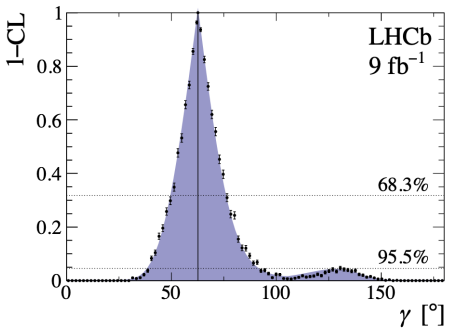
- Larger asymmetries observed for the suppressed $D \to h^+h^-(h^+h^-)$ modes
- First observation of $B^{\pm} \to [\pi^{\pm}K^{\mp}]_D K^{*\pm}$ and $B^{\pm} \to [\pi^{\pm}K^{\mp}\pi^{\pm}\pi^{\mp}]_D K^{*\pm}$ decays

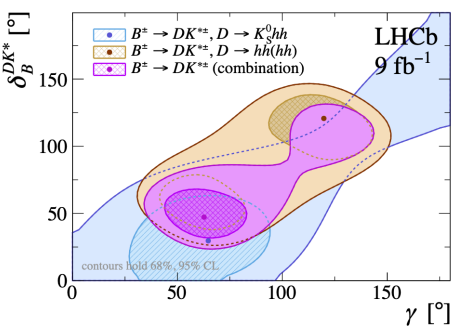


- Asymmetries in Dalitz plot bins for $D \to K^0_S h^{\pm}h^{\mp}$ modes

- The physics parameters of interest are interpreted from the *CP*-violating observables JHEP **02**, 113 (2025)

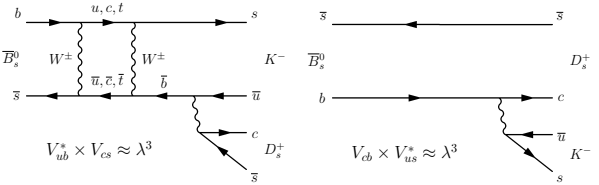
$$\gamma = (63 \pm 13)^{\circ}$$





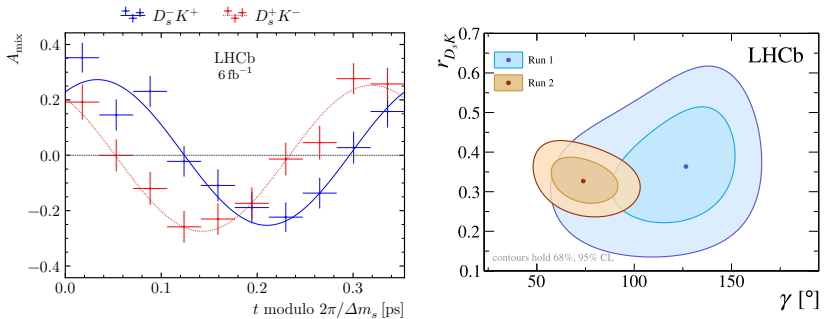
Time dependent CPV in $B_s^0 \to D_s^- K^+$ decays

- Interference between mixing and decay provides access to a relative phase difference $\gamma - 2\beta_s$



- Decay-time distribution is studied to extract *CP*-violating observables

arXiv:2412.14074, JHEP **03**, 139 (2025)

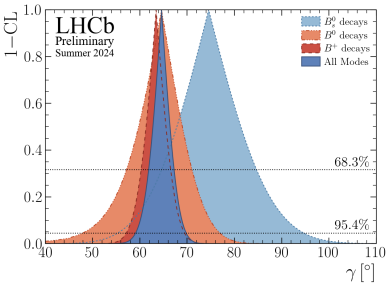


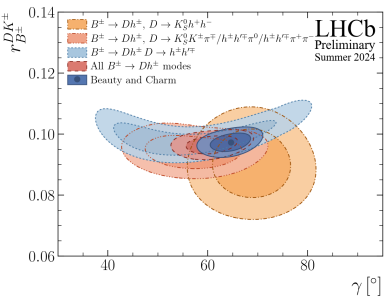
- Latest LHCb combination 2024

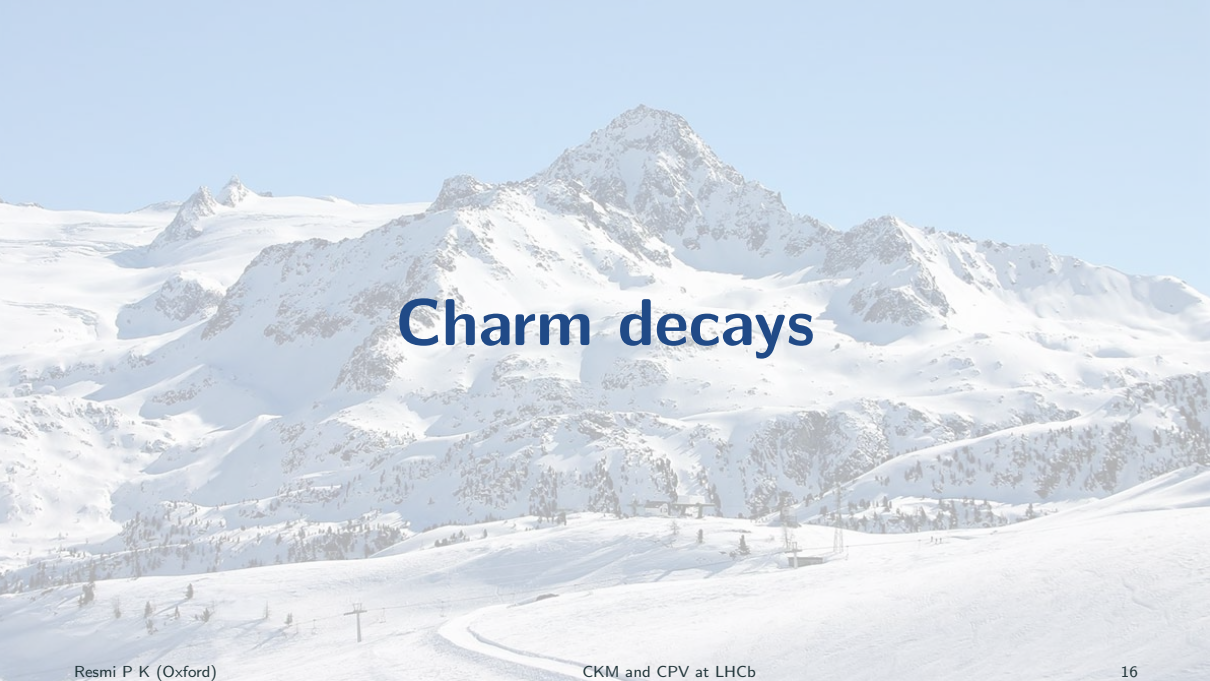
  LHCb-CONF-2024-004

$$\gamma = (64.6 \pm 2.8)^\circ$$

- New/updated measurements from $B^\pm$, B^0 and B_s^0 decays
- Excellent precision below 3°; well beyond the expected sensitivity for Run1-2!
- Consistency between B species now more evident



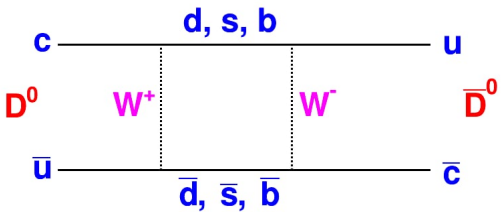




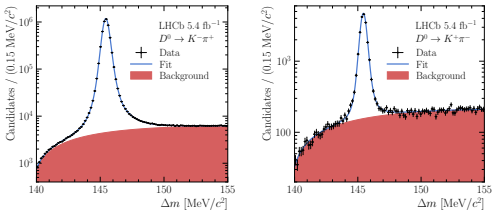
Charm decays

- Down-type quarks in loops ⇒ complementary to strange & beauty

- Short-distance mixing highly suppressed by CKM and GIM
- Need large and clean data samples for precise measurements of SM contributions



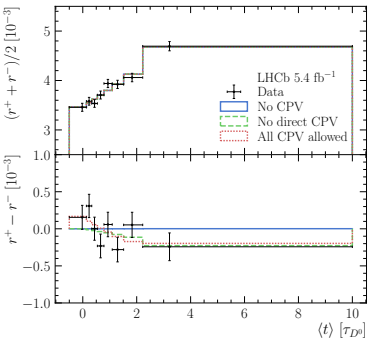
- LHCb able to collect hundreds of millions of charm decays ⇒ perfect environment!
- Struggling to understand if the CPV observed is consistent with SM or BSM



- Measure the ratio between
  - $D^{*+} \to D^0(\to K^+\pi^-)\pi^+ \Rightarrow$ Wrong Sign (WS)
  - $D^{*+} \to D^0(\to K^-\pi^+)\pi^+ \Rightarrow$ Right Sign (RS)

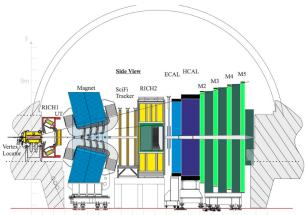
  arXiv:2501.11635, Submitted to JHEP

- WS decays are sensitive to mixing and RS decays cancel lifetime acceptance and detector effects
- Double **tagged** $\overline{B} \to D^{*+}(\to D^0\boldsymbol{\pi^+})\boldsymbol{\mu^-}X$ decays
- Complementary to measurement with prompt sample and larger acceptance at lower decay time
- No evidence of CPV



- Upgraded detector in Run 3

  JINST **19**, P05065 (2024)



- Hardware triggers removed - main systematic limitation in previous measurements
- Asymmetry in production of charm and anticharm due to influence of valence quarks in the colliding protons

$$A_{\text{prod}}(D) \equiv \frac{\sigma(pp \to DX) - \sigma(pp \to \overline{D}X)}{\sigma(pp \to DX) + \sigma(pp \to \overline{D}X)}$$

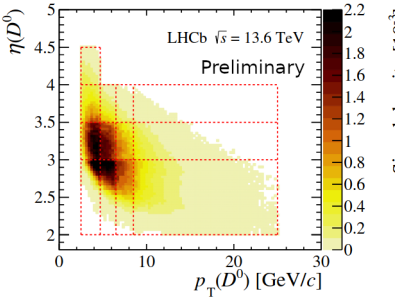
- Input for hadronisation/QCD models and tuning event generators
- Prompt D^0, D^+ and D_s^+ decays produced at $\sqrt{s} = 13.6$ TeV
- Commissioning data from 2022–2023: 167/56 pb^{-1} for $D^0/D^+_{(s)}$
  - $\sim$9.8M D^0, $\sim$155k D^+ and $\sim$179k D_s^+ decays

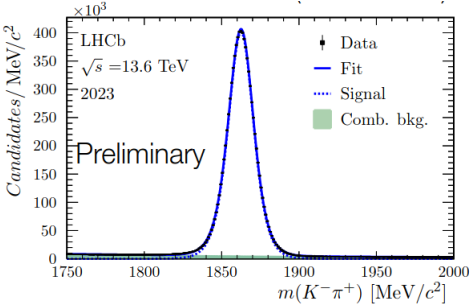
- Data-driven techniques to correct raw asymmetries

LHCb-PAPER-2024-052 (in preparation)

$$A_{\text{prod}}(D^0) = A(D^0 \to K^-\pi^+) - [A(D^{*+} \to (D^0 \to K^-\pi^+)\pi^+_{\text{tag}}) - A(D^{*+} \to (D^0 \to K^-K^+)\pi^+_{\text{tag}})] - A_{CP}(D^0 \to K^-K^+)$$

- Measurements in bins of (p_T, η) to capture possible dependences

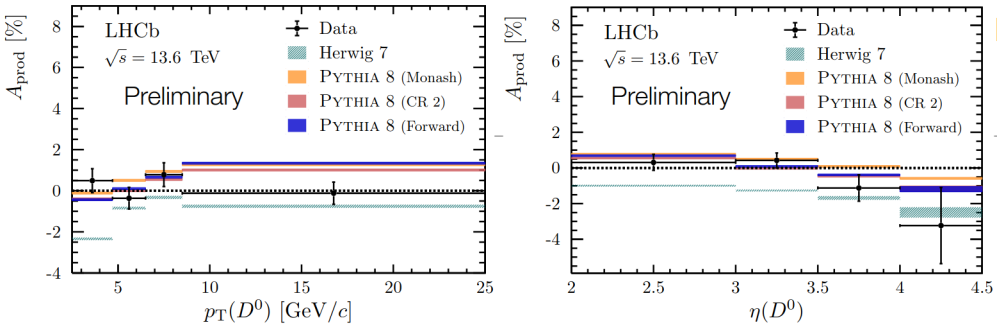




$$A_{\text{prod}}(D^0) = (\ \ 0.07 \pm 0.26(\text{stat}) \pm 0.10(\text{syst}))\%$$
$$A_{\text{prod}}(D^+) = (-0.32 \pm 0.29(\text{stat}) \pm 0.13(\text{syst}))\%$$
$$A_{\text{prod}}(D_s^+) = (\ \ 0.18 \pm 0.26(\text{stat}) \pm 0.07(\text{syst}))\%$$

- Similar statistical precision as in Run 1 with $\sim 1/10^{\text{th}}$ luminosity!

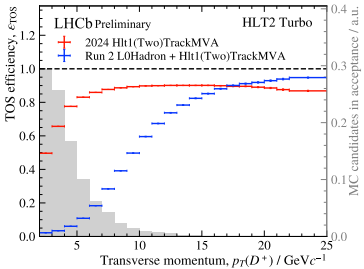
- Comparing data with different event generators
- Similar trend between the different charmed mesons

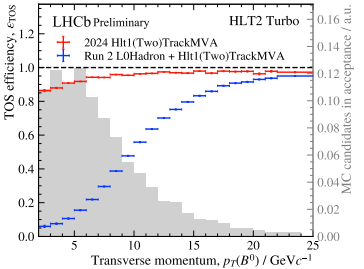


- Overall scale compatible, but kinematic dependence not well reproduced

- LHCb is an excellent place to study the decays of beauty and charm hadrons
- Many results from Run 1-2 datasets
  - **First observation of CPV in baryonic decays!**
  - LHCb γ combination $\Rightarrow$ **sensitivity below 3°**
- **Charm production asymmetries measured at $\sqrt{s} = 13.6$ TeV for the first time**
- Higher efficiency achieved in hadronic modes from fully software trigger in Run 3

LHCb-FIGURE-2024-030





Stay tuned!