Baryonic *CP* Violation at LHCb

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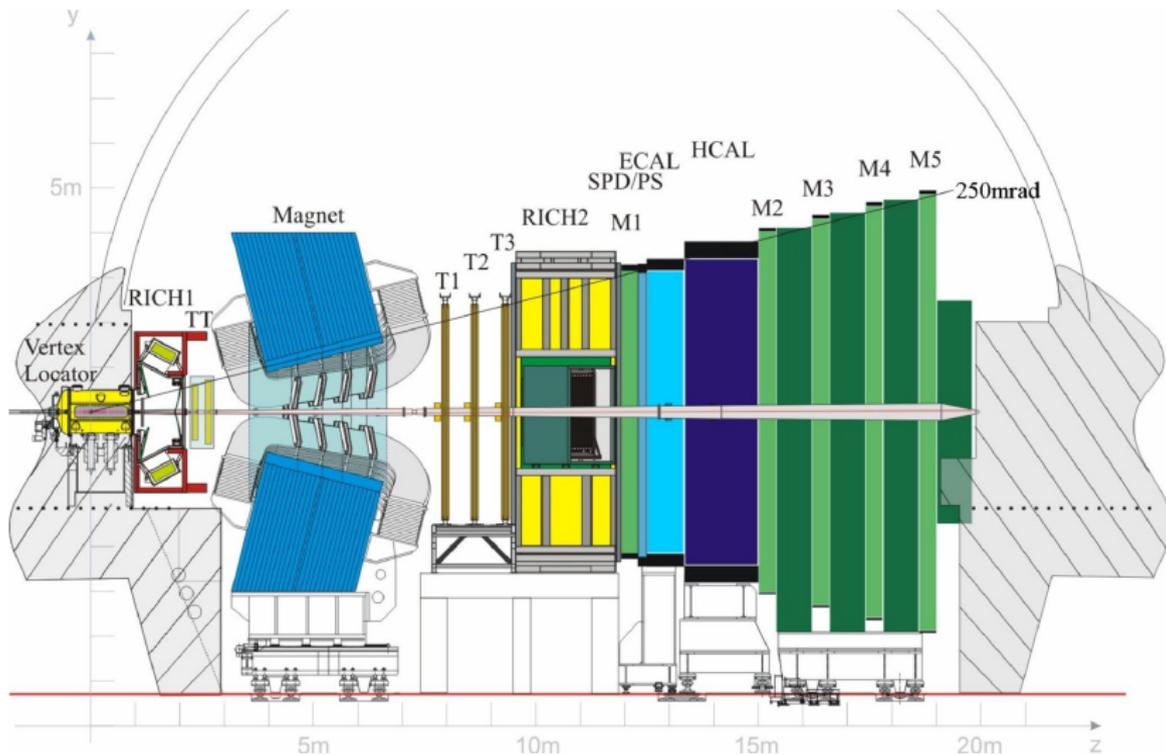
on behalf of the LHCb Collaboration

August 26th, 2025

Introduction

- *CP* Violation (*CP*V) well established in meson decays
  $\rightarrow$ baryonic sector fairly lacking
- *b* quark particularly promising (heavy, long lived)
- Enhancement of penguin-diagram contributions in charmless and doubly-charmed final states
  $\rightarrow$ expect greater *CP*V
- Lack of clear theoretical predictions, due to non-perturbative QCD contributions
- Only direct *CP*V in baryon decays (no oscillation/interference)

$$A_{CP}(H_b \rightarrow f) = \frac{\Gamma(H_b \rightarrow f) - \Gamma(\overline{H}_b \rightarrow \overline{f})}{\Gamma(H_b \rightarrow f) + \Gamma(\overline{H}_b \rightarrow \overline{f})}$$

LHCb Run 1-2 Detector

Ideal setting for b (and c!) physics

- Covers $2 < \eta < 5$ (complements GPD coverage)
- $20\,\mu m$ vertex resolution
- $\Delta p / p \leq 1\%$ momentum resolution ($p \in [5 - 200]\,\text{GeV}/c$)
- Excellent Particle IDentification (PID) capabilities
  - $\varepsilon_{PID}(K \to K) \simeq 95\%$
  - $\varepsilon_{PID}(\pi \to K) < 10\%$
- $40\,\text{fs}$ decay-time resolution

[JINST 3, 8005 (2008)]
[IJMP A 30 (2015) 1530022]

Datasets: Run 1 and Run 2 p-p collisions($\sqrt{s} = 7, 8, 13\,\text{TeV}$)
Integrated luminosity: $9\,\text{fb}^{-1}$ ($3\,\text{fb}^{-1}$ ($\sqrt{s}$=7,8 TeV) + $6\,\text{fb}^{-1}$ ($\sqrt{s}$=13 TeV))

- $\Lambda_b^0 \to ph^-$: *CP* asymmetries [PRD 111 092004]
- $\Lambda_b^0/\Xi_b^0 \to \Lambda h^+ h'^-$: branching ratios and *CP* asymmetries [PRL 134 101802]
- $\Lambda_b^0 \to pK^-\pi^+\pi^-$: *CP* asymmetry [Nature 643 (2025) 1223]
- $\Lambda_b^0/\Xi_b^0 \to pK_S^0 h^-$: branching ratios and *CP* asymmetries [LHCb-PAPER-2025-016]
- $\Lambda_b^0 \to J/\psi ph^-$: *CP* asymmetries [LHCb-PAPER-2025-021][1]

Notation:
h indicates π/K
CP conjugates states are assumed throughout

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[1]Run 2 only

CPV Measurements - General Strategy

CPV observable A_{CP} not directly accessible

$$A_{CP}(\Lambda_b^0 \to f) = \frac{\Gamma(\Lambda_b^0 \to f) - \Gamma(\overline{\Lambda}_b^0 \to \overline{f})}{\Gamma(\Lambda_b^0 \to f) + \Gamma(\overline{\Lambda}_b^0 \to \overline{f})}$$

A_{CP} can be related to the observed countings in the detector accounting for experimental asymmetry effects (A_i)

$$A_{raw}(\Lambda_b^0 \to f) = \frac{N(\Lambda_b^0 \to f) - N(\overline{\Lambda}_b^0 \to \overline{f})}{N(\Lambda_b^0 \to f) + N(\overline{\Lambda}_b^0 \to \overline{f})} \simeq A_{CP} + \sum_i A_i$$

Experimentally Induced Asymmetries

Several asymmetries by the experimental setup:

- $A_{\mathrm{P}}(H_b^0)$ production of the H_b^0 decaying baryon
- $A_{\mathrm{D}}(f)$ detection of the f final state
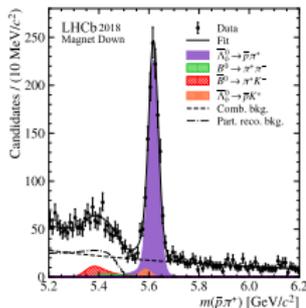- $A_{\mathrm{trig}}(f)$ triggering on f
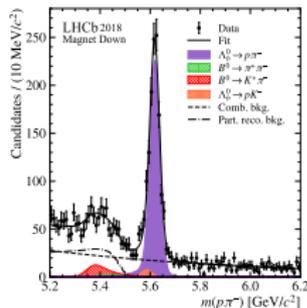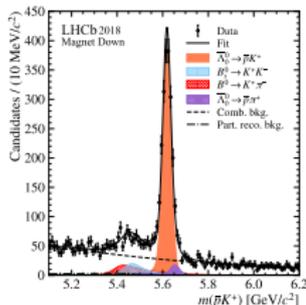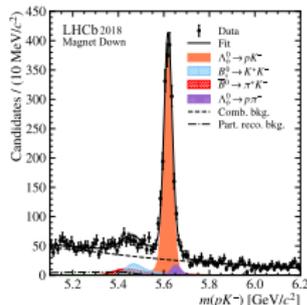- $A_{\mathrm{PID}}(f)$ related to the PID

Partial cancellation of experimental effects can be done with control channels:

- measure $\Delta A_{CP} = A_{CP}^f - A_{CP}^{control}$
- $A_{CP}^{control}$ usually negligible wrt to final measurement precision (Cabibbo-favoured decays, intermediate charmed state)

$\Lambda_b^0 \to ph^-$

[PRD 111 092004]

$\Lambda_b^0 \to ph^-$ good for CPV searches $\to$ similar diagrams to $B^0 \to K^+\pi^-$ (CPV well established here! [JHEP 03(2021)075])

- Run 1 measurement [PLB 787(2018)124] was systematically limited
  - Improve Run 1 measurement with Λ_b^0 production asymmetry ($A_P(\Lambda_b^0)$) and p detection asymmetry ($A_D(p)$) terms [JHEP 10(2021)060]
- New Run 2 analysis
  - avoid $A_P(\Lambda_b^0)$ necessity thanks to $\Lambda_b^0 \to \Lambda_c^+\pi^-$ control sample
+ New strategy for trigger induced asymmetries and PID uncertainties

Final results:
$$A_{CP}(\Lambda_b^0 \to pK^-) = (-1.1 \pm 0.7_{(stat)} \pm 0.4_{(syst)})\%$$
$$A_{CP}(\Lambda_b^0 \to p\pi^-) = (0.2 \pm 0.8_{(stat)} \pm 0.4_{(syst)})\%$$

- No evidence of CPV
- Global averages improved by factor 3
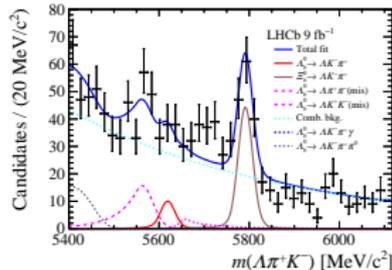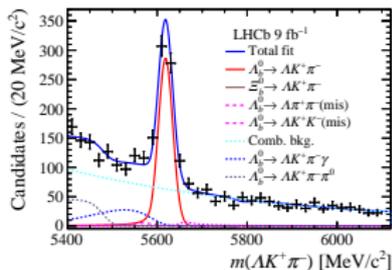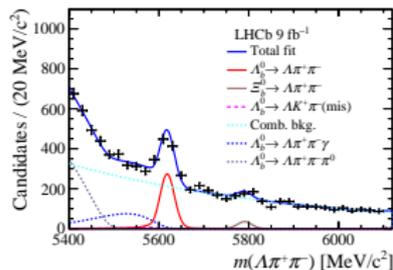- Measurement is statistically limited

[PRD 111 092004]

[PRL 134 101802]

- *CP*V enhancement in $\pi\pi \leftrightarrow KK$ rescattering regions for $B^\pm \to h^\pm h'^+ h''^-$ decays [PRD 108(2023)]
- light resonances may contribute in a similar fashion in $\Lambda_b^0 / \Xi_b^0 \to \Lambda h^+ h'^-$ decays $\to$ possible to observe *CP*V?
- + look into unmeasured branching ratios!
- Use $\Lambda_b^0 \to (\Lambda_c^+ \to \Lambda \pi^+) \pi^-$ decay as control sample (Cabibbo favoured, negligible *CP*V)

$$\frac{\mathcal{B}(\Lambda_b^0(\Xi_b^0) \to \Lambda h^+ h'^-)}{\mathcal{B}(\Lambda_b^0 \to (\Lambda_c^+ \to \Lambda \pi^+) \pi^-)} = \frac{N_{\Lambda_b^0(\Xi_b^0) \to \Lambda h^+ h'^-}}{N_{\Lambda_b^0 \to (\Lambda_c^+ \to \Lambda \pi^+) \pi^-}} \cdot \frac{\varepsilon_{\Lambda_b^0 \to (\Lambda_c^+ \to \Lambda \pi^+) \pi^-}}{\varepsilon_{\Lambda_b^0(\Xi_b^0) \to \Lambda h^+ h'^-}} \cdot \frac{f_{\Lambda_b^0}}{f_{\Lambda_b^0(\Xi_b^0)}}$$

$$\Delta A_{CP}(\Lambda_b^0(\Xi_b^0) \to f) = A_{CP}(\Lambda_b^0(\Xi_b^0) \to f) - A_{CP}(\Lambda_b^0 \to (\Lambda_c^+ \to \Lambda \pi^+) \pi^-)$$

$\mathcal{B}(\Lambda_b^0/\Xi_b^0 \to \Lambda h^+ h'^-)$

$$\mathcal{B}(\Lambda_b^0 \to \Lambda \pi^+ \pi^-) = (\ 5.3 \pm 0.4 \pm 0.5 \pm 0.5_{(\text{norm})}) \cdot 10^{-6} \quad \text{First observation}$$

$$\mathcal{B}(\Xi_b^0 \to \Lambda \pi^+ \pi^-) = (11.0 \pm 2.6 \pm 1.4 \pm 3.8_{(\text{norm})}) \cdot 10^{-6} \quad \text{First evidence} (4\sigma)$$

$$\mathcal{B}(\Lambda_b^0 \to \Lambda K^+ K^-) = (10.7 \pm 0.3 \pm 0.4 \pm 1.1_{(\text{norm})}) \cdot 10^{-6} \quad \text{Confirmed}$$
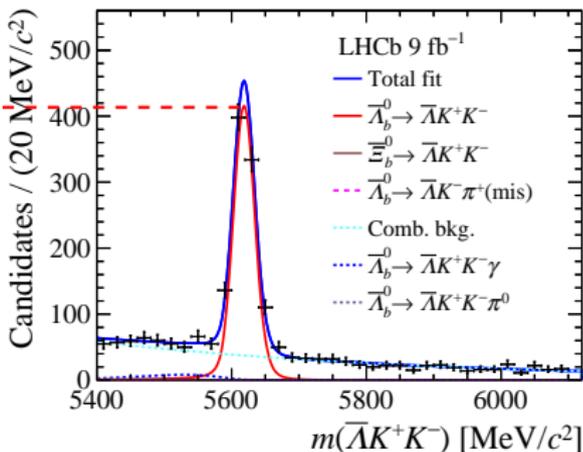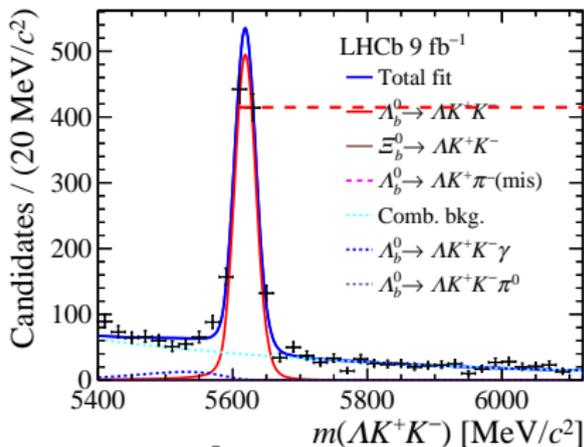
$$\mathcal{B}(\Xi_b^0 \to \Lambda K^+ K^-) < 2.4\,(2.8) \cdot 10^{-6} \text{ at } 90\,(95)\% \text{ CL}$$

$$\mathcal{B}(\Lambda_b^0 \to \Lambda K^+ \pi^-) = (\ 4.6 \pm 0.2 \pm 0.4 \pm 0.5_{(\text{norm})}) \cdot 10^{-6} \quad \text{Confirmed}$$

$$\mathcal{B}(\Xi_b^0 \to \Lambda K^- \pi^+) = (10.4 \pm 1.4 \pm 1.2 \pm 3.5_{(\text{norm})}) \cdot 10^{-6} \quad \text{First observation}$$

[PRL 134 101802]

$C\!PV$ in $\Lambda_b^0/\Xi_b^0 \to \Lambda h^+ h'^-$

$\Delta A_{CP}(\Lambda_b^0 \to \Lambda \pi^+ \pi^-) = -0.013 \pm 0.053 \pm 0.018$

$\Delta A_{CP}(\Lambda_b^0 \to \Lambda K^+ \pi^-) = -0.118 \pm 0.045 \pm 0.021$

$\Delta A_{CP}(\Lambda_b^0 \to \Lambda K^+ K^-) = 0.083 \pm 0.023 \pm 0.016 \qquad 3.1\sigma$ evidence!
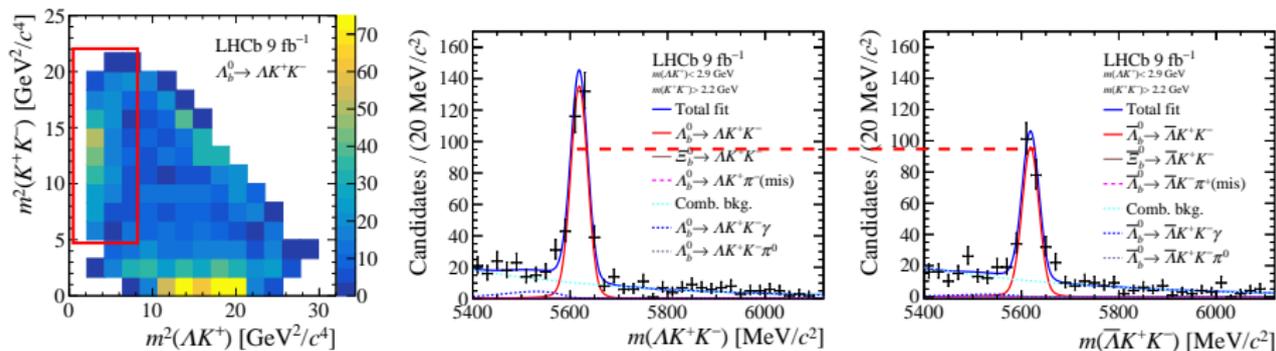
$\Delta A_{CP}(\Xi_b^0 \to \Lambda K^- \pi^+) = 0.27 \pm 0.12 \pm 0.05$

First $C\!PV$ evidence in baryon decays! [PRL 134 101802]

CPV in $\Lambda_b^0 \to \Lambda K^+ K^-$

Look into the Dalitz plots
$\to$ structures in the $N^{*+} \to \Lambda K^+$ and $\phi \to K^+ K^-$ regions

Enhancement of the asymmetry in the N^{*+} region
$(m_{K^+K^-} > 2.20, m_{\Lambda K^+} < 2.90)\,\text{GeV}/c^2$:
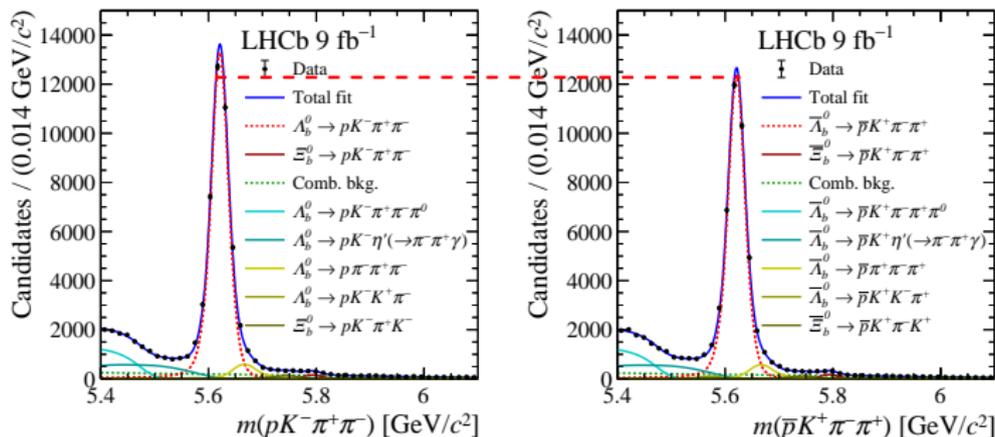
$$\Delta A_{CP} = 0.165 \pm 0.048 \pm 0.017$$

(3.2σ significance)   [PRL 134 101802]

$\Lambda_b^0 \to pK^-\pi^+\pi^-$

Complex dynamic could enhance CPV

Look into the $\Lambda_b^0 \to pK^-\pi^+\pi^-$ decay (against the Cabibbo-favoured $\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\pi^-$ control sample, removes need for $A_P(\Lambda_b^0)$)

$$A_{CP}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (2.45 \pm 0.46 \pm 0.10)\%$$

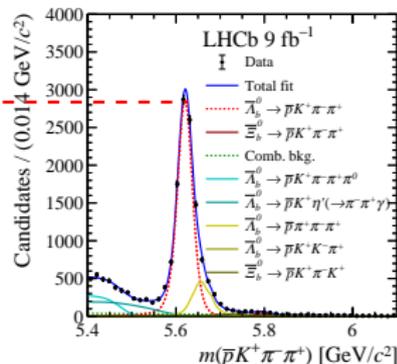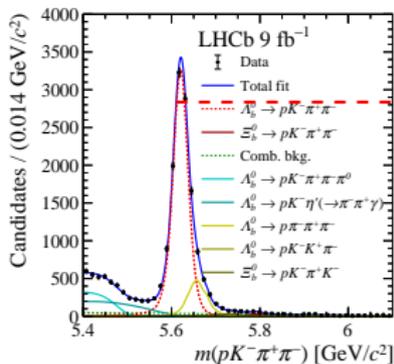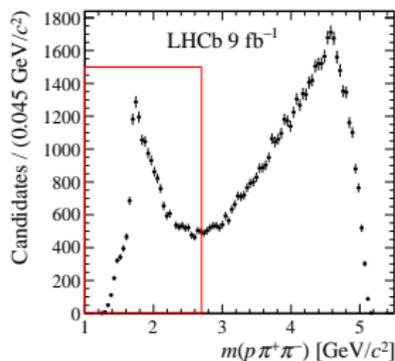First observation (5.2σ) of CPV in baryon decays! [Nature 643 (2025) 1223]

$\Lambda_b^0 \to pK^-\pi^+\pi^-$

Look into A_{CP} for different kinematic regions

- enhancements are observed!

Example: $m_{p\pi^+\pi^-} < 2.7\,\text{GeV}/c^2$ region

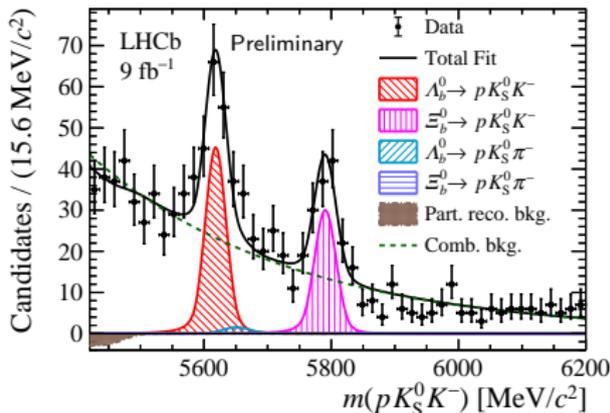$$A_{CP} = (5.4 \pm 0.9 \pm 0.1)\% \quad (6.0\sigma \text{ evidence})$$

[Nature 643 (2025) 1223]

$\Lambda_b^0 / \Xi_b^0 \to p K_S^0 h^-$

[LHCb-PAPER-2025-016] in preparation for JHEP submission

- Improve on 2011 measurement → statistical unc. improved by a factor 9 for $\Lambda_b^0 \to p K_S^0 \pi^-$
- $\Lambda_b^0 \to (\Lambda_c^+ \to p K_S^0) h^-$ control sample

$\mathcal{B}(\Lambda_b^0 \to p K_S^0 \pi^-) = (10.62 \pm 0.21 \pm 0.16 \pm 0.98 \quad\quad) \cdot 10^{-6}$

$\mathcal{B}(\Lambda_b^0 \to p K_S^0 K^-) = (\ 0.61 \pm 0.08 \pm 0.06 \pm 0.06 \quad\quad) \cdot 10^{-6}$ First observation $(8.1\sigma)^2$

$\mathcal{B}(\Xi_b^0 \to p K_S^0 \pi^-) < \ 2.8\,(3.2) \cdot 10^{-6}$ at $90\,(95)\%$ CL
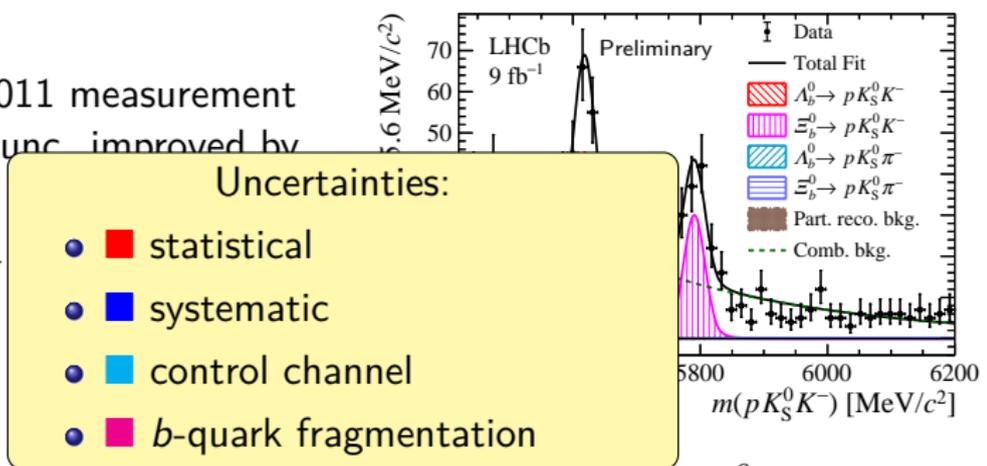
$\mathcal{B}(\Xi_b^0 \to p K_S^0 K^-) = (\ 3.9\ \pm 0.6\ \pm 0.5\ \pm 0.4\ \pm 1.4) \cdot 10^{-6}$ First observation $(8.0\sigma)^2$

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[2]Obtained with stat. and syst. uncertainties on the observed yields

$\Lambda_b^0/\Xi_b^0 \to pK_S^0 h^-$

[LHCb-PAPER-2025-016] in preparation for JHEP submission

- Improve on 2011 measurement → statistical unc. improved by a factor 9 for
- $\Lambda_b^0 \to (\Lambda_c^+ \to$ sample

Uncertainties:

- 🟥 statistical
- 🟦 systematic
- 🟦 control channel
- 🟪 b-quark fragmentation

$\mathcal{B}(\Lambda_b^0 \to pK_S^0\pi^-) = (10.62 \pm 0.21 \pm 0.16 \pm 0.98 \qquad) \cdot 10^{-6}$

$\mathcal{B}(\Lambda_b^0 \to pK_S^0K^-) = (\ 0.61 \pm 0.08 \pm 0.06 \pm 0.06 \qquad) \cdot 10^{-6}$ First observation $(8.1\sigma)^2$
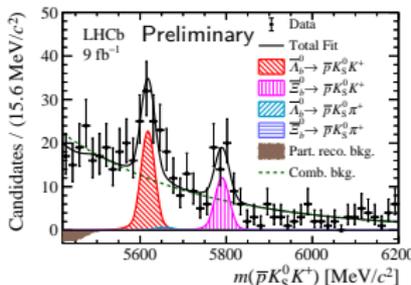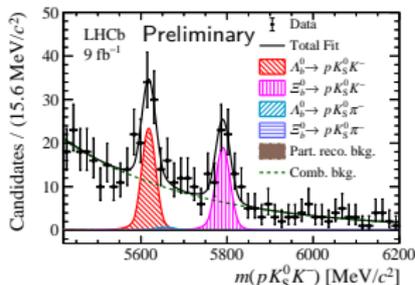
$\mathcal{B}(\Xi_b^0 \to pK_S^0\pi^-) < \ 2.8\,(3.2) \cdot 10^{-6}$ at $90\,(95)\%$ CL

$\mathcal{B}(\Xi_b^0 \to pK_S^0K^-) = (\ 3.9 \ \pm 0.6 \ \pm 0.5 \ \pm 0.4 \ \pm 1.4) \cdot 10^{-6}$ First observation $(8.0\sigma)^2$

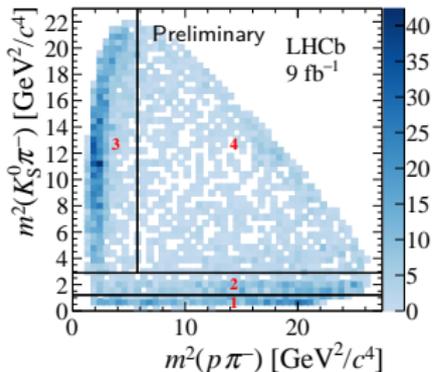^{2}Obtained with stat. and syst. uncertainties on the observed yields

Performed the *CP*V measurements for the observed channels
+ search parameter space for possible local *CP*V

- No hints of *CP*V

All sample:

Channel	ΔA_{CP} [%]		
$\Lambda_b^0 \to pK_S^0\pi^-$	3.4	$\pm\ 1.9$	$\pm\ 0.9$
$\Lambda_b^0 \to pK_S^0 K^-$	2	$\pm\ 13$	$\pm\ 9$
$\Xi_b^0 \to pK_S^0 K^-$	22	$\pm\ 15$	$\pm\ 11$

Enough statistics only to explore
$\Lambda_b^0 \to pK_S^0\pi^-$ kinematic bins:

Bin	ΔA_{CP} [%]
1	$-\ 0.6 \pm 4.0 \pm 1.9$
2	$12.4 \pm 4.2 \pm 1.8$
3	$0.5 \pm 2.4 \pm 1.1$
4	$3.3 \pm 5.5 \pm 2.0$

[LHCb-PAPER-2025-016]

$\Lambda_b^0 \to J/\psi\, p h^-$

[LHCb-PAPER-2025-021] in preparation for Science Bulletin submission

- Fruitful CPV searches in $b \to ccq$ ($q \in [d,s]$) transitions for mesons ($> 3\sigma$ evidence of CPV in $B^+ \to J/\psi\, h^+$, [PRL 134 101801])
- Look into $\Lambda_b^0 \to (J/\psi \to \mu^+\mu^-) p h^-$
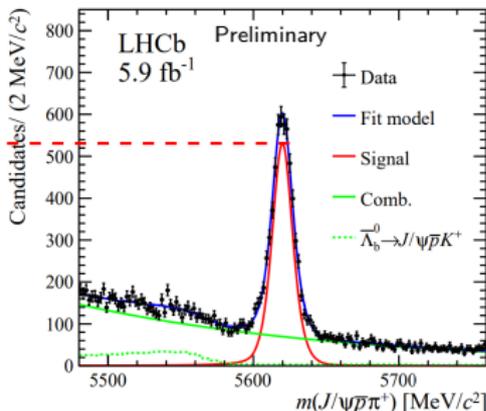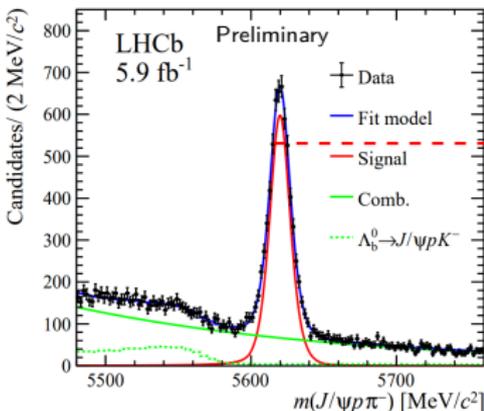
$$\Delta A_{CP} = A_{CP}(\Lambda_b^0 \to J/\psi\, p\pi^-) - A_{CP}(\Lambda_b^0 \to J/\psi\, pK^-)$$

$$\Delta A_{CP} = A_{\text{raw}}(\Lambda_b^0 \to J/\psi\, p\pi^-) - A_{\text{raw}}(\Lambda_b^0 \to J/\psi\, pK^-) + A_{\text{D}}(K^-) - A_{\text{D}}(\pi^-)$$

- Run 1 measurement [JHEP 07(2014)103] statistically limited, no hints of CPV

$$\Delta A_{CP}^{\text{Run 1}} = (5.7 \pm 2.4 \pm 1.2)\%$$

$\Lambda_b^0 \to J/\psi p h^-$

Preliminary results:

- $\Delta A_{CP}^{\text{Run 2}} = (4.03 \pm 1.18 \pm 0.23)\%$
- Run 1 and Run 2 combination (Best Linear Unbiased Estimator)

$$\Delta A_{CP} = (4.31 \pm 1.06 \pm 0.28)\% \quad 3.9\sigma \text{ evidence!}$$

First evidence of CPV in baryon decays to charmonia! [LHCb-PAPER-2025-021]

$\Lambda_b^0 \to J/\psi p h^-$

- Triple-product asymmetry (TPA) [PRD 92 076013]

$$\mathcal{A}_{\hat{T}\text{-odd}} = \frac{1}{2}\left(\frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} \leq 0)}{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} \leq 0)} - \frac{\overline{N}(-\overline{C}_{\hat{T}} > 0) - \overline{N}(-\overline{C}_{\hat{T}} \leq 0)}{\overline{N}(-\overline{C}_{\hat{T}} > 0) - \overline{N}(-\overline{C}_{\hat{T}} \leq 0)}\right)$$

No evidence of TPA!

$C_{\hat{T}} = \vec{p}_{\mu^+} \cdot (\vec{p}_p \times \vec{p}_{\pi^-})$ $\mathcal{A}_{\hat{T}\text{-odd}}(\Lambda_b^0 \to J/\psi p \pi^-) = (-1.37 \pm 1.15)\%$

$\overline{C}_{\hat{T}} = \vec{p}_{\mu^-} \cdot (\vec{p}_{\overline{p}} \times \vec{p}_{\pi^+})$ $\mathcal{A}_{\hat{T}\text{-odd}}(\Lambda_b^0 \to J/\psi p K^-) = (-0.04 \pm 1.28)\%$

- Investigation of the phase space for local CPV enhancement
  Binning schemes
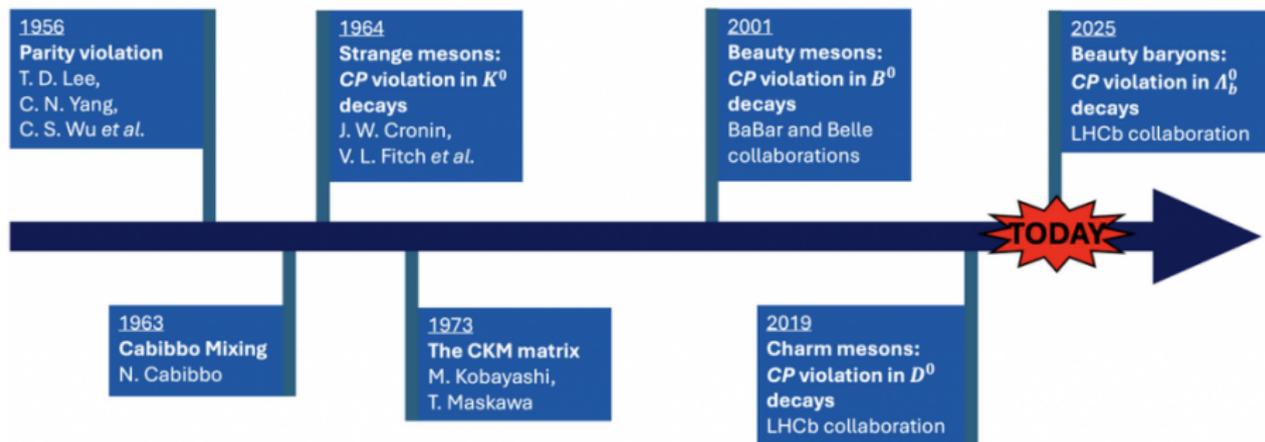 - 4 and 128 equally populated bins of the Dalitz
  - Resonant structures $\Lambda_b^0 \to J/\psi N$ (total of 4 $m(p\pi^-)$ bins)
  - $\Lambda_b^0 \to J/\psi N$ resonances + $p\pi^-$ pair helicity angle ϑ
    (8 total bins, 4 mass, 2 $\cos\vartheta \gtrless 0$)

  No variation of the asymmetries! (neither A_{raw} nor TPA)
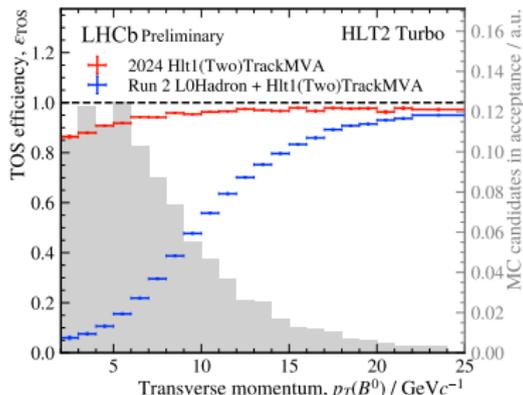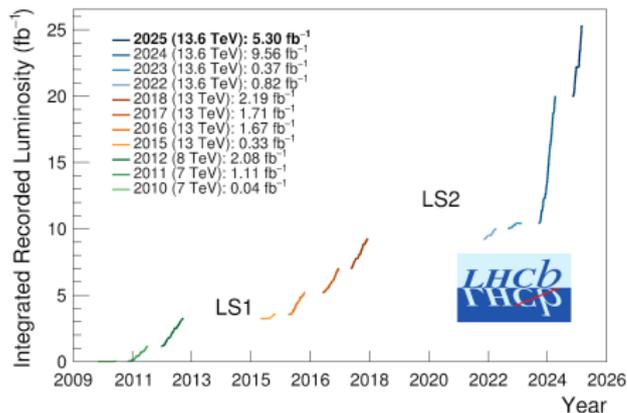 [LHCb-PAPER-2025-021]

Conclusion

Setting new milestone in the *CP*V journey:

> ## Direct *CP* violation in baryon decays

Future

Bright future ahead:

- LHCb Run 3 data taking
  - → Upgraded detector! [JINST 19 (2024) P05065]
  - → surpassed Run 1 and 2 integrated luminosity (2024 alone)
- Fully software trigger: almost doubled efficiency on flagship and core physics decay channels [LHCB-FIGURE-2024-030]

Thank you for your attention!

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