CP Violation in Baryon Decays at LHCb

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on behalf of the LHCb collaboration

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Outline

* Here "h" means K or π

- Introduction
- CP violation in charmless beauty baryon decays
  - $\Lambda_b^0 \to p h^-$ [PRD 111 (2025), 092004]
  - $\Lambda_b^0/\Xi_b^0 \to \Lambda h_1^+ h_2^-$ [PRL 134 (2025) 101802]
  - $\Lambda_b^0/\Xi_b^0 \to p K_s^0 h^-$ [LHCb-PAPER-2025-016, in prep.]
  - $\Lambda_b^0 \to p K^- \pi^+ \pi^-$ [arXiv:2503.16954, accepted by Nature]
- CP violation in beauty baryon to charmonium decays
  - $\Lambda_b^0 \to J/\psi p h^-$ [LHCb-PAPER-2025-021, in prep.]
- CP violation in beauty baryon to open charm decays (decay parameters)
  - $\Lambda_b^0 \to \Lambda_c^0 h^-$ [PRL 133 (2024) 261804]
- Conclusions and Outlook

Introduction

- Violation of CP symmetry is essential to explain the observed matter-antimatter asymmetry in the Universe
- CP violation has been well-established in oscillations and decays of mesons
  - Particularly, B meson decays exhibit CP asymmetries at the level of ~10%
- For baryons, CP violation had never been observed — until recently!

➢ Hyperon: [PRL 129, 131801 (2022)]

- $A_{CP}(\Lambda \to p\pi^-) = (-0.25 \pm 0.48)\%$

➢ Charm baryons: [JHEP 03 (2018) 182]

- $A_{CP}(\Lambda_c^+ \to pK^+K^-) - A_{CP}(\Lambda_c^+ \to p\pi^+\pi^-) = (0.30 \pm 1.1)\%$

➢ Bottom baryons: [PRL 134 (2025) 101802]

- $A_{CP}(\Lambda_b^0 \to \Lambda K^+K^-) = (-8.3 \pm 2.8)\%$
- $A_{CP}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (2.45 \pm 0.47)\%$ [arXiv:2503.16954] ➡ First Observation!

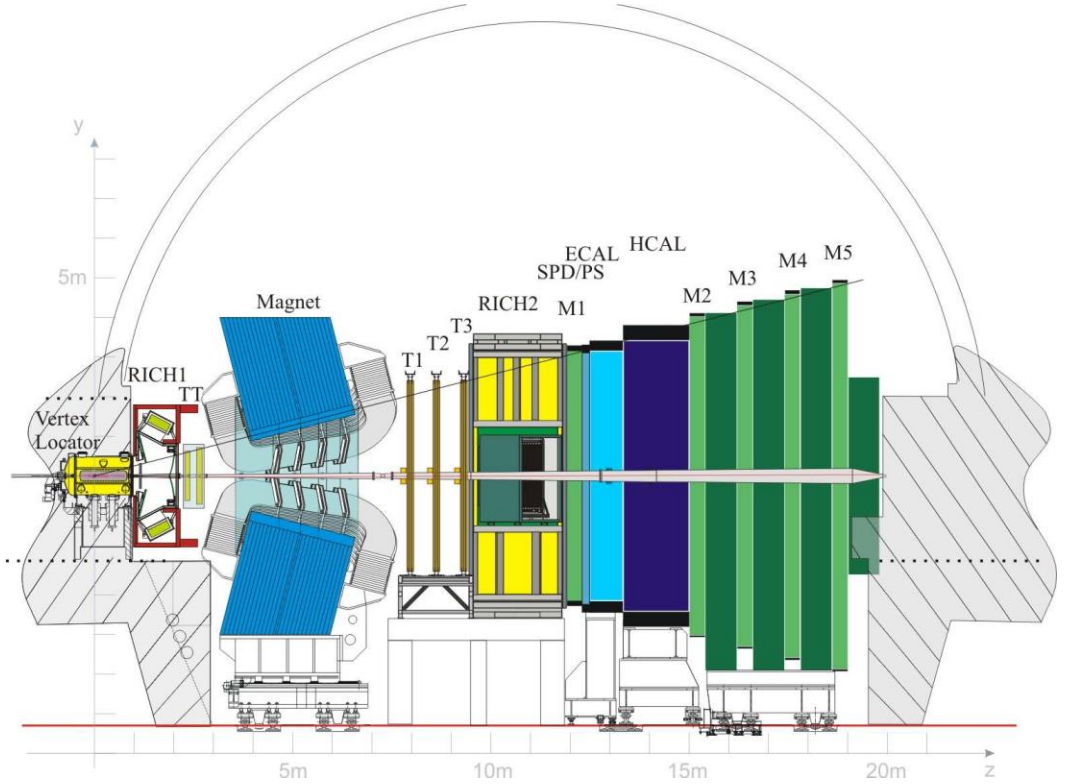
- CP violation in baryons is complementary to meson studies and essential for comprehensive tests of the CKM mechanism

LHCb experiment

- Dedicated experiment at CERN for measurement of b, c hadrons
  - Single-arm forward spectrometer covers $2 < \eta < 5$
  - Excellent vertex resolution
    - $\sigma_{\mathrm{IP}} = 20\ \mu\mathrm{m}$
  - Excellent momentum resolution
    - $\Delta p/p = 0.5 - 1.0\%\ (5 - 200\ GeV/c)$
  - Efficient particle identification
    - $\epsilon(K \to K) \sim 95\%$
    - misID$\epsilon(\pi \to K) \sim 5\%$

❖ LHCb Dataset

❖ Run1 + Run2 (2011-2018): 9 fb^{-1} of pp collisions



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

A_{CP} measurement in $\Lambda_b^0 \to ph^-$ decays

[PRD 111 (2025), 092004]

- Search for CP violation in $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$ decays, using Run1+Run2 samples
- Dynamics analogy to $B^0 \to h^+h^-$ decays

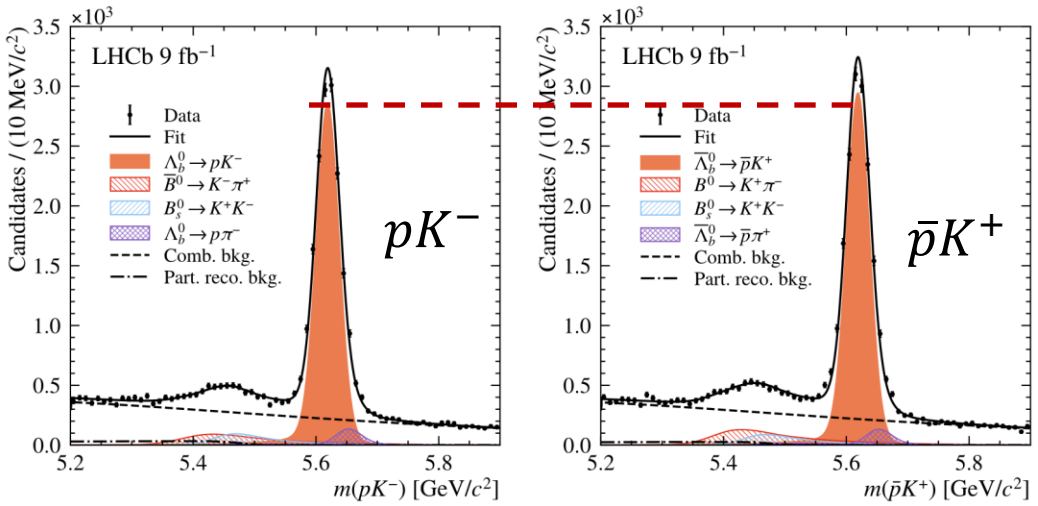
Transition	$b \to u\bar{u}d$		$b \to u\bar{u}s$	
Decays	$B^0 \to \pi^+\pi^-$	$B_s^0 \to \pi^+K^-$	$B^0 \to K^+\pi^-$	$B_s^0 \to K^+K^-$
CPV (%)	-31.4 ± 3.0	22.4 ± 1.2	8.31 ± 0.31	16.2 ± 3.5

- Most precise result in this mode
  - The precision improved by a factor of 3 compared to the PDG value $\begin{cases} A_{CP}^{p\pi^-} = (-2.5 \pm 2.2)\% \\ A_{CP}^{pK^-} = (-2.5 \pm 2.9)\% \end{cases}$
  - Not dominated by systematics anymore

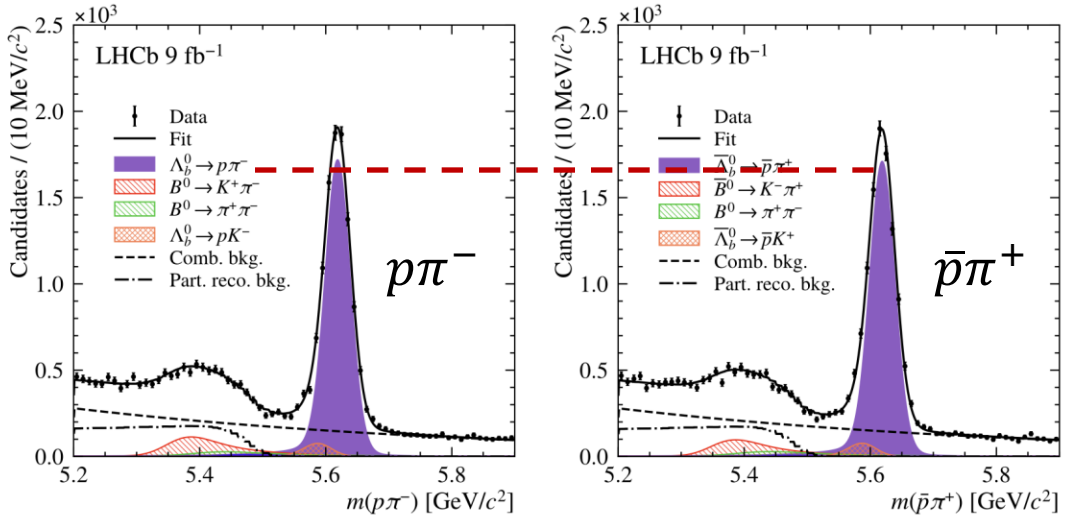
(Dominated by LHCb Run1 measurement)
[PRB 787 (2018) 124-133]

- Sizable CP violation ruled out

$$A_{CP}^{pK^-} = (-1.1 \pm 0.7 \pm 0.4)\%$$



$$A_{CP}^{p\pi^-} = (+0.2 \pm 0.8 \pm 0.4)\%$$

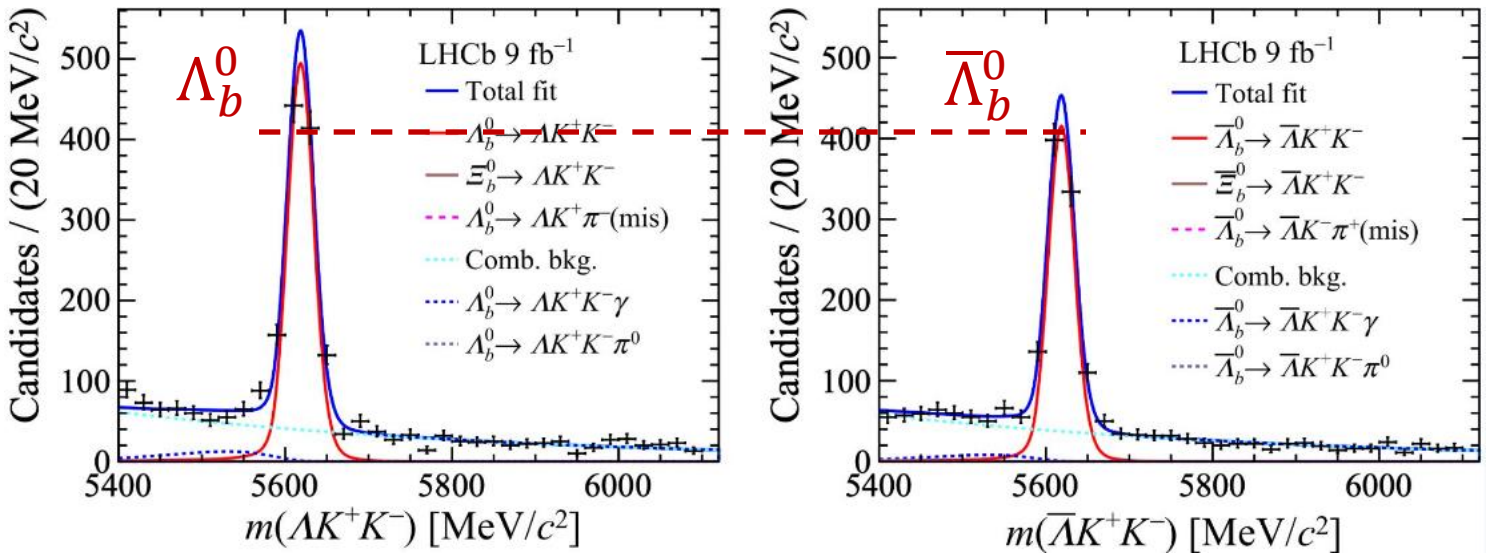


A_{CP} measurement in $\Lambda_b^0/\Xi_b^0 \to \Lambda h_1^+ h_2^-$ decays

[PRL 134 (2025) 101802]

- Study of three Λ_b^0 decays $\Lambda\pi^+\pi^-, \Lambda K^+\pi^-, \Lambda K^+K^-$, and $\Xi_b^0 \to \Lambda K^-\pi^+$ decay, Run1+Run2
  - Control channel: $\Lambda_b^0 \to \Lambda_c^+(\to \Lambda\pi^+)\pi^-$
- Evidence (3.1σ) of direct CP violation is found in $\Lambda_b^0 \to \Lambda K^+K^-$ decay
  - $\Delta A_{CP} = A_{\rm raw}(\text{signal}) - A_{\rm raw}(\text{control}) - \Delta A_{\rm P} - \Delta A_{\rm exp}$

$$\begin{aligned}
\Delta\mathcal{A}^{CP}\left(\Lambda_b^0 \to \Lambda\pi^+\pi^-\right) &= -0.013 \pm 0.053 \pm 0.018,\\
\Delta\mathcal{A}^{CP}\left(\Lambda_b^0 \to \Lambda K^+\pi^-\right) &= -0.118 \pm 0.045 \pm 0.021,\\
\Delta\mathcal{A}^{CP}\left(\Lambda_b^0 \to \Lambda K^+K^-\right) &= 0.083 \pm 0.023 \pm 0.016,\\
\Delta\mathcal{A}^{CP}\left(\Xi_b^0 \to \Lambda K^-\pi^+\right) &= 0.27 \pm 0.12 \pm 0.05,
\end{aligned}$$



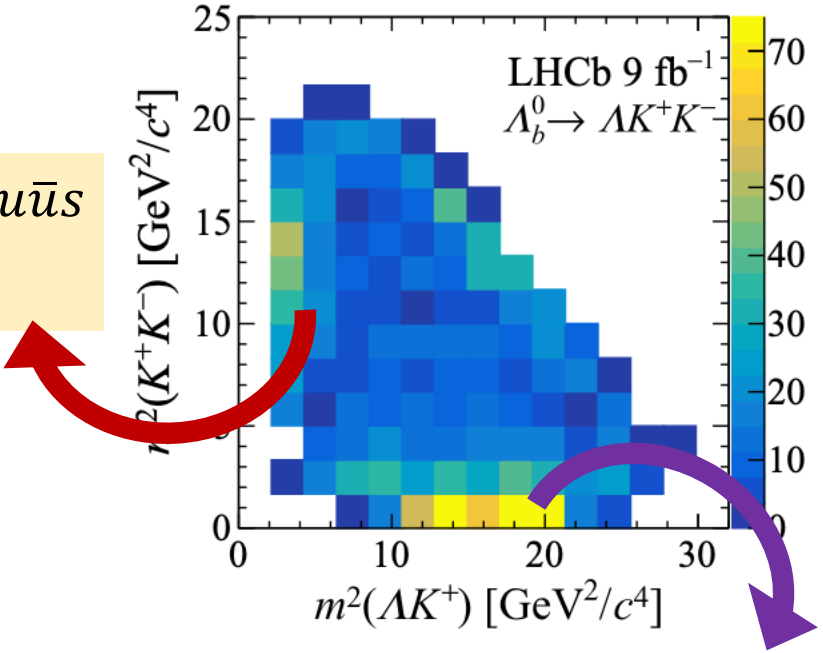
A_{CP} measurement in $\Lambda_b^0/\Xi_b^0 \to \Lambda h_1^+ h_2^-$ decays

[PRL 134 (2025) 101802]

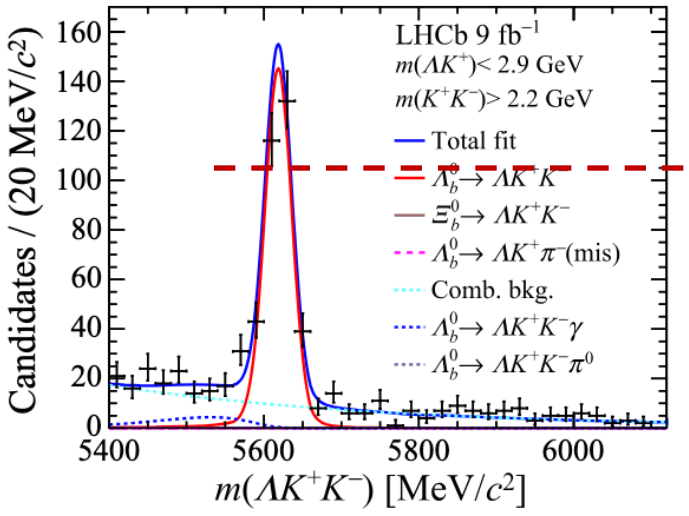
- $\Lambda_b^0 \to \Lambda K^+ K^-$ is dominated by intermediate $N^{*+}(\to \Lambda K^+)$ and $\phi(\to K^+K^-)$ resonances
- In the region dominated by the N^{*+} resonance, local A_{CP} show 3.2σ evidence: $m_{\Lambda K^+} < 2.9$ GeV

$\Lambda_b^0 \to N^{*+}(\to \Lambda K^+)K^-$: possibly via $b \to u\bar{u}s$

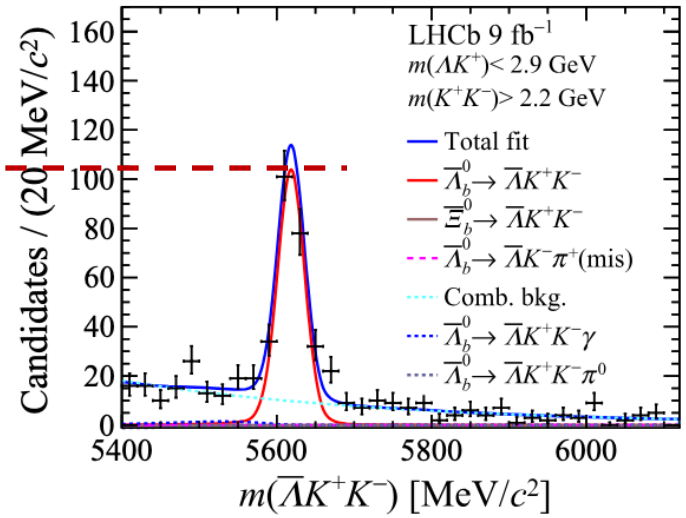
$\Delta A_{CP}(N^{*+}K^-) = 0.165 \pm 0.048 \pm 0.017$



$\Lambda_b^0 \to N^{*+}K^-$



$\bar{\Lambda}_b^0 \to N^{*-}K^+$



$m_{K^+K^-} < 1.1$ GeV (consistent with zero)

$\Lambda_b^0 \to \Lambda\phi(\to K^+K^-)$ or non-resonant:

$\Delta A_{CP}(\Lambda\phi) = 0.150 \pm 0.055 \pm 0.021$

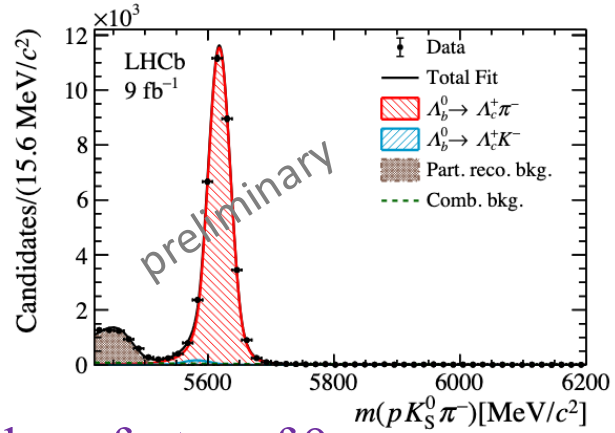
Study of $\Lambda_b^0/\Xi_b^0 \to pK_s^0h^-$ decays

[LHCb-PAPER-2025-016] , in preparation
To be submitted to Sci. Bull.

[New!]

- Study of Λ_b^0 and Ξ_b^0 baryon to the final states of $pK_s^0\pi^-$ and $pK_s^0K^-$, Run1+Run2
  - Update of previous analysis used only 2011 data
  - Control channel: $\Lambda_b^0 \to \Lambda_c^+(\to pK_s^0)\pi^-$

Control channel:
$\Lambda_b^0 \to \Lambda_c^+(\to K_s^0p)\pi^-$

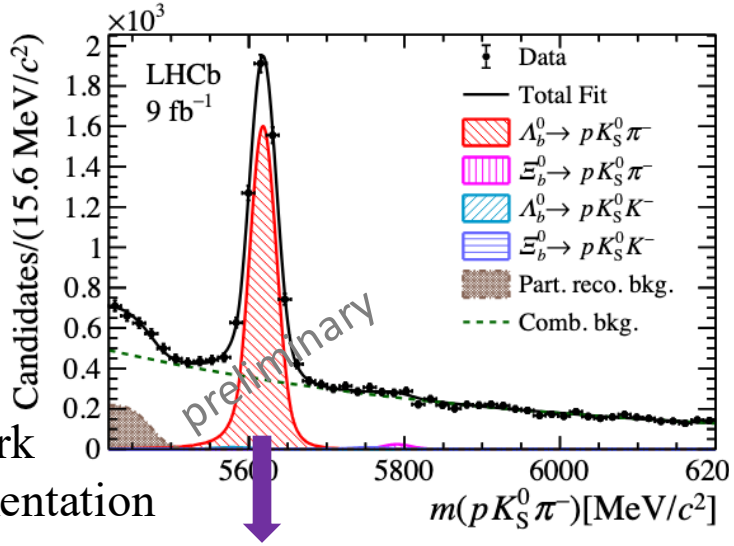


- Measurement of all 4 BFs
  - Observation of $\Lambda_b^0 \to pK_s^0\pi^-$ with statistical precision improved by a factor of 9
  - First Observation of 2 decay

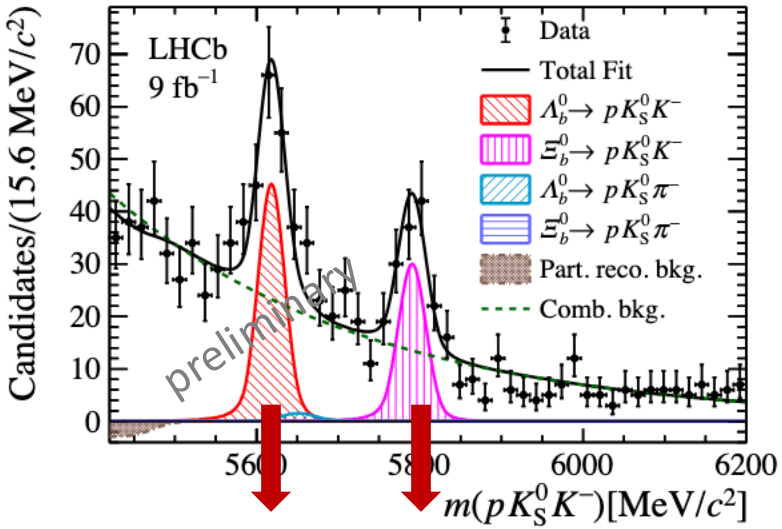
preliminary

	Result $[\times 10^{-6}]$
$\mathcal{B}(\Lambda_b^0 \to pK_S^0\pi^-)$	$10.62 \pm 0.21 \pm 0.16 \pm 0.98$
$\mathcal{B}(\Lambda_b^0 \to pK_S^0K^-)$	$0.61 \pm 0.08 \pm 0.06 \pm 0.06$
$\mathcal{B}(\Xi_b^0 \to pK_S^0\pi^-)$	$< 2.8\,(3.2)$ at $90\,(95)\%$ CL
$\mathcal{B}(\Xi_b^0 \to pK_S^0K^-)$	$3.9 \pm 0.6 \pm 0.5 \pm 0.4 \pm 1.4$

stat. syst. control mode b-quark fragmentation fractions



Observation with higher precision



First Observation!

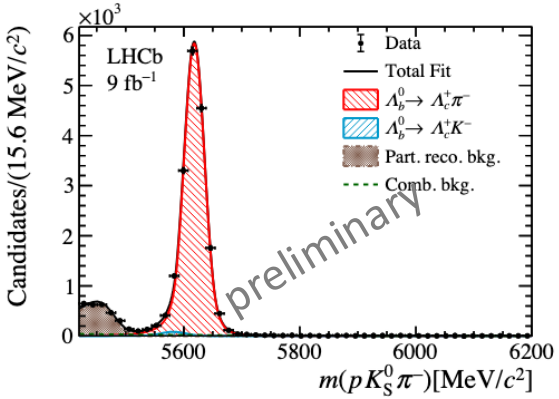
Study of $\Lambda_b^0/\Xi_b^0 \to pK_s^0h^-$ decays

[LHCb-PAPER-2025-016] , in preparation
To be submitted to Sci. Bull. **[New!]**

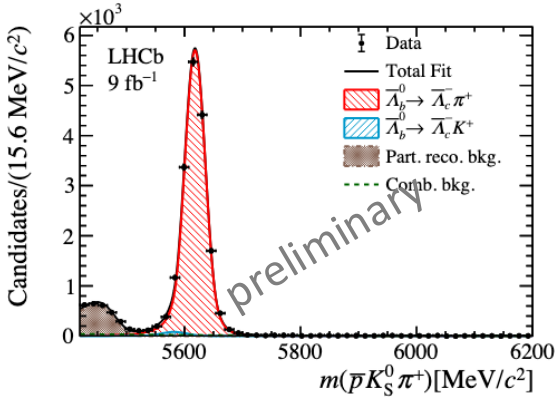
- A_{CP} measurement in 3 observed decays
  - $A_{CP}(\text{signal}) = \Delta A_{\text{raw}} - \Delta A^P - \Delta A^{\text{exp}}$

➢ Control channel

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

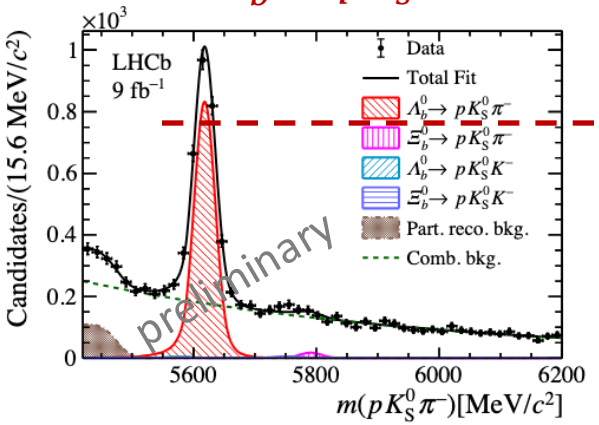


$\overline{\Lambda}_b^0 \to \overline{\Lambda}_c^-\pi^+$

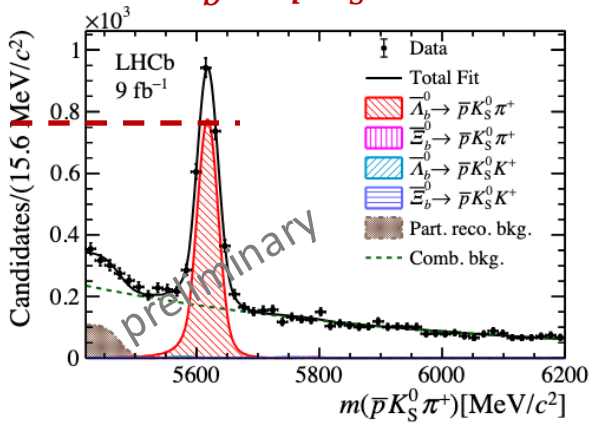


➢ Signal channel

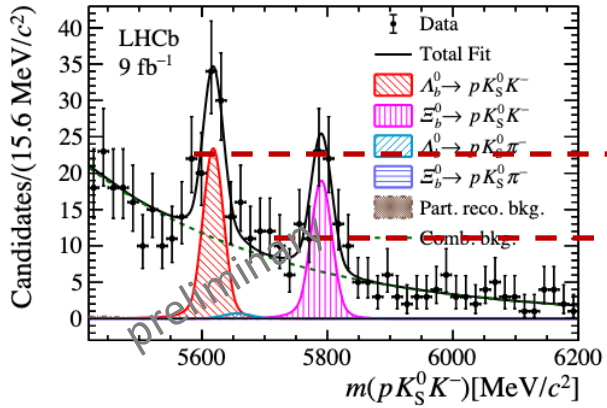
$\Lambda_b^0 \to pK_s^0\pi^-$



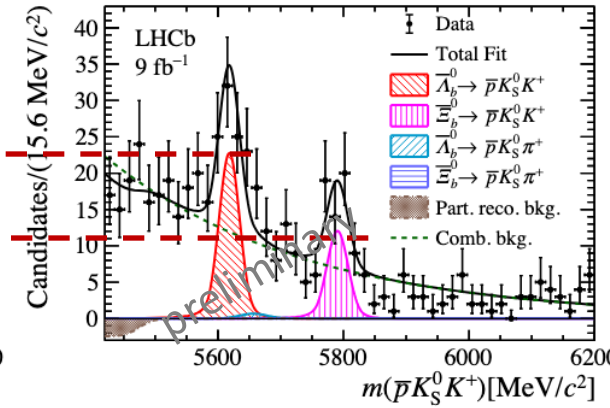
$\overline{\Lambda}_b^0 \to \bar{p}K_s^0\pi^+$



$\Lambda_b^0 \to pK_s^0K^-$



$\overline{\Lambda}_b^0 \to \bar{p}K_s^0K^+$

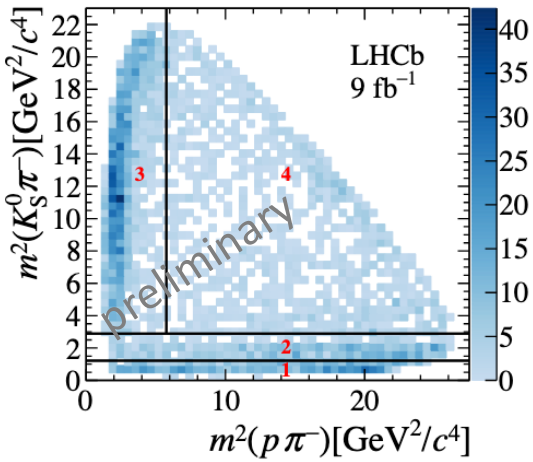


Study of $\Lambda_b^0/\Xi_b^0 \to pK_s^0h^-$ decays

[LHCb-PAPER-2025-016] , in preparation
To be submitted to Sci. Bull.

[New!]

- Local A_{CP} for $\Lambda_b^0 \to pK_s^0\pi^-$ investigated
  - N^*, K^{*-} resonances observed
  - A_{CP} measured in 4 bins



- No CP violation is found
  - Global A_{CP} in 3 decay modes

preliminary

	Result [%]
$\mathcal{A}^{CP}$ $(\Lambda_b^0 \to pK_S^0\pi^-)$	$3.4 \pm 1.9 \pm 0.9$
$\mathcal{A}^{CP}$ $(\Lambda_b^0 \to pK_S^0K^-)$	$2 \pm 13 \pm 9$
$\mathcal{A}^{CP}$ $(\Xi_b^0 \to pK_S^0K^-)$	$22 \pm 15 \pm 11$

  - Local A_{CP} in 4 regions of $\Lambda_b^0 \to pK_s^0\pi^-$ decay

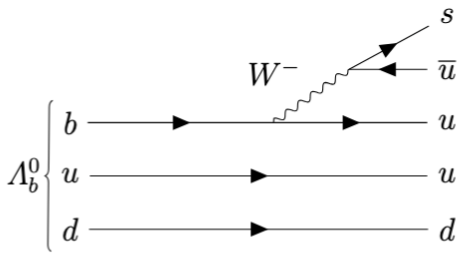
preliminary

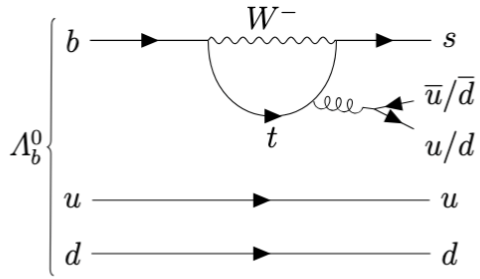
	$m(p\pi^-)$	$m(K_S^0\pi^-)$	Yield	$\mathcal{A}^{CP}$ [%]
Bin 1	-	$< 1.1\,\text{GeV}/c^2$	821 ± 34	$-0.6 \pm 4.0 \pm 1.9$
Bin 2	-	$[1.1, 1.7]\,\text{GeV}/c^2$	870 ± 40	$12.4 \pm 4.2 \pm 1.8$
Bin 3	$< 2.4\,\text{GeV}/c^2$	$> 1.7\,\text{GeV}/c^2$	2200 ± 50	$0.5 \pm 2.4 \pm 1.1$
Bin 4	$> 2.4\,\text{GeV}/c^2$	$> 1.7\,\text{GeV}/c^2$	840 ± 50	$3.3 \pm 5.5 \pm 2.0$

A_{CP} measurement in $\Lambda_b^0 \to pK^-\pi^+\pi^-$ decays

[arXiv:2503.16954, accepted by Nature]

- Search for CP violation in $\Lambda_b^0 \to pK^-\pi^+\pi^-$ decays
  - $\boldsymbol{A_{CP} = \frac{\Gamma(\Lambda_b^0 \to p K^-\pi^+\pi^-) - \Gamma(\bar{\Lambda}_b^0 \to \bar{p} K^+\pi^-\pi^+)}{\Gamma(\Lambda_b^0 \to p K^-\pi^+\pi^-) + \Gamma(\bar{\Lambda}_b^0 \to \bar{p} K^+\pi^-\pi^+)}}$
- Amplitudes of the tree and penguin transitions are expected to have comparable contributions





➡ Sizeable weak phase difference

- Rich resonances

$\Lambda_b^0 \to N^{*+}(p\pi^+\pi^-)K^-$, $pK^*(K^-\pi^+\pi^-)$

$\Lambda_b^0 \to \Lambda^*(pK^-)f(\pi^+\pi^-)$, $N^{*0}(p\pi^-)K^*(\pi^+K^-)$

➡ Possible strong phase difference

- Cancelling production and detection asymmetries: $A_{CP} = \Delta A_{\text{raw}} - \Delta A_{\text{prod}} - \Delta A_{\text{exp}}$
  - Control channel: $\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\pi^-$
  - Same final state, no CP violation expected

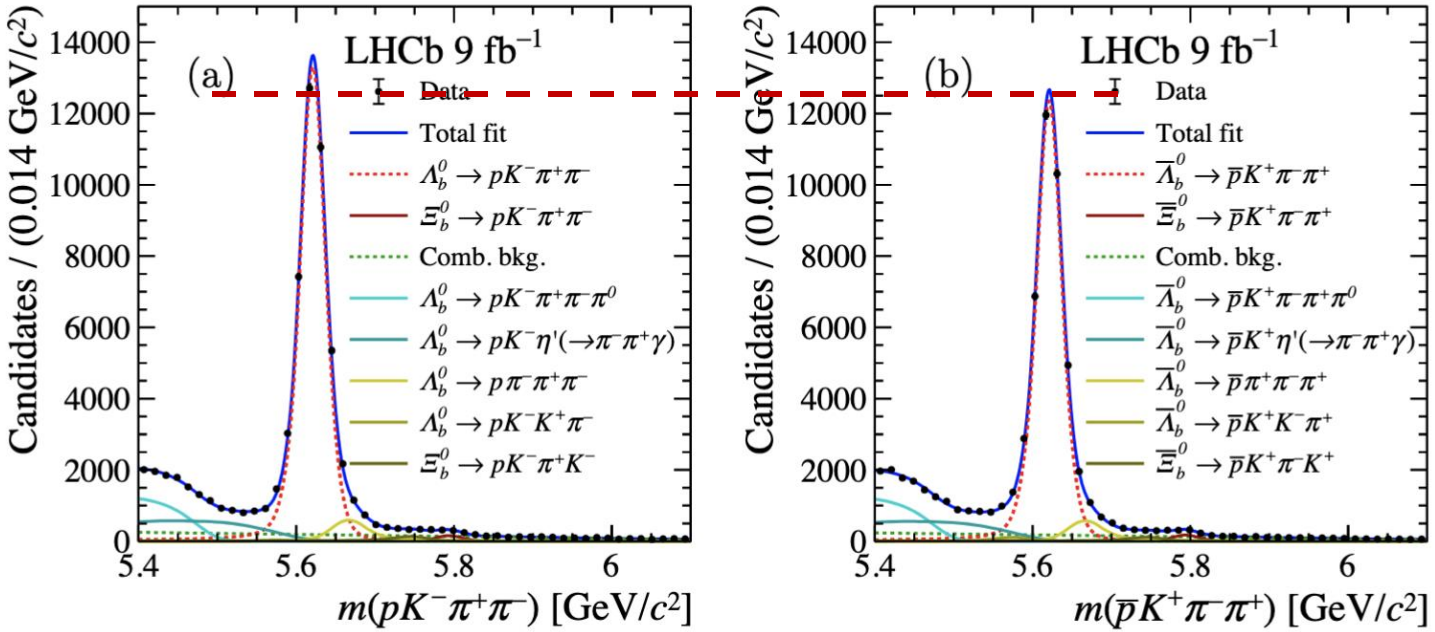
A_{CP} measurement in $\Lambda_b^0 \to pK^-\pi^+\pi^-$ decays [arXiv:2503.16954, accepted by Nature]

➢ First observation of CPV in baryonic decays

- $A_{CP} = (2.45 \pm 0.46 \pm 0.10)\%$ **5.2σ**

➢ Signal channel

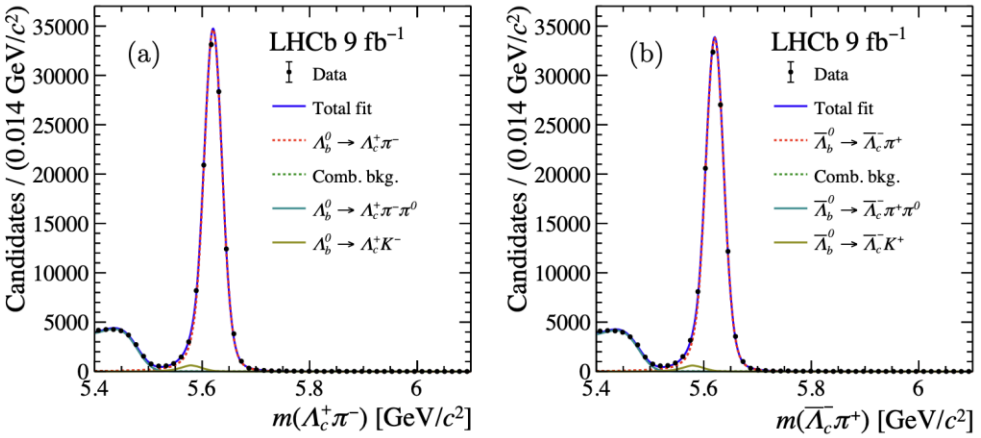
$\Lambda_b^0 \to pK^-\pi^+\pi^-$ $\quad$ $\overline{\Lambda}_b^0 \to \bar{p}K^+\pi^-\pi^+$



$A_{\text{raw}}(\text{signal}) = (3.71 \pm 0.39)\%$

➢ Control channel

$\Lambda_b^0 \to \Lambda_c^+\pi^-$ $\quad$ $\overline{\Lambda}_b^0 \to \overline{\Lambda}_c^-\pi^+$



$A_{\text{raw}}(\text{control}) = (1.25 \pm 0.23)\%$

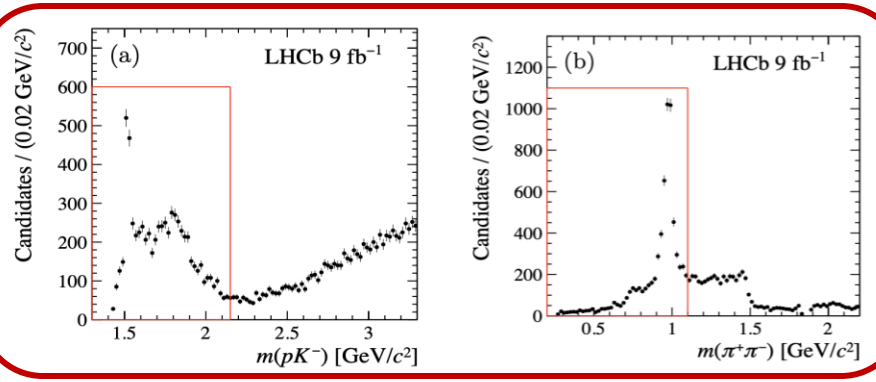
A_{CP} measurement in $\Lambda_b^0 \to pK^-\pi^+\pi^-$ decays [arXiv:2503.16954, accepted by Nature]

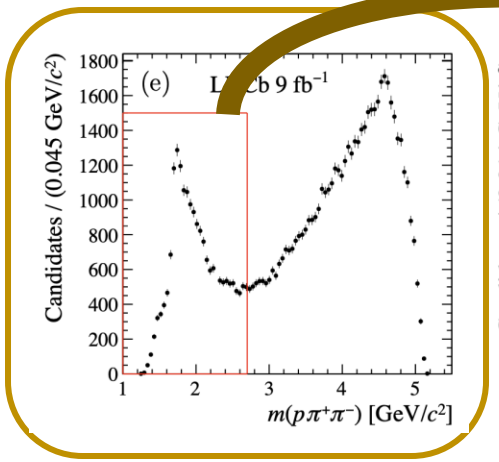
➢Local A_{CP} reaching 6σ

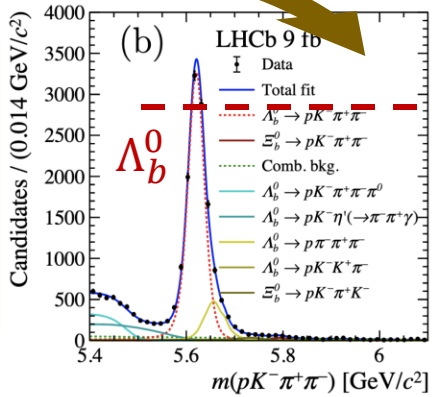
- Interference between resonance states induces phase-space-dependent CPV
- Most significant local CPV found in N^+ resonances regions

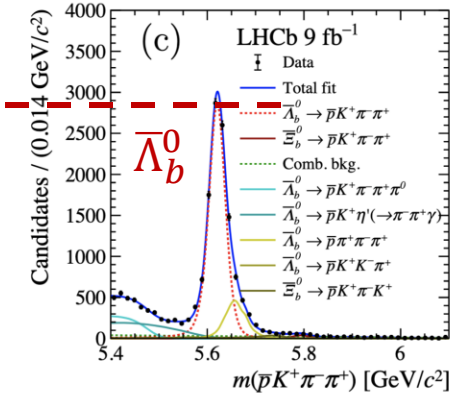
Decay topology	Mass region (GeV/c^2)	$\mathcal{A}_{CP}$	
$\Lambda_b^0 \to R(pK^-)R(\pi^+\pi^-)$	$m_{pK^-} < 2.2$ $m_{\pi^+\pi^-} < 1.1$	$(5.3 \pm 1.3 \pm 0.2)\%$	4σ
	$m_{p\pi^-} < 1.7$		
$\Lambda_b^0 \to R(p\pi^-)R(K^-\pi^+)$	$0.8 < m_{\pi^+K^-} < 1.0$ or $1.1 < m_{\pi^+K^-} < 1.6$	$(2.7 \pm 0.8 \pm 0.1)\%$	
$\Lambda_b^0 \to R(p\pi^+\pi^-)K^-$	$m_{p\pi^+\pi^-} < 2.7$	$(5.4 \pm 0.9 \pm 0.1)\%$	6σ
$\Lambda_b^0 \to R(K^-\pi^+\pi^-)p$	$m_{K^-\pi^+\pi^-} < 2.0$	$(2.0 \pm 1.2 \pm 0.3)\%$	

❖ Λ resonances ❖ $f_0(980)$ resonances







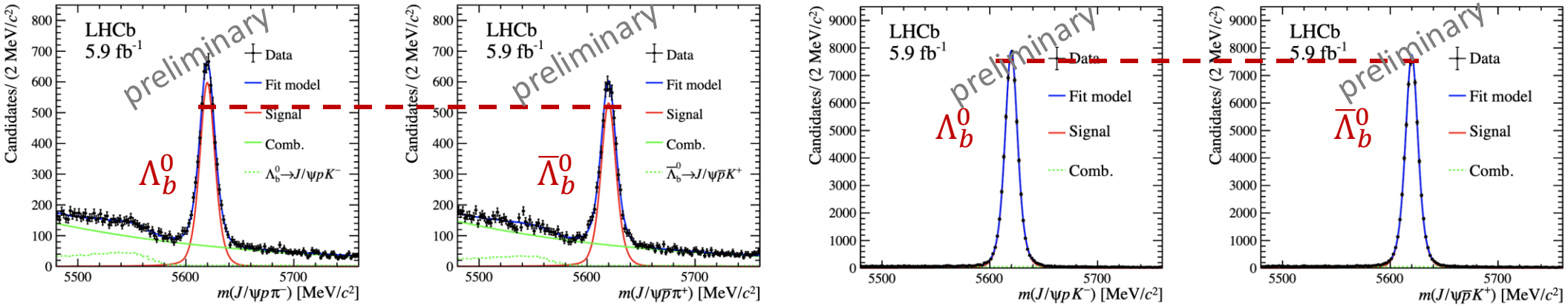


❖ N^+ resonances

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

[LHCb-PAPER-2025-021], in preparation **[New!]**

- Study of $\Lambda_b^0 \to J/\psi p\pi^-$ and $\Lambda_b^0 \to J/\psi p K^-$ decays, Run1+Run2
  - **First evidence of CP violation in B meson decay to charmonium** [PRL 134, 101801 (2025)]
    - $A_{CP}\,(B^+ \to J/\psi\pi^+) - A_{CP}\,(B^+ \to J/\psi K^+) = (1.29 \pm 0.49 \pm 0.08)\%$, $\mathbf{3.2\sigma}$
  - No CPV in b-baryon to charmonium observed yet [JHEP 07 (2014) 103]
    - $A_{CP}(\Lambda_b^0 \to J/\psi p\pi^-) - A_{CP}(\Lambda_b^0 \to J/\psi p K^-) = (5.7 \pm 2.4 \pm 1.2)\%$
- Measurement of the CP asymmetry difference ΔA_{CP}
  - $\Delta A_{CP} = A_{\rm raw}(\Lambda_b^0 \to J/\psi p\pi^-) - A_{\rm raw}(\Lambda_b^0 \to J/\psi p K^-) + A_{\rm D}(K^-) - A_D(\pi^-)$
  - LHCb Run2:



$A_{raw}(\Lambda_b^0 \to J/\psi p\pi^-) = (5.94 \pm 1.14)\,\%$ $\quad$ $A_{raw}(\Lambda_b^0 \to J/\psi p K^-) = (0.98 \pm 0.30)\,\%$

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

[LHCb-PAPER-2025-021], in preparation **[New!]**

- Measurement of the CP asymmetry difference ΔA_{CP}
  - Weight the $\Lambda_b^0 \to J/\psi p K^-$ sample to cancel the $A_P(\Lambda_b^0)$, $A_D(p)$, and also trigger asymmetry
    - Corrected Run2 result: $\Delta A_{CP} = (4.03 \pm 1.18 \pm 0.23)\%$ $\mathbf{3.3\sigma}$
  - Combined with the LHCb Run1 results with the Best Linear Unbiased Estimate (BLUE) method
    - $\Delta A_{CP} = (4.31 \pm 1.06 \pm 0.28)\%$ $\mathbf{3.9\sigma}$
    - **First evidence of CP violation in beauty baryon to charmonium decays!**

- Measure the triple-product asymmetry (TPA) for the two decay modes
  - Triple product
    Λ_b^0: $C_T \equiv \vec{p}_{\mu^+} \cdot (\vec{p}_p \times \vec{p}_{\pi^-})$
    $\bar{\Lambda}_b^0$: $\bar{C}_T \equiv \vec{p}_{\mu^-} \cdot (\vec{p}_{\bar{p}} \times \vec{p}_{\pi^+})$
  - Asymmetry $\mathcal{A}_{\hat{T}} = \frac{\Gamma(C_T>0)-\Gamma(C_T<0)}{\Gamma(C_T>0)+\Gamma(C_T<0)}$
  - Under CP: $C_T \to -\bar{C}_T$, $\mathcal{A}_{\hat{T}} \to \bar{\mathcal{A}}_{\hat{T}}$
  - CP violation variable: $\mathcal{A}_{\mathrm{T-odd}} = \frac{1}{2}(\mathcal{A}_{\hat{T}} - \bar{\mathcal{A}}_{\hat{T}})$

$\mathcal{A}_{\mathbf{T-odd}}(J/\psi p\pi^-) = (\mathbf{-1.37 \pm 1.15})\%$

$\mathcal{A}_{\mathbf{T-odd}}(J/\psi p K^-) = (\mathbf{-0.04 \pm 0.28})\%$

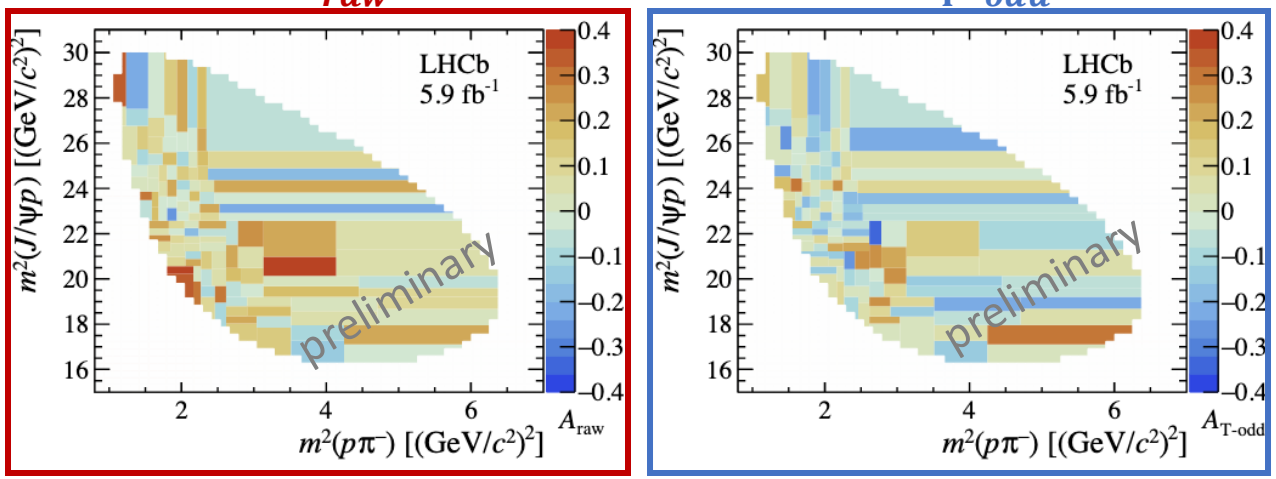
No evidence of TPA found!

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

[LHCb-PAPER-2025-021], in preparation **[New!]**

- Measurement of the local CP asymmetry with **4 binning schemes**
  - 1: Split the $J/\psi p\pi^-$ data sample evenly in Dalitz-plot (4 bins)
  - 2: Split according to resonances in $M(p\pi^-)$ spectrum (4 bins)
  - 3: Split according to $p\pi^-$ resonances and boosting angle $\theta_{p\pi}$ (8 bins)
  - 4: Split evenly into 128 bins
- Both raw asymmetry A_{raw} and TPA $\mathcal{A}_{\mathrm{T-odd}}$ are measured
  - No significant variation of asymmetries across the phase space

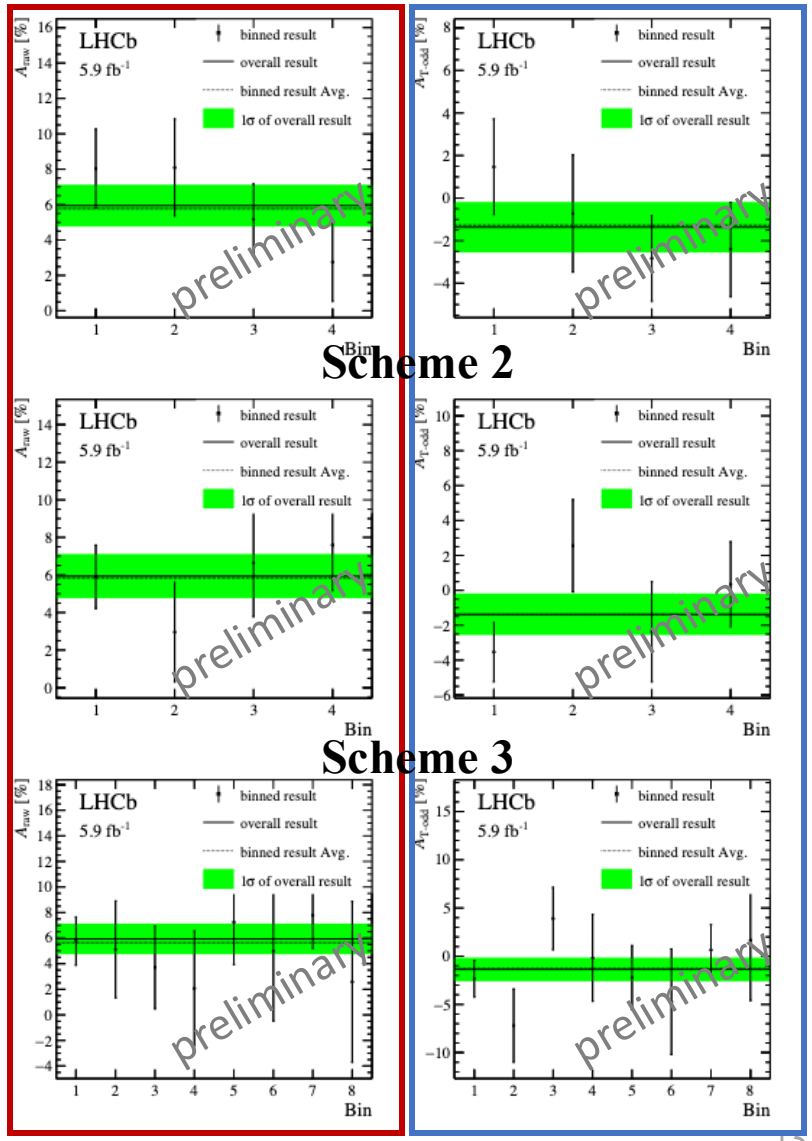
A_{raw} **Scheme 4** $\mathcal{A}_{\mathrm{T-odd}}$



A_{raw} **Scheme 1** $\mathcal{A}_{\mathrm{T-odd}}$

Scheme 2

Scheme 3

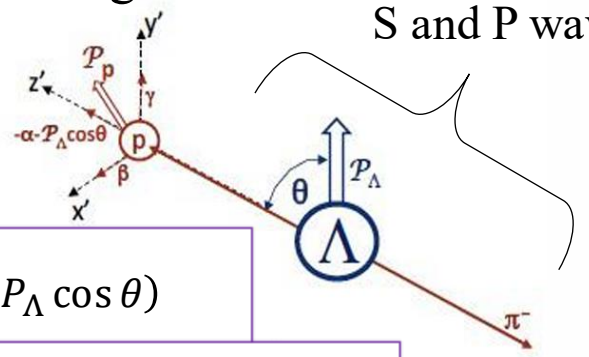


Study of decay parameters in $\Lambda_b^0 \to \Lambda_c^+ h^-$ decays

[PRL 133 (2024) 261804]

[Phys. Rev. 108 (1957) 1645]

- Decay parameters: proposed by Lee & Yang to study P violation in hyperon decay $\Lambda \to p\pi^-$
  - Between $p\pi^-$, there are both P-violating S-wave and P-conserving P-wave
  - Decay parameters $\boldsymbol{\alpha, \beta, \gamma}$ indicate the extent of P violation
  - The same definition in the Λ_b^0, Λ_c^+ decays from a spin-half baryon to a spin-half baryon and a pseudoscalar meson



$$\frac{d\Gamma}{d\cos\theta} = \frac{1}{2}\Gamma(1 + \boldsymbol{\alpha} P_\Lambda \cos\theta)$$

$$P_p = \frac{(\boldsymbol{\alpha} + P_\Lambda \cos\theta)z' + \boldsymbol{\beta} P_\Lambda x' + \boldsymbol{\gamma} P_\Lambda y'}{1 + \boldsymbol{\alpha} P_\Lambda \cos\theta}$$

$$\alpha \equiv \frac{2\mathrm{Re}(S^*P)}{|S|^2 + |P|^2},$$
$$\beta \equiv \frac{2\mathrm{Im}(S^*P)}{|S|^2 + |P|^2},$$
$$\gamma \equiv \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2},$$
$$\text{with } \alpha^2 + \beta^2 + \gamma^2 = 1,$$

- **CPV observables** can also be defined using the decay parameters of CP-conjugated processes
  - $\bar{\alpha}, \bar{\beta}, \bar{\gamma}$ are the decay parameters of anti-baryon decays
  - $\Delta\delta$ ($\Delta\phi$) is the strong (week) phase difference between S- and P-waves

$$A_\alpha = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} = -\tan\Delta\delta \tan\Delta\phi$$
$$R_{\beta_1} = \frac{\beta + \bar{\beta}}{\alpha - \bar{\alpha}} = \tan\Delta\phi$$
$$R_{\beta_2} = \frac{\beta - \bar{\beta}}{\alpha - \bar{\alpha}} = \tan\Delta\delta.$$

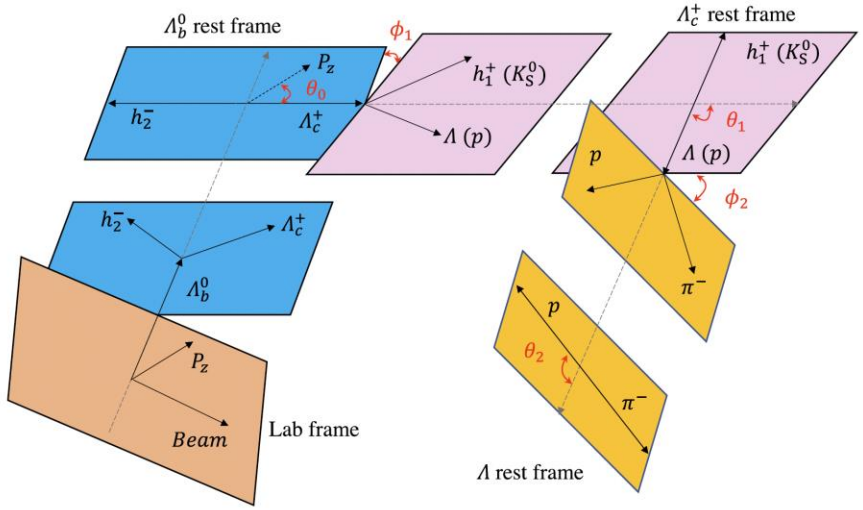
❖Clean observables, less polluted by experimental effects

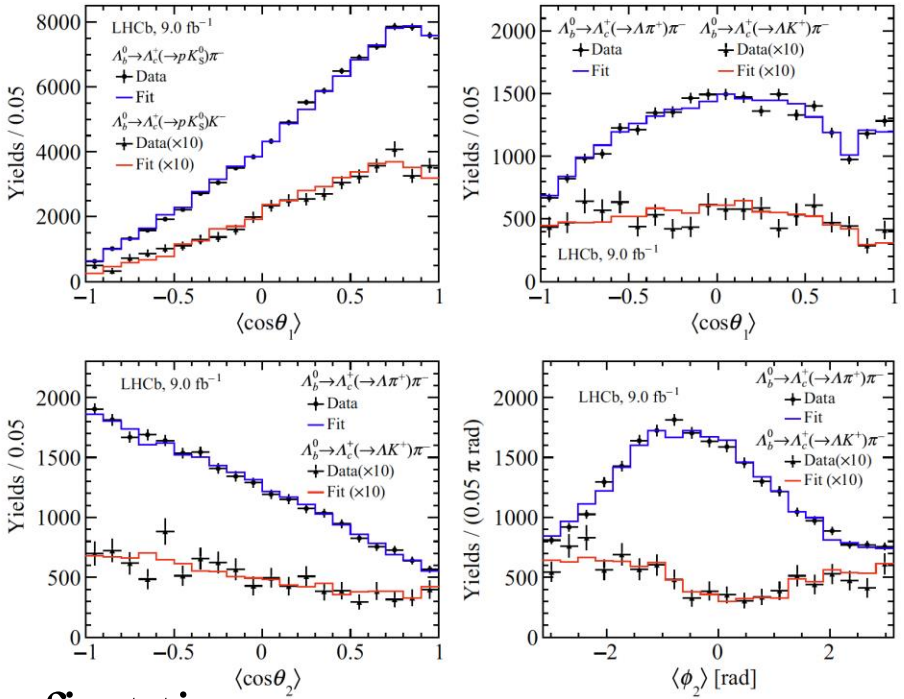
❖Complementary to decay rate asymmetry

Beauty and charm baryon decay parameters

[PRL 133 (2024) 261804]

- Study of $\Lambda_b^0 \to \Lambda_c^+ h^-$ $(h = \pi, K)$ with $\Lambda_c^+ \to \Lambda h^+$, $\Lambda \to p\pi^-$ or $\Lambda_c^+ \to p K_S^0$, Run1+Run2
- Simultaneous angular analysis of 6 decays





- $\Lambda_b^0 \to \Lambda_c^+ h^-$ decay parameters are measured for the first time
  - CP violating parameters A_{CP}^{α} consistent with CP symmetry
  - No CP violation in β, γ or phases as well
  - Weak and strong phase difference determined:

	$\Lambda_b^0 \to \Lambda_c^+ \pi^-$	$\Lambda_b^0 \to \Lambda_c^+ K^-$
$\Delta\phi$ (weak phase)	0.01 ± 0.02	-0.03 ± 0.14
$\Delta\delta$ (strong phase)	2.693 ± 0.017	2.57 ± 0.19

Conclusions & Outlook

- LHCb provides an excellent environment to study CP violation in baryon decays
  - Numerous new results from Run 1 & 2 data
  - **First observation of CPV in baryonic decays!**

- A major step forward in understanding CP violation
  - While generally smaller than in mesons, **baryonic CPV can be significant under specific conditions**
  - The complex dynamics of baryon decays call for **innovative analysis techniques**

- Future prospects
  - Huge increase in sample size expected for Run 3 with higher hadronic selection efficiencies
  - Exciting opportunities to deepen our understanding of CP violation