26th International Symposium on Spin Physics
A Century of Spin

PEKING UNIVERSITY

# Baryon CP violation Measurements at LHCb

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**on behalf of the LHCb collaboration**

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# Outline

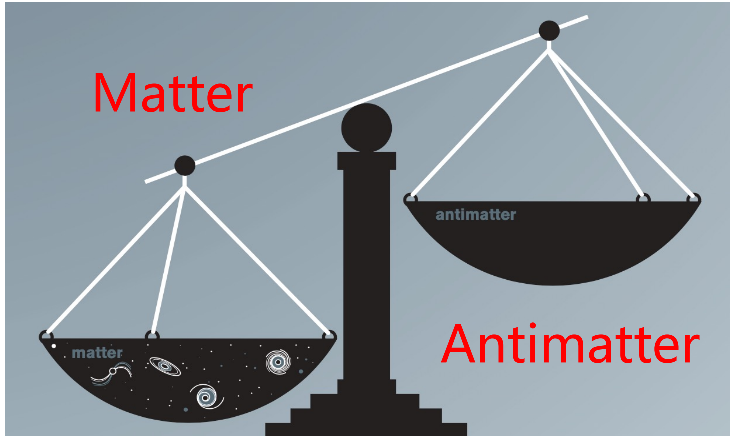
- Introduction
- CP violation in charmless beauty baryon decays
  - $\Lambda_b^0 \to ph^-$ [PRD 111 (2025), 092004]
  - $\Lambda_b^0/\Xi_b^0 \to \Lambda h_1^+ h_2^-$ [PRL 134 (2025) 101802]
  - $\Lambda_b^0/\Xi_b^0 \to pK_S^0 h^-$ [arXiv:2508.17836]
  - $\Lambda_b^0 \to pK^-\pi^+\pi^-$ Nature 643 (2025) 1223
- CP violation in beauty baryon to charmonium decays
  - $\Lambda_b^0 \to J/\psi ph^-$ [arXiv:2509.16103]
- CP violation in beauty baryon to open charm decays
  - $\Lambda_b^0 \to \Lambda_c^0 h^-$ [PRL 133 (2024) 261804]
- Summary and Outlook

* $h = K$ or $\pi$

# Introduction

- Violation of CP symmetry (CPV) is essential to explain the observed matter-antimatter asymmetry in the Universe


Sakharov conditions




- CPV in Standard Model (CKM mechanism) insufficient to account for observed asymmetry

- Understanding CP violation within the SM and searching for CP violation beyond are important frontiers in particle physics

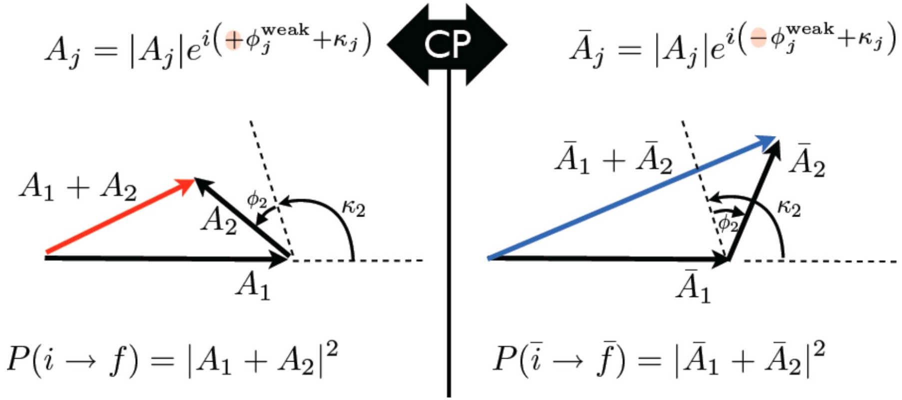
# CP violation in the SM

- CP violating weak phases in quark mixing (CKM) matrix

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Single independent phase parameter $\delta$ rules them all

- Interference of (at least) two amplitudes generates CP violation




Two amplitudes have both weak and strong phase differences

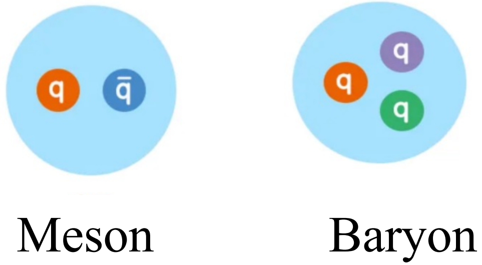
Strong phase difference

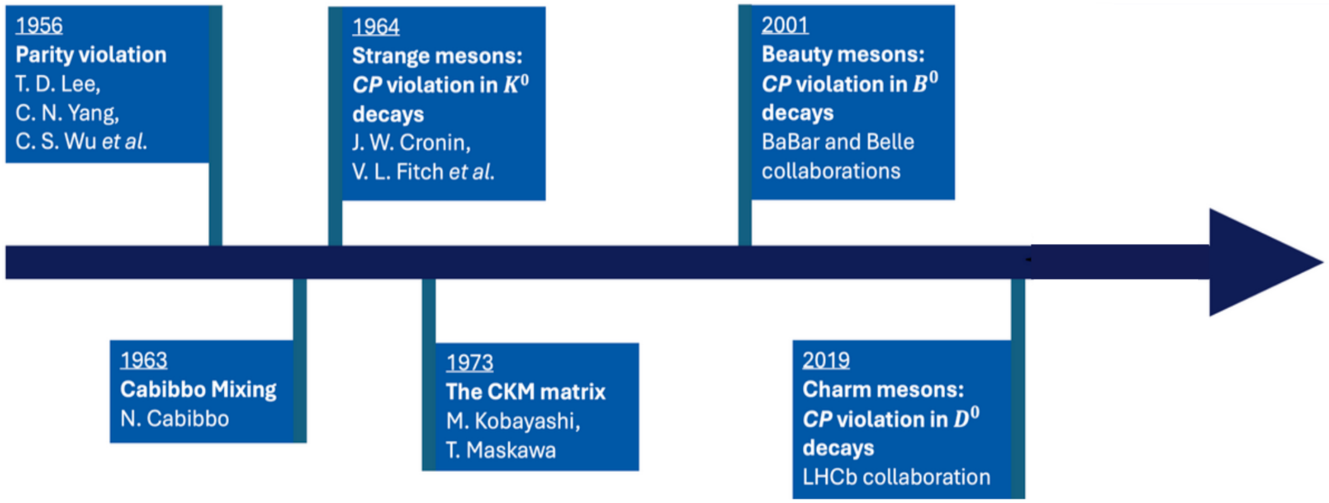
$$P(i \to f) - P(\bar{i} \to \bar{f}) = -4|A_1||A_2| \sin(\boxed{\phi_2}) \sin(\boxed{\kappa_2})$$

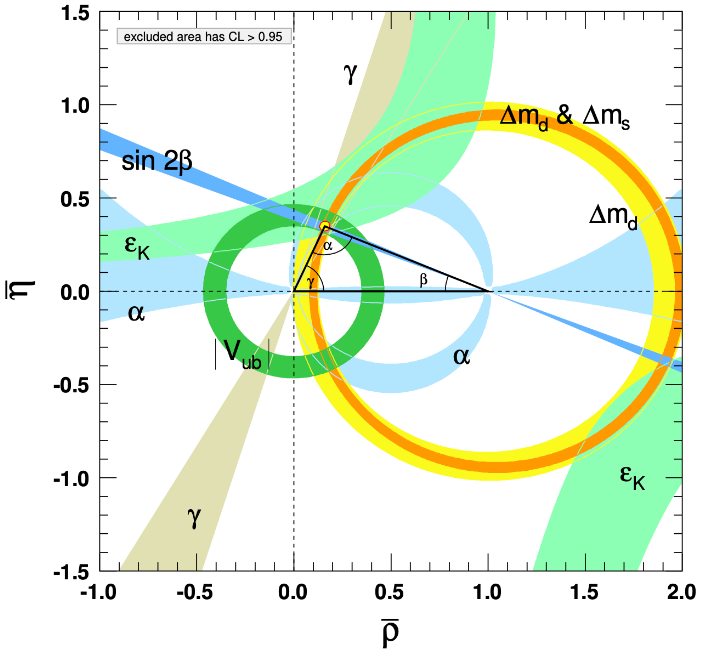
Weak phase difference

# CP violation in mesons

- CP violation well-established in all types of meson systems
  - 1964: CP violation in $K$-meson
  - 2001: CP violation in $B$-meson
  - 2019: CP violation in $D$-meson
- Precision measurements to test SM and search for new physics



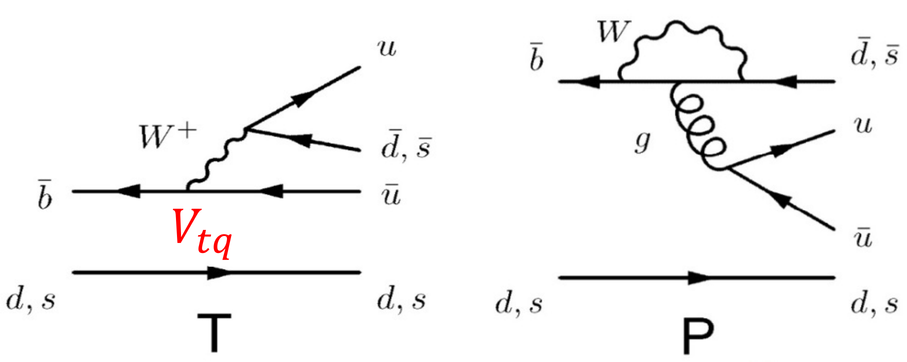



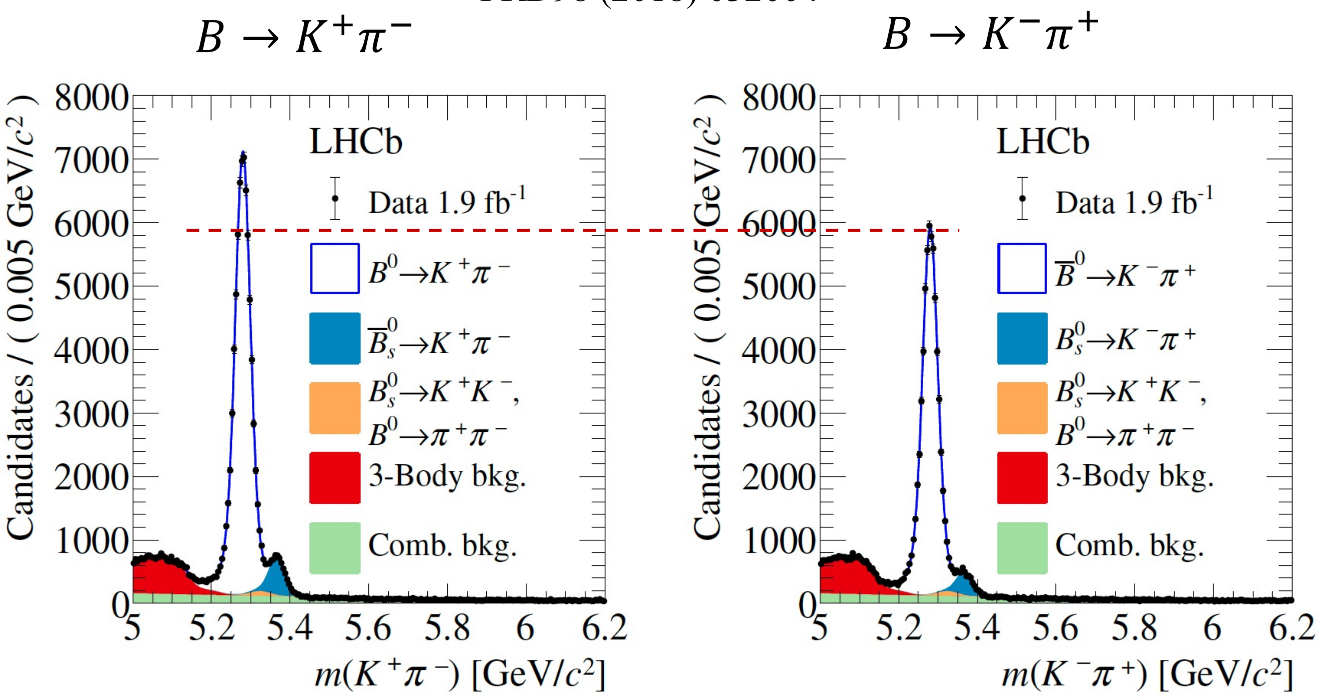
# $B$-meson CP violation

- Large CP violation expected in charmless decays due to tree & loop interference

$b \to u\bar{u}d, \quad b \to u\bar{u}s$




PRD98 (2018) 032004



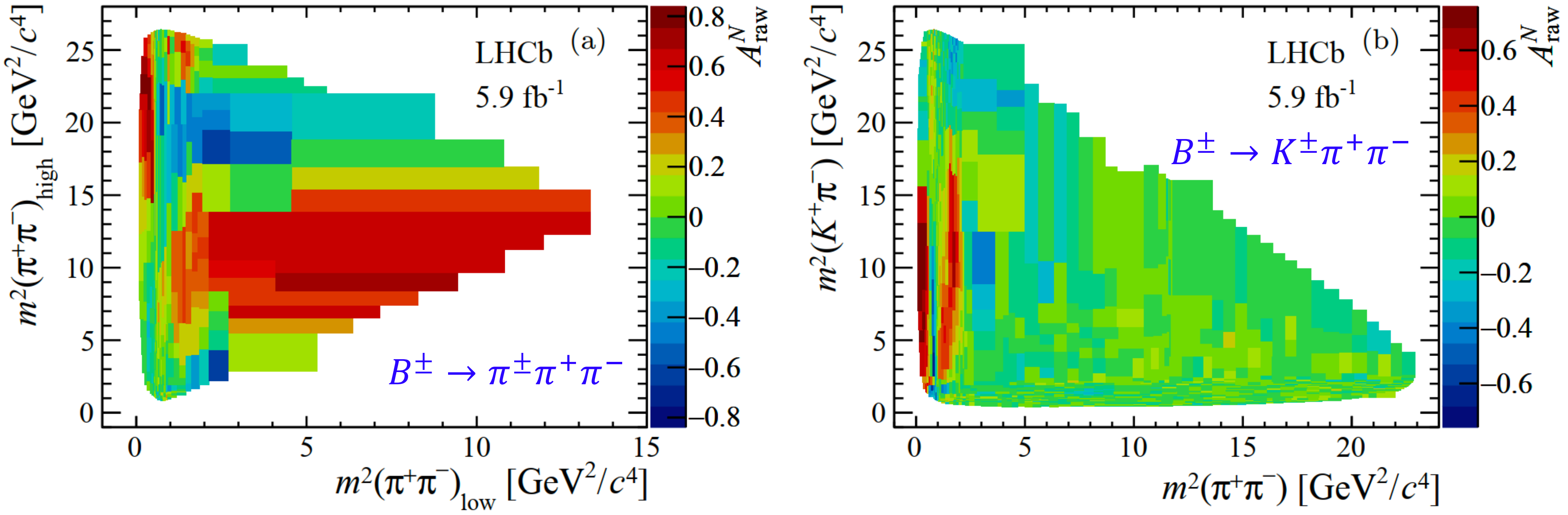

$$\boxed{A_{CP}^{\bar{B}^0 \to K^-\pi^+} = -0.083 \pm 0.005}$$

$$\boxed{A_{CP}^{\bar{B}_s^0 \to K^+\pi^-} = 0.236 \pm 0.017}$$

# Multibody decays

Varying strong phases and resonance compositions across phase space

$$A_{CP} = \frac{2|\mathcal{A}_2/\mathcal{A}_1|\sin(\delta_1-\delta_2)\sin(\phi_1-\phi_2)}{1+|\mathcal{A}_2/\mathcal{A}_1|^2+2|\mathcal{A}_2/\mathcal{A}_1|\cos(\delta_1-\delta_2)\cos(\phi_1-\phi_2)}$$

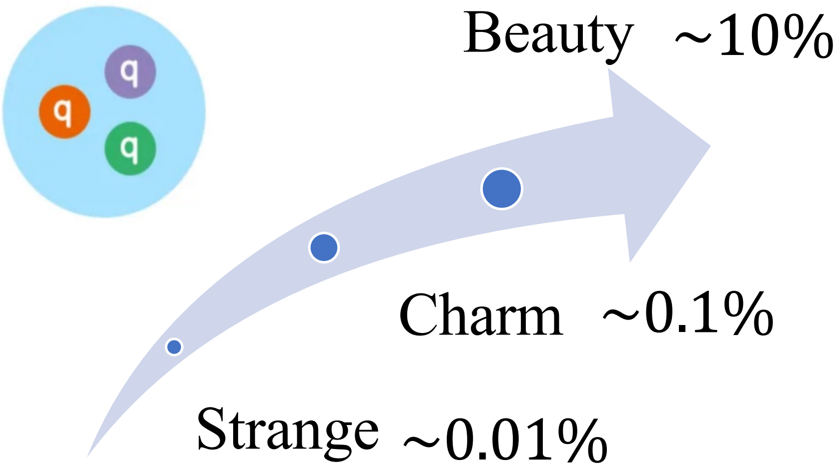



PRD108(2023)012008

# Baryon CP violation

- Complementary to meson studies, comprehensive test of SM
- Predicted in SM but only observed recently

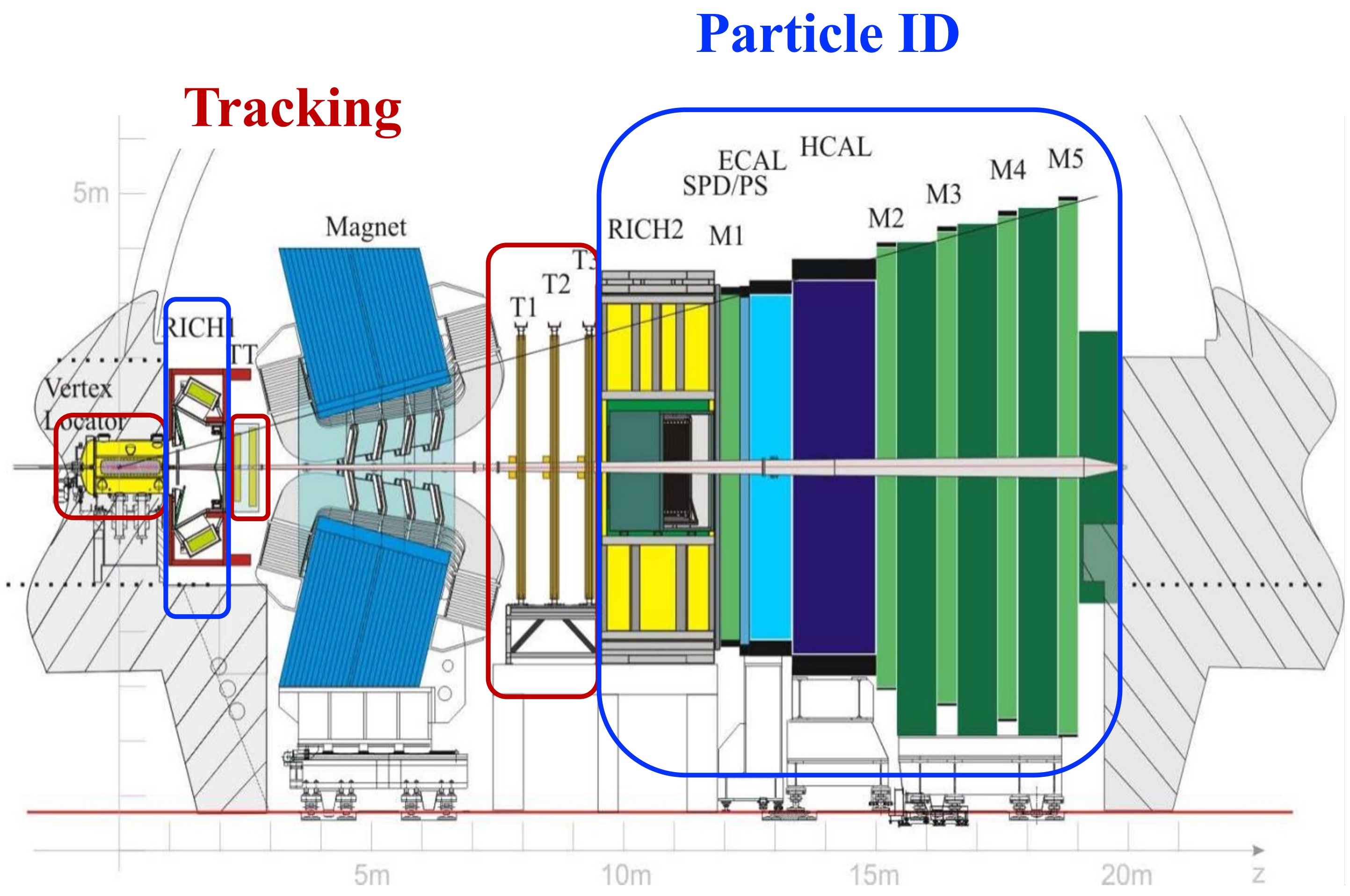
Rough estimate of baryon CPV magnitudes:




| Decays | Measurements | Data | References |
|---|---|---|---|
| $\Lambda_b^0 \to pK_S^0\pi^-$ | $A_{CP}$ | 1 fb$^{-1}$ | JHEP 04 (2014) 087 |
| $\Lambda_b^0 \to \Lambda hh'$ | $A_{CP}$ | 3 fb$^{-1}$ | JHEP 05 (2016) 081 |
| $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ | TPA<br>energy test | 3 fb$^{-1}$<br>6.6 fb$^{-1}$ | NP 13 (2017) 391<br>PRD 102 (2020) 051101 |
| $\Lambda_b^0 \to pK^-\mu^+\mu^-$ | $A_{CP}$ | 3 fb$^{-1}$ | JHEP 06 (2017) 108 |
| $\Lambda_c^+ \to ph^-h^+$ | $A_{CP}$ | 3 fb$^{-1}$ | JHEP 03 (2018) 182 |
| $\Lambda_b^0 \to pK^-/p\pi^-$ | $A_{CP}$ | 3 fb$^{-1}$ | PLB 787 (2018) 124 |
| $\Lambda_b^0 \to ph^-h^+h^-$ | TPA | 3 fb$^{-1}$ | JHEP 08 (2018) 039 |
| $\Lambda_b^0 \to ph^-h^+h^-$ | $A_{CP}$ | 3 fb$^{-1}$ | EPJC 79 (2019) 745 |
| $\Xi_b^- \to pK^-K^-$ | Amplitude | 5 fb$^{-1}$ | PRD 104 (2020) 052010 |
| $\Xi_c^+ \to pK^-\pi^+$ | kNN | 3 fb$^{-1}$ | EPJC 80 (2020) 986 |
| $\Lambda_b^0 \to pD^0K^-$ | Miranda $S_{CP}^i$ | 9 fb$^{-1}$ | PRD104 (2021) 112008 |
| $\Lambda_b^0 \to \Lambda\gamma$ | Polarization | 3 fb$^{-1}$ | PRD105 (2022) L051104 |
| $\Lambda_b^0 \to ph^-$ | $A_{CP}$ | 9 fb$^{-1}$ | PRD111 (2025) 092004 |
| $\Lambda_b^0 \to \Lambda_c^+h^-$ | Decay parameter | 9 fb$^{-1}$ | PRL 133 (2024) 261804 |
| $\Lambda_b^0 \to \Lambda hh'$ | $A_{CP}$ | 9 fb$^{-1}$ | PRL 134 (2025) 101802 |
| $\Lambda_b^0 \to pK^-\pi^+\pi^-$ | $A_{CP}$ | 9 fb$^{-1}$ | Nature 643 (2025) 1223 |

# LHCb detector

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022



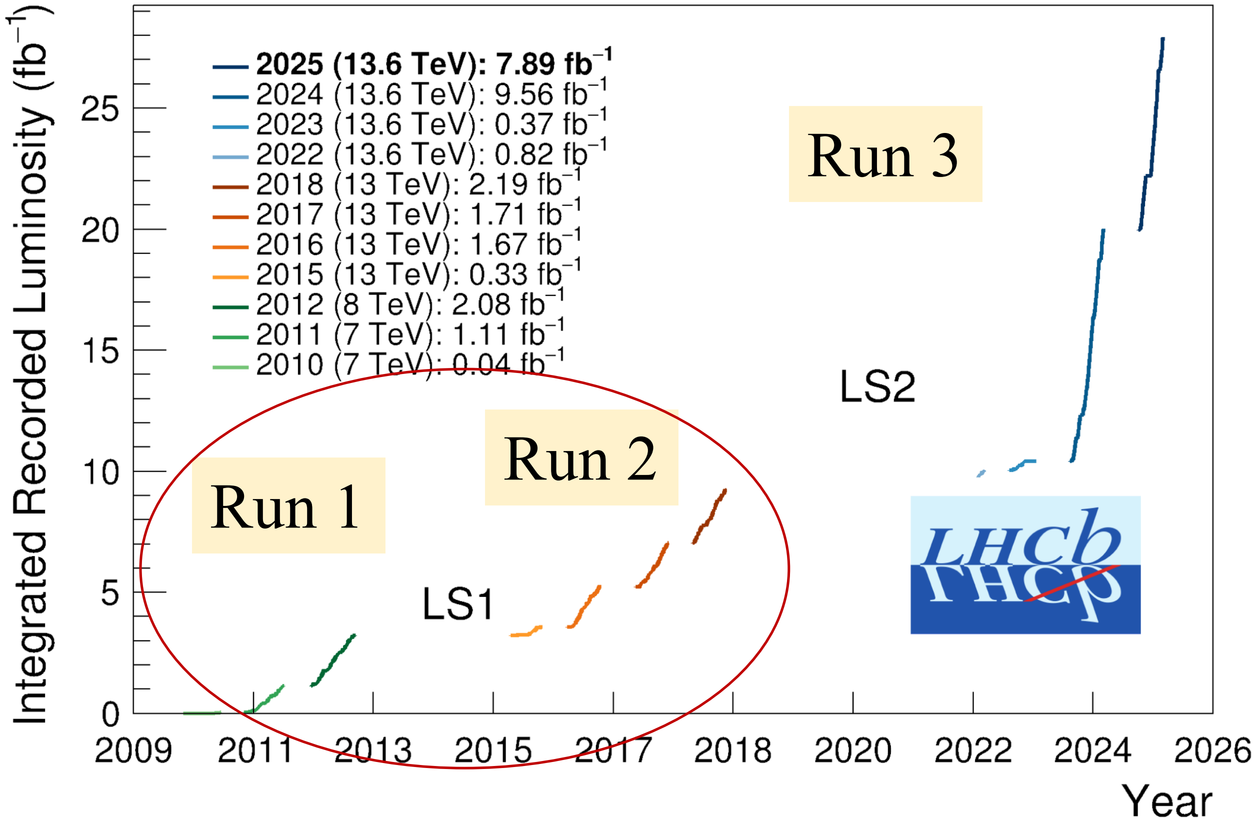

Run 1-2 detector

- ✓ Excellent vertexing
  $\sigma_\tau \sim 45$ fs for $B_s^0 \to J/\psi\phi$ decay
- ✓ Precise momentum measurement
  $\Delta p/p = 0.5 - 1\%$ ($5 \sim 200$ GeV/$c$)
- ✓ Hadron PID
  $\epsilon(K \to K), \epsilon(p \to p) > 90\%$
- ✓ Muon PID
  $\epsilon(\mu \to \mu) \sim 90\%$ for $1 - 3\%$ $\pi \to \mu$ misID rate

# LHCb data

- $pp$ collisions: $\sqrt{s} = 7, 8, 13, 13.6$ TeV, $\int \mathcal{L} dt > 25\ \text{fb}^{-1}$

$\sigma(b\bar{b}, 13\ \text{TeV}) \approx 0.5\ \text{mb}$, $\sigma(c\bar{c}) \approx 20 \times \sigma(b\bar{b})$




Results here with only Run 1 and Run 2 data

# CP violation measurement

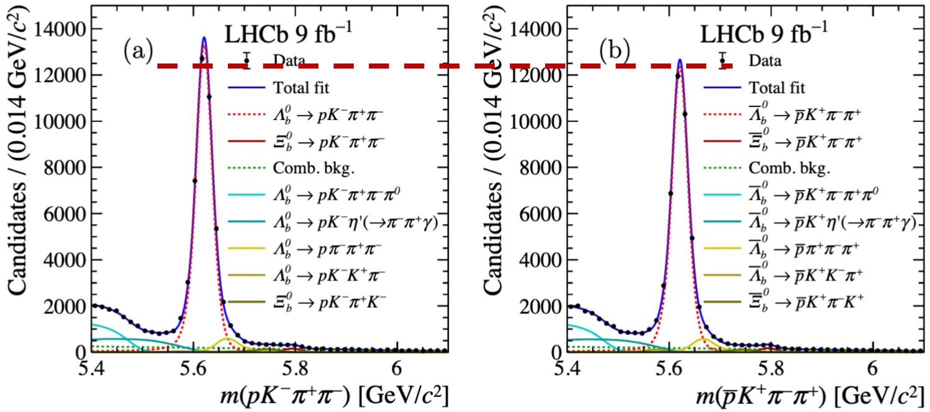
- CPV manifested as difference between particle antiparticle decay rates

$$A_{CP} = \frac{\Gamma\left(\Lambda_b^0 \to X\right) - \Gamma\left(\bar{\Lambda}_b^0 \to \bar{X}\right)}{\Gamma\left(\Lambda_b^0 \to X\right) + \Gamma\left(\bar{\Lambda}_b^0 \to \bar{X}\right)}$$

- Counting yields of particle and antiparticle decays

$$A_{raw} = \frac{N\left(\Lambda_b^0 \to X\right) - N\left(\bar{\Lambda}_b^0 \to \bar{X}\right)}{N\left(\Lambda_b^0 \to X\right) + N\left(\bar{\Lambda}_b^0 \to \bar{X}\right)}$$

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




- Experimental and production asymmetries need to be subtracted

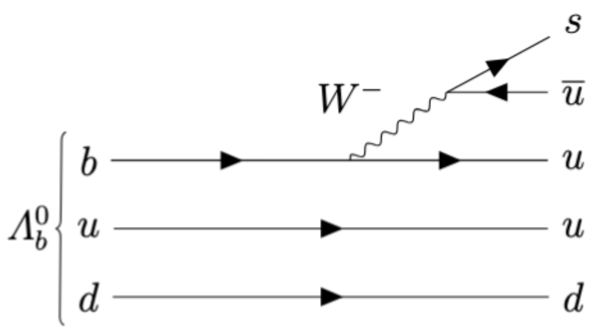
[Nature 643 (2025) 1223]

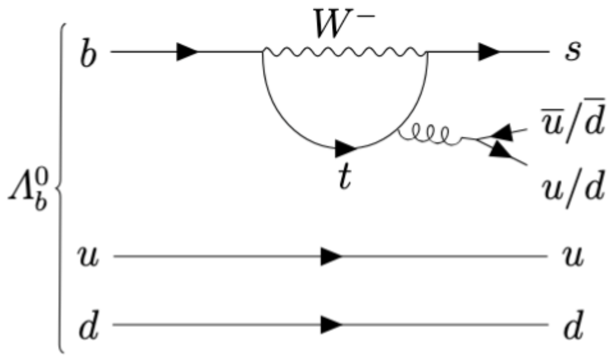
$$A_{CP} = A_{raw} - A_{\mathrm{exp}} - A_{\mathrm{P}}$$

- Control channel is included in some results, and the difference of CPV is measured

$$\Delta A_{CP} = A_{CP}(\mathbf{sig}) - A_{CP}(\mathbf{control})$$

# CP violation in charmless beauty baryon decays

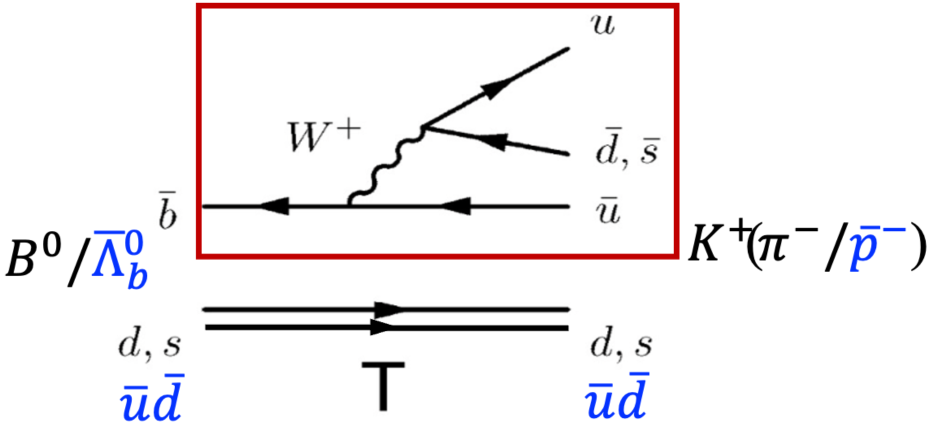


# Charmless $\Lambda_b^0 \to ph^-$ decays

- $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$ decay analogy to $B^0 \to h^+h^-$ decays
- $\mathcal{O}(5\%)$ CP violation predicted as for $B$-mesons

PRD 102 (2012) 034033
PRD 95 (2017) 093001




| 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 (%) | $-31.4 \pm 3.0$ | $22.4 \pm 1.2$ | $8.31 \pm 0.31$ | $16.2 \pm 3.5$ |

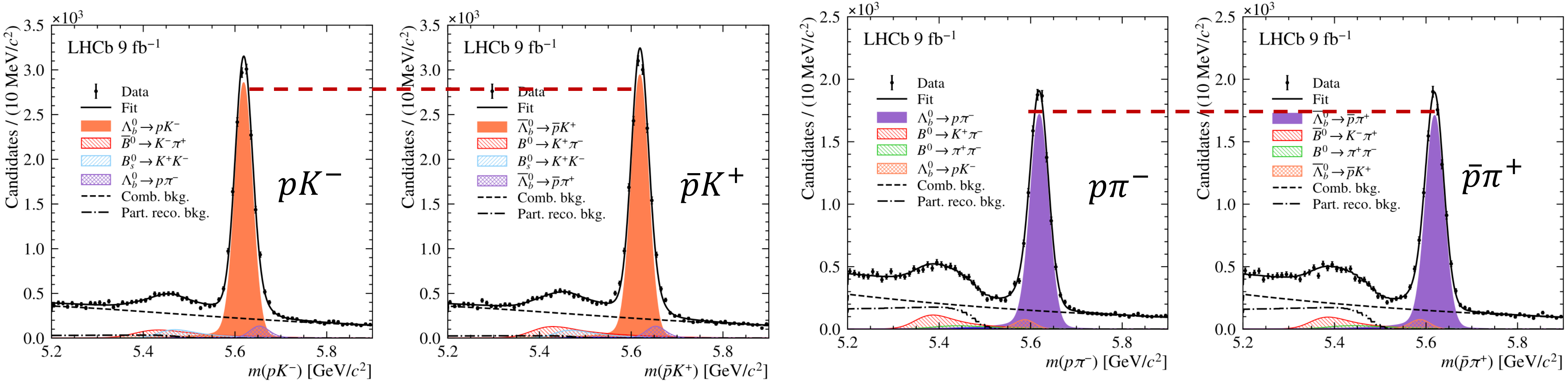
# CP violation for $\Lambda_b^0 \to ph^-$ decays

[PRD 111 (2025), 092004]

- Sizable CP violation not established

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

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

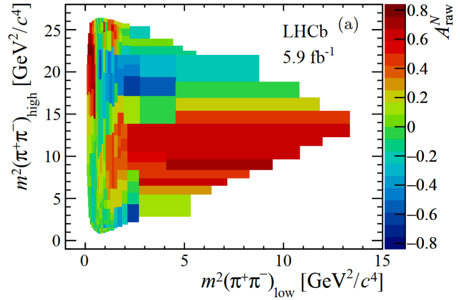



- Most precise result in this mode
  - Precision improved by a factor of 3 compared to known value
  - Statistical uncertainties dominated

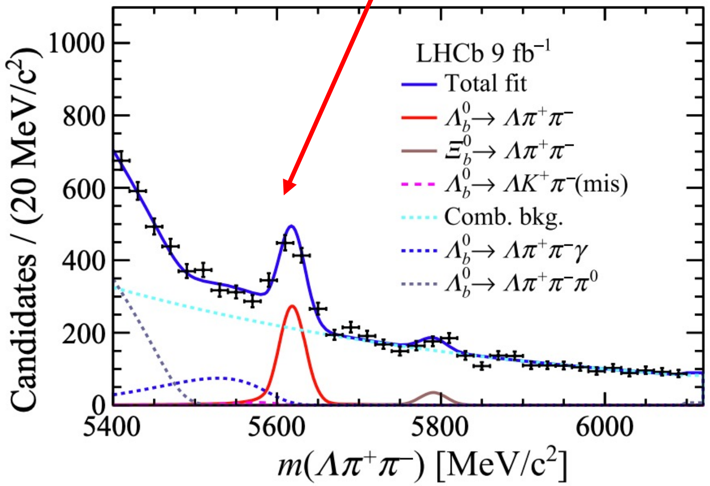
# Charmless $\Lambda_b^0/\Xi_b^0 \to \Lambda h_1^+ h_2^-$ decays

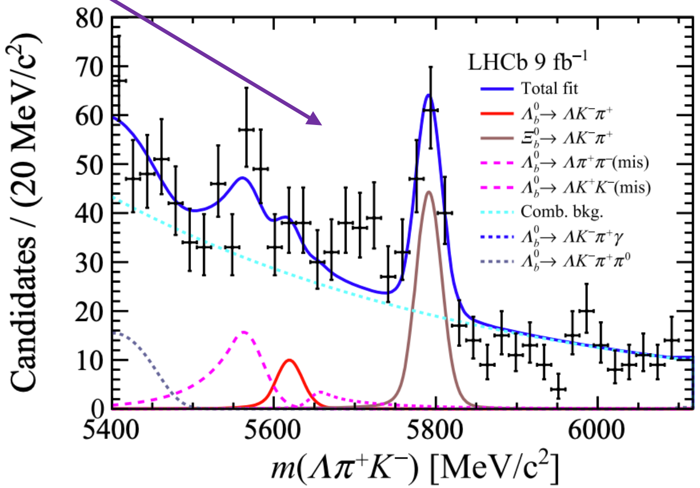
[PRL 134 (2025) 101802]

- Three $\Lambda_b^0$ decays $\Lambda\pi^+\pi^-, \Lambda K^+\pi^-, \Lambda K^+K^-$ and $\Xi_b^0 \to \Lambda K^-\pi^+, \Lambda\pi^+\pi^-$decays studies
  - Analogy to $B^+ \to h^+h^-h^+$ decays, where CP violation pattern observed
  - Control channel: $\Lambda_b^0 \to \Lambda_c^+(\to \Lambda\pi^+)\pi^-$




- Branching fraction measured for these decays
  - $\Lambda_b^0 \to \Lambda\pi^+\pi^-$, $\Xi_b^0 \to \Lambda K^-\pi^+$ observed for the first time




| Decay | $\mathcal{B}(\times 10^{-6})$ |
|---|---|
| $\Lambda_b^0 \to \Lambda\pi^+\pi^-$ | $5.3 \pm 0.4 \pm 0.5 \pm 0.5$ |
| $\Lambda_b^0 \to \Lambda K^+\pi^-$ | $4.6 \pm 0.2 \pm 0.4 \pm 0.5$ |
| $\Lambda_b^0 \to \Lambda K^+K^-$ | $10.7 \pm 0.3 \pm 0.4 \pm 1.1$ |
| $\Xi_b^0 \to \Lambda\pi^+\pi^-$ | $11.0 \pm 2.6 \pm 1.4 \pm 3.8$ |
| $\Xi_b^0 \to \Lambda K^-\pi^+$ | $10.4 \pm 1.4 \pm 1.2 \pm 3.5$ |

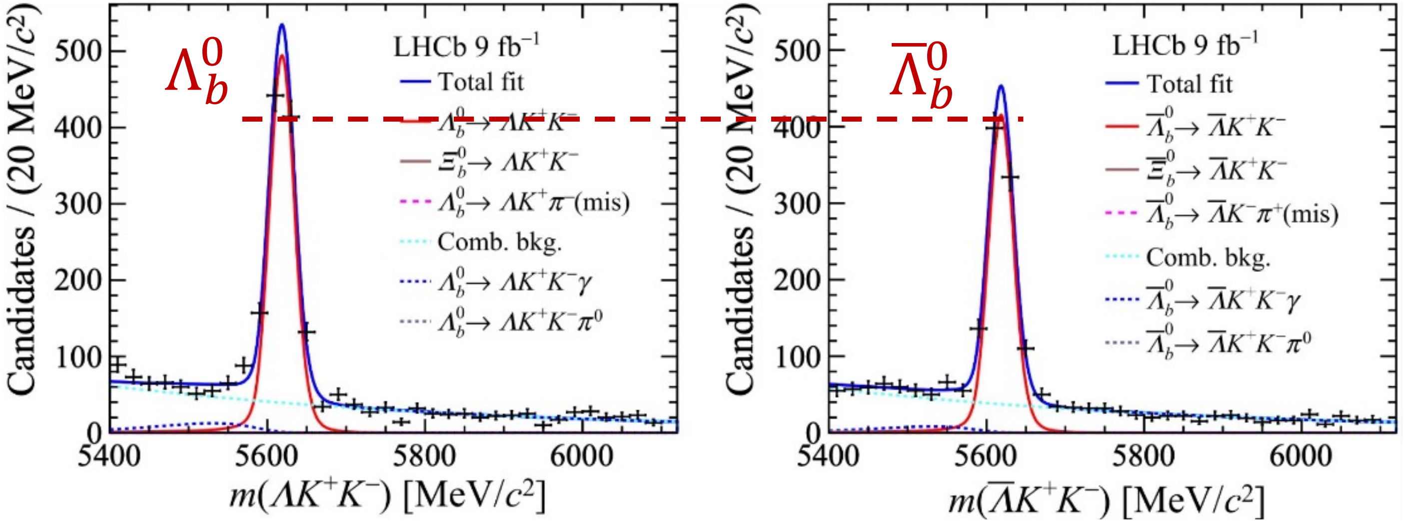
# $A_{CP}$ measurement in $\Lambda_b^0/\Xi_b^0 \to \Lambda h_1^+ h_2^-$ decays

[PRL 134 (2025) 101802]

- $\Delta A_{CP}$ determined for 4 channels
  - $\Delta A_{CP} = A_{\text{raw}}(\text{signal}) - A_{\text{raw}}(\text{control}) - \Delta A_{\text{P}} - \Delta A_{\text{exp}}$

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

- Evidence (3.1$\sigma$) of direct CP violation is found in $\Lambda_b^0 \to \Lambda K^+K^-$ decay



# Local CP asymmetry for $\Lambda_b^0 \to \Lambda K^+ K^-$

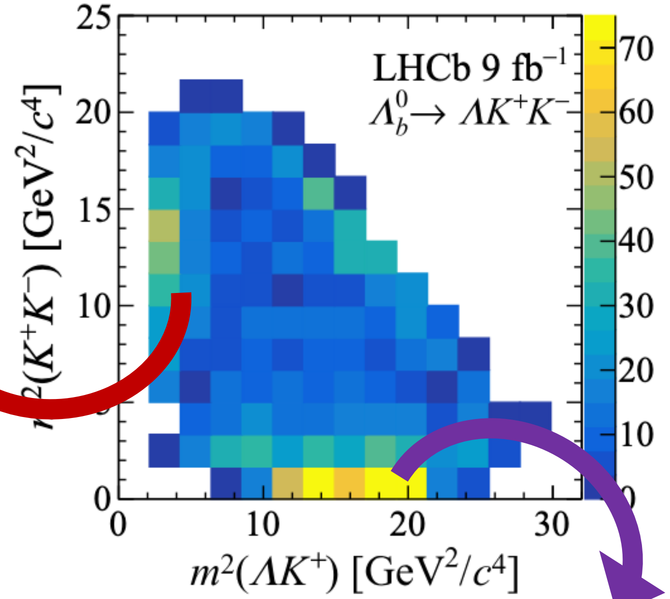
[PRL 134 (2025) 101802]

- $\Lambda_b^0 \to \Lambda K^+ K^-$ dominated by intermediate $N^{*+}(\to \Lambda K^+)$ and $\phi(\to K^+K^-)$ resonances
- Evidence of CP violation in $N^{*+}$ resonance region

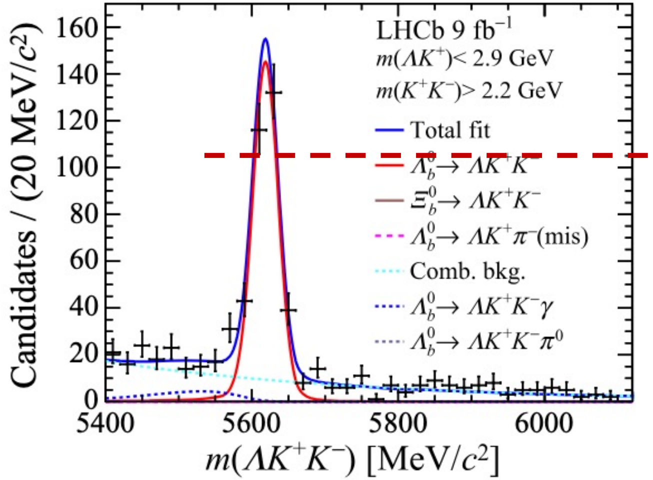
$\boxed{m_{\Lambda K^+} < 2.9\text{ GeV}}$

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

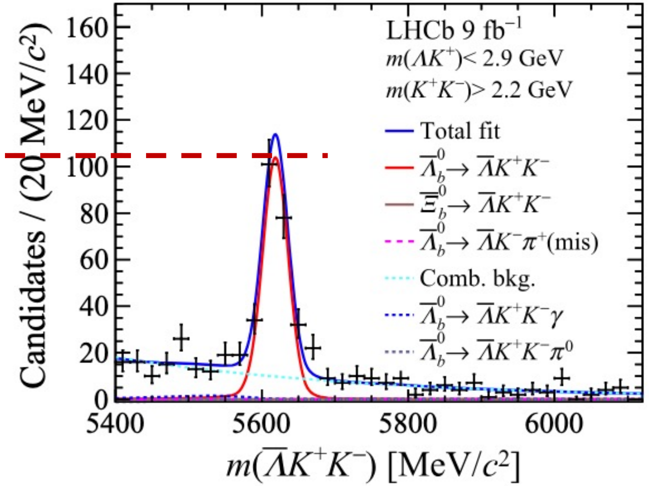
$\Delta A_{CP}(N^{*+}K^-) = 0.165 \pm 0.048 \pm 0.017$




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




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




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

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

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

# Local CP asymmetries

PRL 134 (2025) 101802

$m_{\Lambda K^+} < 2.3$ GeV

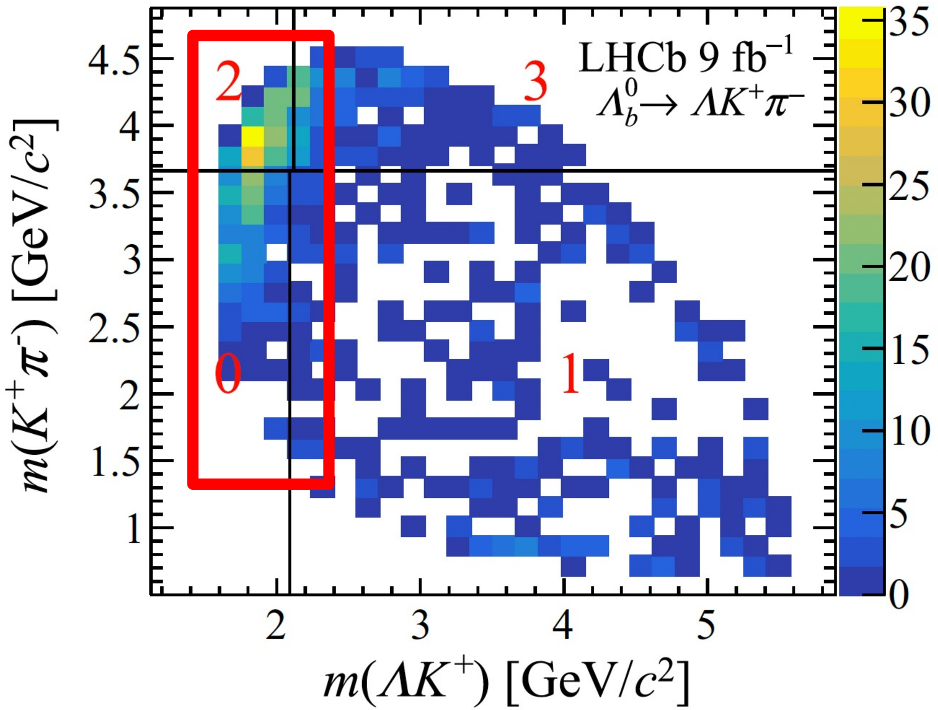
$\Lambda_b^0 \to N^{*+}(\to \Lambda K^+)\pi^-$

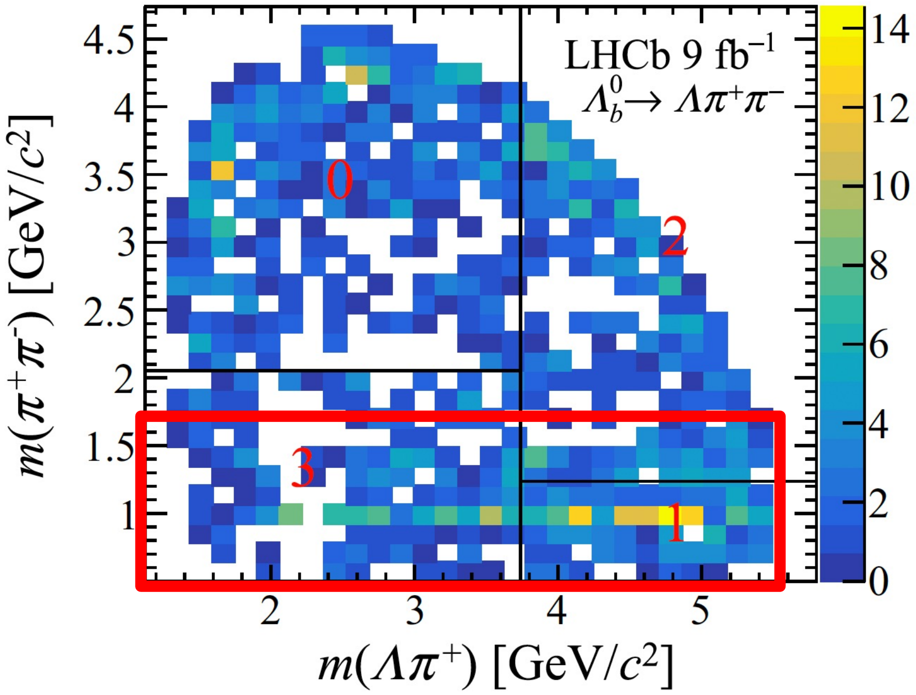
$\Delta A_{CP}(N^{*+}\pi^-) = -0.078 \pm 0.051 \pm 0.027$

$m_{\pi^+\pi^-} < 1.7$ GeV

$\Lambda_b^0 \to \Lambda f(\pi^+\pi^-)$

$\Delta A_{CP}(\Lambda f) = 0.088 \pm 0.069 \pm 0.021$



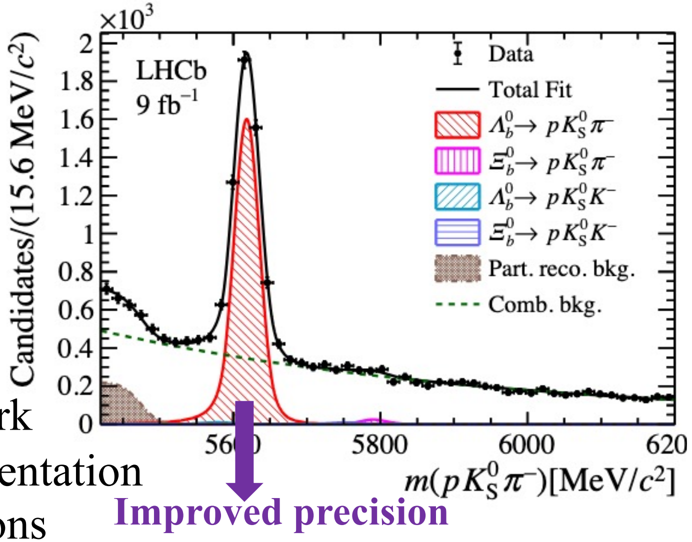
# Charmless $\Lambda_b^0/\Xi_b^0 \to pK_s^0 h^-$ decays

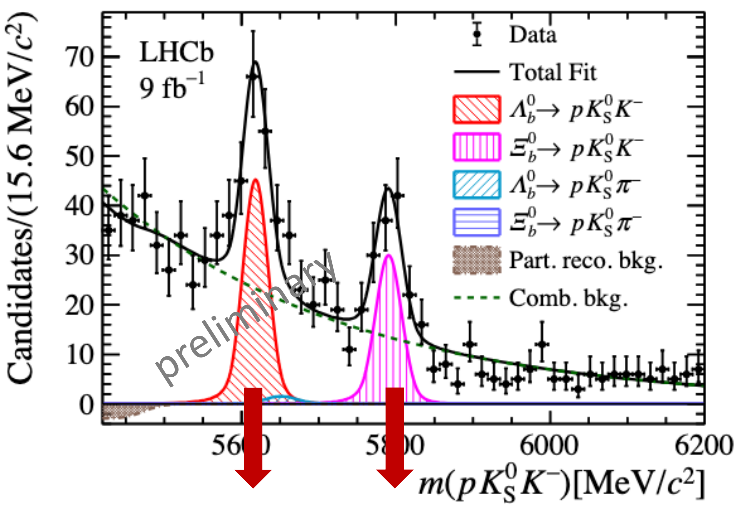
[arXiv:2508.17836 ]

- $\Lambda_b^0/\Xi_b^0 \to pK_s^0 h^-$ decays similar to $\Lambda h_1^+ h_2^-$, just different hadronization processes
  - ➢ Control channel: $\Lambda_b^0 \to \Lambda_c^+(\to pK_s^0)\pi^-$
- Branching fraction measured for $\Lambda_b^0 \to pK_s^0\pi^-$, $\Lambda_b^0/\Xi_b^0 \to pK_s^0 K^-$ decays
  - ➢ First observation of $\Lambda_b^0/\Xi_b^0 \to pK_s^0 K^-$ decays
  - ➢ $\Lambda_b^0 \to pK_s^0\pi^-$ branching fraction improved by a factor of 9

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

stat. syst. control mode $b$-quark fragmentation fractions



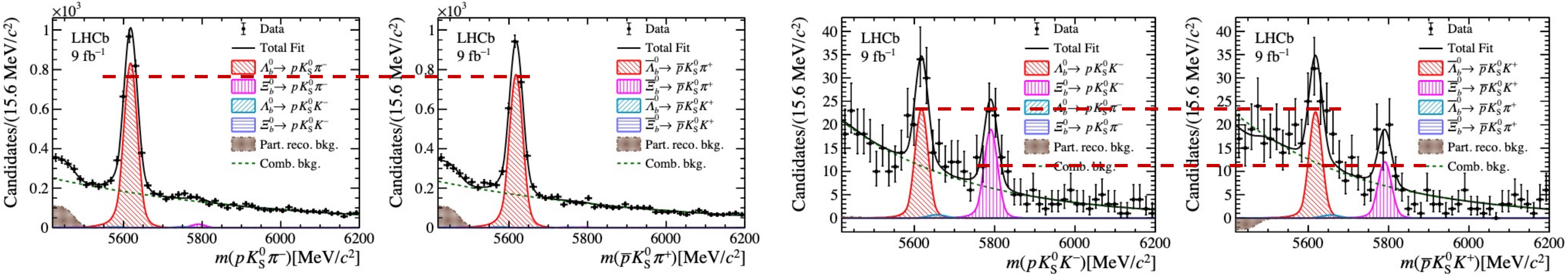
# CP violation

[arXiv:2508.17836]

- Measurements for $\Lambda_b^0/\Xi_b^0 \to pK_s^0K^-$ and $\Lambda_b^0 \to pK_s^0\pi^-$ decays
  - $\Delta A_{CP} = \Delta A_{\text{raw}} - \Delta A_P - \Delta A_{\text{exp}}$
- No significant CP violation found

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

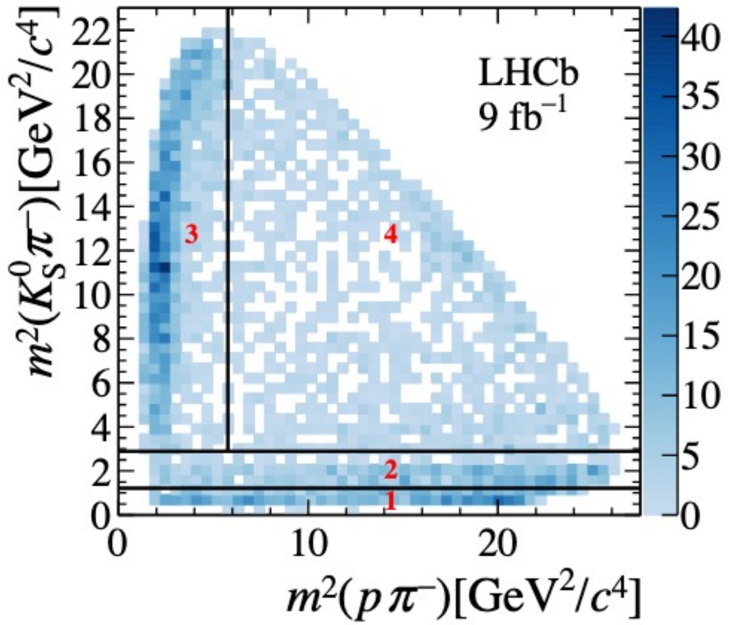
$\Lambda_b^0 \to pK_s^0\pi^-$ $\quad$ $\overline{\Lambda}_b^0 \to \bar{p}K_s^0\pi^+$ $\quad$ $\Lambda_b^0 \to pK_s^0K^-$ $\quad$ $\overline{\Lambda}_b^0 \to \bar{p}K_s^0K^+$



# Local CP violation

[arXiv:2508.17836]

- Local CP violation for $\Lambda_b^0 \to pK_s^0\pi^-$ investigated
  - Binning according to identified $N^{**0}, K^{*-}$ resonances
- No significant localized CP violation found




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

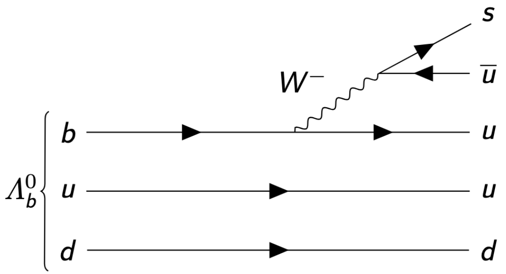
| | $m(p\pi^-)$ | $m(K_S^0\pi^-)$ | Yield | $\mathcal{A}^{CP}$ [%] |
|---|---|---|---|---|
| Bin 1 | - | $< 1.1\,\mathrm{GeV}/c^2$ | $821 \pm 34$ | $-0.6 \pm 4.0 \pm 1.9$ |
| Bin 2 | - | $[1.1, 1.7]\,\mathrm{GeV}/c^2$ | $870 \pm 40$ | $12.4 \pm 4.2 \pm 1.8$ |
| Bin 3 | $< 2.4\,\mathrm{GeV}/c^2$ | $>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

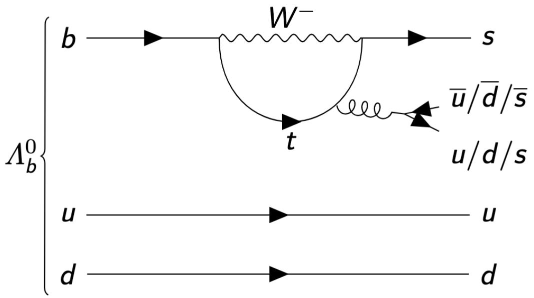
$K^*(892)^+$
$K_J^*(1400)^+$
$N^{**0}$

# The $\Lambda_b^0 \to pK^-\pi^+\pi^-$ decay

[Nature 643 (2025) 1223]

- Contributed by tree and loop diagrams




- Rich resonances

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

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

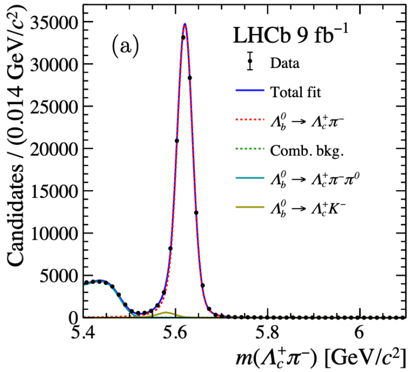
- Large yield and high signal purity
- Golden mode available to reduce nuisance asymmetries for CPV

$\boldsymbol{\Lambda_b^0 \to \Lambda_c^+(pK^-\pi^+)\pi^-}$ control mode: same initial and final state as signal decay, allows to cancel production and detection asymmetries

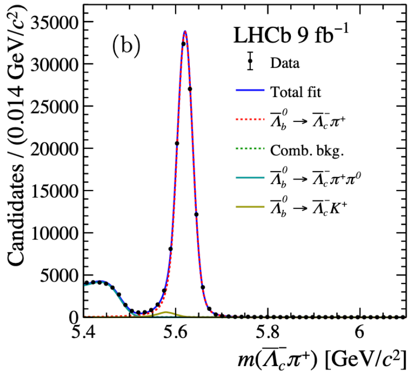
$$A_{\text{yield}} = A_{CP} + A_{\text{P}} + \Delta A_{\text{exp}}$$

$$A_{\text{yield}}\left(\Lambda_b^0 \to \Lambda_c^+\pi^-\right) = (1.25 \pm 0.23)\%$$

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



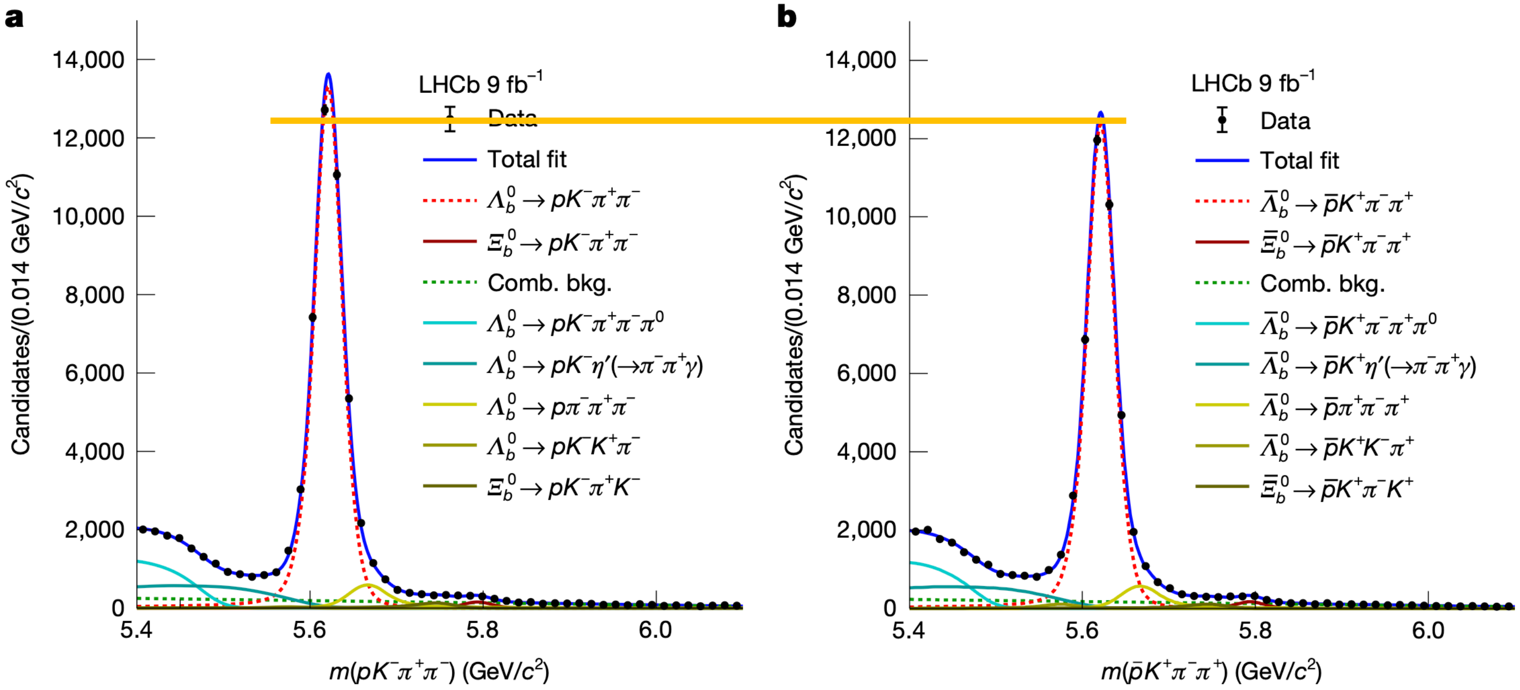

$\overline{\Lambda}_b^0 \to \overline{\Lambda}_c^-\pi^+$



# Raw yield asymmetry of $\Lambda_b^0 \to pK^-\pi^+\pi^-$

Nature 643 (2025) 1223

➢ Maximum-likelihood fits to mass spectra to extract signal yield




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

$N_{\text{yield}} =$ $(4.184 \pm 0.025)\times 10^4$

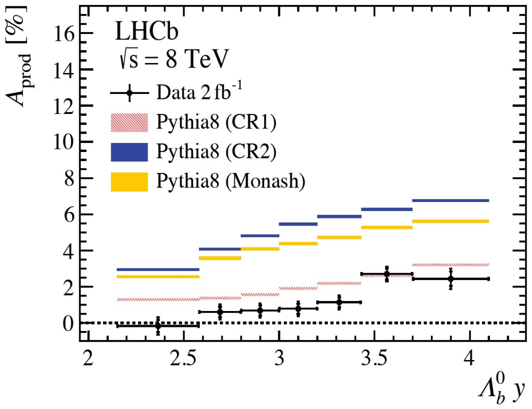
$\overline{N}_{\text{yield}} =$ $(3.885 \pm 0.023)\times 10^4$

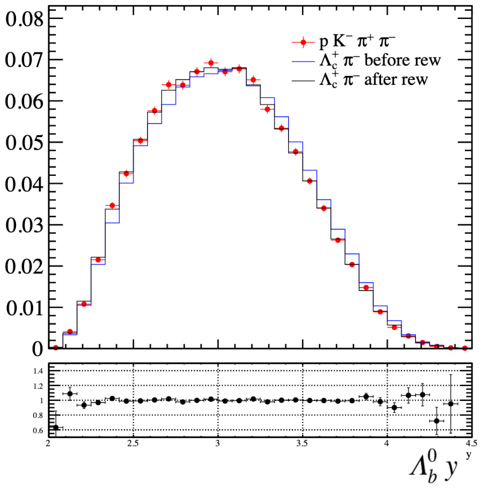
# Corrections for experimental bias

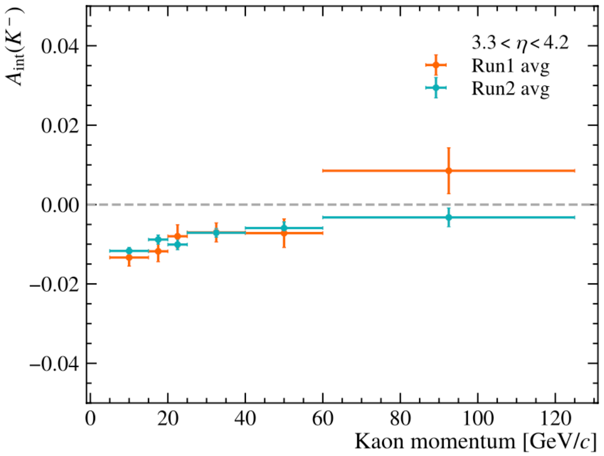
Nature 643 (2025) 1223

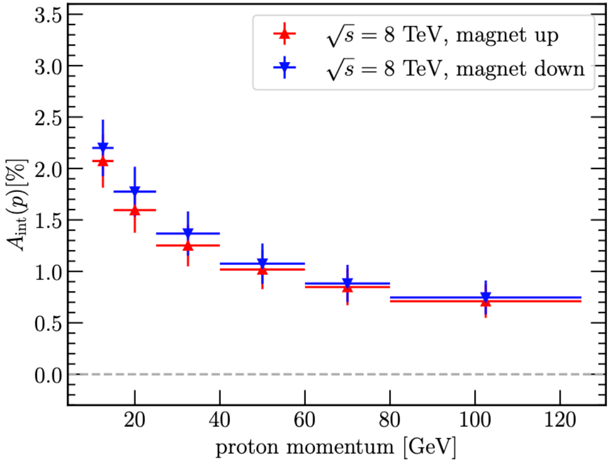
$$A_{CP} = \Delta A_{\text{yield}} - \Delta A_{\text{P}} - \Delta A_{\text{exp}}$$

- Production asymmetry: cancelled by matching $\Lambda_b^0$ kinematics of control to signal mode
- Detection asymmetry: candidate by candidate correction depending on final state kinematics




$$\Delta A_{\text{prod}} = 0$$

$$\Delta A_{\text{exp}} = 0.01\%$$

# Systematic uncertainties

Nature 643 (2025) 1223

## From nuisance asymmetries

| Contribution | Run 1 | Run 2 |
|---|---|---|
| Detection asymmetry difference | $(0.055 \pm 0.128)\%$ | $(0.081 \pm 0.050)\%$ |
| PID asymmetry difference | $(0.026 \pm 0.141)\%$ | $(-0.028 \pm 0.002)\%$ |
| Trigger asymmetry difference | $(-0.039 \pm 0.029)\%$ | $(-0.050 \pm 0.008)\%$ |
| Total nuisance asymmetry difference | $(0.042 \pm 0.193)\%$ | $(0.003 \pm 0.051)\%$ |

## From signal extraction

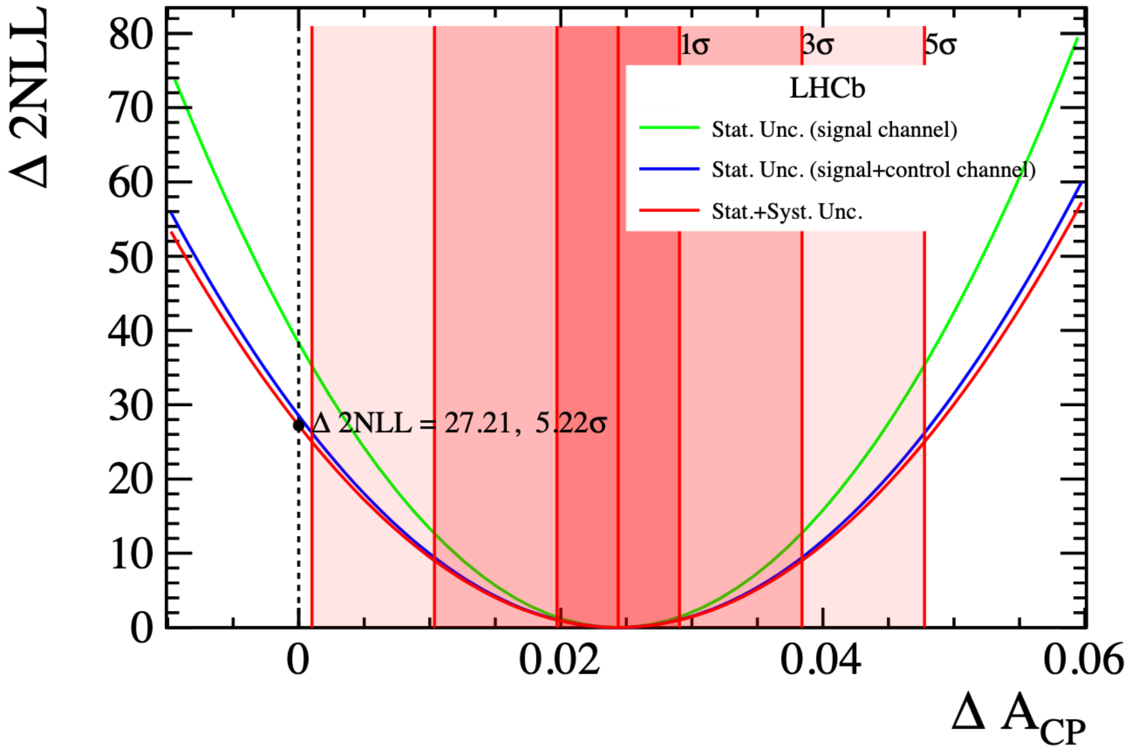
| Contribution | Run 1 | Run 2 |
|---|---|---|
| Nuisance asymmetry difference | 0.193% | 0.051% |
| Mass fit | 0.044% | 0.067% |
| Total systematic uncertainty | 0.198% | 0.084% |

Total: 0.10%

# First observation of CP violation

Nature 643 (2025) 1223

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




Rule out CP symmetry ($5.2\sigma$) and large CP violation

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

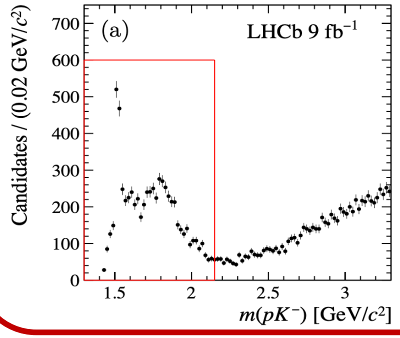
Nature 643 (2025) 1223

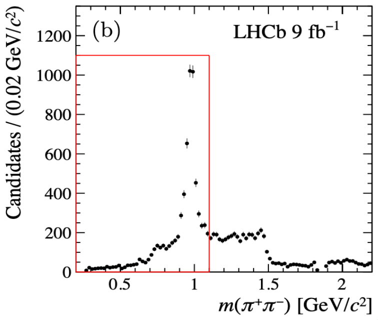
- Four dominating phase space structures
- Local $A_{CP}$ reaching $6\sigma$
  - Interference between resonance states induces phase-space-dependent CPV
  - Most significant local CPV found in $N^{**+}$ resonances regions

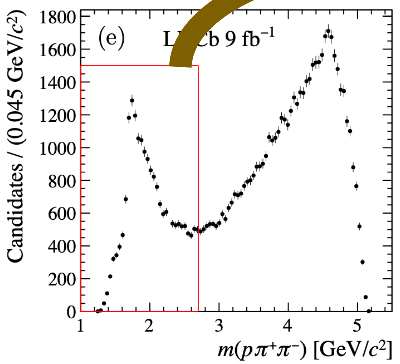
| Decay topology | Mass region (GeV/$c^2$) | $\mathcal{A}_{CP}$ | |
|---|---|---|---|
| $\Lambda_b^0 \to R(pK^-)R(\pi^+\pi^-)$ | $m_{pK^-} < 2.2$<br>$m_{\pi^+\pi^-} < 1.1$ | $(5.3 \pm 1.3 \pm 0.2)\%$ | **$4\sigma$** |
| $\Lambda_b^0 \to R(p\pi^-)R(K^-\pi^+)$ | $m_{p\pi^-} < 1.7$<br>$0.8 < m_{\pi^+K^-}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

$\Lambda$ resonances

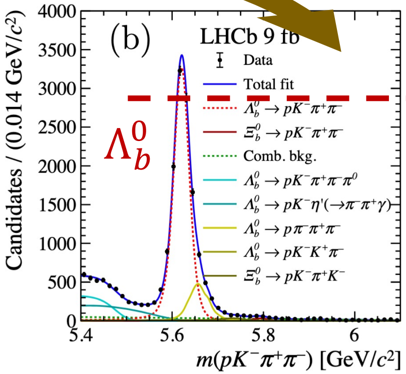
$f_0$ resonances

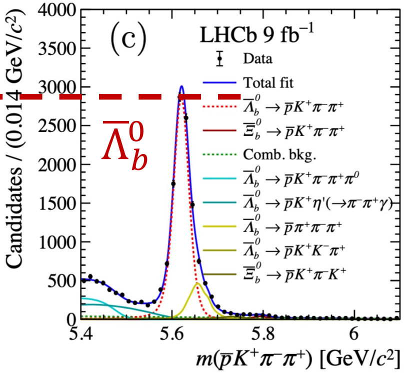


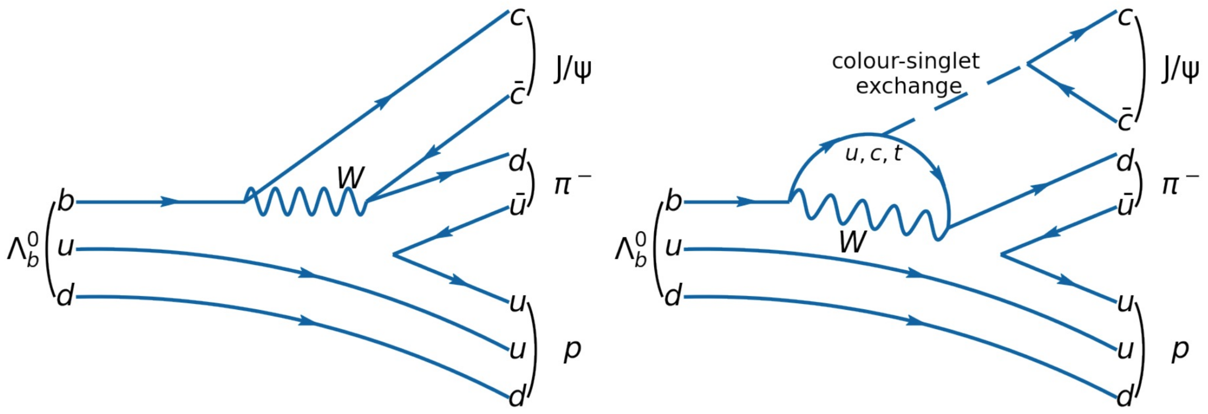




$N^{**+}$ resonances



# CP violation in beauty baryon to charmonium decays



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

- $b \to c\bar{c}q$ process, sensitive to charm loop (pollution to $B$-mixing phase measurement)

$b \to c\bar{c}s$:

$$A_f \sim (V_{cs}^* V_{cb})T + (V_{us}^* V_{ub})P^u$$

$$A\lambda^2 \qquad (\rho - i\eta)A\lambda^4$$

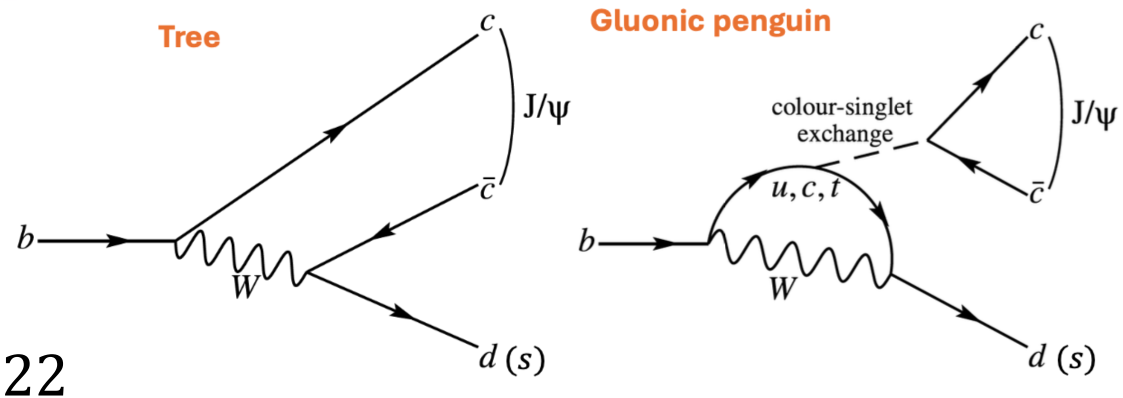
$b \to c\bar{c}d$:

$$A_f \sim (V_{cd}^* V_{cb})T + (V_{td}^* V_{tb})P^t$$

$$-A\lambda^3 \qquad (1 + \rho + i\eta)A\lambda^3$$

Loop contribution relatively enhanced

$\lambda \sim 0.22$




- Recent evidence of CP violation in analogy $B^+ \to J/\psi \pi^+$ decays

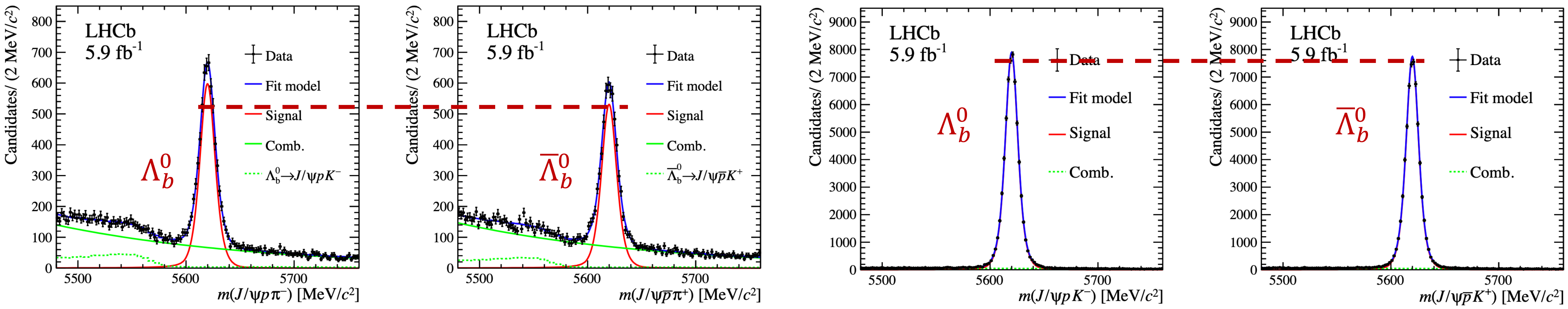
$$\Delta\mathcal{A}^{CP} \equiv \mathcal{A}^{CP}(B^+ \to J/\psi \pi^+) - \mathcal{A}^{CP}(B^+ \to J/\psi K^+) = (1.42 \pm 0.43 \pm 0.08) \times 10^{-2} \qquad (3.2\sigma)$$

# CP violation of $\Lambda_b^0 \to J/\psi p h^-$ decays

[arXiv:2509.16103]

- Relative CP asymmetry between $\Lambda_b^0 \to J/\psi p K^-$ and $\Lambda_b^0 \to J/\psi p \pi^-$ decays
  - ➢ $\Delta A_{CP} = (4.31 \pm 1.06 \pm 0.28)\%$ **$3.9\sigma$**
  - ➢ First evidence of CP violation in beauty baryon to charmonium decays

$\Lambda_b^0 \to J/\psi p \pi^-$ $\Lambda_b^0 \to J/\psi p K^-$

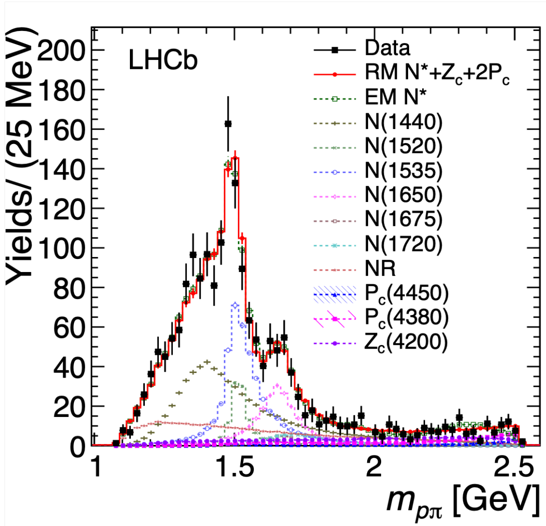


# Local CP violation for $\Lambda_b^0 \to J/\psi p \pi^-$ decay

[arXiv:2509.16103]

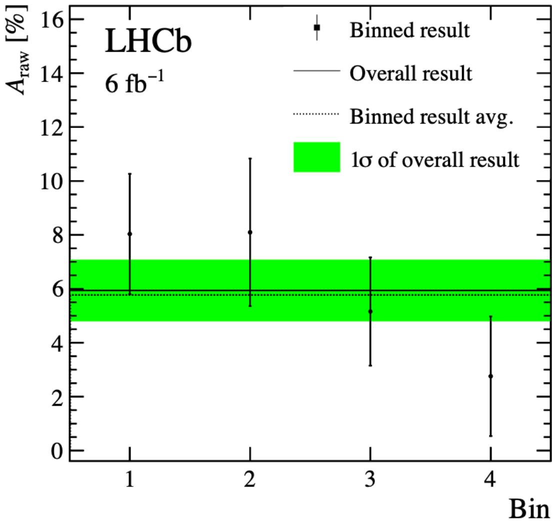
- Decay dominated by various $N^{**0}(\to p\pi^-)$ resonances and possibly exotics
- Various binning schemes for phase space, no strong dependence observed
  - Evenly in Dalitz-plot in 4 bins
  - According to $N^{**0}$ resonances with or without helicity angle binning

$N^{**0}$ contributions

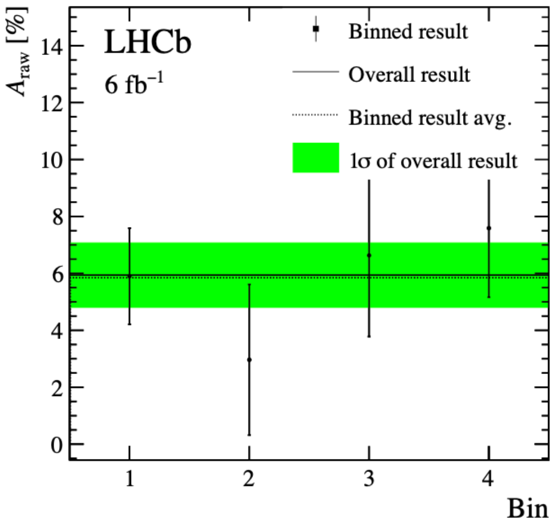



PRL 117 (2016) 082003

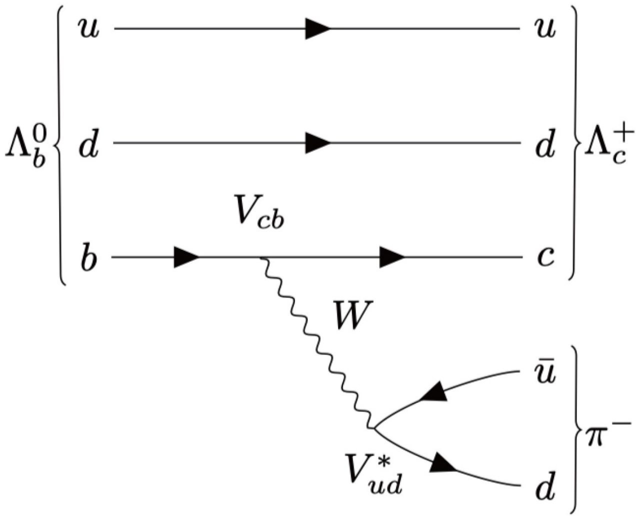
4-Dalitz bins




$N^{**0}$ bins



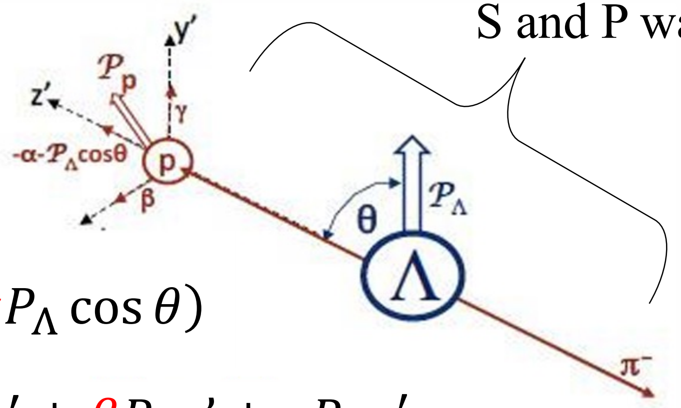
# CP violation in beauty baryon to open charm decays



# Baryon decay parameters

- Proposed by Lee & Yang to study P violation in hyperon decay $\Lambda \to p\pi^{+}$
  - ➢ Initial and final **spins** permits two partially waves, S and P, defining decay parameters

$$\frac{1}{2} \to \frac{1}{2} + 0$$




S and P waves

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

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

$$\alpha \equiv \frac{2\mathrm{Re}(S^* P)}{|S|^2 + |P|^2},$$

$$\beta \equiv \frac{2\mathrm{Im}(S^* P)}{|S|^2 + |P|^2},$$

$$\gamma \equiv \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2},$$

with $\alpha^2 + \beta^2 + \gamma^2 = 1$,

Parity violating observables: $\alpha(\Lambda, \bar{\Lambda})$, $\beta(\Lambda, \bar{\Lambda})$, $\gamma(\Lambda, \bar{\Lambda})$

CP violating observables: $A_{CP}^{\alpha} \equiv \frac{\alpha(\Lambda)+\alpha(\bar{\Lambda})}{\alpha(\Lambda)-\alpha(\bar{\Lambda})}$ …

Addition to decay rate asymmetry

# Beauty and charm baryon decay parameters

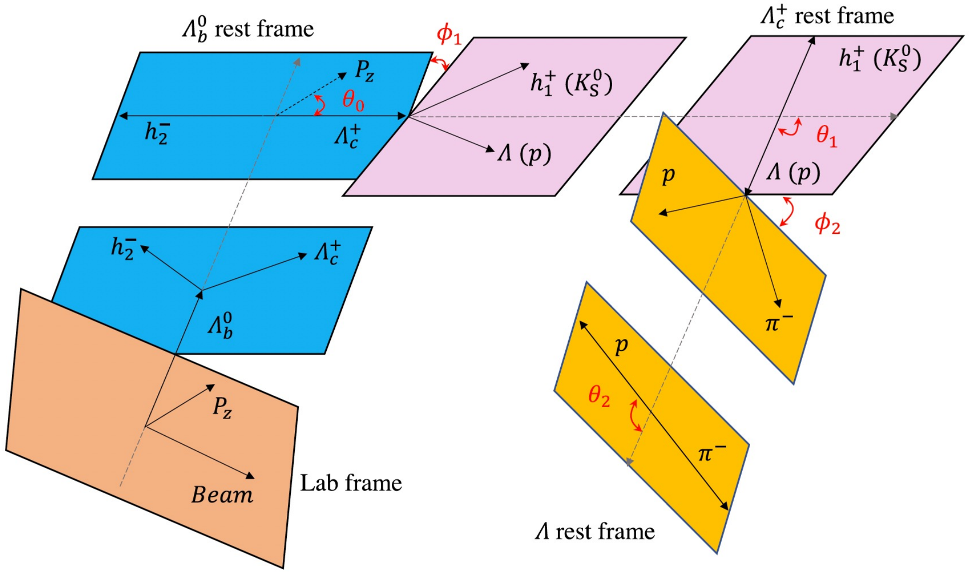
PRL 133 (2024) 261804

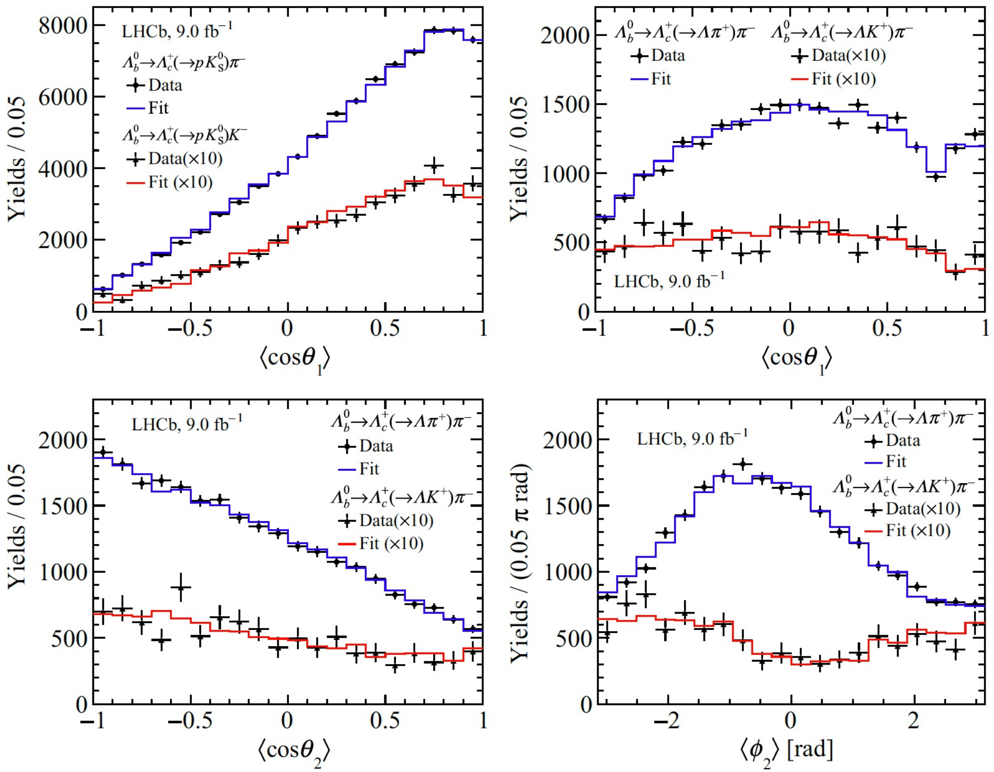
- Simultaneous angular analysis of 6 decays

  $\Lambda_b^0 \to \Lambda_c^+ h^- \ (h = \pi, K)$

  with $\Lambda_c^+ \to \Lambda\, h^+,\ \Lambda \to p\, \pi^-$

  or $\Lambda_c^+ \to p K_s^0$




$$\frac{d^3\Gamma}{d\cos\theta_1 d\cos\theta_2 d\phi_2} \propto (1 + \alpha_{\Lambda_b^0}\alpha_{\Lambda_c^+}\cos\theta_1 + \alpha_{\Lambda_c^+}\alpha_\Lambda\cos\theta_2 + \alpha_{\Lambda_b^0}\alpha_\Lambda\cos\theta_1\cos\theta_2 - \alpha_{\Lambda_b^0}\gamma_{\Lambda_c^+}\alpha_\Lambda\sin\theta_1\sin\theta_2\cos\phi_2 + \alpha_{\Lambda_b^0}\beta_{\Lambda_c^+}\alpha_\Lambda\sin\theta_1\sin\theta_2\sin\phi_2)$$

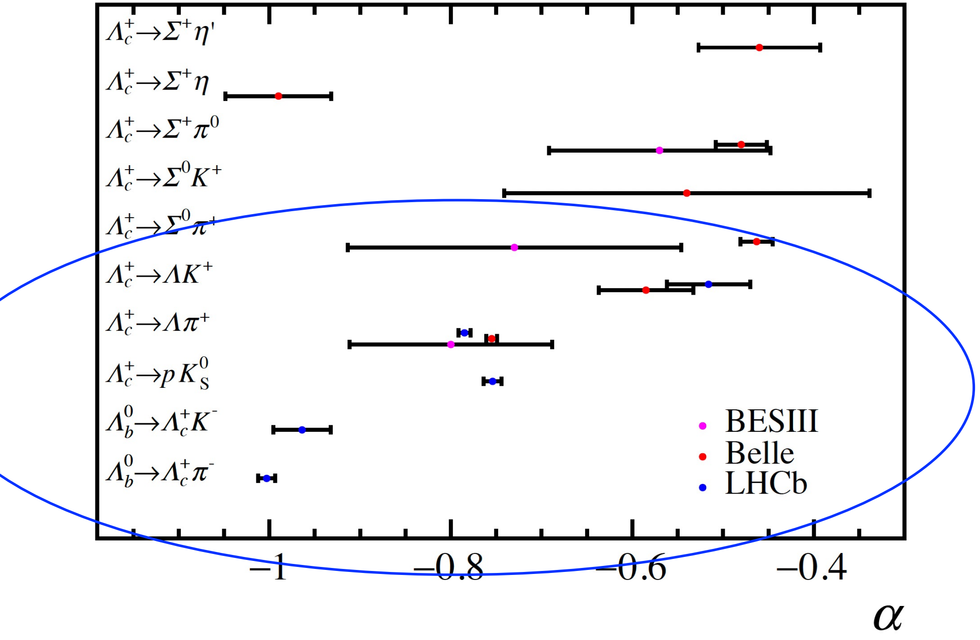
# P and CP violation

PRL 133 (2024) 261804

## P violating $\alpha$ parameters

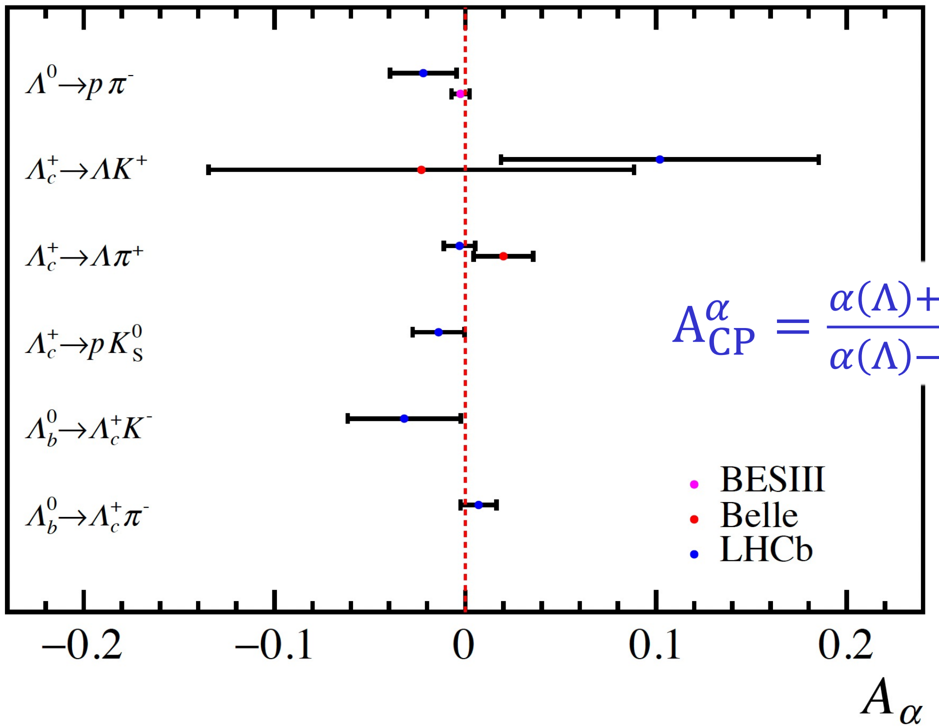
- First time for $\Lambda_b^0 \to \Lambda_c^+ h^-$ decays
- Most precise for $\Lambda_c^+$ decays
- Confirmation of BESIII for $\alpha(\Lambda \to p\pi^-)$

Consistent with Belle and BESIII




## CP violating $A_{CP}^{\alpha}$ parameters

Consistent with CP symmetry




$$A_{\mathrm{CP}}^{\alpha} = \frac{\alpha(\Lambda)+\alpha(\bar{\Lambda})}{\alpha(\Lambda)-\alpha(\bar{\Lambda})}$$

# More for $\Lambda_c^+ \to \Lambda h^+$ decays

PRL 133 (2024) 261804

- No CP violation in $\beta$, $\gamma$ or phases
- Weak phases consistent with zero, non-zero strong phases

| Decay | $\Lambda_c^+ \to \Lambda\pi^+$ | $\Lambda_c^+ \to \Lambda K^+$ |
|---|---|---|
| $\beta$ | $0.368 \pm 0.019 \pm 0.008$ | $0.35 \pm 0.12 \pm 0.04$ |
| $\bar{\beta}$ | $-0.387 \pm 0.018 \pm 0.010$ | $-0.32 \pm 0.11 \pm 0.03$ |
| $\gamma$ | $0.502 \pm 0.016 \pm 0.006$ | $-0.743 \pm 0.067 \pm 0.024$ |
| $\bar{\gamma}$ | $0.480 \pm 0.016 \pm 0.007$ | $-0.828 \pm 0.049 \pm 0.013$ |
| $\Delta$ (rad) | $0.633 \pm 0.036 \pm 0.013$ | $2.70 \pm 0.17 \pm 0.04$ |
| $\bar{\Delta}$ (rad) | $-0.678 \pm 0.035 \pm 0.013$ | $-2.78 \pm 0.13 \pm 0.03$ |
| $\Delta\phi$ (weak phase) | $0.01 \pm 0.02$ | $-0.03 \pm 0.14$ |
| $\Delta\delta$ (strong phase) | $2.693 \pm 0.017$ | $2.57 \pm 0.19$ |

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

$$\beta_{\Lambda_c^+} = \sqrt{1 - (\alpha_{\Lambda_c^+})^2}\sin\Delta_{\Lambda_c^+}$$

$$\gamma_{\Lambda_c^+} = \sqrt{1 - (\alpha_{\Lambda_c^+})^2}\cos\Delta_{\Lambda_c^+}$$

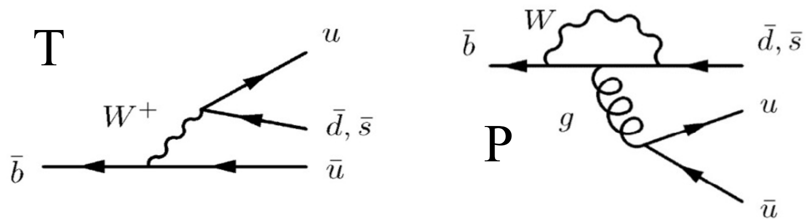
$\Delta_{\Lambda_c^+}$: phase difference between two helicity amplitudes

- Inputs for global fit PRD111 (2025) 034011

# **Spin** makes a difference

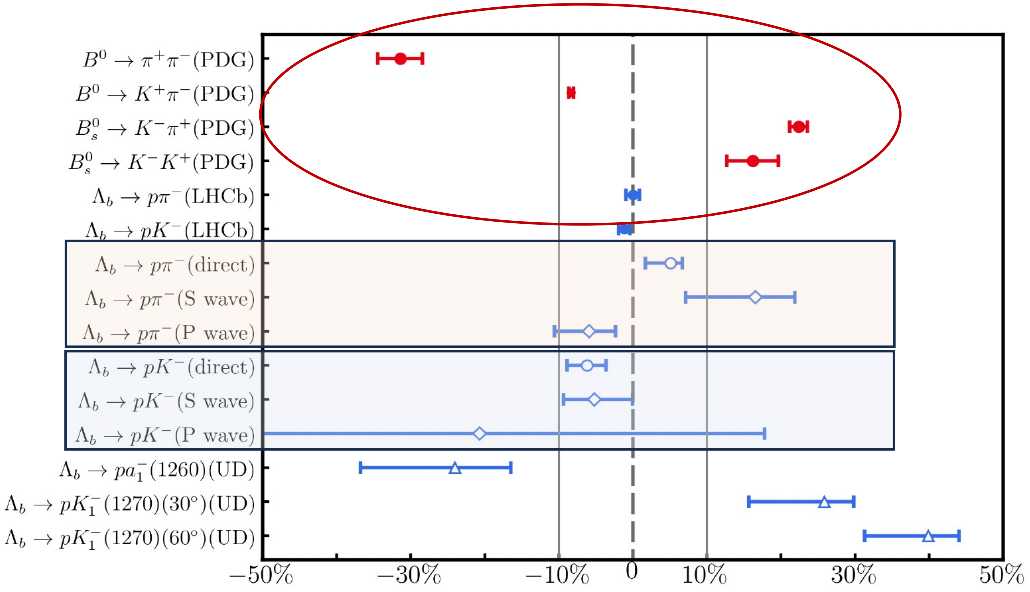
- Why CP violation in baryons generally smaller?
  - ➢ One diagram (tree) overwhelming ?
  - ➢ Small strong phase difference ?
- Dynamics more complex than mesons
  - ➢ Three body system; multiple amplitudes
- Possible cancellation of S and P amplitudes for CP violation

$$A_{CP} \propto \left|\frac{P}{T}\right| \sin(\delta_T - \delta_P)\sin(\phi_T - \phi_P)$$




$$A_{CP}^{\mathrm{dir}} \approx \kappa_S A_{CP}^{S\text{-wave}} + \kappa_P A_{CP}^{P\text{-wave}}$$

PRL134 (2025) 22, 221801



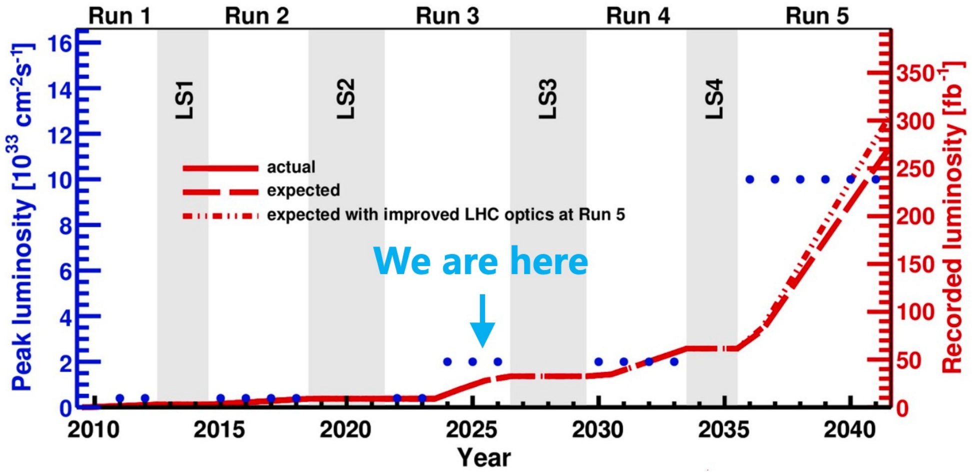


# Summary and outlook

- Baryon CP violation: complementary to mesons as test of SM and search for new physics
- LHCb experiment: intensive studies of baryon CP violation
  - ➢ First observation in $\Lambda_b^0 \to pK^-\pi^+\pi^-$
  - ➢ Evidence in $\Lambda_b^0 \to \Lambda K^+K^-$ and $\Lambda_b^0 \to J/\psi p h^-$
  - ➢ Precise measurements using decay parameters
- Patterns and puzzles: generally small, explained by SM?
- More opportunities at future LHCb
  - ➢ Increased data and advanced techniques


Many thanks !

LHCb schedule



# Backup

# Constrain penguin pollution

- Decay amplitudes: $\frac{\textbf{penguin}}{\textbf{tree}} \equiv -b_f e^{i\rho_f} e^{i\gamma}, \quad = a e^{i\theta} e^{i\gamma}\ (b \to c\bar{c}d); \quad = \epsilon a' e^{i\theta'} e^{i\gamma}\ (b \to c\bar{c}s)$

$$A(B^+ \to J/\psi\pi^+) = -\lambda A_{tree}(1 + a e^{i\theta} e^{i\gamma}),\ A(B^+ \to J/\psi K^+) = \left(1 - \frac{\lambda^2}{2}\right) A'_{tree}(1 + \epsilon a' e^{i\theta'} e^{i\gamma})$$

- Assuming SU(3) symmetry: $a = a', \theta = \theta'$ $\quad \lambda \sim 0.23, \epsilon \equiv \frac{\lambda^2}{1-\lambda^2} = 0.056$

**68% CL:**

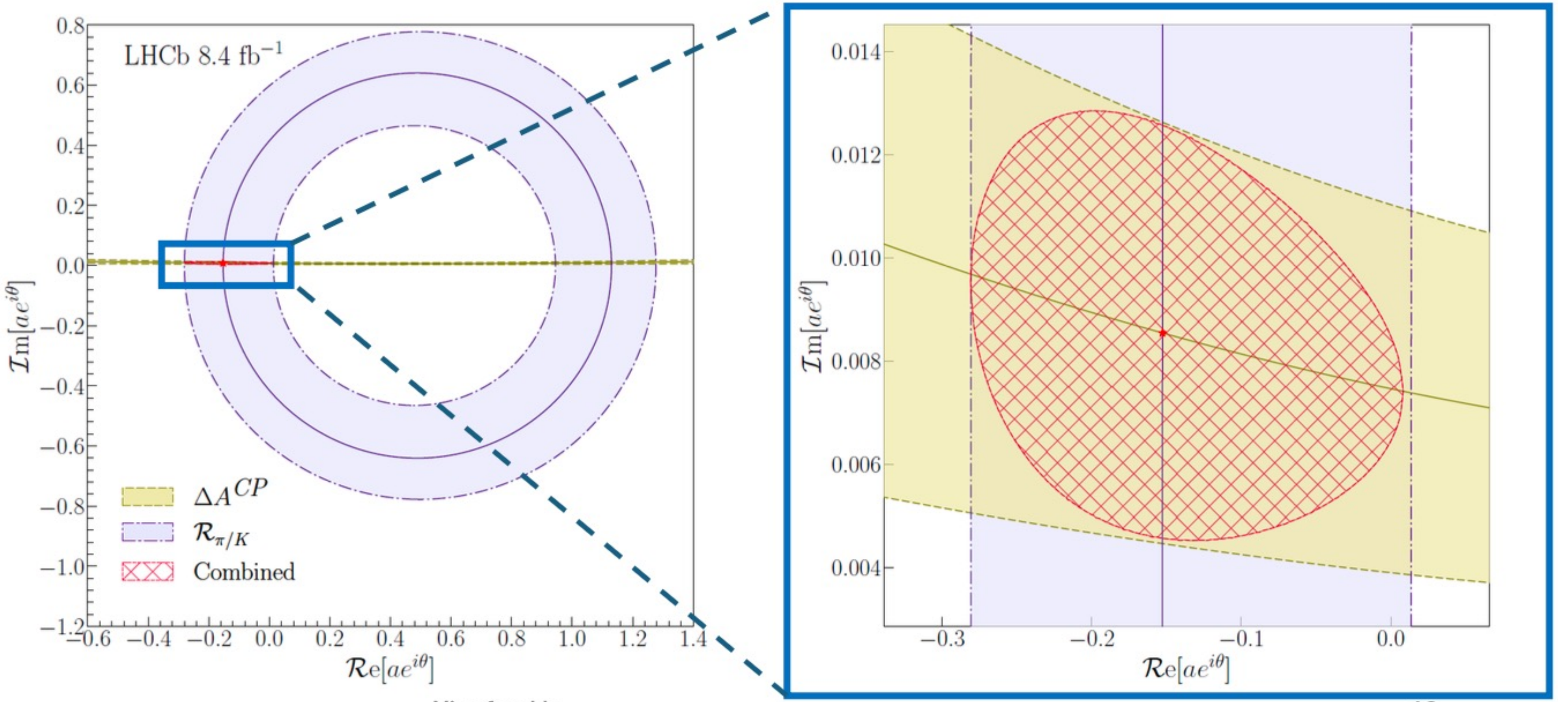
External results:

$$\frac{A'_{tree}}{A_{tree}} = 1.32 \pm 0.07$$

(*J. Phys. G:* **48 (2021)** 065002)

γ=(64.6 ± 2.8)°

(LHCb-CONF-2024-004)




7/30/2025 Xiaofan Hu 13

# Extracting weak and strong phases

- **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 (weak) phase difference between S- and P-waves

[PRL 129 (2022)131801]
[Sci.Bull. 68 (2023) 583-592]
[PRL 133 (2024) 261804]

- Clean observables, less polluted by experimental effects
- Complementary to decay rate asymmetry

$$A_\alpha = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} = -\tan\Delta\delta \tan\Delta\phi$$

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

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