CP violation in baryon decays @ LHCb

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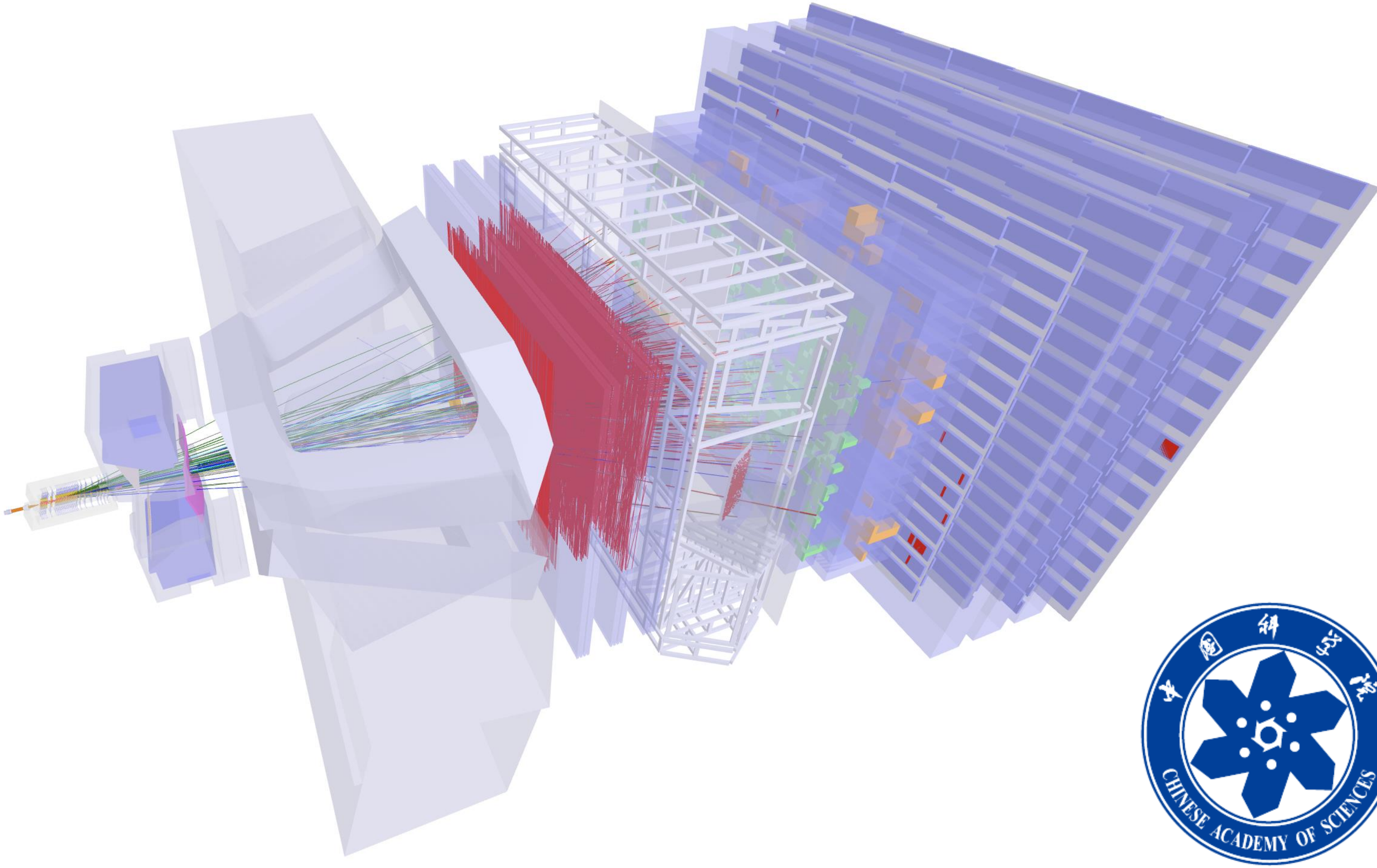
IHEP, CAS
26 April 2025



Baryon asymmetry in the Universe

- "Why is there more matter than antimatter?"
  - One of the 125 questions listed by *Sciences* in 2005
- Sakharov conditions in baryogenesis:
  - Baryon number violation
  - C and CP violation
  - Out of thermal equilibrium
- CP violation
  - One of the main purpose of LHCb experiment

CP violation

- The only source of CP violation in the Standard Model is through CKM mechanism

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} + \mathcal{O}(10^{-3})$$

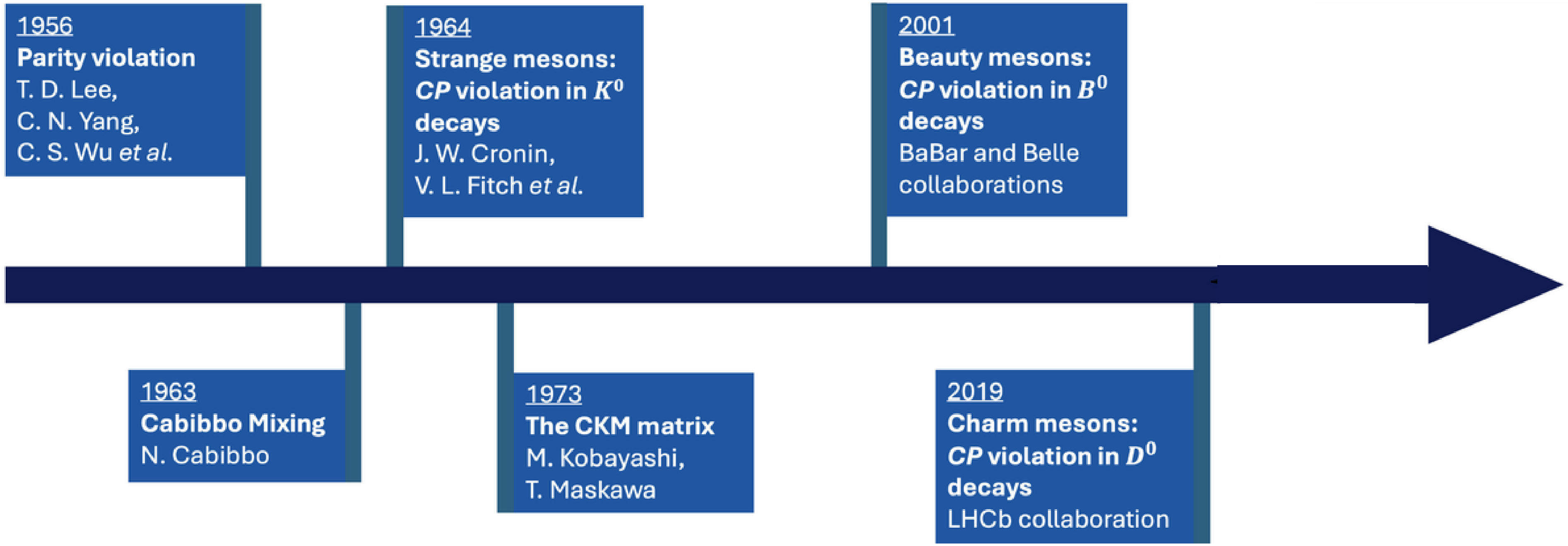
  - Quark mixing matrix
  - A single phase parameter gives rise to quark CPV
  - However, insufficient to explain baryon asymmetry in the universe

$$J_Y \sim J_{CP} \prod \frac{\left(m_{U_i}^2 - m_{U_j}^2\right)}{v^2} \prod \frac{\left(m_{D_i}^2 - m_{D_j}^2\right)}{v^2} \ll \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

  - Beyond SM CP violation needed

CP violation in meson decays

- Well established, in K, B, Bs, and D systems



- Only found in meson systems before 2025
- Baryon CPV could appear in decays mediated by similar quark transition as known CP-violating meson decays

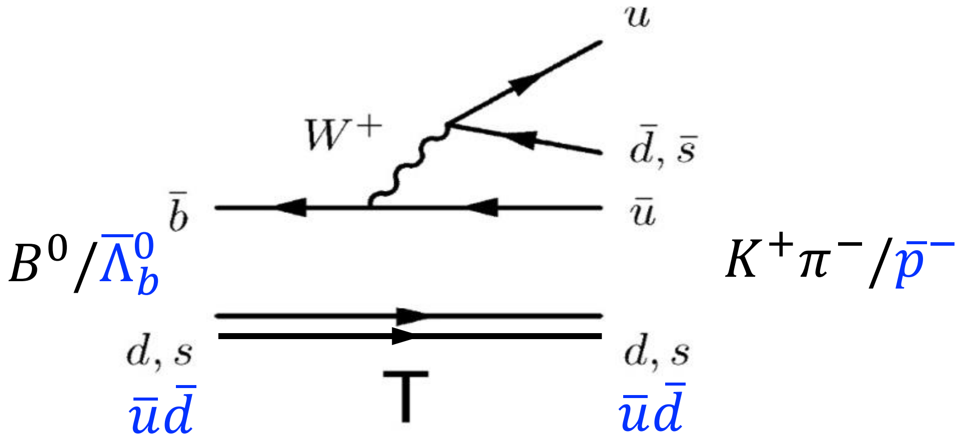
Baryonic CP violation searches @ LHCb

	Methods	Data	Paper
$\Lambda_b^0 \to pK^-/p\pi^-$	A_{CP}	3fb^{-1}	PLB 787 (2018) 124-133
$\Lambda_b^0 \to pK_S^0\pi^-$	$A_{CP}, \Delta A_{CP}$	1fb^{-1}	JHEP 04 (2014) 087
$\Lambda_b^0 \to pD^0K^-$	Miranda S_{CP}^i	9fb^{-1}	PRD104 (2021) 112008
$\Lambda_b^0 \to \Lambda hh'$	$A_{CP}, \Delta A_{CP}$	3fb^{-1}	JHEP05(2016)081
$\Lambda_b^0 \to pK^-\mu^+\mu^-$	ΔA_{CP}	3fb^{-1}	JHEP 06 (2017) 108
$\Lambda_b^0 \to \Lambda\gamma$	photon polarization asy.	3fb^{-1}	PRD105 (2022) L051104
$\Lambda_b^0/\Xi_b^0 \to ph^-h^+h^-$	ΔA_{CP}, TPA, Energy test	3fb^{-1}&6.6fb^{-1}	EPJC (2019) 79:745 PRD 102 (2020) 051101
$\Xi_b^- \to pK^-K^+$	Amplitude analysis	5fb^{-1}	Phys. Rev. D 104, 052010
$\Lambda_c^+ \to pK^-K^+/p\pi^-\pi^+$	ΔA_{CP}	3fb^{-1}	JHEP 03 (2018) 182
$\Xi_c^0 \to pK^-\pi^+$	kNN	3fb^{-1}	EPJC 2020, 80, 986

arXiv:2412.13958, accepted by PRD

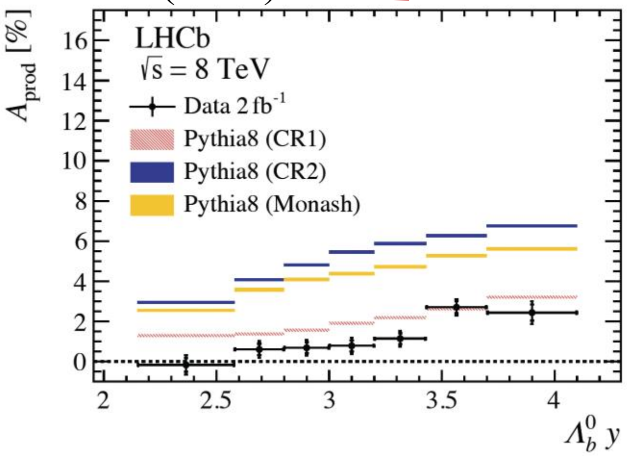
CP violation in $\Lambda_b^0 \to p h^-$ decays

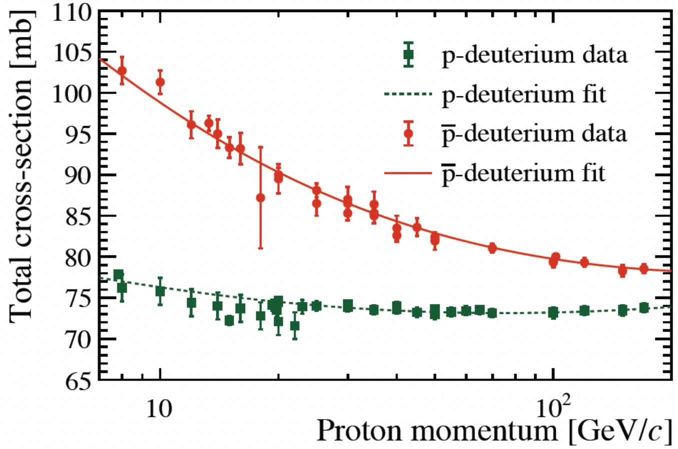
- Large yield and high purity
- CP violation predicted: ~5%
  PRD 102 (2012) 034033
  PRD 95 (2017) 093001

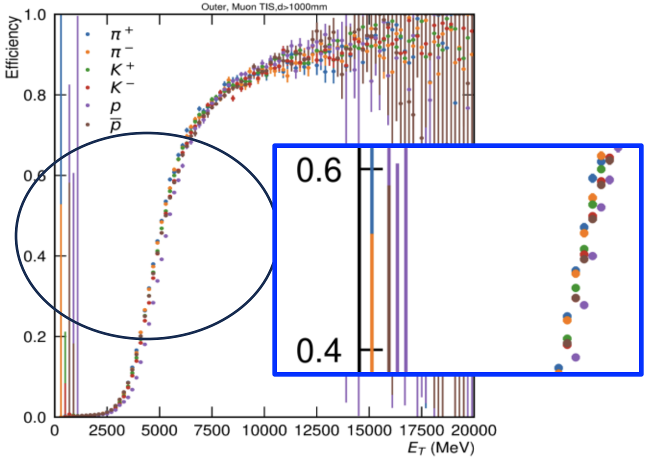


- Crucial to control systematics
- $A_{CP} = A_{raw} - A_{\text{prod}} - A_{\text{detection}} - A_{\text{PID}} - A_{\text{trigger}}$

JHEP 10 (2021) 060







arXiv:2412.13958, accepted by PRD

CP violation in $\Lambda_b^0 \to ph^-$ decays

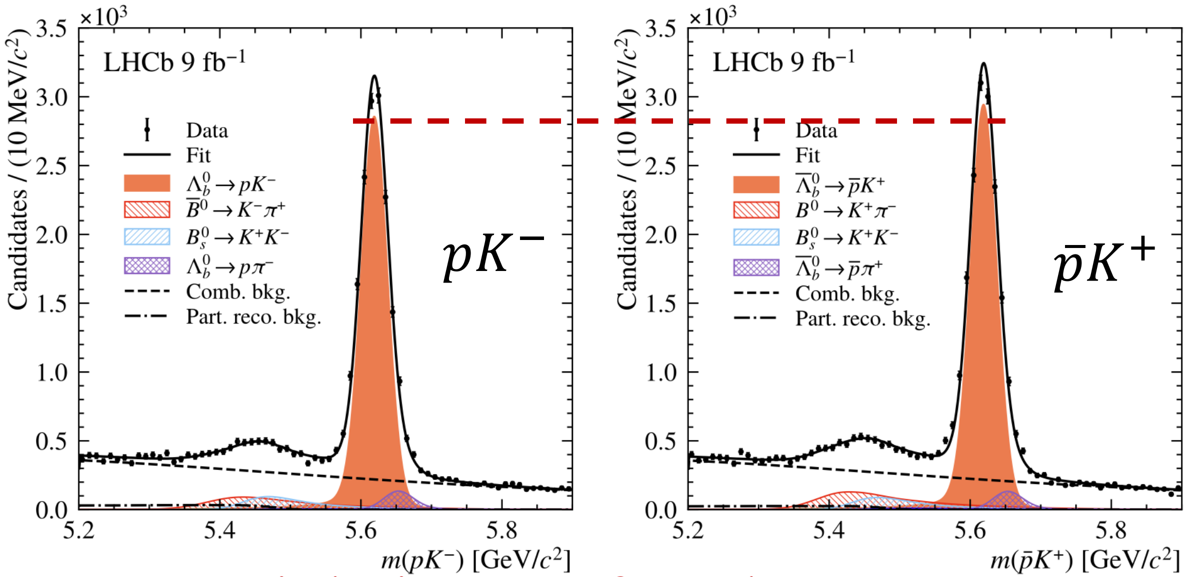
- Data driven corrections and use control mode $\left(\Lambda_b^0 \to \Lambda_c^+(pK^-\pi^+)\pi^-\right)$ to cancel nuisance asymmetries

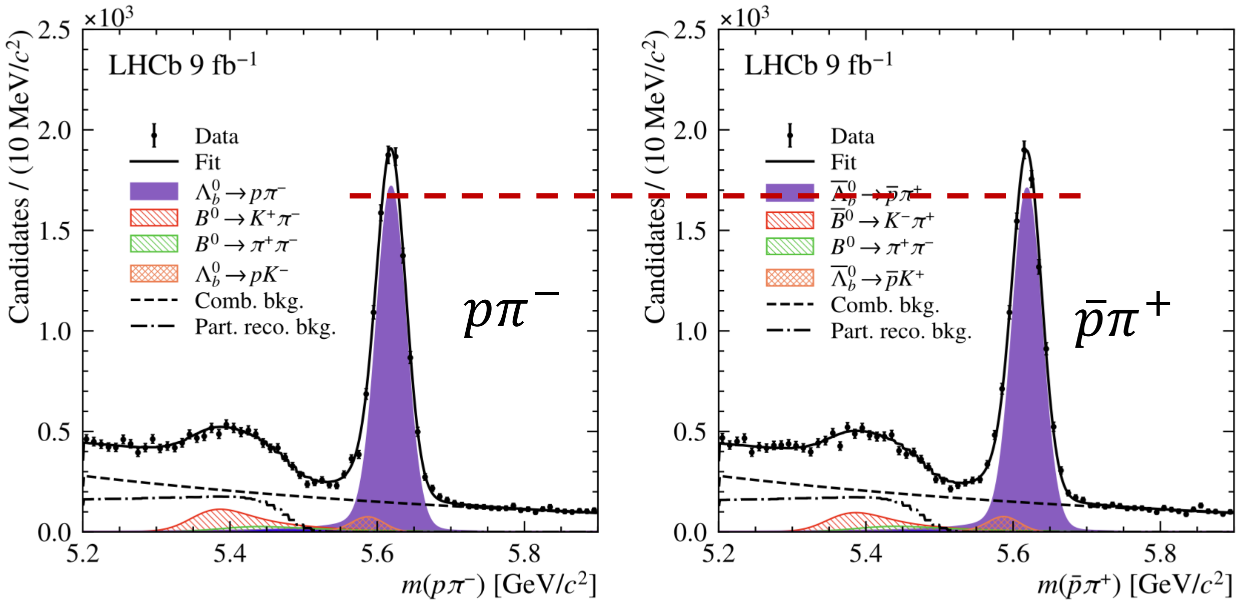
$$A_{CP}^{pK^-} = \Delta A_{\rm raw} - \Delta A_{\rm D}^{p} - \Delta A_{\rm D}^{K^-} - \Delta A_{\rm PID} - \Delta A_{\rm P}^{\Lambda_b^0} - \Delta A_{\rm T} - A_{\rm D}^{\pi^-} - A_{\rm D}^{\pi^+} + A_{CP}^{\Lambda_c^+\pi^-}$$

$$A_{CP}^{p\pi^-} = \Delta A_{\rm raw} - \Delta A_{\rm D}^{p} - \Delta A_{\rm D}^{\pi^-} - \Delta A_{\rm PID} - \Delta A_{\rm P}^{\Lambda_b^0} - \Delta A_{\rm T} - A_{\rm D}^{K^-} - A_{\rm D}^{\pi^+} + A_{CP}^{\Lambda_c^+\pi^-}$$

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

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

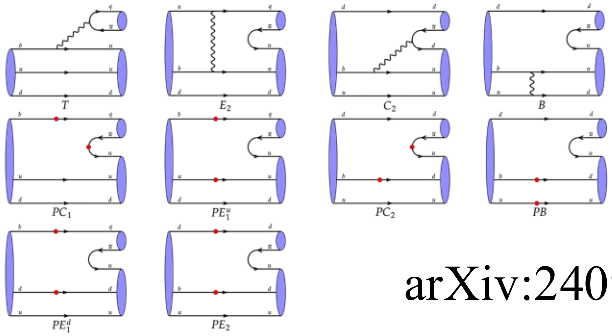




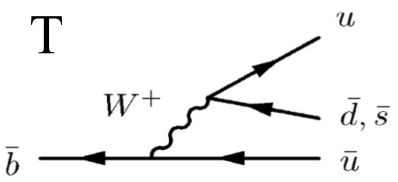
- CP violation not found

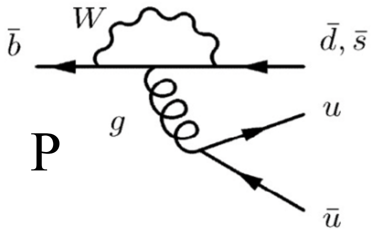
Why so small?

- $A_{CP} \propto \left|\frac{P}{T}\right| \sin(\delta_T - \delta_P)\sin(\phi_T - \phi_P)$
  - One diagram overwhelming? small strong phase difference?
- Dynamics more complex than mesons



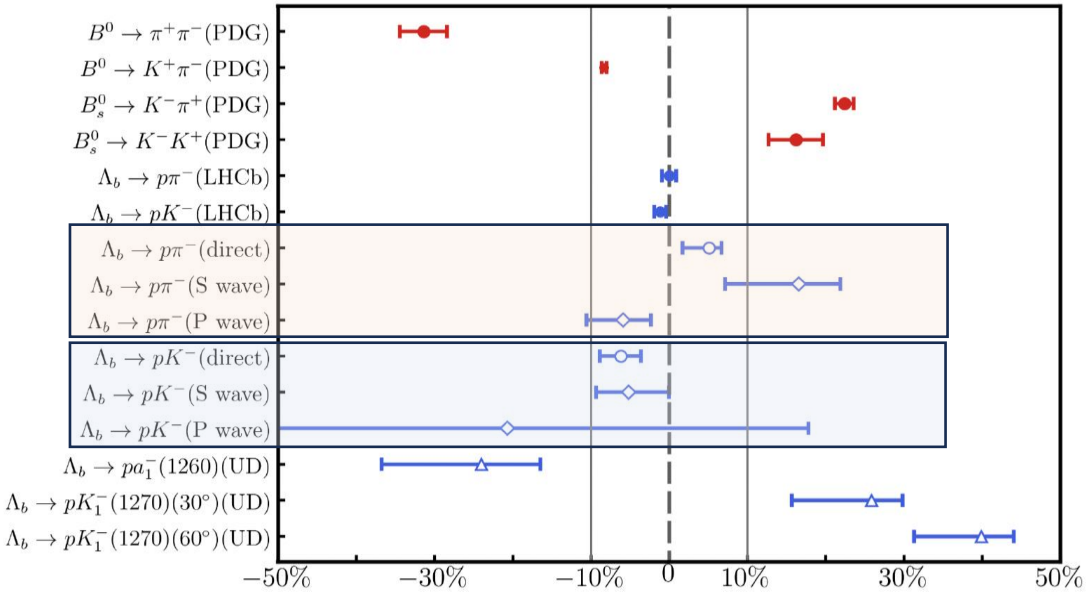
arXiv:2409.02821





➢ Possible cancellation of S and P amplitudes

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



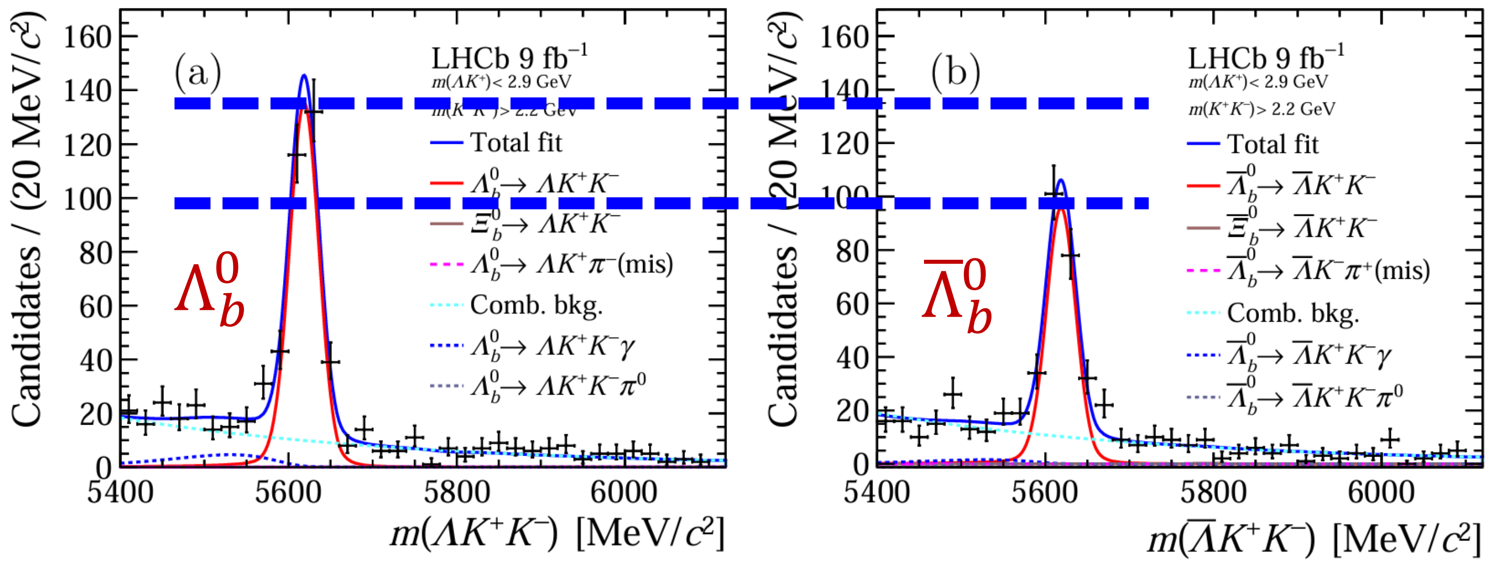
Favoring multiple body decays

CP asymmetry in $\Lambda_b^0 \to \Lambda h_1^+ h_2^-$ decays

- Three Λ_b^0 decays $\Lambda\pi^+\pi^-$、 $\Lambda K^+\pi^-$、 ΛK^+K^-; one Ξ_b^0 decay
- $\Lambda_b^0 \to \Lambda_c^+(\to \Lambda\pi^+)\pi^-$ as control channel

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

3.1σ, evidence for CPV



$\Lambda_b^0 \to \Lambda K^+K^-$ decay

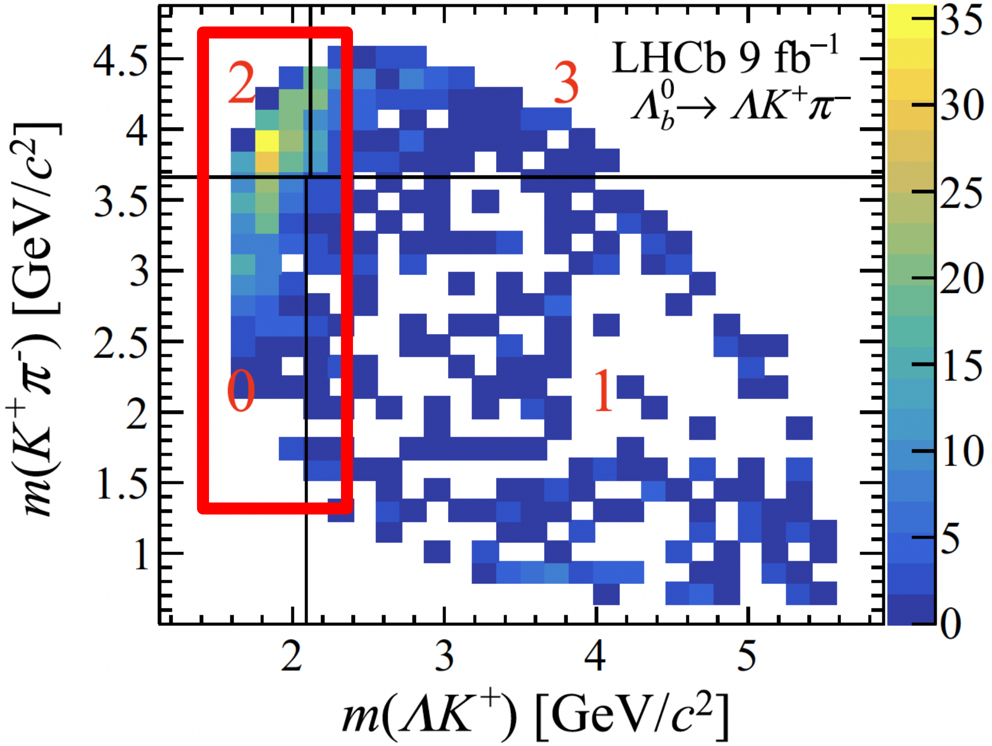
PRL 134 (2025) 101802

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

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

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

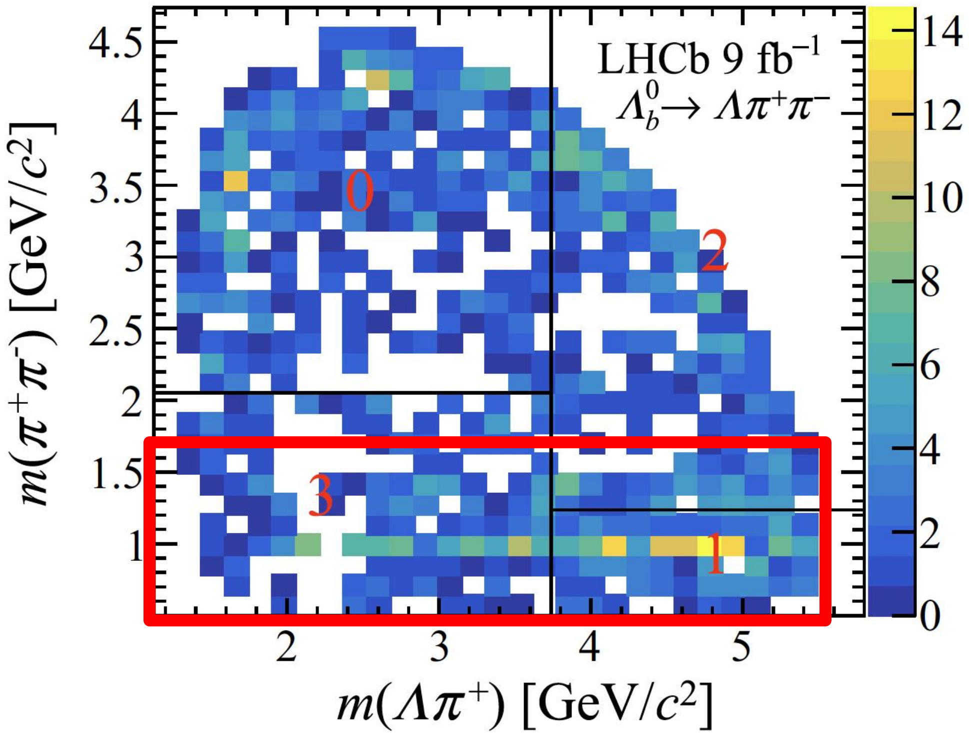
$\Delta A_{CP}(N^{*+}\pi^-) = -0.078 \pm 0.051 \pm 0.027$



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

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

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



PRL 134 (2025) 101802

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

- Two resonance-dominated regions

$m_{K^+K^-} < 1.1$ GeV

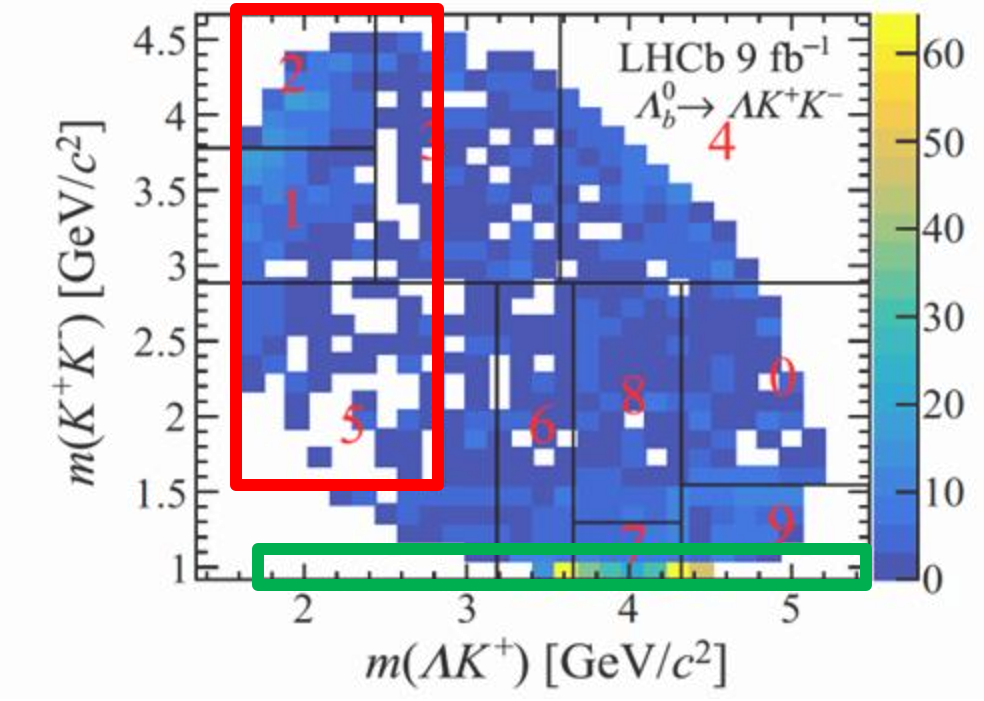
$\Lambda_b^0 \to \Lambda\phi(\to K^+K^-)$ or non-resonant:

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

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

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

$\Delta A_{CP}(N^{*+}K^-) = 0.165 \pm 0.048 \pm 0.017$ (local 3.2σ)



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

Several related N^{*+} channels to cross-check

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

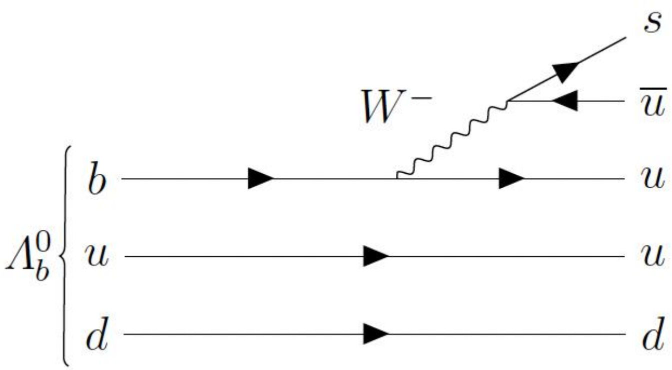
$N^{*+} \to p\pi^+\pi^- \quad \Rightarrow \quad \Lambda_b^0 \to N^{*+}(p\pi^+\pi^-)K^-$

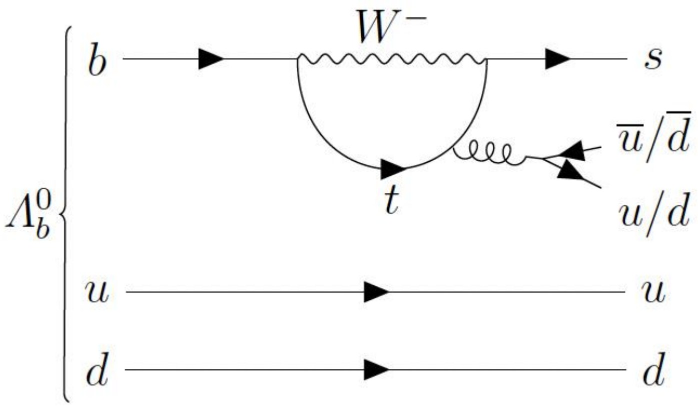
$N^{*+} \to p\pi^0 \quad \Rightarrow \quad \Lambda_b^0 \to N^{*+}(\to p\pi^0)K^-$

J.P. Wang, F.S. Yu, CPC 48 (2024) 101002

CP asymmetry in $\Lambda_b^0 \to p\, K^- \pi^+ \pi^-$

- A_{CP} arises from interference between the tree- and loop-level amplitudes





- Rich resonance structures
  - $\Lambda_b^0 \to N^{*+}(p\,\pi^+\pi^-)K^-,\ p\,K^{*-}(K^-\pi^+\pi^-),\ \Lambda(p\,K^-)f(\pi^+\pi^-),$ $N^{*0}(p\,\pi^-)K^{*0}(K^-\pi^+)$
- Control channel $\Lambda_b^0 \to \Lambda_c^+(p\,K^-\pi^+)\pi^-$ to subtract these nuisance asymmetries

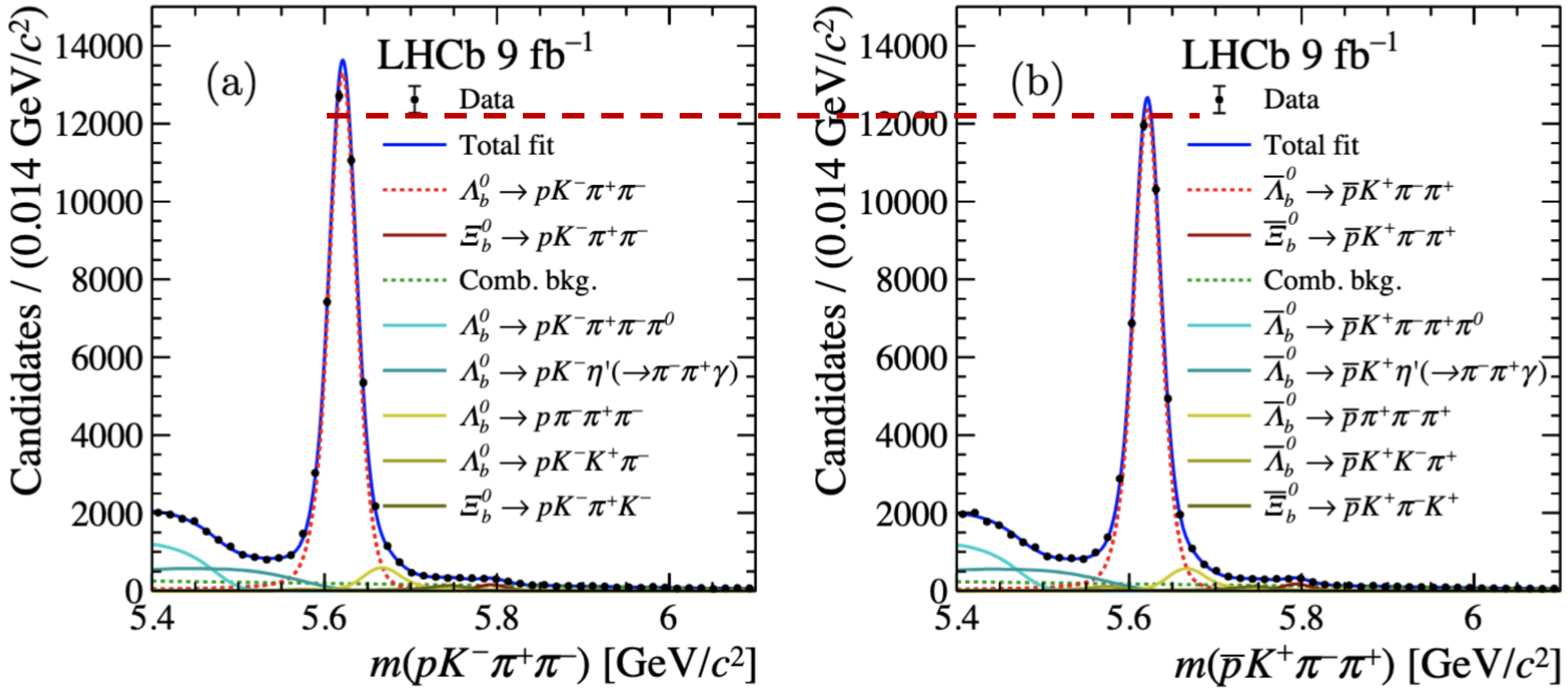
CP asymmetry in $\Lambda_b^0 \to p\,K^-\pi^+\pi^-$

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

(5.2σ significance)

First observation of baryon CP violation

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



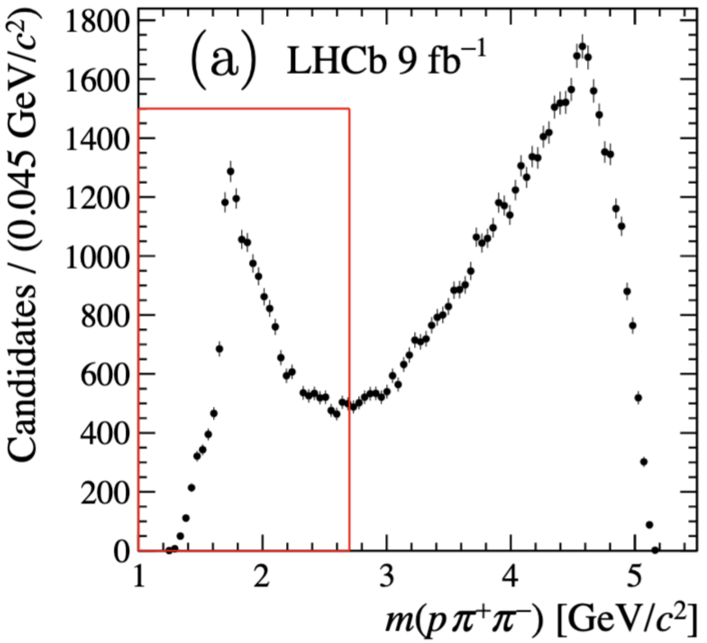
arXiv:2503.16954

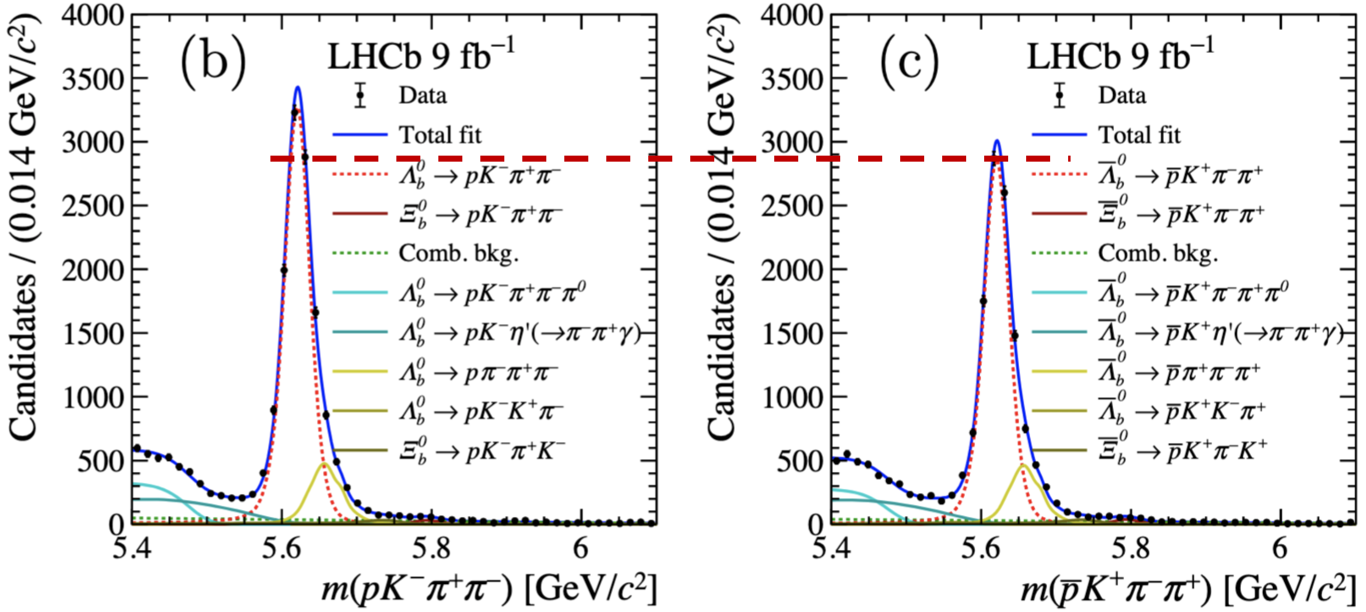
Local CP violation in selected regions of the phase space

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

(6.0σ)

N^{*+} resonance region





1956
Parity violation
T. D. Lee,
C. N. Yang,
C. S. Wu *et al.*

1963
Cabibbo Mixing
N. Cabibbo

1964
Strange mesons:
***CP* violation in K^0 decays**
J. W. Cronin,
V. L. Fitch *et al.*

1973
The CKM matrix
M. Kobayashi,
T. Maskawa

2001
Beauty mesons:
***CP* violation in B^0 decays**
BaBar and Belle collaborations

2019
Charm mesons:
***CP* violation in D^0 decays**
LHCb collaboration

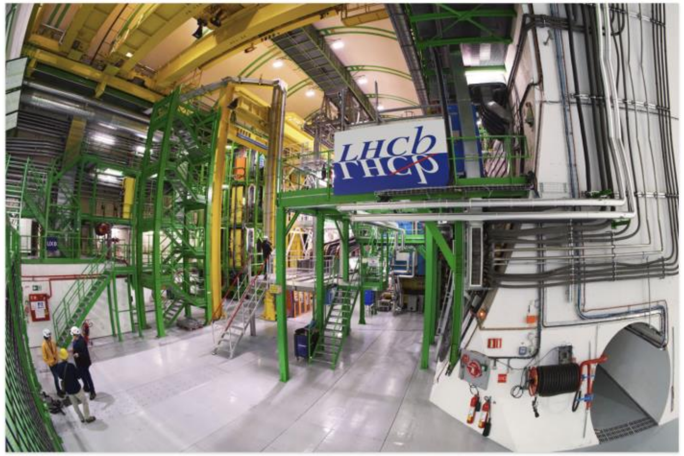
24.3.2025

2025
Beauty baryons:
***CP* violation in Λ_b^0 decays**
LHCb collaboration

A new piece in the matter–antimatter puzzle

The LHCb experiment at CERN has revealed a fundamental asymmetry in the behaviour of particles called baryons

25 MARCH, 2025



View of the LHCb experiment in its underground cavern (image: CERN)

Conclusions and prospects

- CP violation is a rich field of study
- Essential to precisely test the SM and constraint/guide New Physics models
- LHCb has a leading role for CP violation searches
- Direct CP violation in baryon decays observed

- 2024 sample size comparable to the sum of Run 1&2

- More results will come!