LHCb实验重子CP破坏进展

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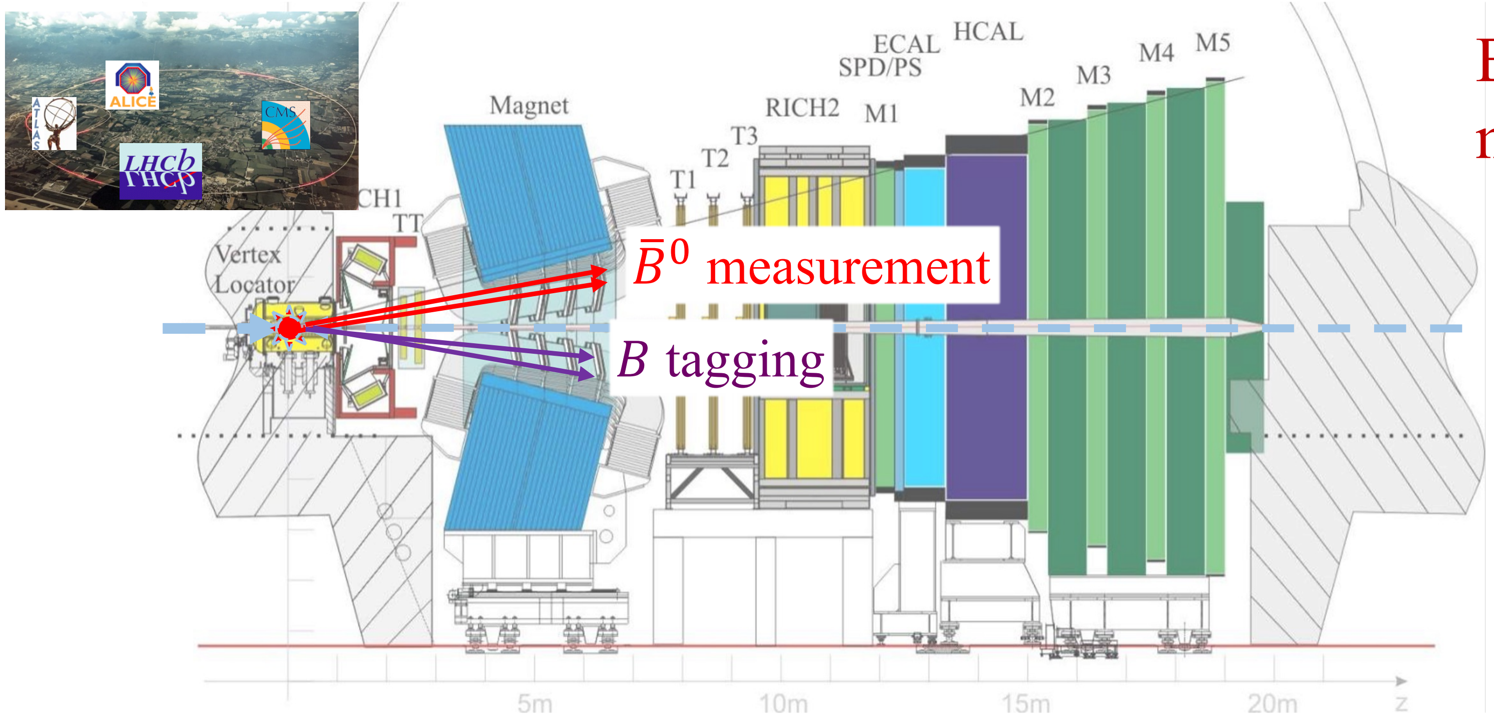
LHCb experiment

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

- Dedicated experiment at CERN to measure b, c hadrons



Excellent vertexing, hadron PID, momentum; flexible trigger …

Main topics

- Heavy flavor and CP violation
- Rare decay
- QCD: production, spectroscopy
- EW and Higgs
- Heavy ion

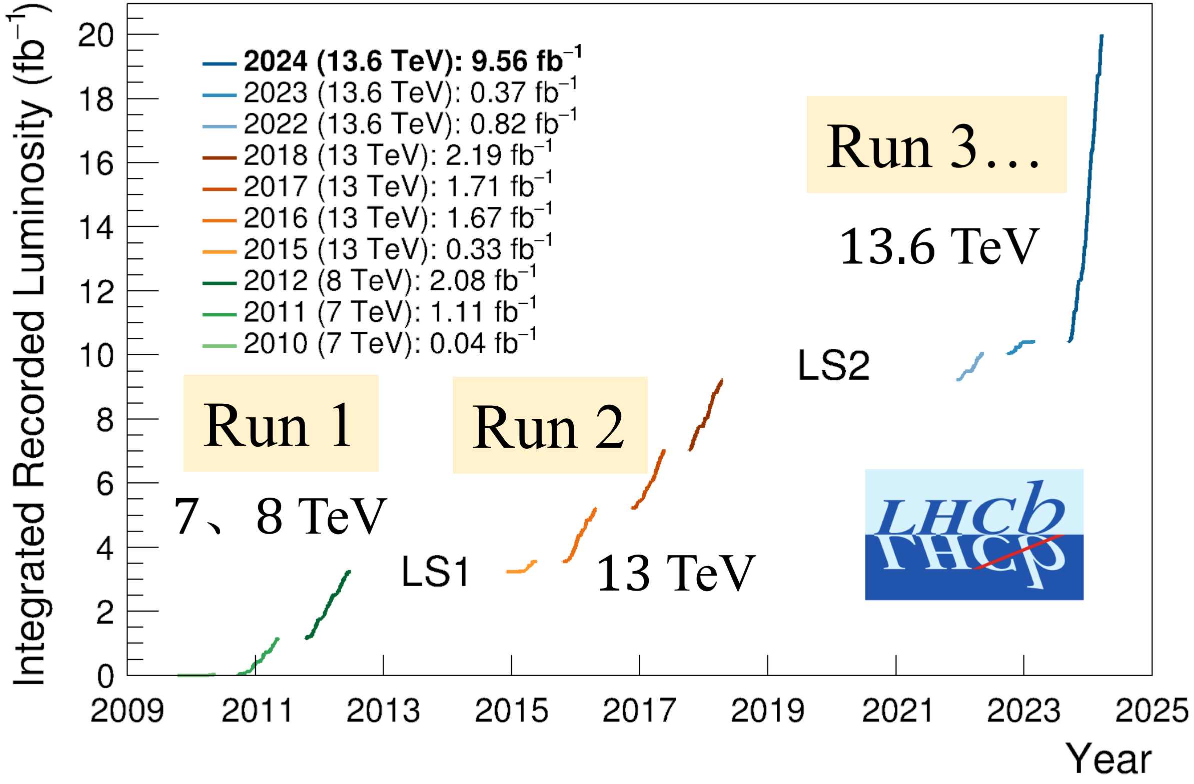
LHCb中国组：清华大学、华中师范大学、高能物理研究所、中国科学院大学、武汉大学、湖南大学、华南师范大学、北京大学、兰州大学、中国科学技术大学、西北工业大学、河南师范大学

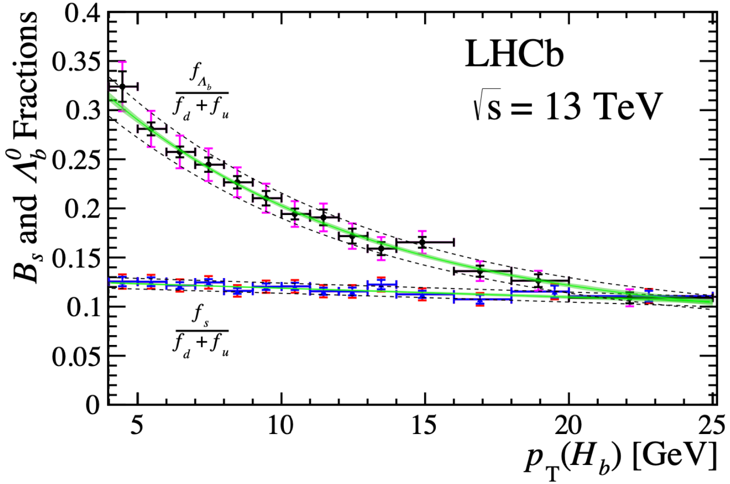
LHCb data

- pp collisions at $\sqrt{s} = 7,\ 8, 13, 13.6\text{TeV}, \int \mathcal{L} = 20\ \text{fb}^{-1}$
- All species produced with large rates

JHEP 05 (2017) 074
PRL 118 (2017) 052002
PRD 100 (2019) 031102(R)

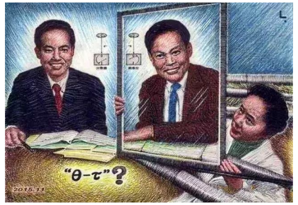
$\sigma(pp \to b\bar{b}X, 13\ \text{TeV}) \approx 0.5\ \text{mb}$ $\quad B^+ : B^0 : B_s^0 : \Lambda_b^0 \approx 4 : 4 : 1 : 2$





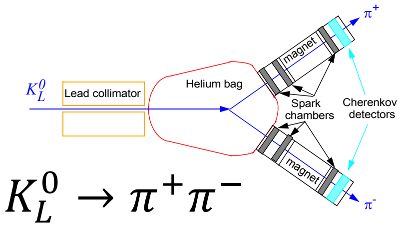
PRD 100 (2019) 031102(R)

Brief history of CP violation



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

1963
Cabibbo Mixing
N. Cabibbo

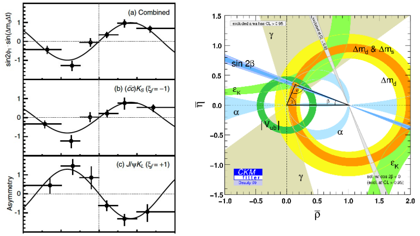


$$K_L^0 \to \pi^+\pi^-$$

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

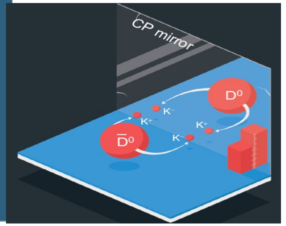
1973
The CKM matrix
M. Kobayashi,
T. Maskawa

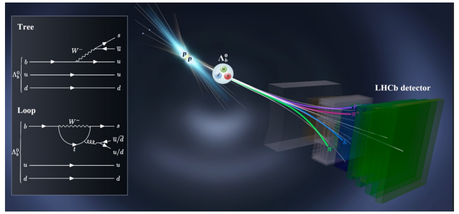
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



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

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





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

TODAY

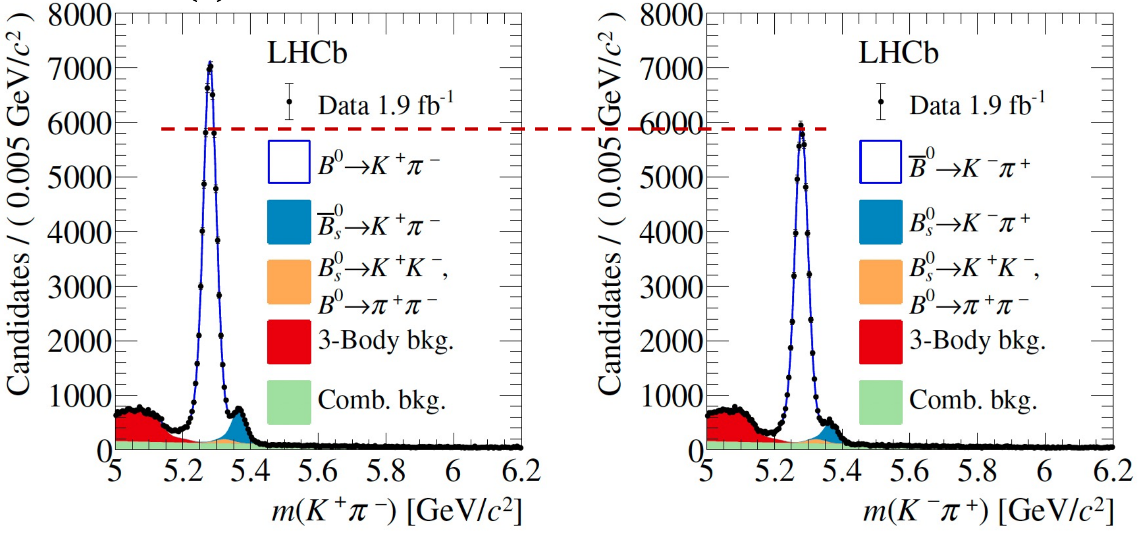
Direct CP violation for beauty mesons

- Two body decays

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

$$A_{CP}^{B_s^0\to K^-\pi^+} = +0.236 \pm 0.017$$

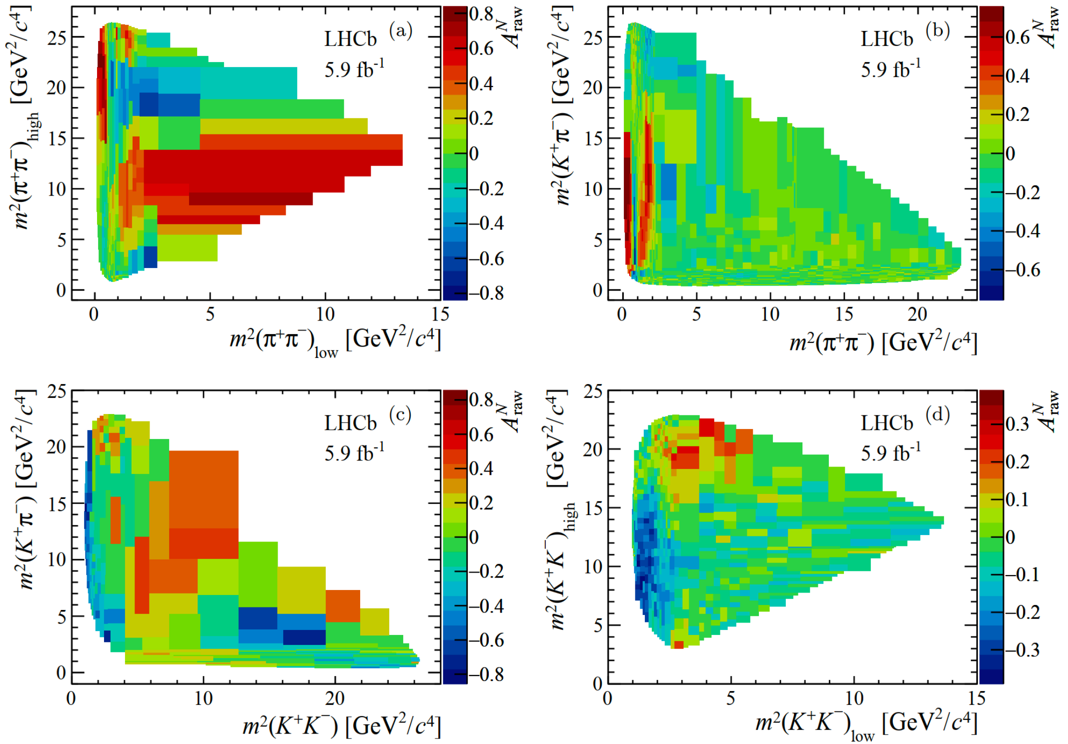
$B_{(s)} \to K^+\pi^-$ $\quad$ $B_{(s)} \to K^-\pi^+$



PRD98 (2018) 032004

- Three body decays

$B^\pm \to \pi^\pm\pi^+\pi^-$ $\quad$ $B^\pm \to K^\pm\pi^+\pi^-$



$B^\pm \to \pi^\pm K^+K^-$ $\quad$ $B^\pm \to K^\pm K^+K^-$

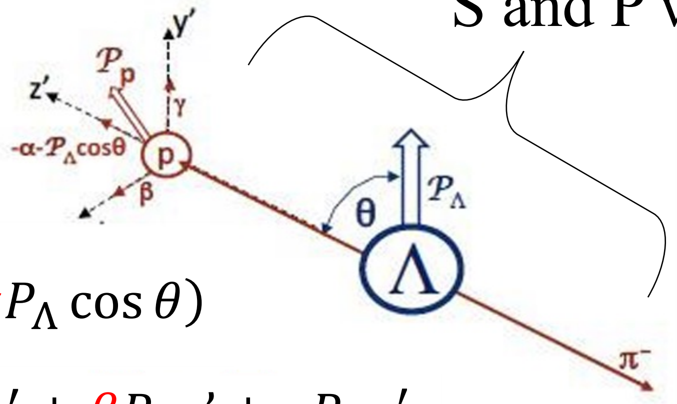
Recent LHCb baryonic CP violation measurements

Long list of efforts by LHCb

Decay	Methods	Data	Reference
$\Lambda_b^0 \to pK_s^0\pi^-$	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, energy test	3 fb^{-1} 6.6 fb^{-1}	Nature Physics 13 (2017) 391 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
$\Lambda_b^0 \to \Lambda\gamma$	photon polarization	3 fb^{-1}	PRD105 (2022) L051104
$\Lambda_b^0 \to ph^-$	A_{CP}	9 fb^{-1}	arXiv:2412.13958, PRD accepted
$\Lambda_b^0 \to \Lambda_c^+h^-$	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}	arXiv:2503.16954, submitted to Nature

CP violation with decay parameters

- Decay parameters proposed by Lee & Yang to study P violation in hyperon decay



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

Complementary to decay rate asymmetry

- Clean observables, less polluted by experimental effects

Beauty and charm baryon decay parameters

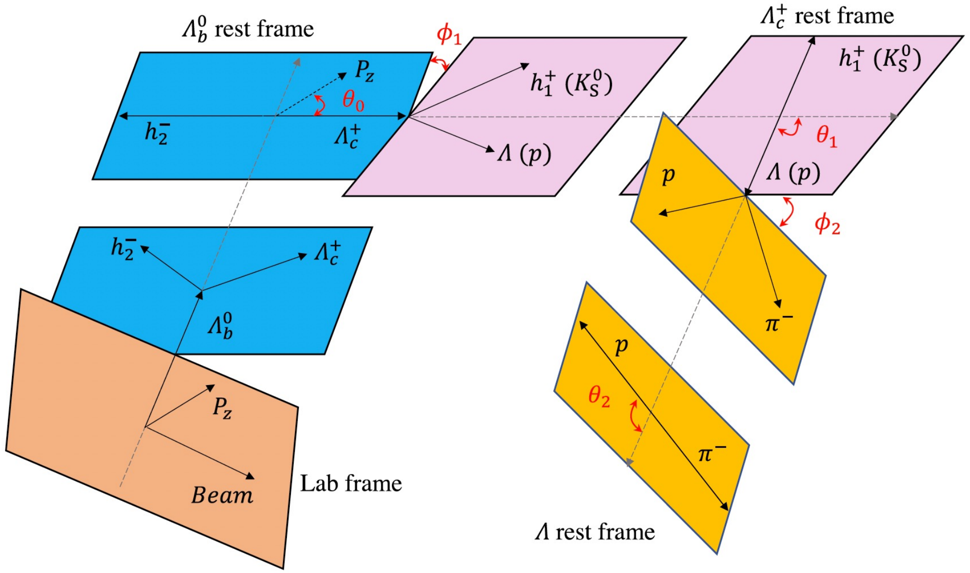
- Simultaneous angular analysis of 6 decays

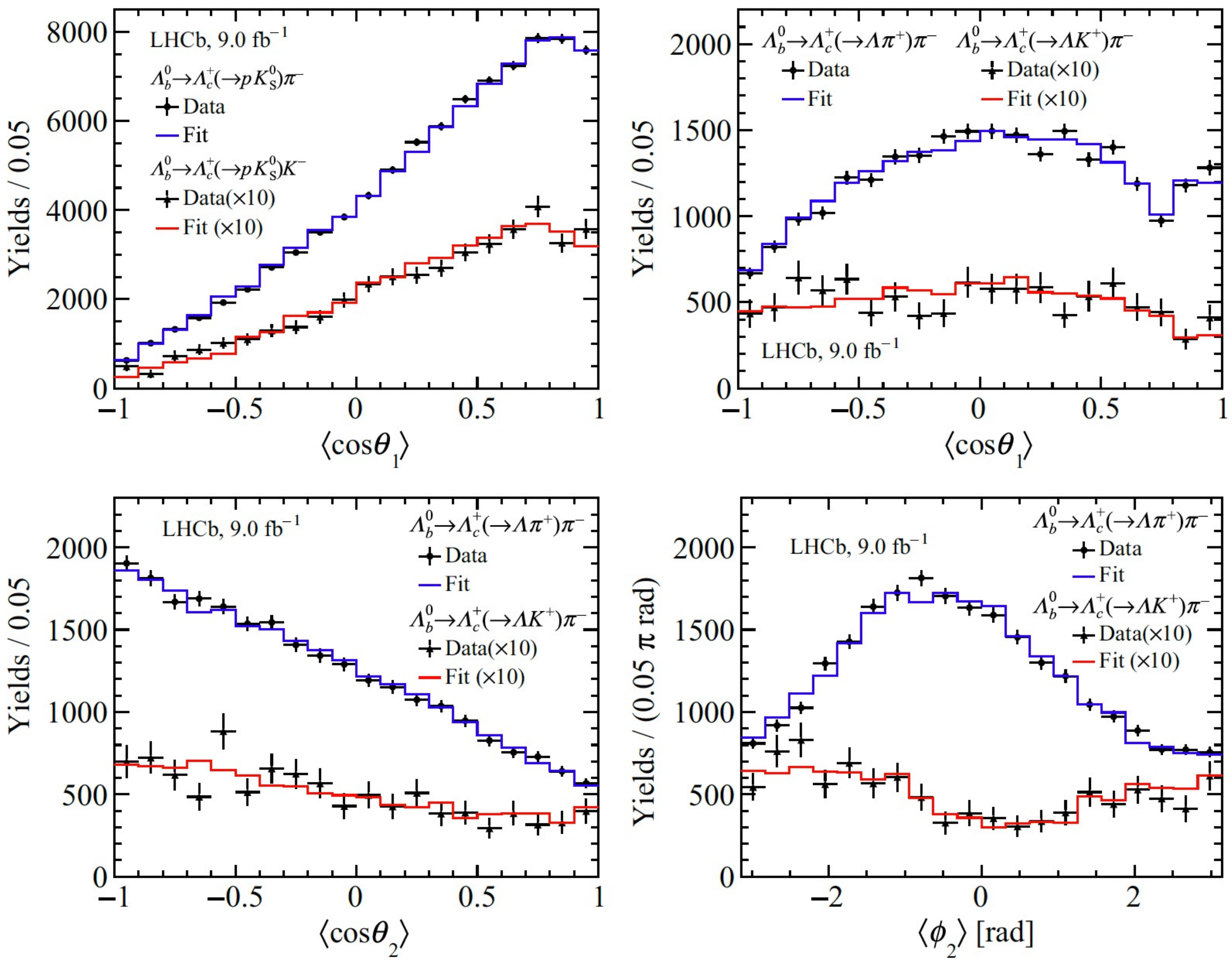
PRL 133 (2024) 261804

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

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

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





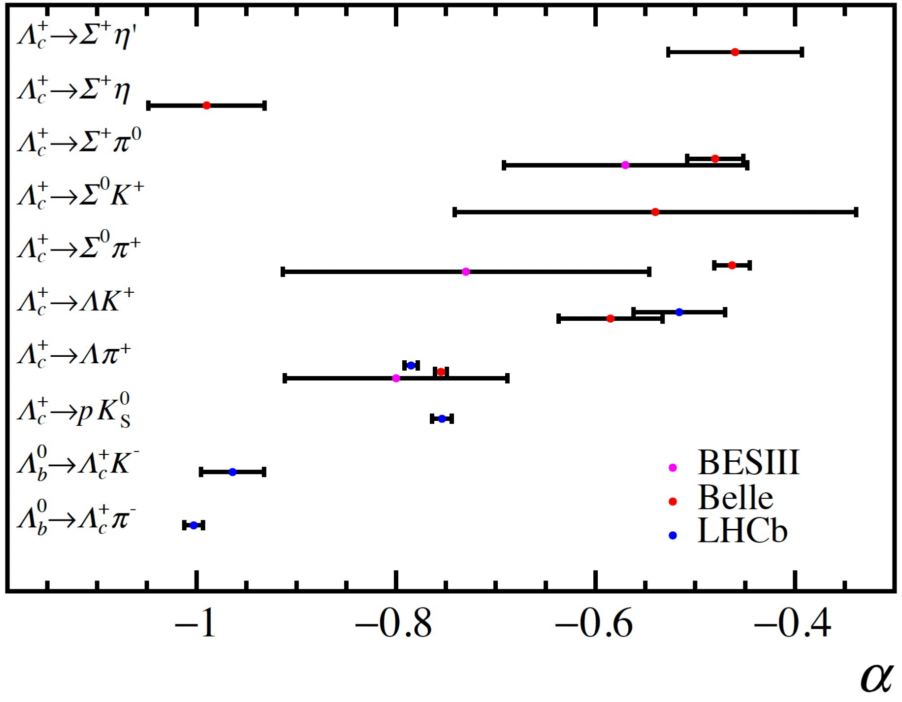
P and CP violation

PRL 133 (2024) 261804

P violating observable α

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

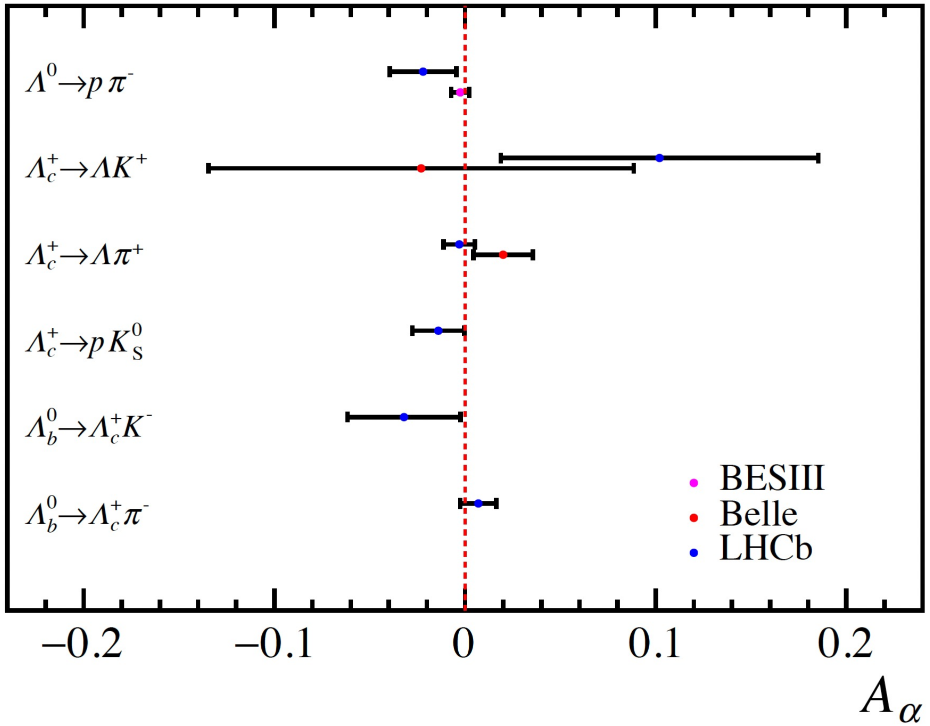
Consistent with Belle and BESIII



CP violating observable A_{CP}^{α}

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

Consistent with CP symmetry



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

PRL 133 (2024) 261804

- No CP violation in β, γ or total phases
- Weak phases consistent with zero, non-zero strong phases

Decay	$\Lambda_c^+ \to \Lambda\pi^+$	$\Lambda_c^+ \to \Lambda K^+$
β	$0.368 \pm 0.019 \pm 0.008$	$0.35 \pm 0.12 \pm 0.04$
$\bar{\beta}$	$-0.387 \pm 0.018 \pm 0.010$	$-0.32 \pm 0.11 \pm 0.03$
γ	$0.502 \pm 0.016 \pm 0.006$	$-0.743 \pm 0.067 \pm 0.024$
$\bar{\gamma}$	$0.480 \pm 0.016 \pm 0.007$	$-0.828 \pm 0.049 \pm 0.013$
Δ (rad)	$0.633 \pm 0.036 \pm 0.013$	$2.70 \pm 0.17 \pm 0.04$
$\bar{\Delta}$ (rad)	$-0.678 \pm 0.035 \pm 0.013$	$-2.78 \pm 0.13 \pm 0.03$
R_β	$0.012 \pm 0.017 \pm 0.005$	$-0.04 \pm 0.15 \pm 0.02$
R'_β	$-0.481 \pm 0.019 \pm 0.009$	$-0.65 \pm 0.17 \pm 0.07$
$\Delta\phi$ (weak phase)	0.01 ± 0.02	-0.03 ± 0.14
$\Delta\delta$ (strong phase)	2.69 ± 0.02	2.57 ± 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

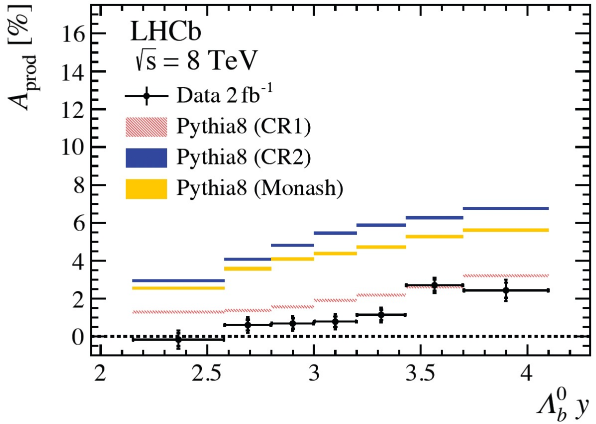
Inputs for global fit: H.-Y. Cheng, F. Xu, H. Zhong, PRD111 (2025) 034011

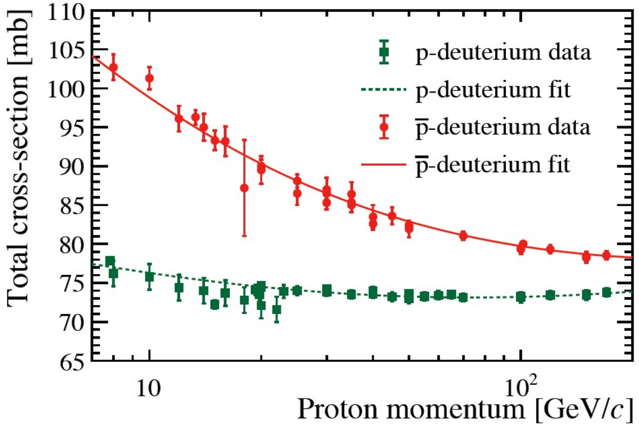
Crucial to control systematics

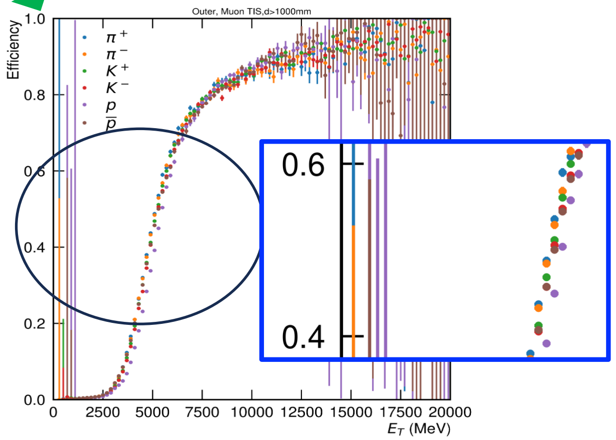
- Subtraction of experiment induced asymmetries (~ 1%, similar to/larger than CPV itself)

$$A_{\text{yield}} = A_{CP} + A_{\text{prod}} + A_{\text{detection}} + A_{\text{PID}} + A_{\text{trigger}}$$

JHEP 10 (2021) 060







- Data driven corrections, use control mode to reduce/remove systematics

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

e.g. $\Lambda_b^0 \to \Lambda_c^+(pK^-\pi^+)\pi^-$

Usually good cancellation, slightly limited by control sample size

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

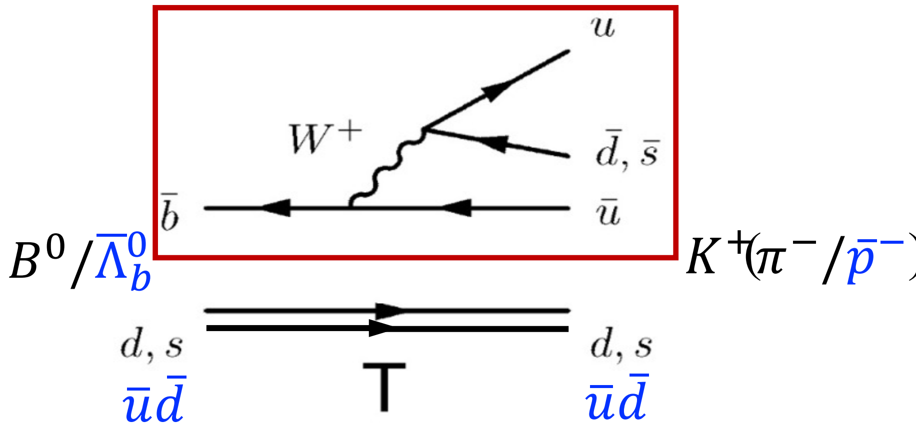
arXiv:2412.13958

- Dynamics analogy to $B^0 \to h^+ h^-$ decays

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

- CP violation predicted: ~5%

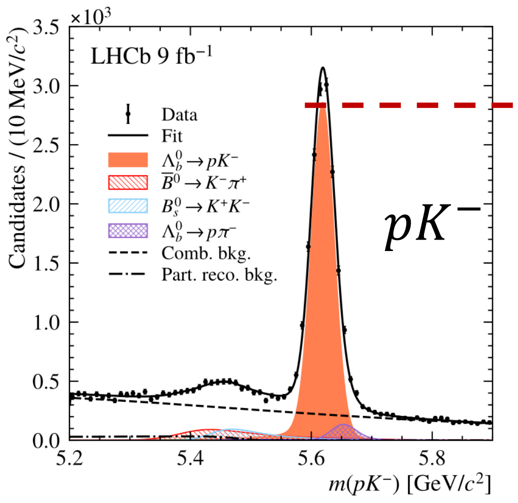
PRD 102 (2012) 034033
PRD 95 (2017) 093001

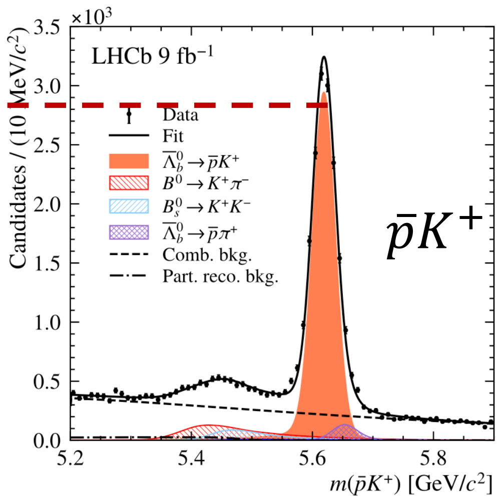


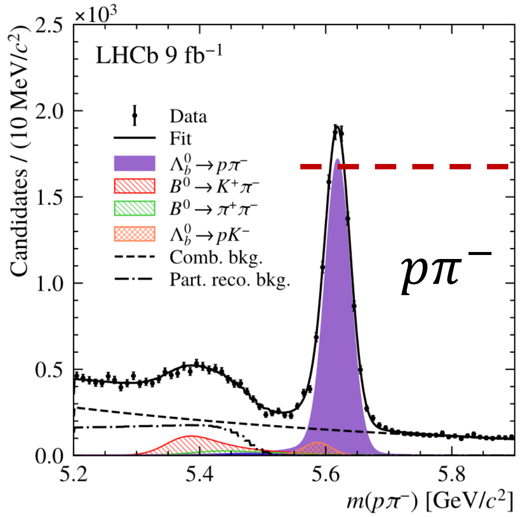
- Sizable CP violation ruled out

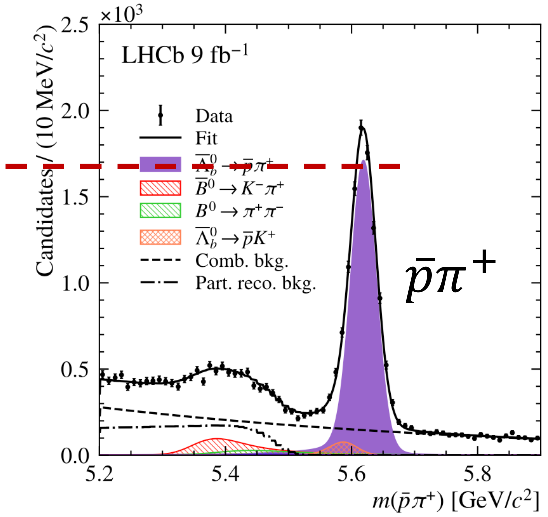
$A_{CP}^{pK^-} = (-1.1 \pm 0.7 \pm 0.4)\%$

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









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

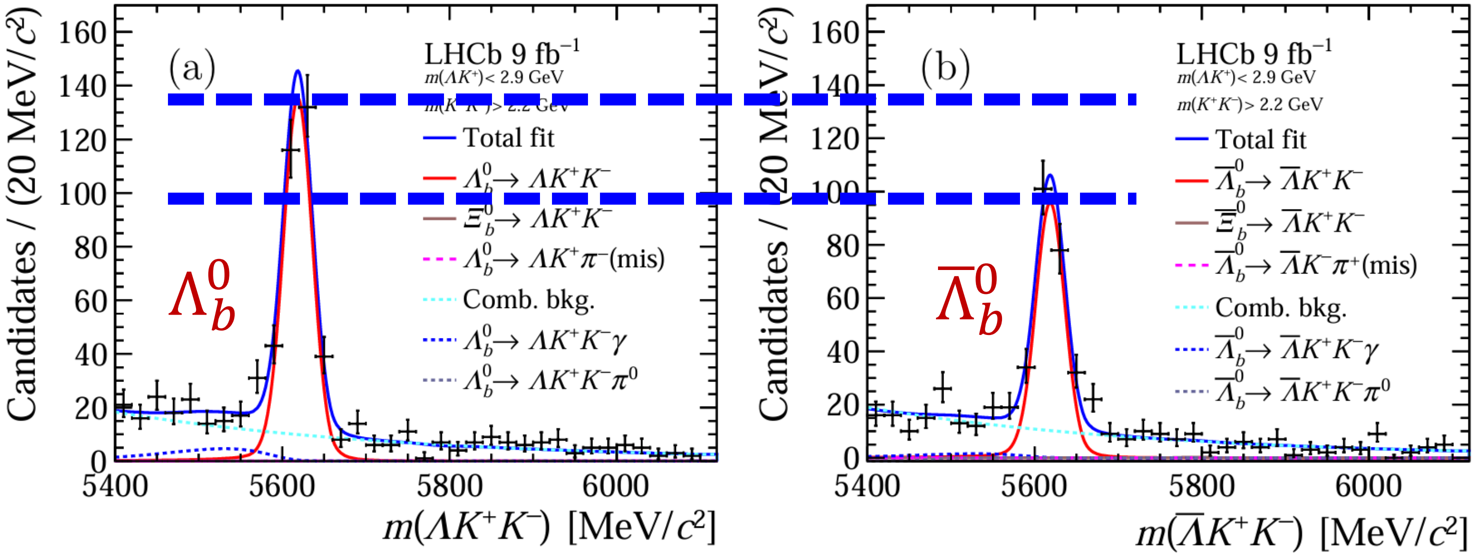
PRL 134 (2025) 101802

- Three Λ_b^0 decays $\Lambda\pi^+\pi^-$、 $\Lambda K^+\pi^-$、 ΛK^+K^-, and $\Xi_b^0 \to \Lambda K^-\pi^+$decay
- $\Lambda_b^0 \to \Lambda_c^+(\to \Lambda\pi^+)\pi^-$ as control channel

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

3.1σ, evidence for CPV in baryons

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



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

PRL 134 (2025) 101802

- In analogy to $B^+ \to K^+K^+K^-$ decay
- 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)

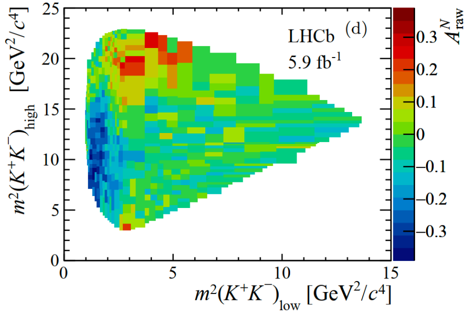
- Many N^{*+} contributing to $\Lambda_b^0 \to N^{*+}K^-$

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

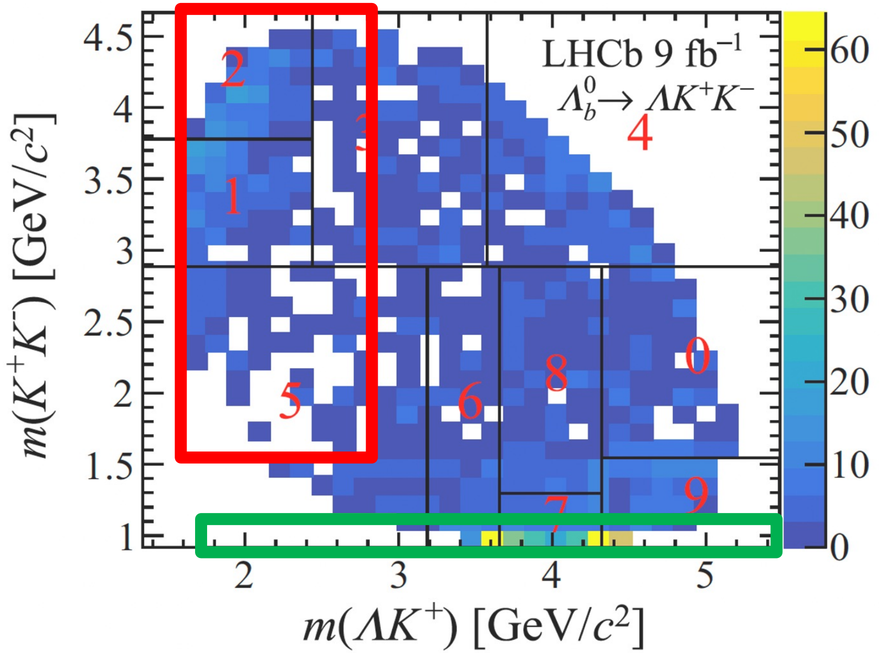
$N^{*+} \to \Lambda K^+ \quad \Rightarrow \Lambda_b^0 \to N^{*+}(\Lambda K^+)K^-$

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

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



$B^\pm \to K^\pm K^+ K^-$ raw asymmetry



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

More local CP asymmetries

PRL 134 (2025) 101802

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

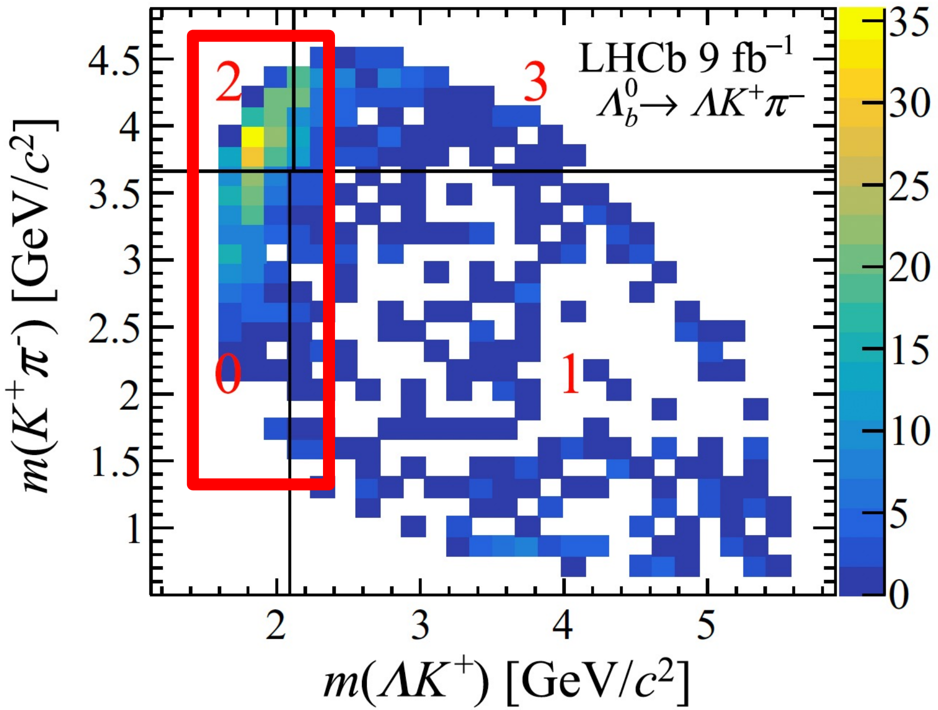
$\Lambda_b^0 \to N^{*+}(\to \Lambda K^+)\pi^-$

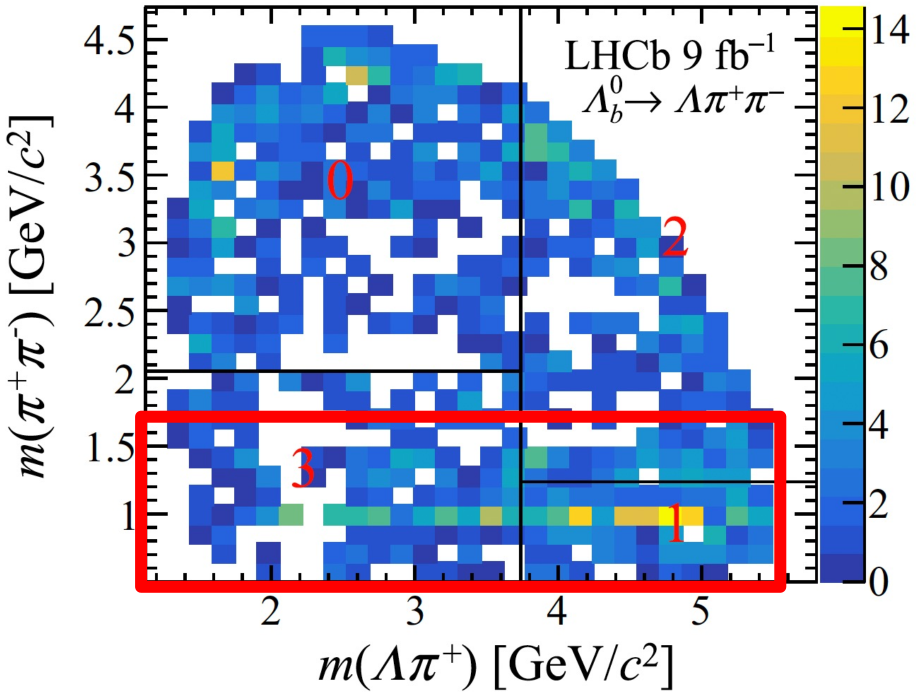
$\Delta A_{CP}(N^{*+}\pi^-) = -0.078 \pm 0.051 \pm 0.027$

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

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

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

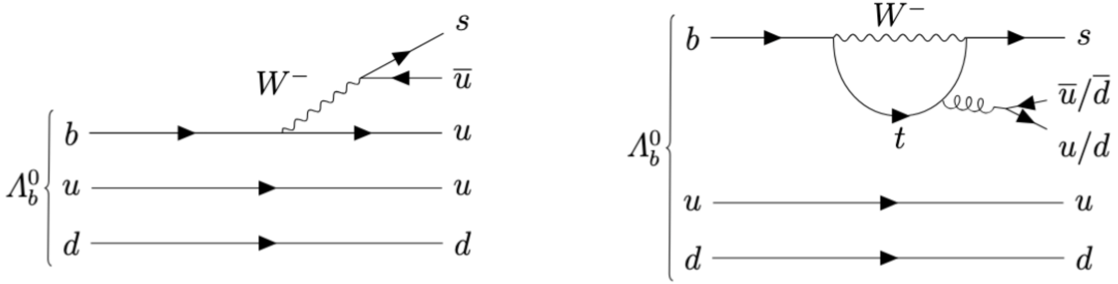




Study of $\Lambda_b^0 \to pK^-\pi^+\pi^-$ decays with Run 1+2

arXiv:2503.14954

- Contributed by tree and loop diagrams



- Rich resonances

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

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

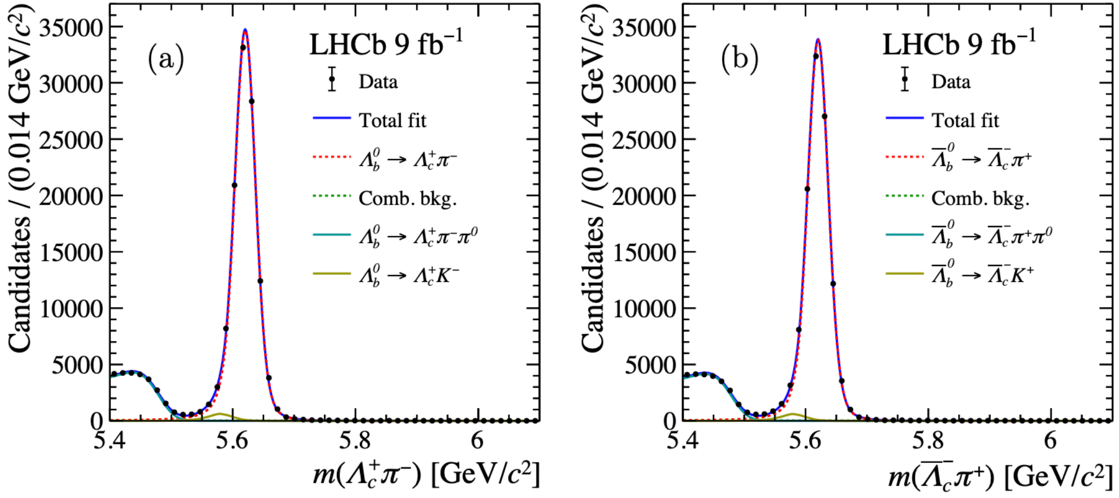
- Cancelling production and detection asymmetries

Control channel: $\Lambda_b^0 \to \Lambda_c^+(pK^-\pi^+)\pi^-$
same final state, no CP violation expected

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

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

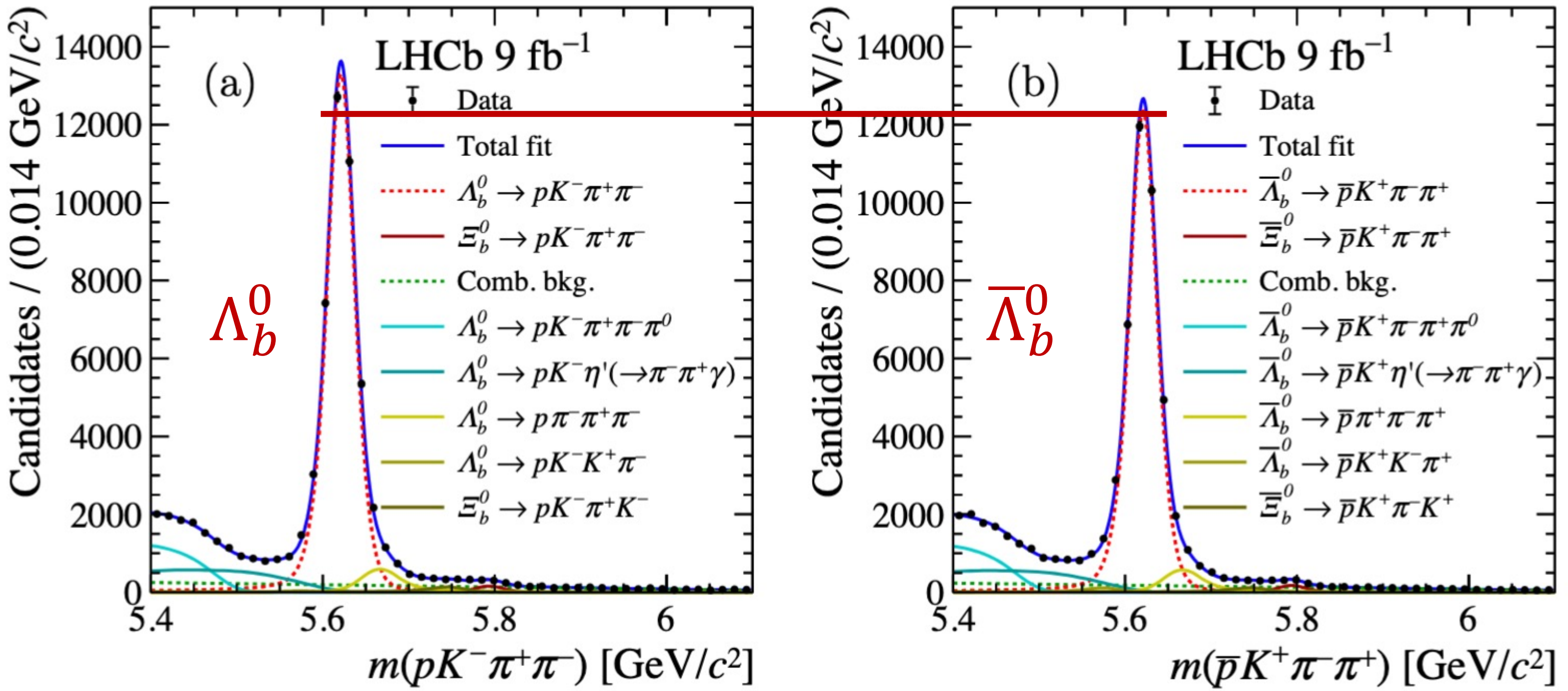
$\Lambda_b^0 \to \Lambda_c^+\pi^-$ $\overline{\Lambda}_b^0 \to \overline{\Lambda}_c^-\pi^+$



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

arXiv:2503.14954

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



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

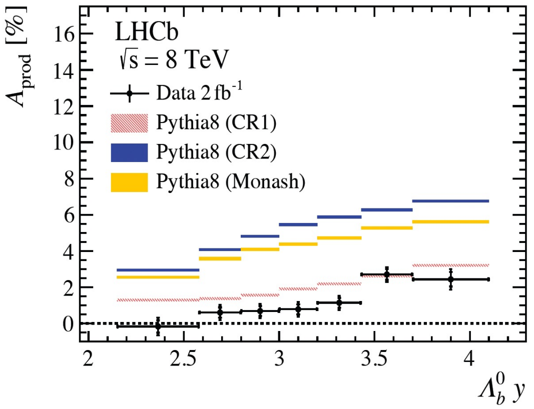
$N_{\text{yield}}^{\Lambda_b^0} = (4.184 \pm 0.025)\times 10^4$

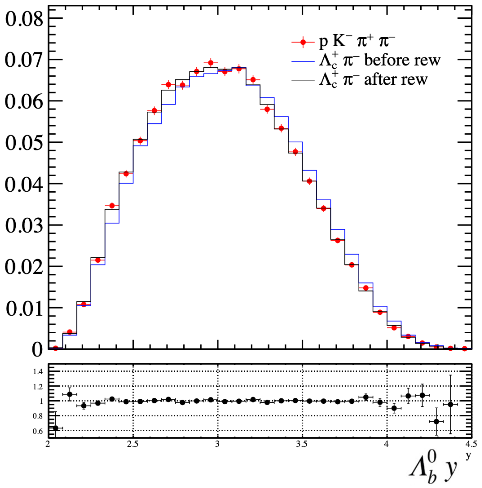
$N_{\text{yield}}^{\overline{\Lambda}_b^0} = (3.885 \pm 0.023)\times 10^4$

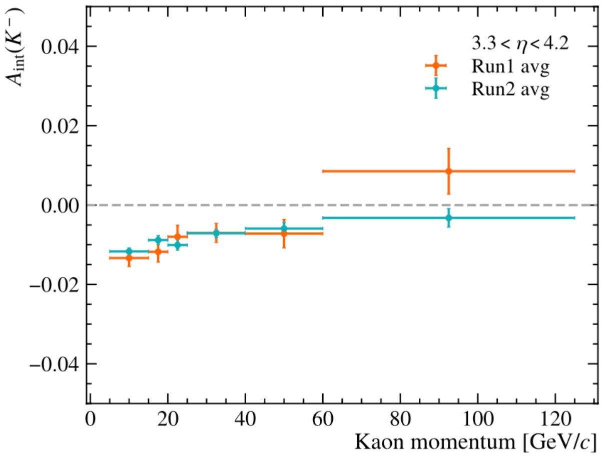
Corrections for experimental bias

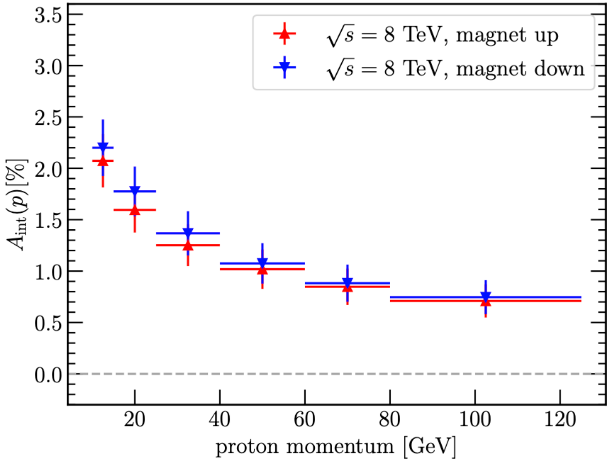
$$A_{CP} = \Delta A_{\text{yield}} - \Delta A_{\text{prod}} - \Delta A_{\text{exp}}$$

- Production asymmetry: cancelled by matching Λ_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

arXiv:2503.14954

From experimental bias

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

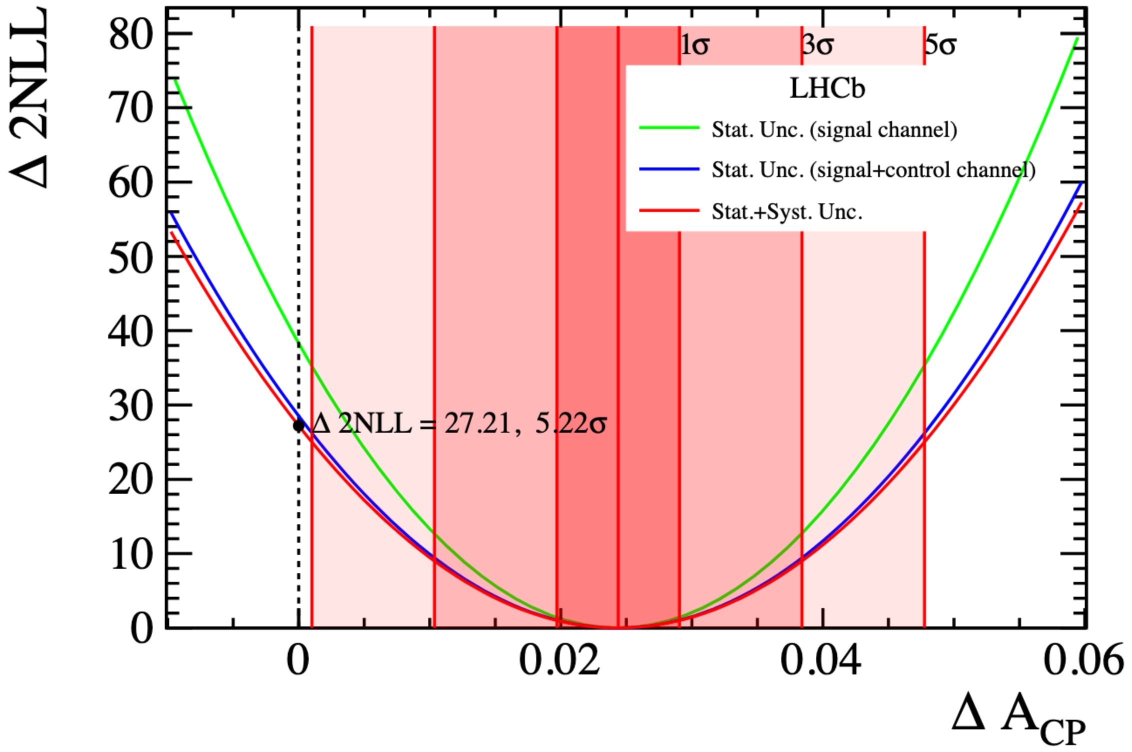
Contribution	Run 1	Run 2
Nuisance asymmetry difference	0.193%	0.051%
Mass fit	0.044%	0.067%
Total systematic uncertainty	0.198%	0.084%

→ 0.10%

First observation of CP violation

arXiv:2503.14954

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



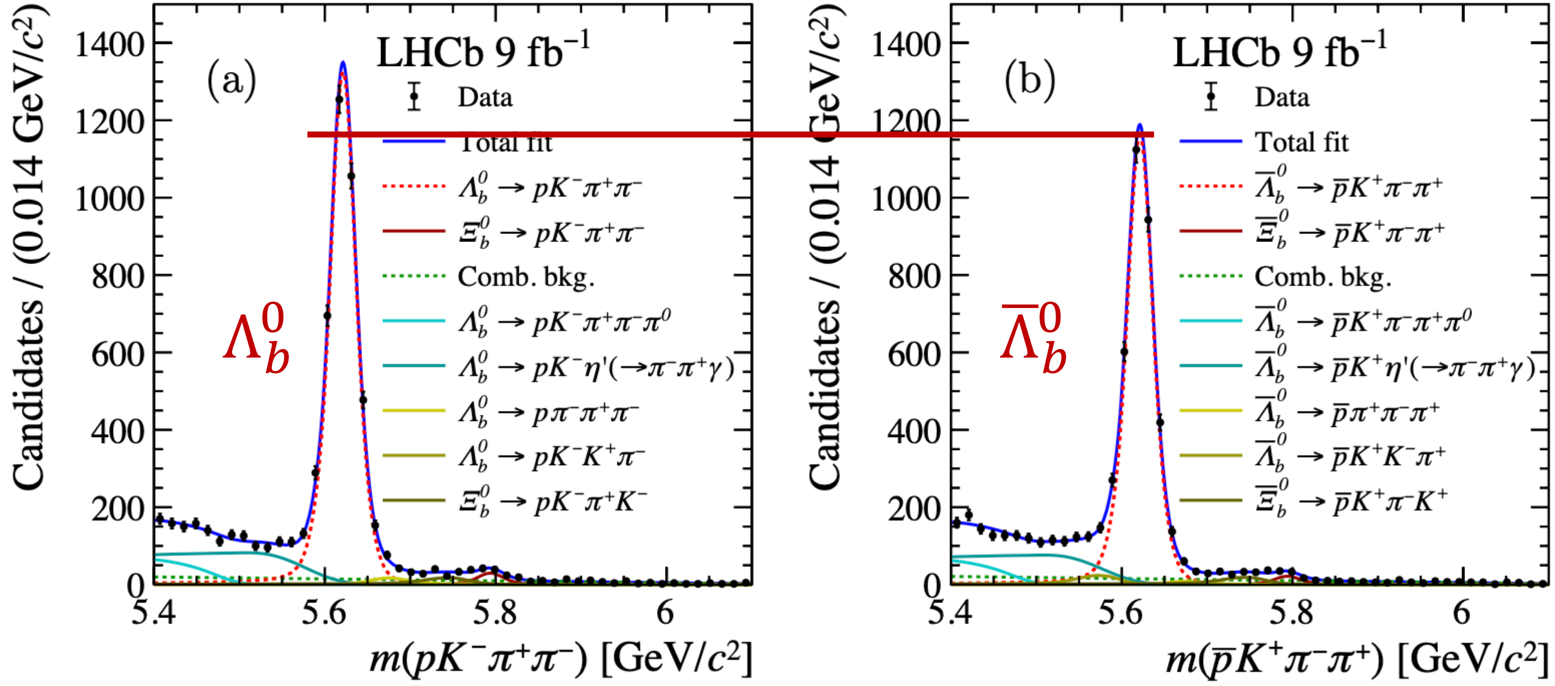
Rule out CP symmetry at 5.2σ, and large CP violation

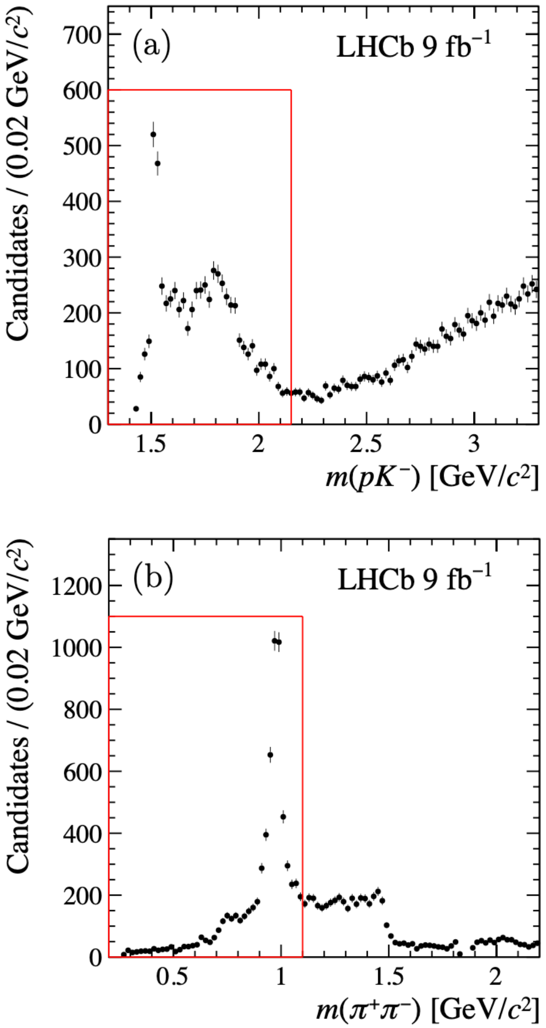
CP asymmetry in resonance regions 1

arXiv:2503.14954

Decay topology	Mass region (GeV/c^2)	$\mathcal{A}_{CP}$
$\Lambda_b^0 \to R(pK^-)R(\pi^+\pi^-)$	$m_{pK^-} < 2.2$ $m_{\pi^+\pi^-} < 1.1$	$(5.3 \pm 1.3 \pm 0.2)\%$

$> 3\sigma$

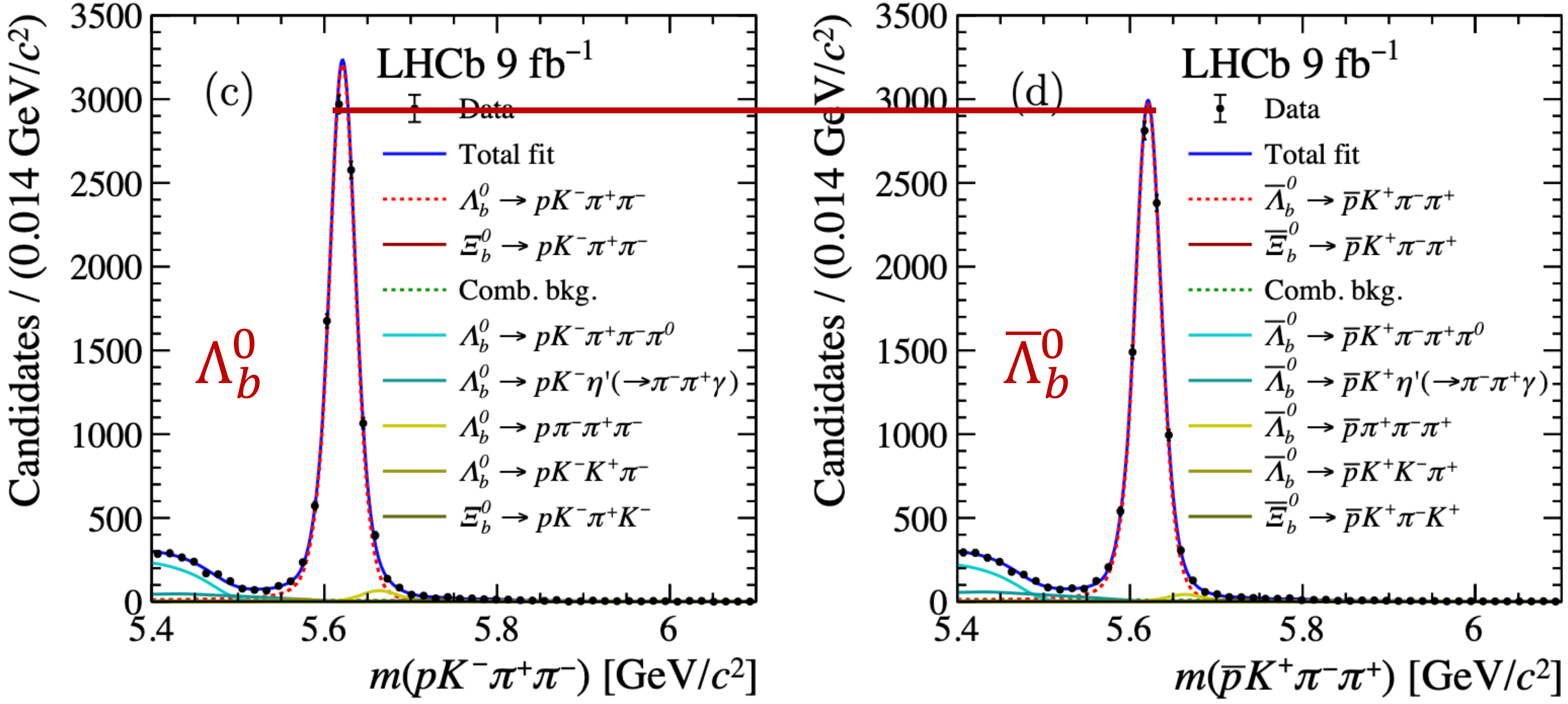


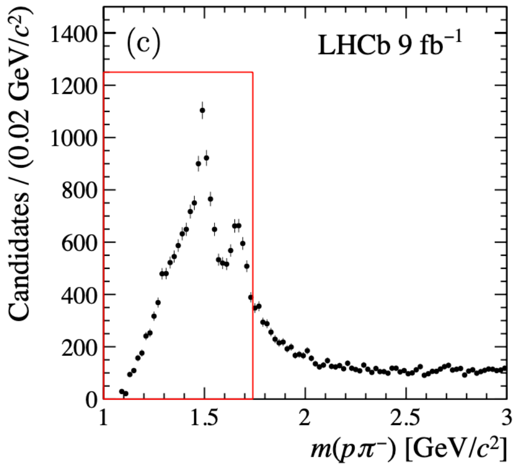


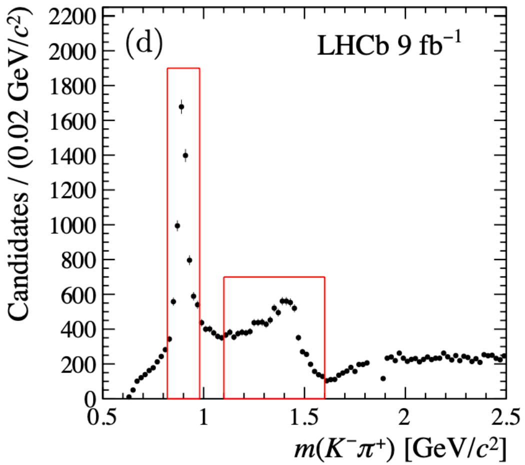
CP asymmetry in resonance regions 2

arXiv:2503.14954

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



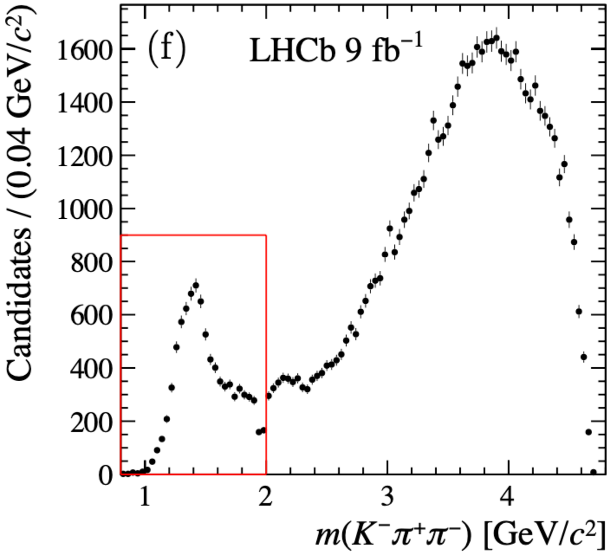


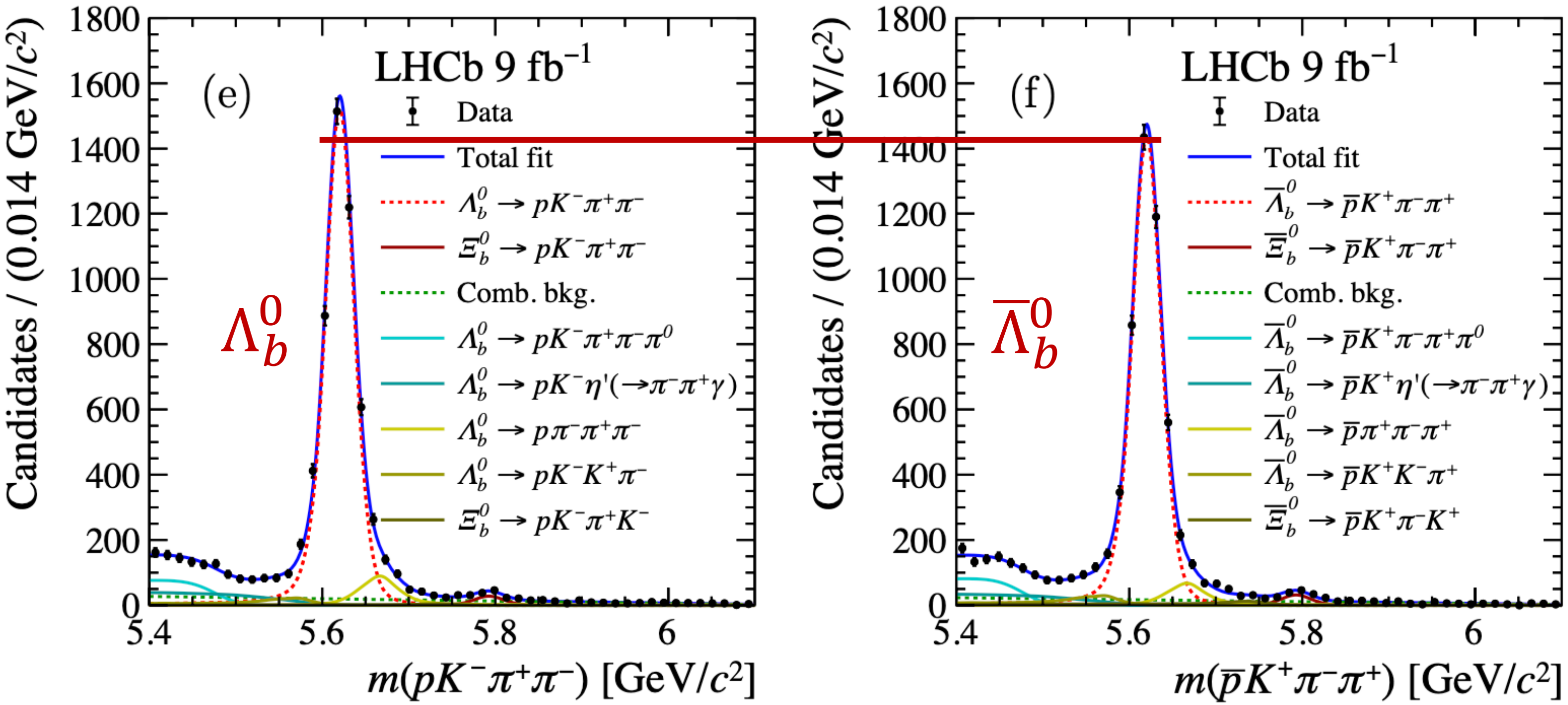


CP asymmetry in resonance regions 3

arXiv:2503.14954

Decay topology	Mass region (GeV/c^2)	$\mathcal{A}_{CP}$
$\Lambda_b^0 \to R(K^-\pi^+\pi^-)p$	$m_{K^-\pi^+\pi^-} < 2.0$	$(2.0 \pm 1.2 \pm 0.3)\%$



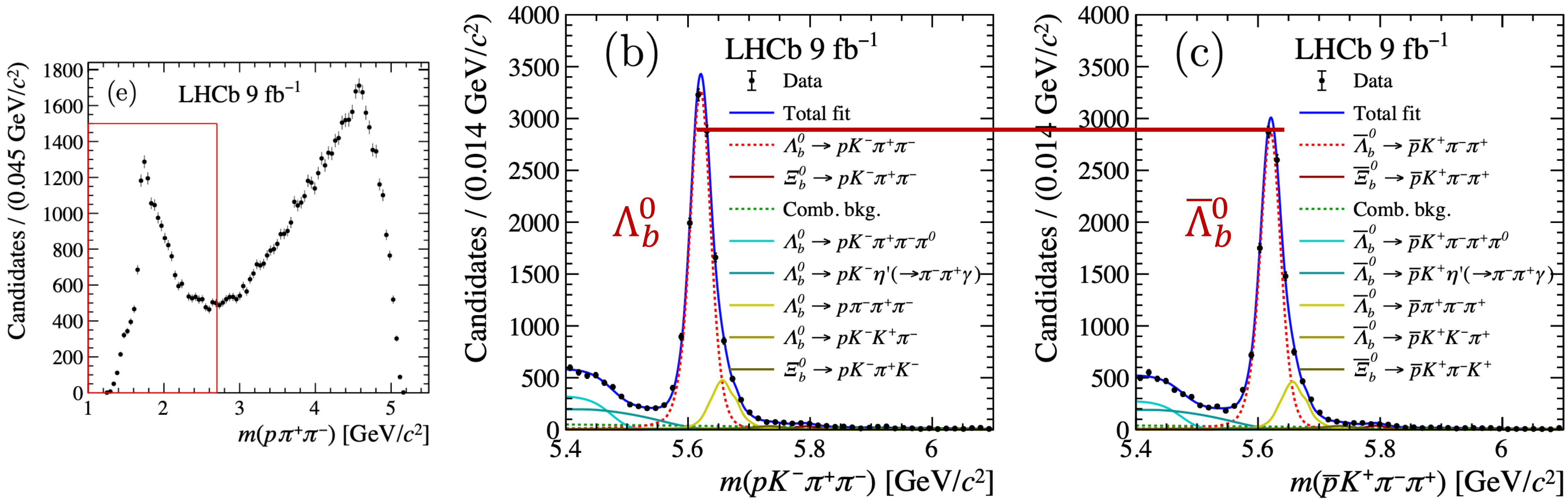


CP asymmetry in resonance regions 4

arXiv:2503.14954

Decay topology	Mass region (GeV/c^2)	$\mathcal{A}_{CP}$
$\Lambda_b^0 \to R(p\pi^+\pi^-)K^-$	$m_{p\pi^+\pi^-} < 2.7$	$(5.4 \pm 0.9 \pm 0.1)\%$

6.0σ



What does it tell us

- **CP violation do exist in baryons**,
  a milestone in study of CP violation

First observation of CP violation in baryon decays – an important milestone in the history of particle physics.

Yesterday, at the Rencontres de Moriond EW, the LHCb collaboration reported the first observation of CP violation in baryon decays. The corresponding publication, submitted to Nature, appeared on arXiv. Differences in the properties of matter and antimatter, arising from the so-called phenomenon of CP violation, had been observed in the past using the decays of K, B and D mesons, i.e. of particles composed of a quark-antiquark pair containing strange, beauty and charm quarks, respectively. However, despite decades of experimental searches, CP violation has not been observed yet in the decays of baryons, composed of three quarks, i.e., the type of matter that makes up the visible universe. The result announced today constitutes the first observation of CP violation in baryon decays.

- **CP violation in baryons unexpectedly small**,
  dynamics more complex than mesons

- **Is it SM or new physics?** Likely SM, but more studies needed to quantify

- **Can it explain BAU?** CKM itself insufficient

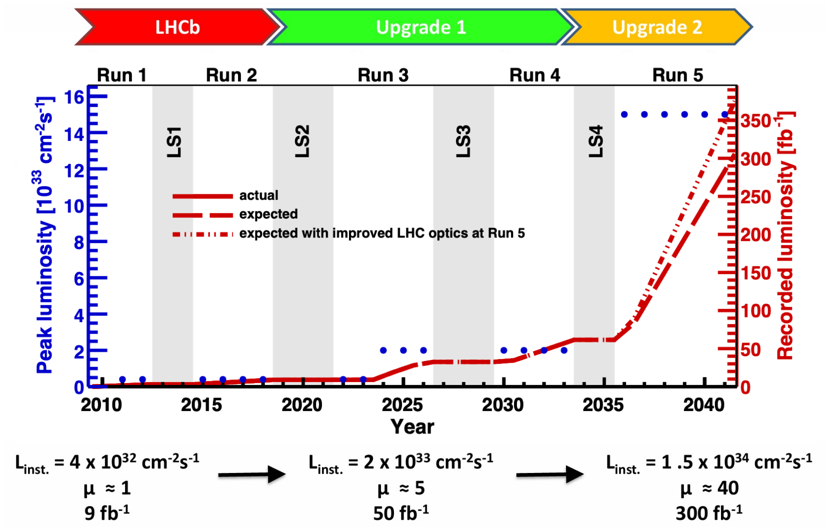
J.P. Wang, F.S. Yu,
CPC 48 (2024) 101002

$$10^{-18}(\text{CKM}) \ll 10^{-10}\ (\text{observation})$$

New physics needed

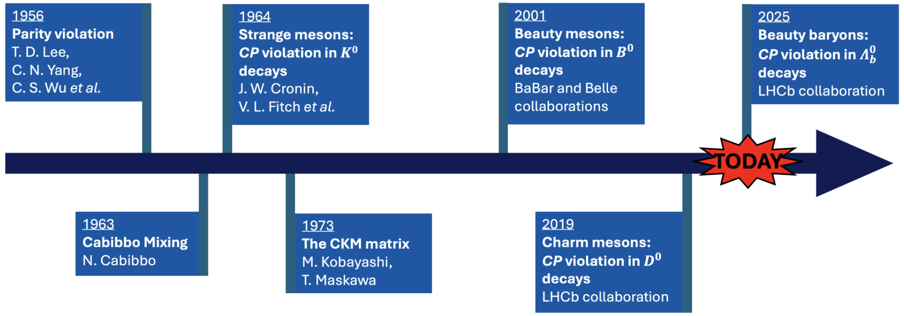
CP violation in future

- Many more data by LHCb: more measurements and more precise



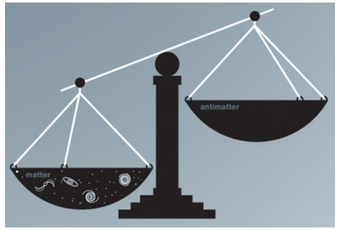
Opportunities in future

- Confirmation
- CPV in new decays, charm baryon?
- Differential measurements
- Unexpected observations ?
- …



CPV sources

Lepton
Higgs
EDM
…



Ultimate goal

谢谢！

Backup slides

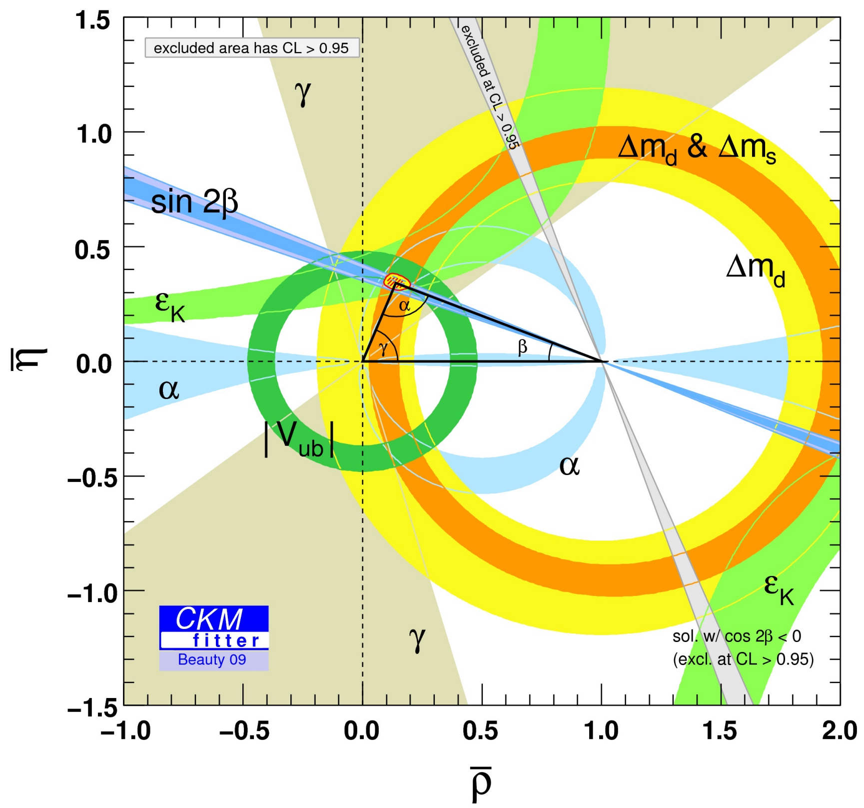
Moriond会议现场

CERN采访

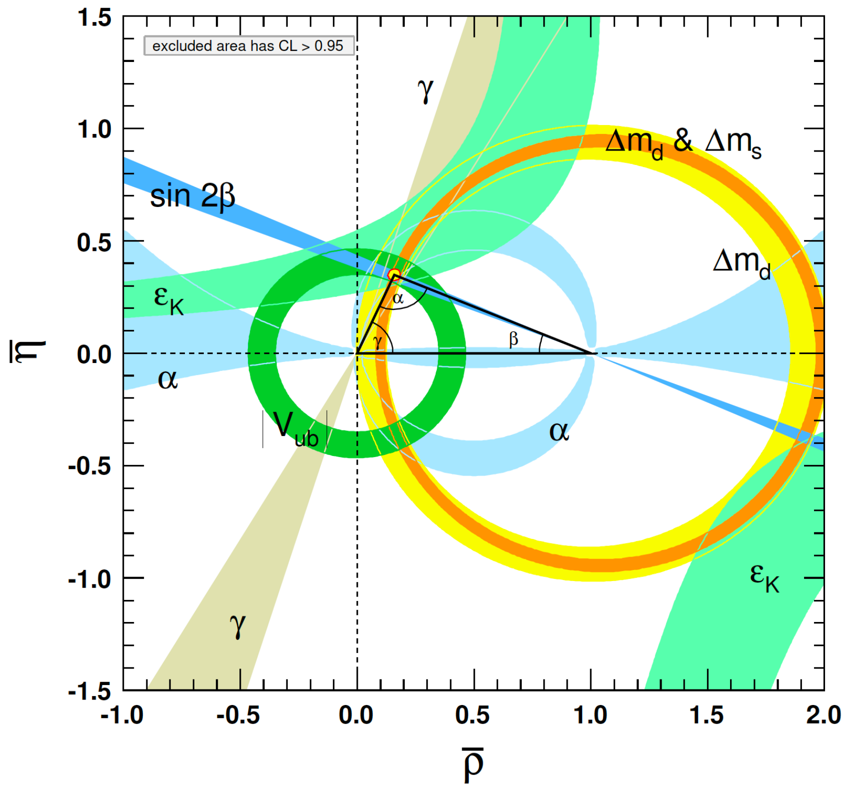
Source：CERN/LHCb

Global analysis of CKM mechanism (4 parameters)

When LHC started



Current status



$A = 0.826^{+0.018}_{-0.015}$ $\lambda = 0.22500 \pm 0.00067$ $\bar{\rho} = 0.159 \pm 0.010$ $\bar{\eta} = 0.348 \pm 0.010$

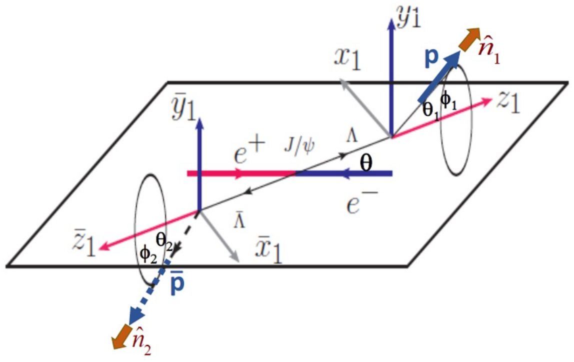
$$\alpha + \beta + \gamma = (173 \pm 6)^{\circ}$$

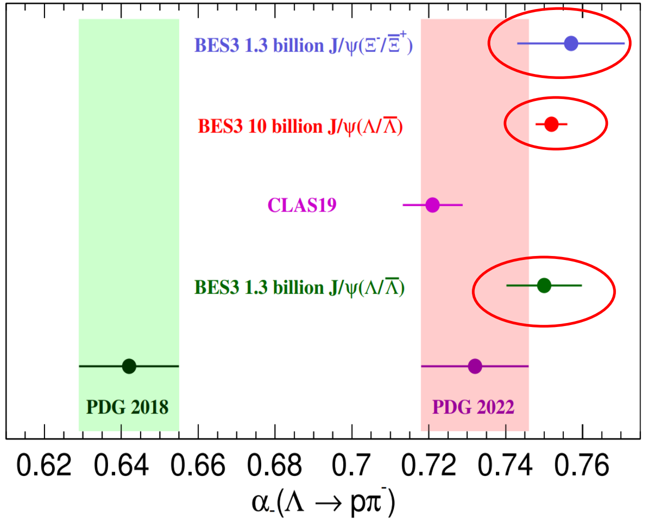
Decay parameters and CPV in hyperons

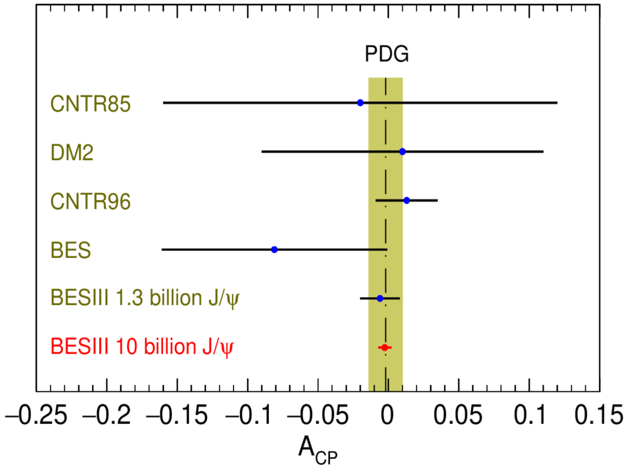
- Pioneering work to probe CPV in $J/\psi \to \Lambda\bar{\Lambda}$

Nat. Phys. 15 (2019) 631
PRL129(2022) 131801

Entangled Λ and $\bar{\Lambda}$





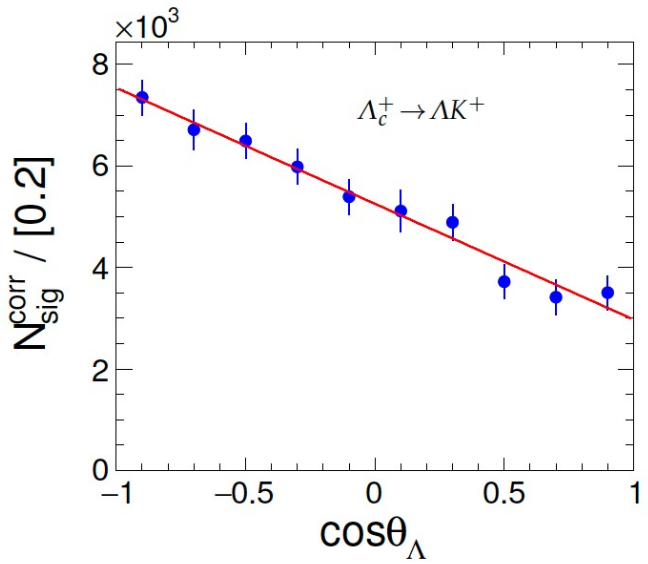


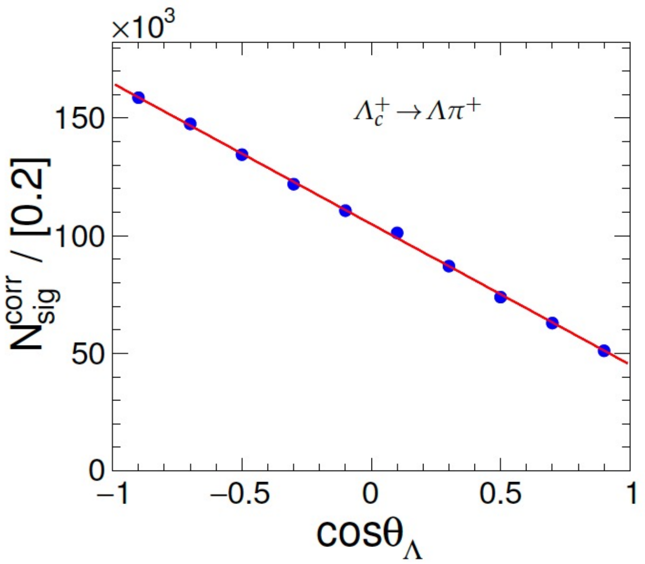
- Many other ψ to hyperon channels explored, no sign of CP violation

Decay	$\Lambda\bar{\Lambda}$	$\Sigma^+\bar{\Sigma}^-$	$\Xi^-\bar{\Xi}^+$	$\Xi^0\bar{\Xi}^0$
A_{CP}	-0.0025 ± 0.0046 ± 0.0012	-0.004 ± 0.037 ± 0.010	-0.006 ± 0.013 ± 0.006	-0.0054 ± 0.0065 ± 0.0031
	PRL129 (2022) 131801	PRL125 (2020) 052004	Nature 606 (2022) 64	PRD108 (2023) 3

Decay parameters and CPV in charm baryons

Decay	$\alpha_{\Lambda_c^+}\alpha_-$	$\alpha_{\overline{\Lambda}_c^-}\alpha_+$	$\alpha_{\Lambda_c^+}$	$\alpha_{\overline{\Lambda}_c^-}$	$\mathcal{A}_{CP}^{\alpha}$
$\Lambda_c^+ \to \Lambda\pi^+$	-0.418 ± 0.053	-0.442 ± 0.053	-0.566 ± 0.076	-0.592 ± 0.106	-0.023 ± 0.116
$\Lambda_c^+ \to \Lambda K^+$	-0.582 ± 0.006	-0.565 ± 0.006	-0.784 ± 0.010	$+0.754 \pm 0.020$	$+0.020 \pm 0.015$
$\Lambda_c^+ \to \Sigma^0\pi^+$	$+0.43 \pm 0.18$	-0.37 ± 0.21	-0.58 ± 0.26	-0.49 ± 0.31	$+0.08 \pm 0.38$
$\Lambda_c^+ \to \Sigma^0 K^+$	-0.340 ± 0.016	-0.358 ± 0.017	-0.452 ± 0.032	$+0.473 \pm 0.042$	-0.023 ± 0.045





No sign of CP violation

S.S. Tang, L.-K. Li, X.-Y. Zhou and C.-P. Shen, Symmetry 15 (2023) 91

CKM matrix up to λ^6

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + \frac{1}{2}A^2\lambda^5[1 - 2(\rho + i\eta)] & 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4(1 + 4A^2) & A\lambda^2 \\ A\lambda^3[1 - (1 - \lambda^2)(\rho + i\eta)] & -A\lambda^2 + \frac{1}{2}A\lambda^4[1 - 2(\rho + i\eta)] & 1 - \frac{1}{2}A^2\lambda^4 \end{pmatrix} + \mathcal{O}(\lambda^6)$$

LHCb Upgrade II sensitivities

CERN Yellow Rep.Monogr. 7 (2019) 867

Table 10.1: Summary of prospects for future measurements of selected flavour observables. The projected LHCb sensitivities take no account of potent detector improvements, apart from in the trigger. Unless indicated otherwise the Belle-II sensitivies are taken from Ref. [568].

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	GPDs Phase II
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	0.1 [255]	0.022	0.036	0.006	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	0.1 [254]	0.029	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.07, 0.04, 0.11	–	0.02, 0.01, 0.03	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [123]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [152]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [569]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi \phi$	49 mrad [32]	14 mrad	–	4 mrad	22 mrad [570]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [37]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	150 mrad [571]	60 mrad	–	17 mrad	Under study [572]
a_{sl}^s	33×10^{-4} [193]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [186]	3%	1%	1%	–
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [244]	34%	–	10%	21% [573]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [244]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c l^- \bar{\nu}_l}$ **LUV studies**					
$R(D^*)$	9% [199, 202]	3%	2%	1%	–
$R(J/\psi)$	25% [202]	8%	–	2%	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [574]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [222]	4.3×10^{-5}	3.5×10^{-5}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [210]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

$\delta < 1\%$

Uncertainty reduced by factor ~10

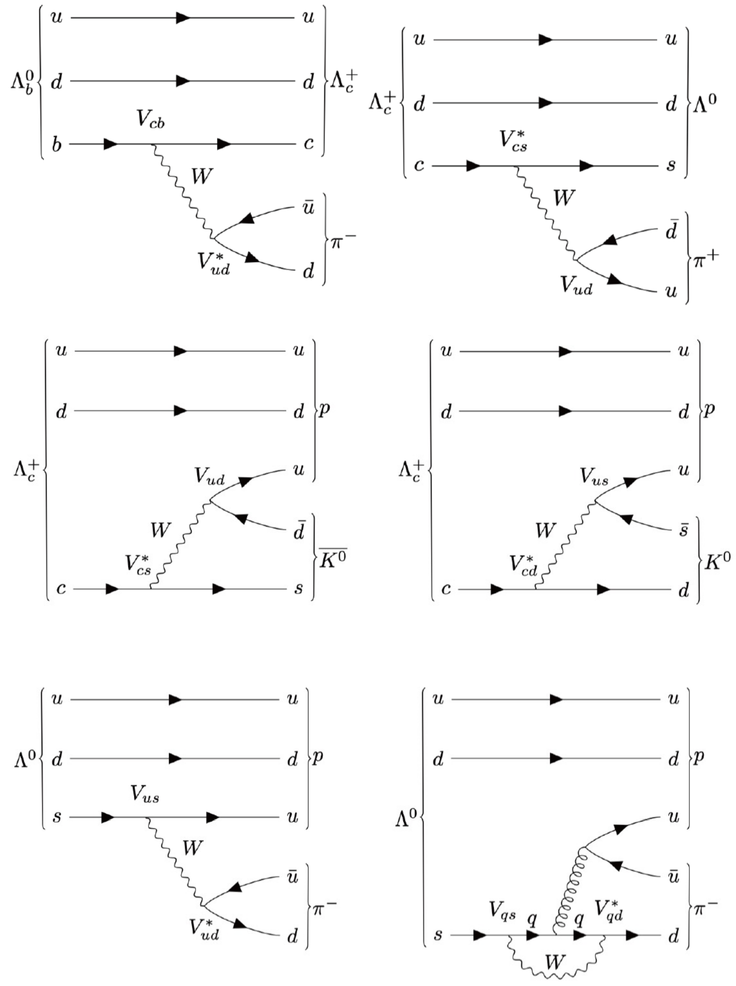
1% level precision

High precision charm physics

More information for decay paramerters

$$\frac{\mathrm{d}^3\Gamma}{\mathrm{d}\cos\theta_0\mathrm{d}\cos\theta_1\mathrm{d}\phi_1} \propto 1 + \alpha_{\Lambda_b^0}\alpha_{\Lambda_c^+}\cos\theta_1 + P_z\cdot(\alpha_{\Lambda_b^0}\cos\theta_0 + \alpha_{\Lambda_c^+}\cos\theta_0\cos\theta_1 - \gamma_{\Lambda_b^0}\alpha_{\Lambda_c^+}\sin\theta_0\sin\theta_1\cos\phi_1 + \beta_{\Lambda_b^0}\alpha_{\Lambda_c^+}\sin\theta_0\sin\theta_1\sin\phi_1)$$

$$\begin{aligned}
\frac{\mathrm{d}^5\Gamma}{\mathrm{d}\cos\theta_0\mathrm{d}\cos\theta_1\mathrm{d}\phi_1\mathrm{d}\cos\theta_2\mathrm{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_z\cdot(\alpha_{\Lambda_b^0}\cos\theta_0 + \alpha_{\Lambda_c^+}\cos\theta_0\cos\theta_1 + \alpha_{\Lambda_b^0}\alpha_{\Lambda_c^+}\alpha_{\Lambda}\cos\theta_0\cos\theta_2 \\
& + \alpha_{\Lambda}\cos\theta_0\cos\theta_1\cos\theta_2 - \gamma_{\Lambda_b^0}\alpha_{\Lambda_c^+}\sin\theta_0\sin\theta_1\cos\phi_1 + \beta_{\Lambda_b^0}\alpha_{\Lambda_c^+}\sin\theta_0\sin\theta_1\sin\phi_1 \\
& - \gamma_{\Lambda_c^+}\alpha_{\Lambda}\cos\theta_0\sin\theta_1\sin\theta_2\cos\phi_2 + \beta_{\Lambda_c^+}\alpha_{\Lambda}\cos\theta_0\sin\theta_1\sin\theta_2\sin\phi_2 \\
& - \gamma_{\Lambda_b^0}\alpha_{\Lambda}\sin\theta_0\sin\theta_1\cos\theta_2\cos\phi_1 + \beta_{\Lambda_b^0}\alpha_{\Lambda}\sin\theta_0\sin\theta_1\cos\theta_2\sin\phi_1 \\
& + \beta_{\Lambda_b^0}\beta_{\Lambda_c^+}\alpha_{\Lambda}\sin\theta_0\sin\theta_2\cos\phi_1\cos\phi_2 + \beta_{\Lambda_b^0}\gamma_{\Lambda_c^+}\alpha_{\Lambda}\sin\theta_0\sin\theta_2\cos\phi_1\sin\phi_2 \\
& + \gamma_{\Lambda_b^0}\beta_{\Lambda_c^+}\alpha_{\Lambda}\sin\theta_0\sin\theta_2\sin\phi_1\cos\phi_2 + \gamma_{\Lambda_b^0}\gamma_{\Lambda_c^+}\alpha_{\Lambda}\sin\theta_0\sin\theta_2\sin\phi_1\sin\phi_2 \\
& - \gamma_{\Lambda_b^0}\gamma_{\Lambda_c^+}\alpha_{\Lambda}\sin\theta_0\cos\theta_1\sin\theta_2\cos\phi_1\cos\phi_2 \\
& + \gamma_{\Lambda_b^0}\beta_{\Lambda_c^+}\alpha_{\Lambda}\sin\theta_0\cos\theta_1\sin\theta_2\cos\phi_1\sin\phi_2 \\
& + \beta_{\Lambda_b^0}\gamma_{\Lambda_c^+}\alpha_{\Lambda}\sin\theta_0\cos\theta_1\sin\theta_2\sin\phi_1\cos\phi_2 \\
& - \beta_{\Lambda_b^0}\beta_{\Lambda_c^+}\alpha_{\Lambda}\sin\theta_0\cos\theta_1\sin\theta_2\sin\phi_1\sin\phi_2),
\end{aligned}$$



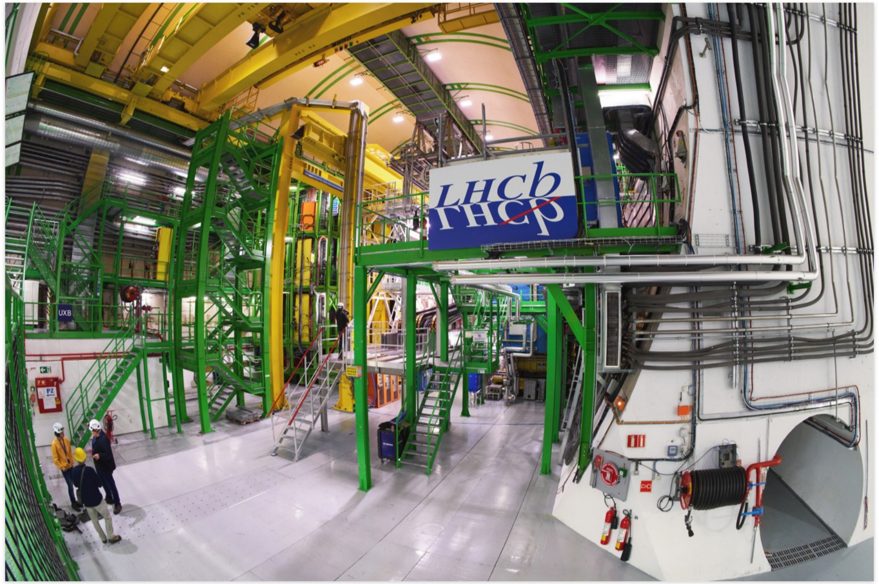
First observation of CP violation in baryons by LHCb

25/Mar/2025

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)

Yesterday, at the annual *Rencontres de Moriond* conference taking place in La Thuile, Italy, the LHCb collaboration at CERN reported a new milestone in our understanding of the subtle yet profound differences between matter and antimatter. In its analysis of large quantities of data produced by the Large Hadron Collider

CONFERENCE LATEST POSTS PHYSICS RESULTS

Observation of the different behaviour of baryonic matter and antimatter.

By Joel Closier

MAR 25, 2025 #baryon, #bottom, #cp violation, #Lambdab

First observation of CP violation in baryon decays – an important milestone in the history of particle physics.

Yesterday, at the Rencontres de Moriond EW, the LHCb collaboration reported the first observation of CP violation in baryon decays. The corresponding publication, submitted to Nature, appeared on arXiv. Differences in the properties of matter and antimatter, arising from the so-called phenomenon of CP violation, had been observed in the past using the decays of K, B and D mesons, i.e. of particles composed of a quark-antiquark pair containing strange, beauty and charm quarks, respectively. However, despite decades of experimental searches, CP violation has not been observed yet in the decays of baryons, composed of three quarks, i.e., the type of matter that makes up the visible universe. The result announced today constitutes the first observation of CP violation in baryon decays.