LHCb实验重子CP破坏研究

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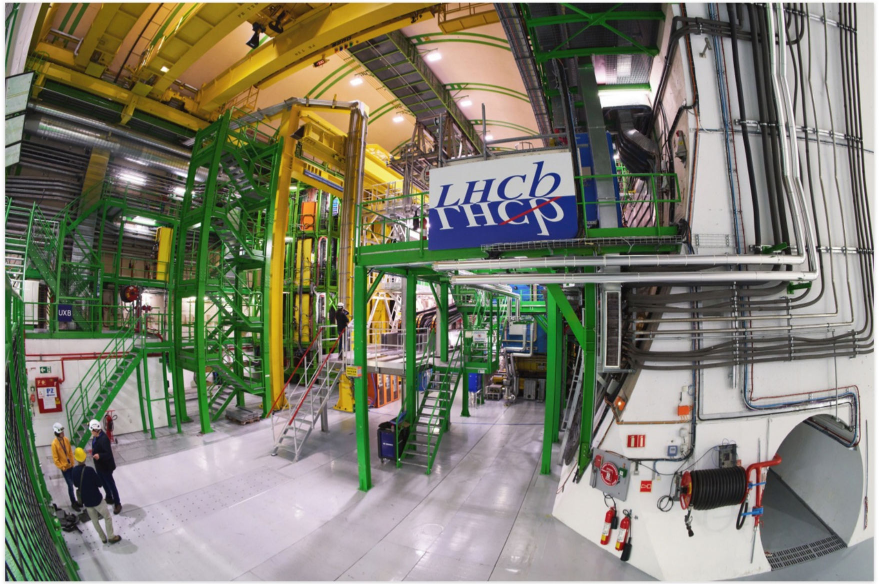
First observation of CP violation in baryons by LHCb

25/03/2025

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.

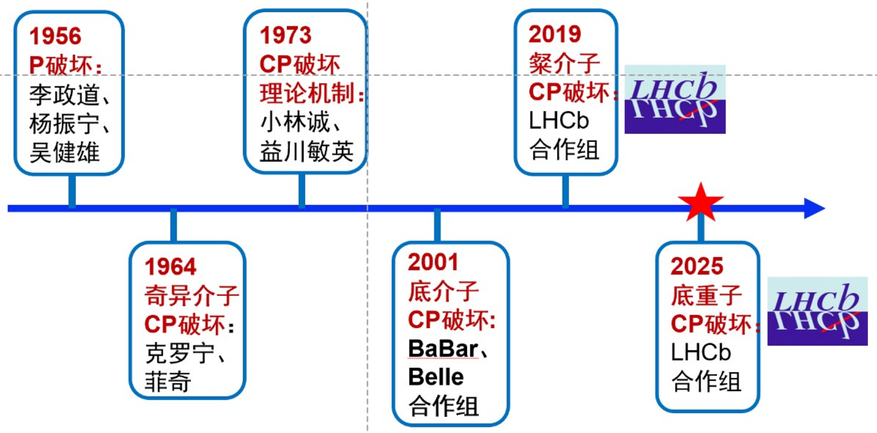
Outline

- **What is LHCb**
- What is CP violation
- CP violation in mesons
- CP violation in baryons

电荷-宇称对称性破坏：从介子到重子的跨越

—探索基本对称性破坏的新里程碑—

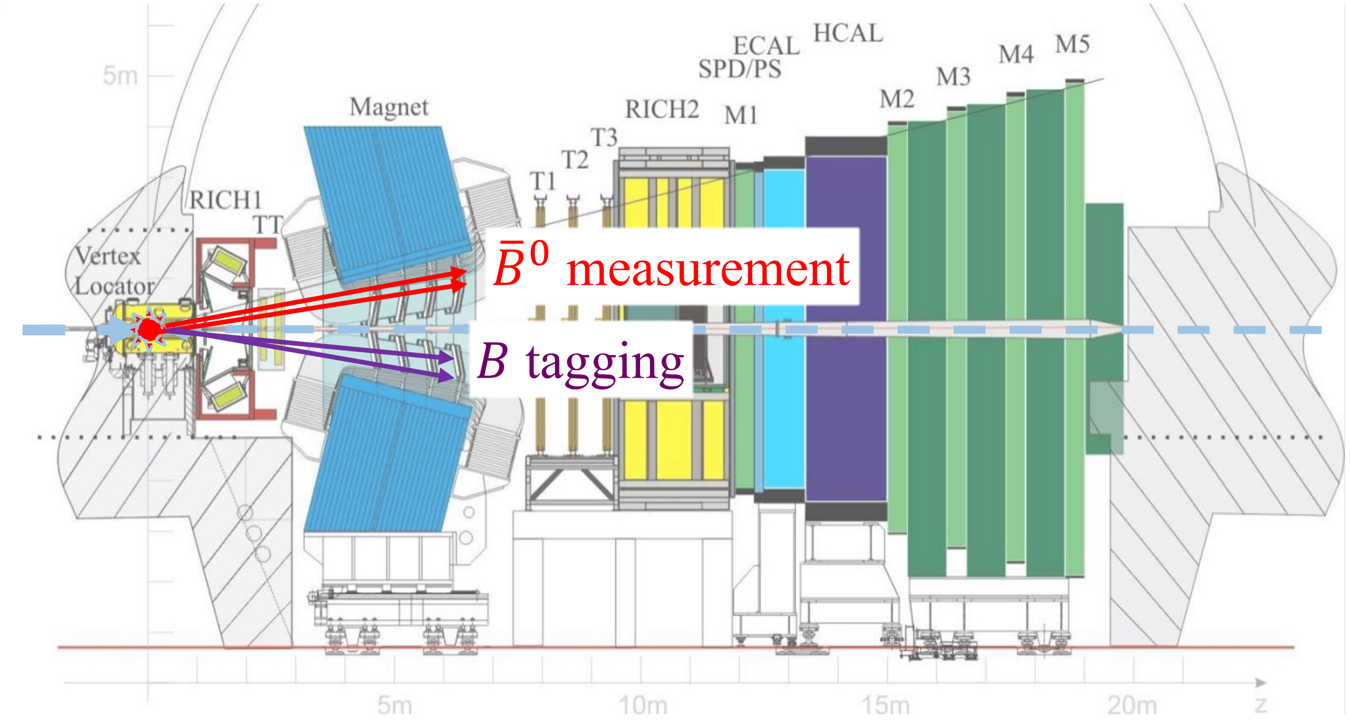
谢跃红，华中师范大学



粒子物理研究所论坛（IOPP Forum），2025年4月1日

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

- Dedicated experiment at CERN for measurement of b, c hadrons



主要研究内容

- 重味物理与CP破坏
- 稀有衰变与新物理
- 强子产生与谱学，QCD
- 电弱物理与Higgs物理
- 重离子物理，…

Excellent vertexing, hadron PID, momentum; flexible trigger …

LHCb合作组：24个国家，100家单位，1800多名成员

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

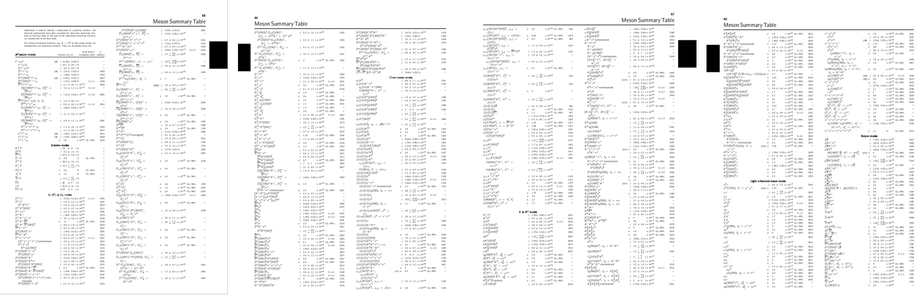
LHCb cares about charged hadron species

- b-hadrons have many decay modes (500+ known)

  Each is unique and contributes to relevant measurements

  Measured exclusively!

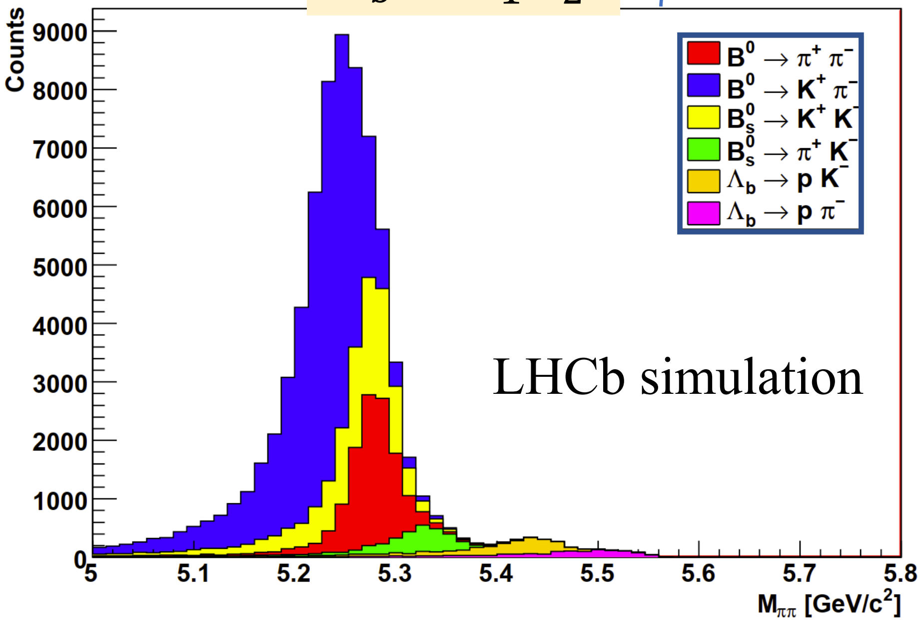
  But one decay could pollute the other, due to mis-identification (misID) of decay products, in particularly among decays with $p^{\pm}, K^{\pm}, \pi^{\pm}$



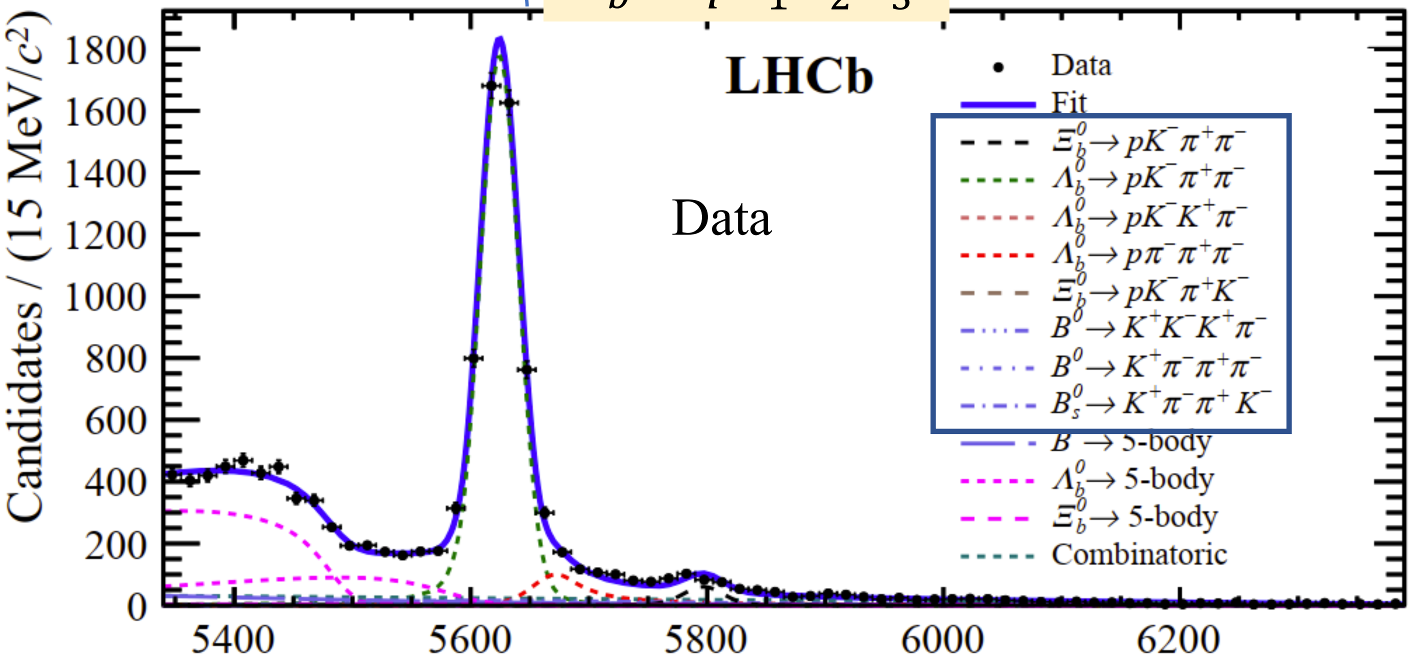
B^{+} decays (Particle Data Group2020)

Core flavor physics at LHCb

$H_b \rightarrow h_1^+ h_2^-$



$H_b \rightarrow p h_1^+ h_2^- h_3^-$

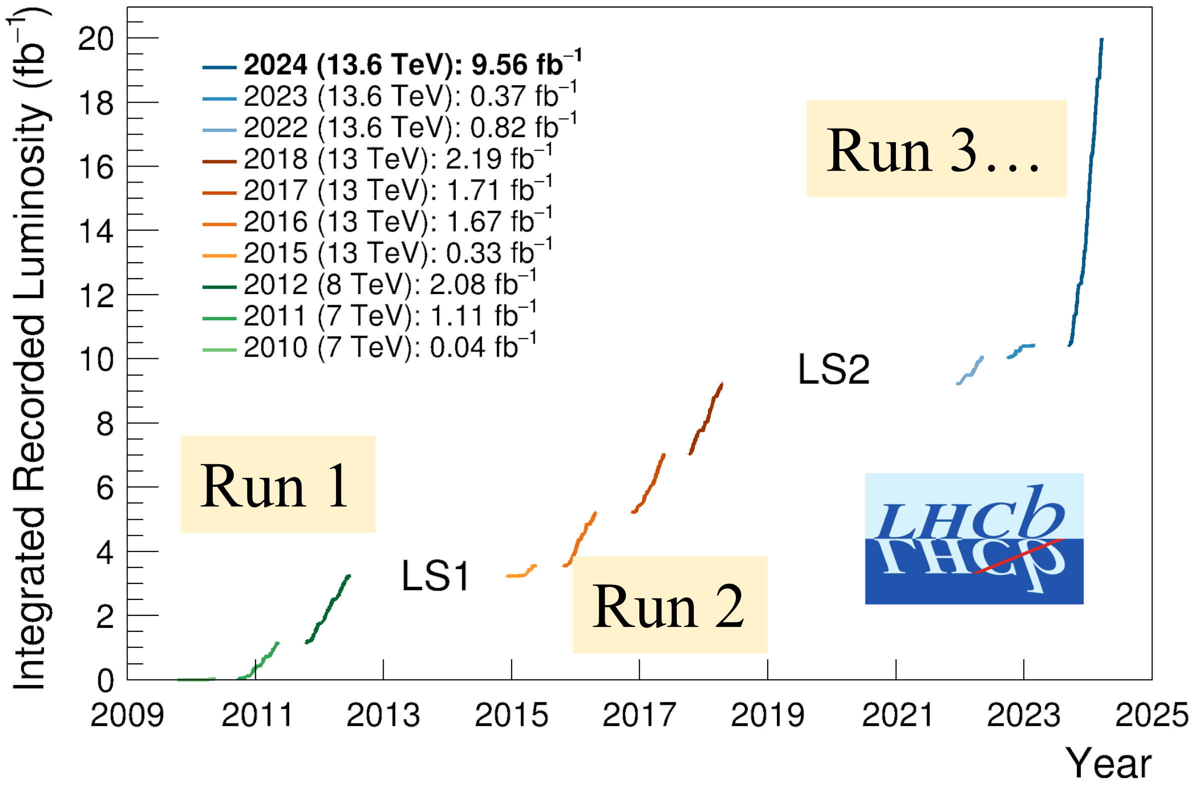


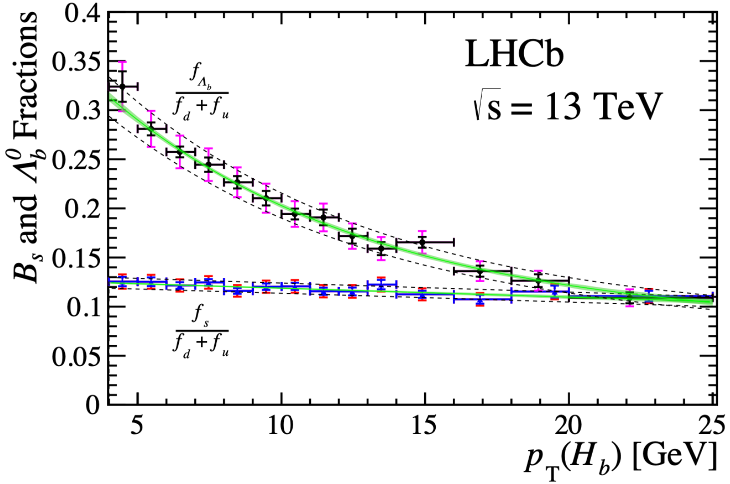
LHCb data

- 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)

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





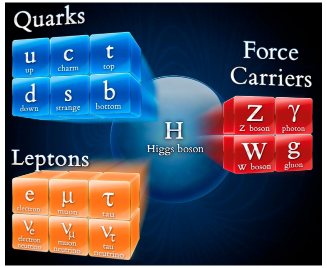
PRD 100 (2019) 031102(R)

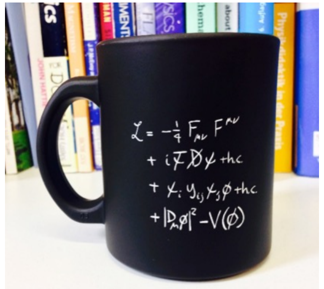
Outline

- What is LHCb
- **What is CP violation**
- CP violation in mesons
- CP violation in baryons

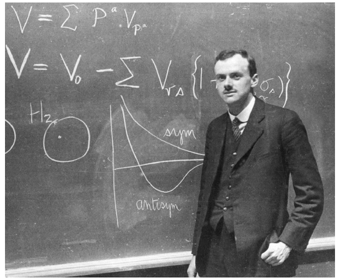
Particle and antiparticle follow different laws

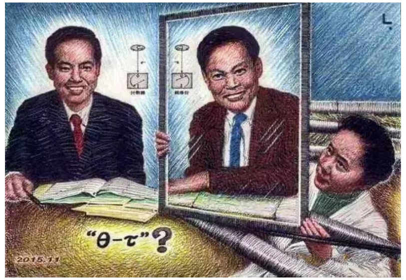
- Quest for fundamental elements and laws of nature

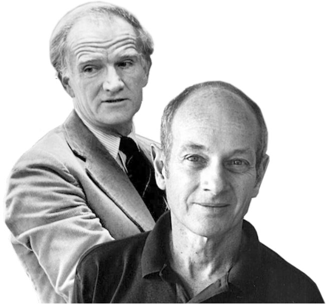




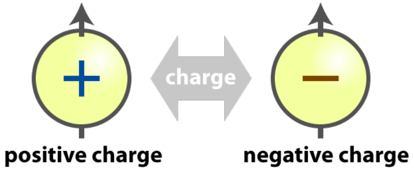
Prediction of antimatter	Parity violation	Charge-Parity violation
$(i\partial_\mu \gamma^\mu - m)\psi = 0$	$^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni} + \beta + \bar{\nu}_e$	$K_L^0 \rightarrow \pi^+\pi^-$



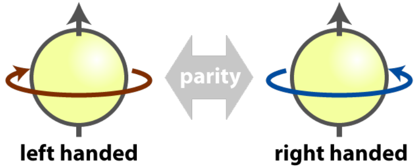




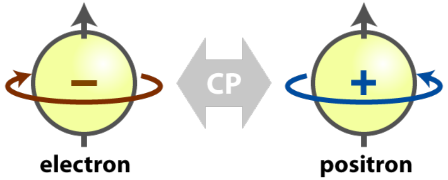
Charge conjugation



Parity



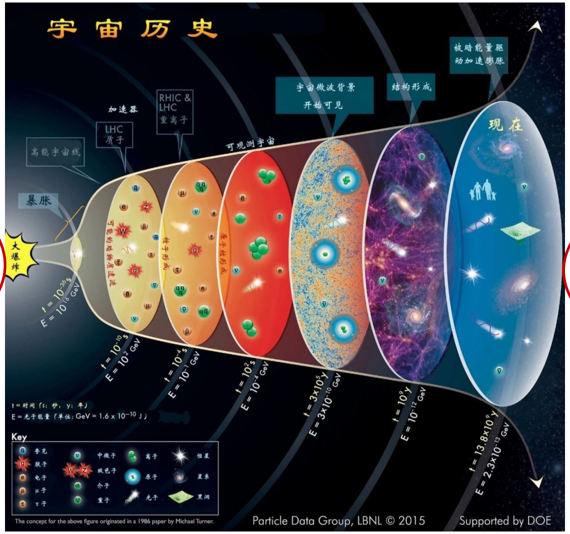
Charge-Parity

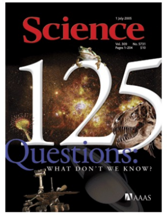


Why CP violation

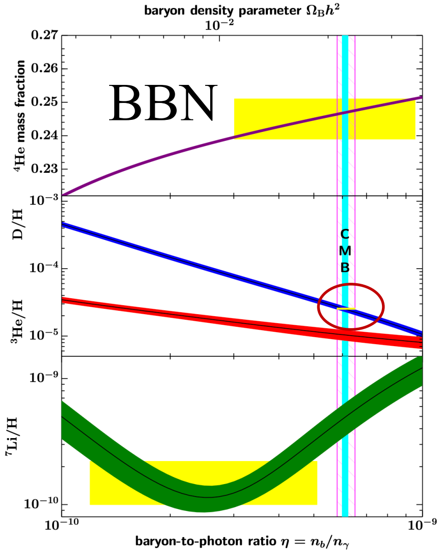
- Matter and antimatter imbalance in Universe (BAU)

Matter = Antimatter



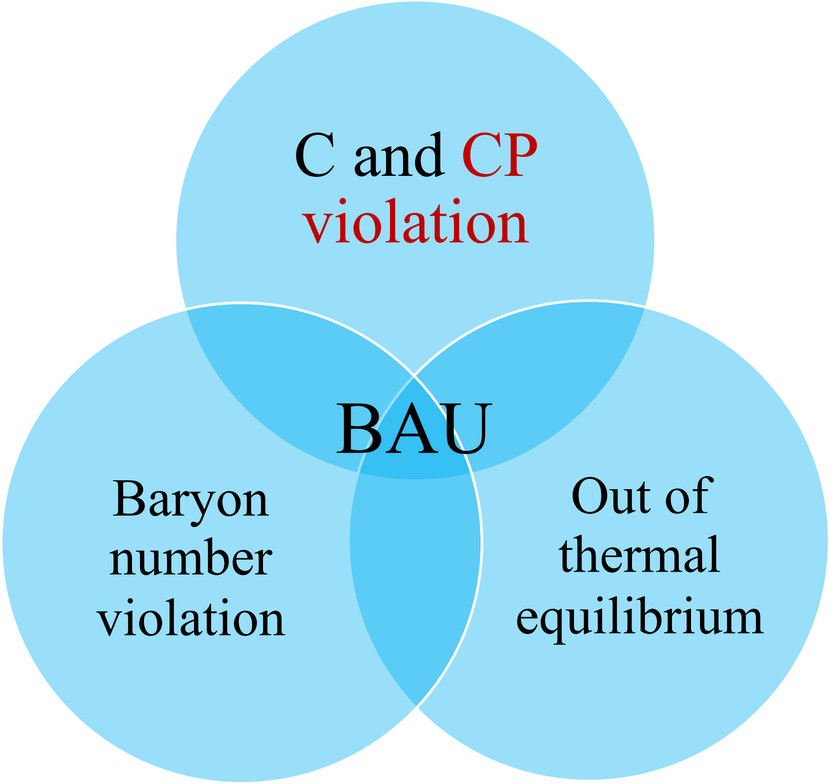


Almost no antimatter



$$n_{\bar{\mathcal{B}}} \ll n_{\mathcal{B}}, \quad \frac{n_b}{n_\gamma} \approx 6\times10^{-10}$$

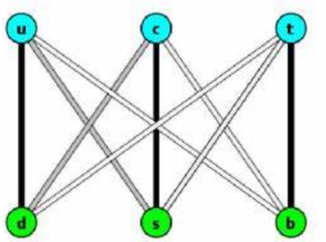
- Sakharov conditions

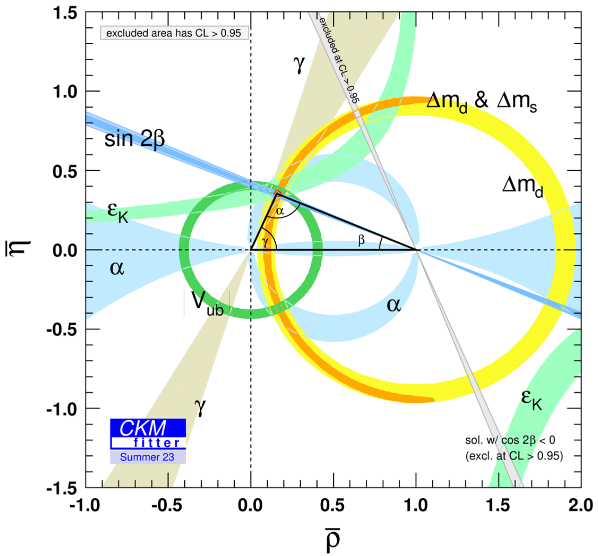


CP violation in the SM

- CKM mechanism

  - ➢ Quark mixing matrix





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

A single phase parameter gives rise to quark CPV

- ✓ Unitarity: four independent parameters
- ✓ CP violation: phases and dynamics

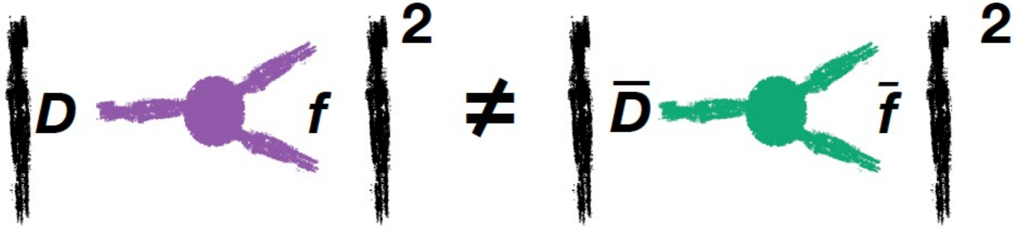
- ➢ CKM established and tested through precision measurements
- ➢ But insufficient to explain BAU

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

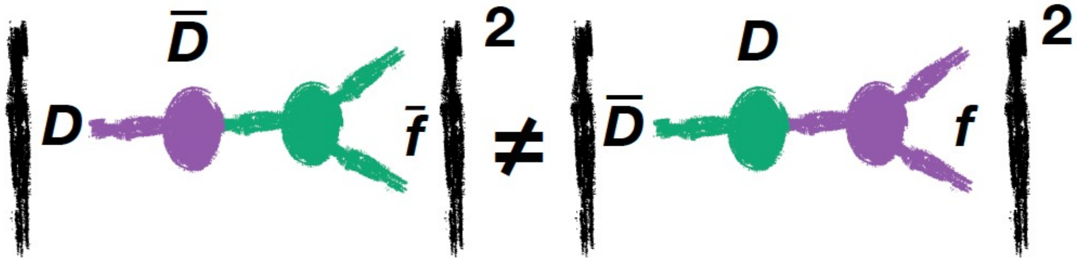
CP violation beyond SM needed! Leave no stones unturned

Three types of CP violation

- CPV in the **decay** occurs if $|A_f|^2 \neq |\bar{A}_{\bar{f}}|^2$



Direct CP violation, only possible one for baryons



- CPV in **mixing** occurs if $|q/p| \neq 1$

- Indirect CPV in **interference** between *mixing* and *decay* occurs if $\phi_f \equiv arg(q\bar{A}_{\bar{f}}/pA_f) \neq 0$

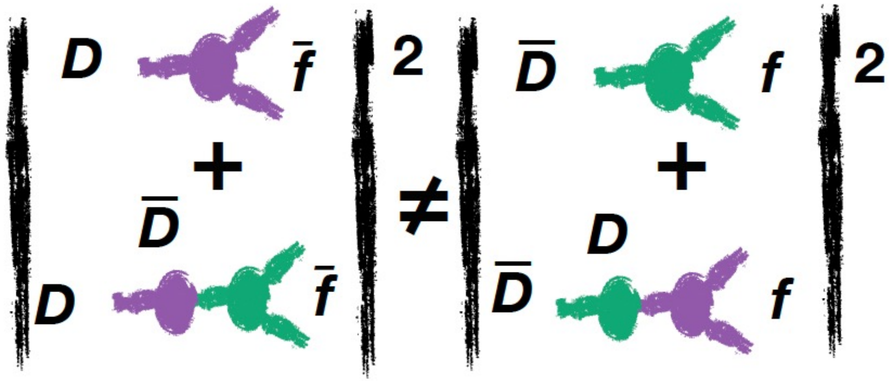
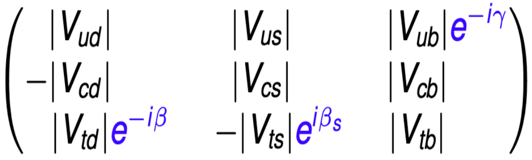


Figure by Serena Maccolini

Direct CP violation

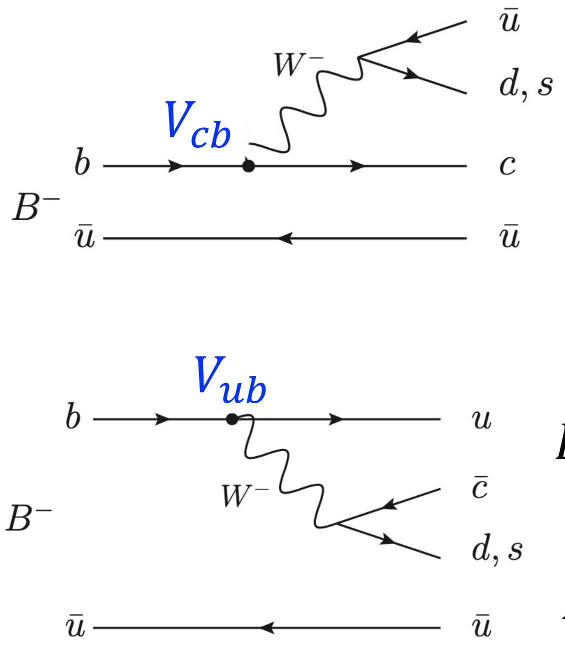
- Interference between two decay paths

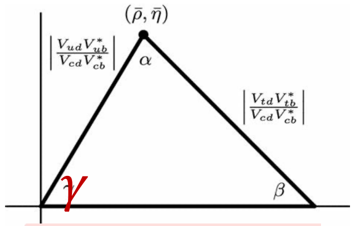


Strong phase difference   Weak phase difference

$$A_{CP} \equiv \frac{\Gamma_f - \bar{\Gamma}_{\bar{f}}}{\Gamma_f + \bar{\Gamma}_{\bar{f}}} = \frac{2|\mathcal{A}_2/\mathcal{A}_1|\sin\boxed{(\delta_1-\delta_2)}\sin\boxed{(\phi_1-\phi_2)}}{1+|\mathcal{A}_2/\mathcal{A}_1|^2+2|\mathcal{A}_2/\mathcal{A}_1|\cos(\delta_1-\delta_2)\cos(\phi_1-\phi_2)}$$

- Tree diagrams (measuing γ)



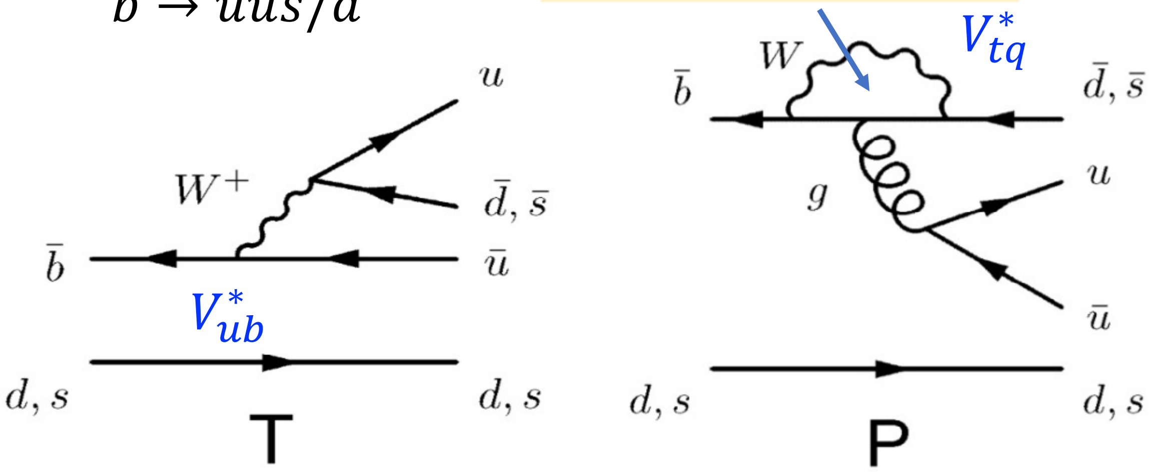


$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

- Tree and loop diagrams

$b \to u\bar{u}s/d$

New physics in loop?



Outline

- What is LHCb
- What is CP violation
- **CP violation in mesons**
- CP violation in baryons

CPV in K mesons

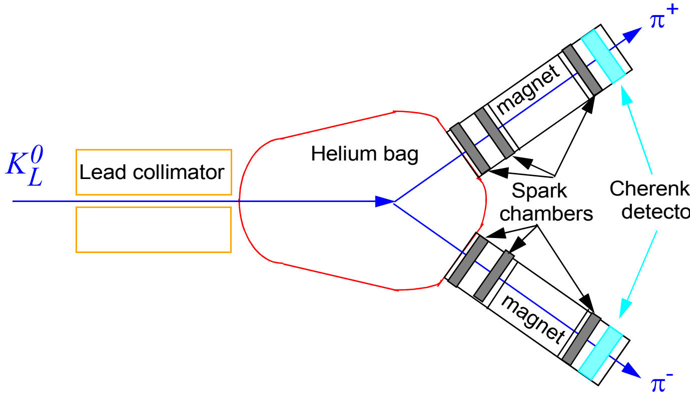
CPV in K^0 - $\bar{K}^0$ mixing

$$A(K^0 \to \bar{K}^0) \propto 1 - \bar{\epsilon}$$
$$A(\bar{K}^0 \to K^0) \propto 1 + \bar{\epsilon}$$

$$|K_L\rangle \propto (1+\bar{\epsilon})|K^0\rangle - (1-\bar{\epsilon})|\bar{K}^0\rangle$$

0.2% of the time!

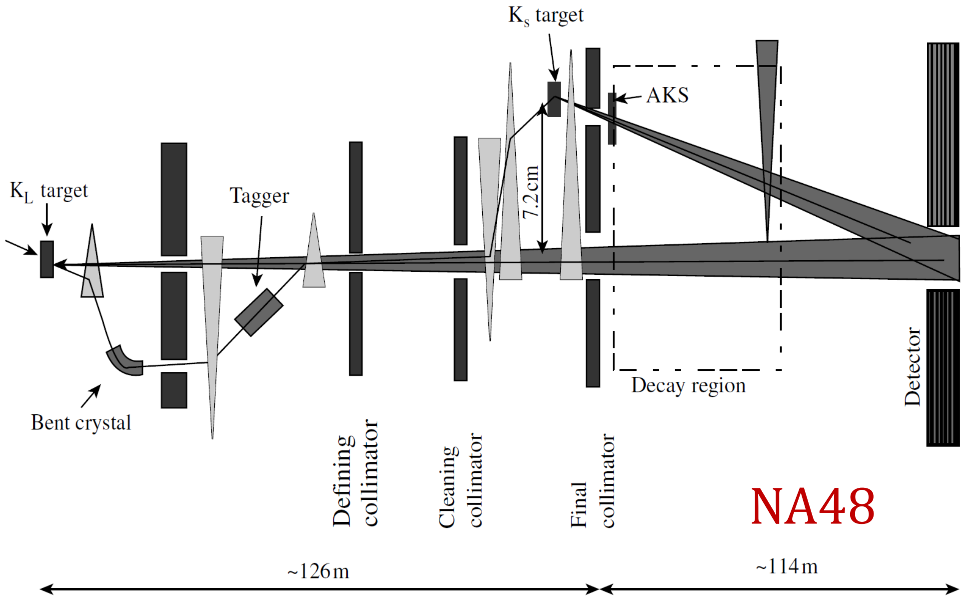
$\bar{\epsilon} \neq 0$



Direct CPV

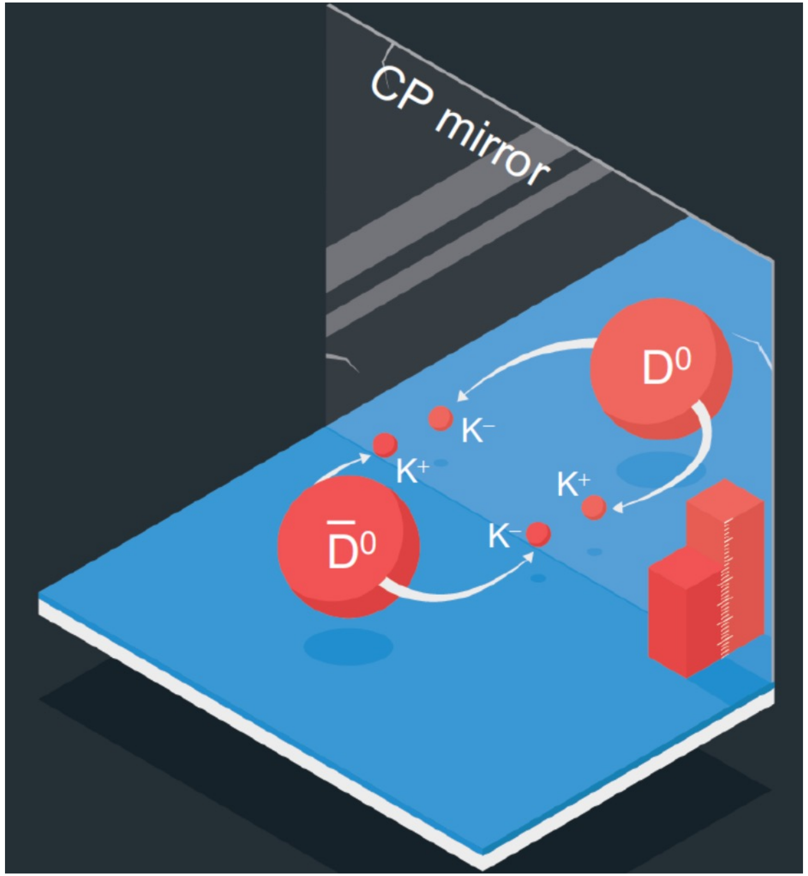
$$\eta_{+-} \equiv \frac{\langle \pi^+\pi^- | K_L\rangle}{\langle \pi^+\pi^- | K_S\rangle} \neq \eta_{00} \equiv \frac{\langle \pi^0\pi^0 | K_L\rangle}{\langle \pi^0\pi^0 | K_S\rangle}$$

$$\epsilon'/\epsilon \sim 10^{-3}$$



NA48

Direct CPV in charm

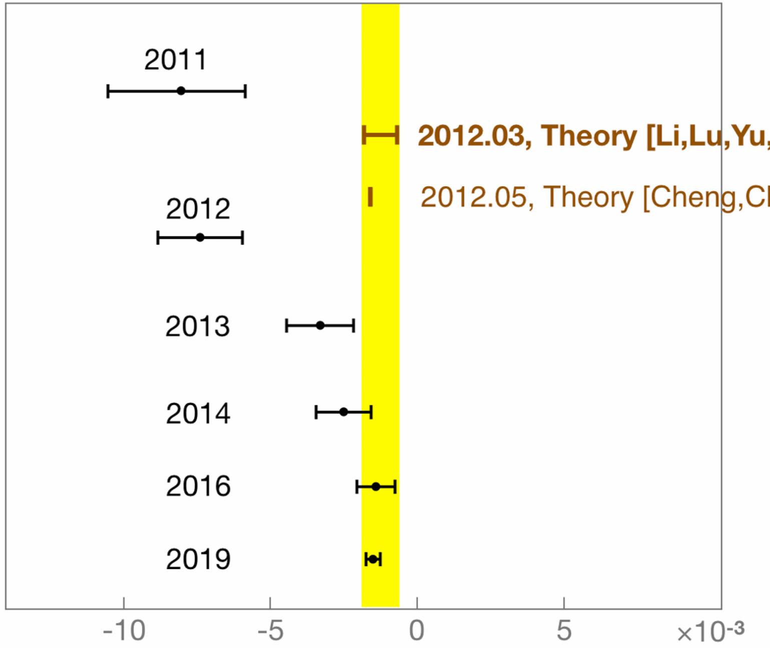


CP asymmetries difference between $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

$$= (-1.54 \pm 0.29)\times 10^{-3}$$

PRL 122 (2019) 211803

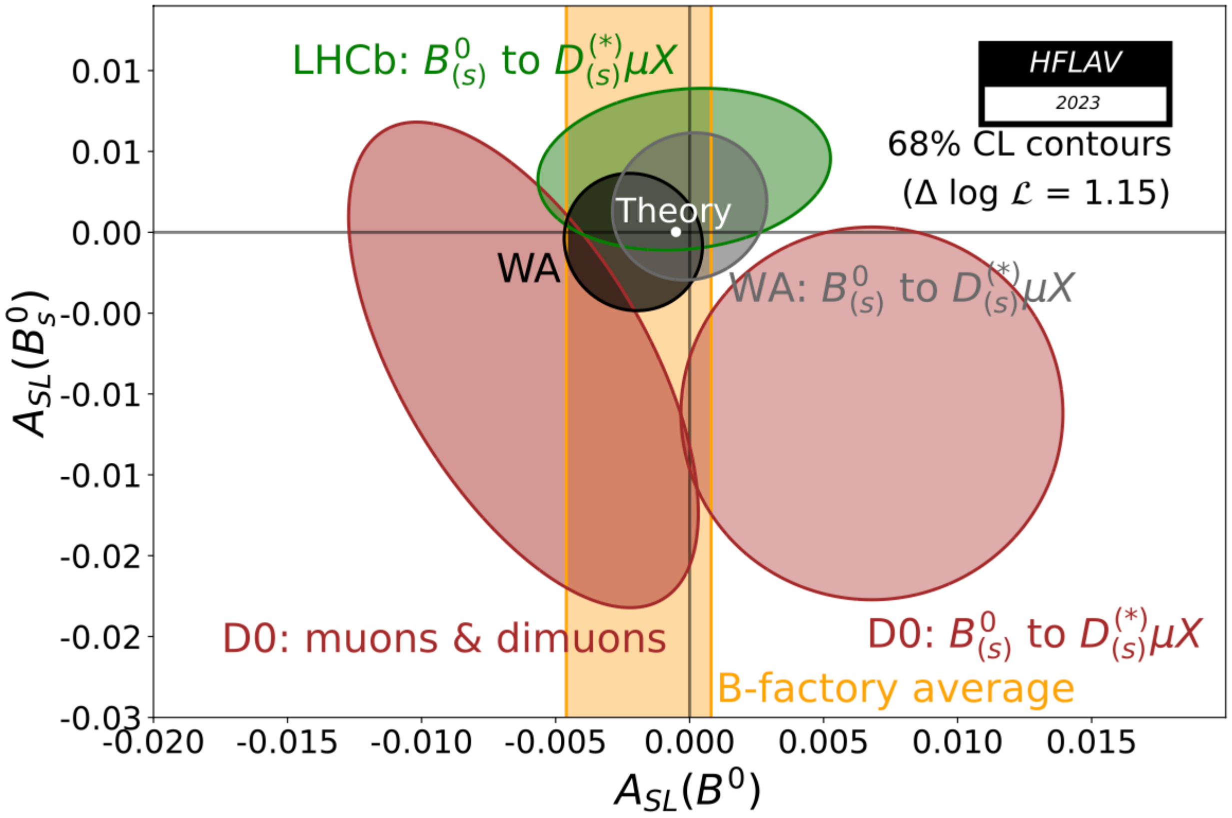


Beauty: CPV in mixing

$$|B_1\rangle = p|B^0_{(s)}\rangle + q|\bar{B}^0_{(s)}\rangle$$
$$|B_2\rangle = p|B^0_{(s)}\rangle - q|\bar{B}^0_{(s)}\rangle$$

Oscillation asymmetry

$$\mathcal{A}^d_{\rm SL} = \frac{N(\overline{B}^0(t) \to \ell^+\nu_\ell X) - N(B^0(t) \to \ell^-\overline{\nu}_\ell X)}{N(\overline{B}^0(t) \to \ell^+\nu_\ell X) + N(B^0(t) \to \ell^-\overline{\nu}_\ell X)}$$



$$\mathcal{A}^d_{\rm SL} = -0.0021 \pm 0.0017$$
$$\mathcal{A}^s_{\rm SL} = -0.0006 \pm 0.0028$$

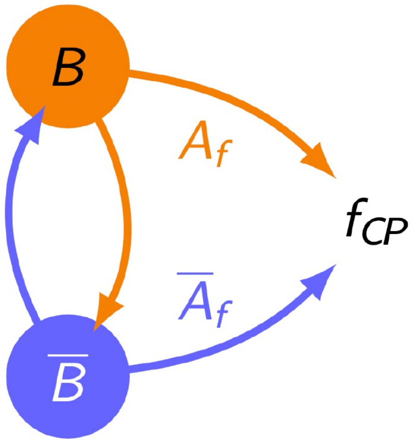
$$\Longleftrightarrow \quad |q_d/p_d| = 1.0010 \pm 0.0008$$
$$\Longleftrightarrow \quad |q_s/p_s| = 1.0003 \pm 0.0014$$

No hint of CPV in mixing

SM: $\mathcal{A}^d_{\rm SL} \sim 10^{-4}$, $\mathcal{A}^s_{\rm SL} \sim 10^{-5}$

Eur.Phys.J.ST 233 (2024) 359

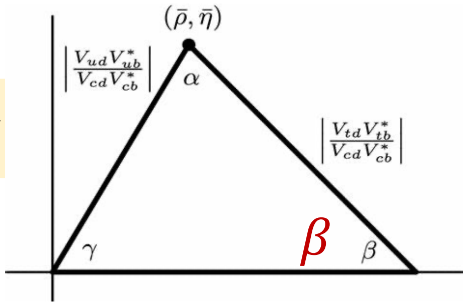
Beauty: mixing induced CPV



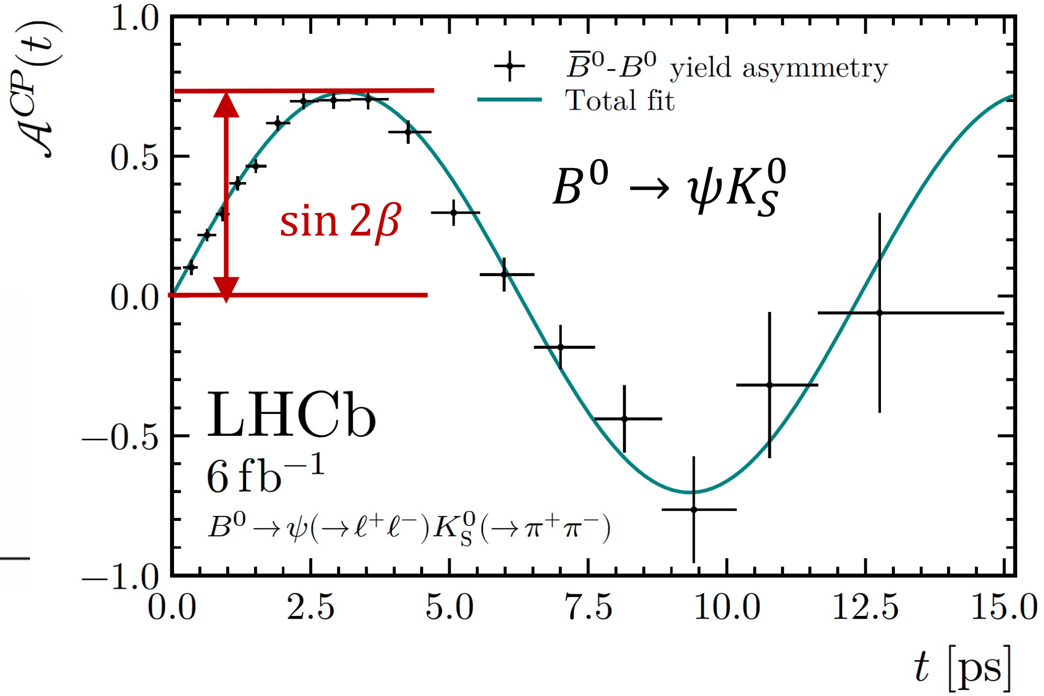
Interference between mixing and decay, sensitive to relative phase

β angle with $B^0 \to \psi K_S^0$ decay

$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$



PRL132 (2024) 021801



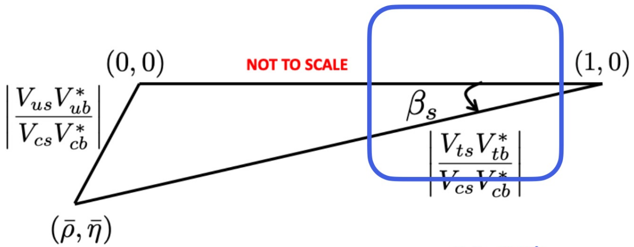
$$A_{CP}(t) = \frac{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\bar{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} \propto -\eta_f \cdot \boxed{\sin 2\beta} \cdot \sin(\Delta m t)$$

$$S_{\psi K_S^0}^{\text{Run 2}} = 0.716 \pm 0.013 \pm 0.008$$

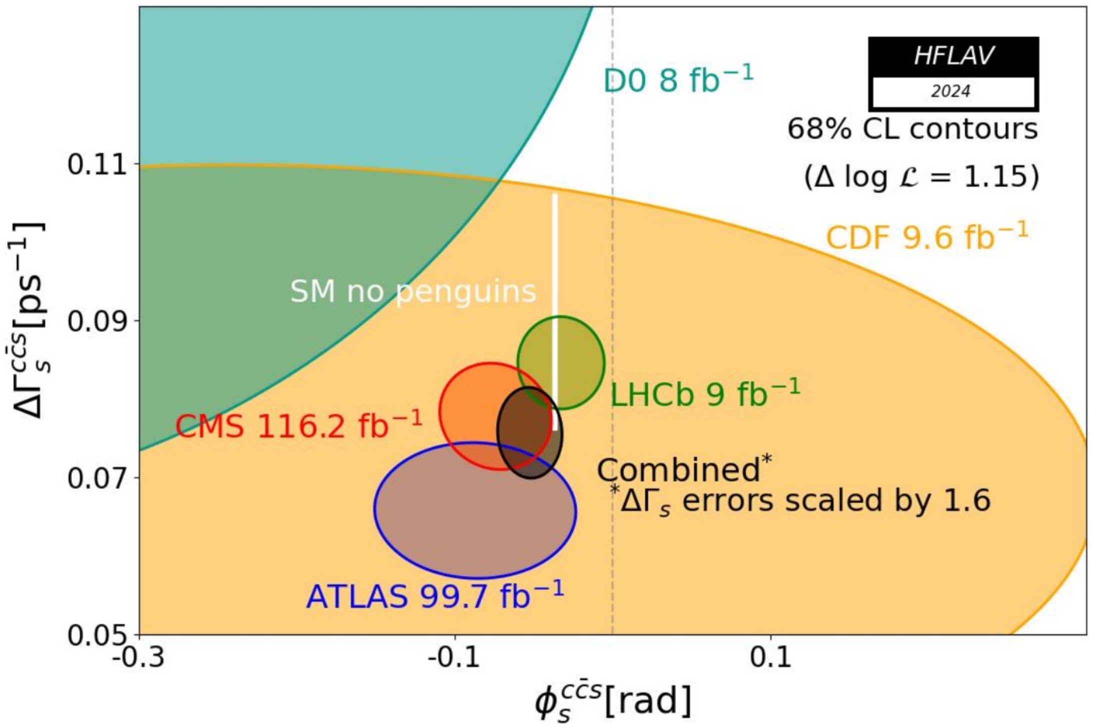
$$C_{\psi K_S^0}^{\text{Run 2}} = 0.012 \pm 0.012 \pm 0.003$$

Beauty: mixing induced CPV

$\phi_s^{c\bar{c}s}$ with $B_s^0 \to J/\psi\phi$, $D_s^+ D_s^-$ decays



$\phi_s \approx -2\beta_s = 2arg(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*})$



Combination: $\phi_s^{c\bar{c}s} = -0.052 \pm 0.013$ rad

Evidence of CP violation

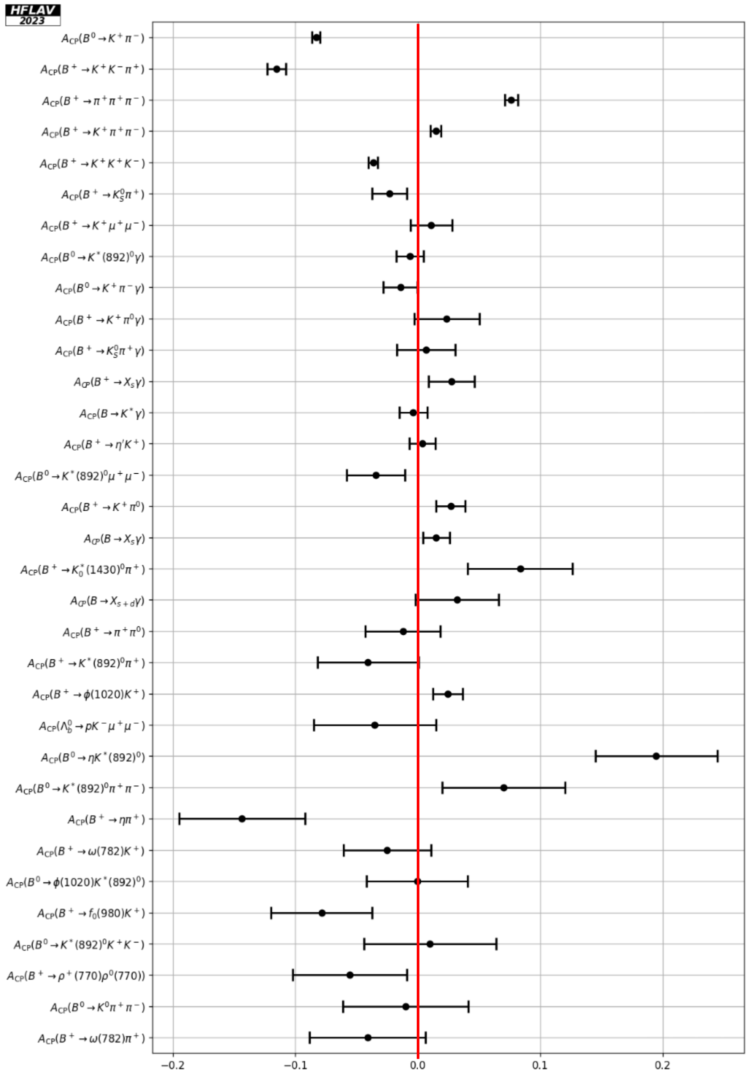
Consistent with global fit [CKMFitter]

$\phi_s^{SM} = -0.037 \pm 0.001$ rad

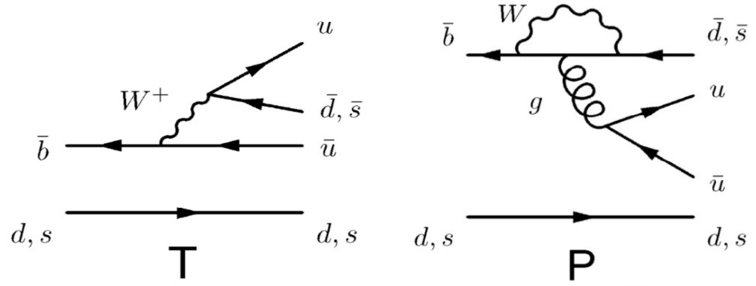
PRL132 (2024) 051082

Beauty: direct CPV

Charmless decays



Interference tween tree and penguin diagrams

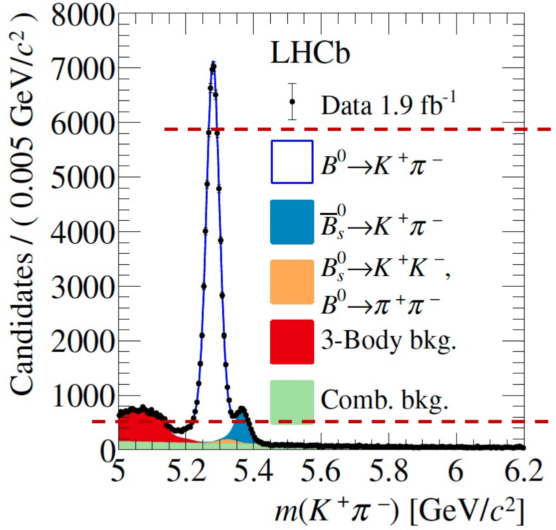


Possibly large CPV

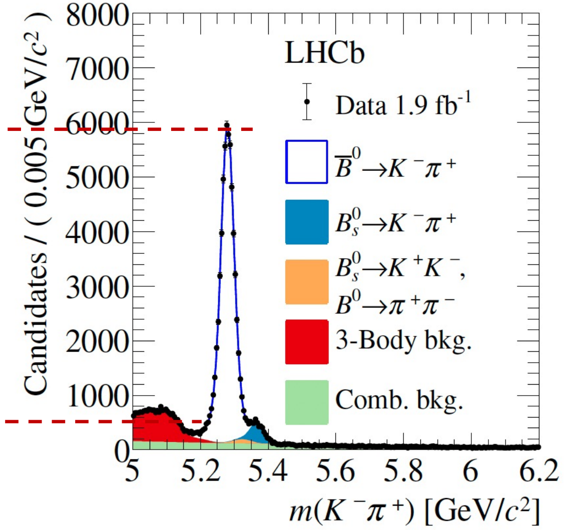
$$\boxed{A_{CP}^{B^0 \to K^+\pi^-} = -0.083 \pm 0.005}$$

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

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



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



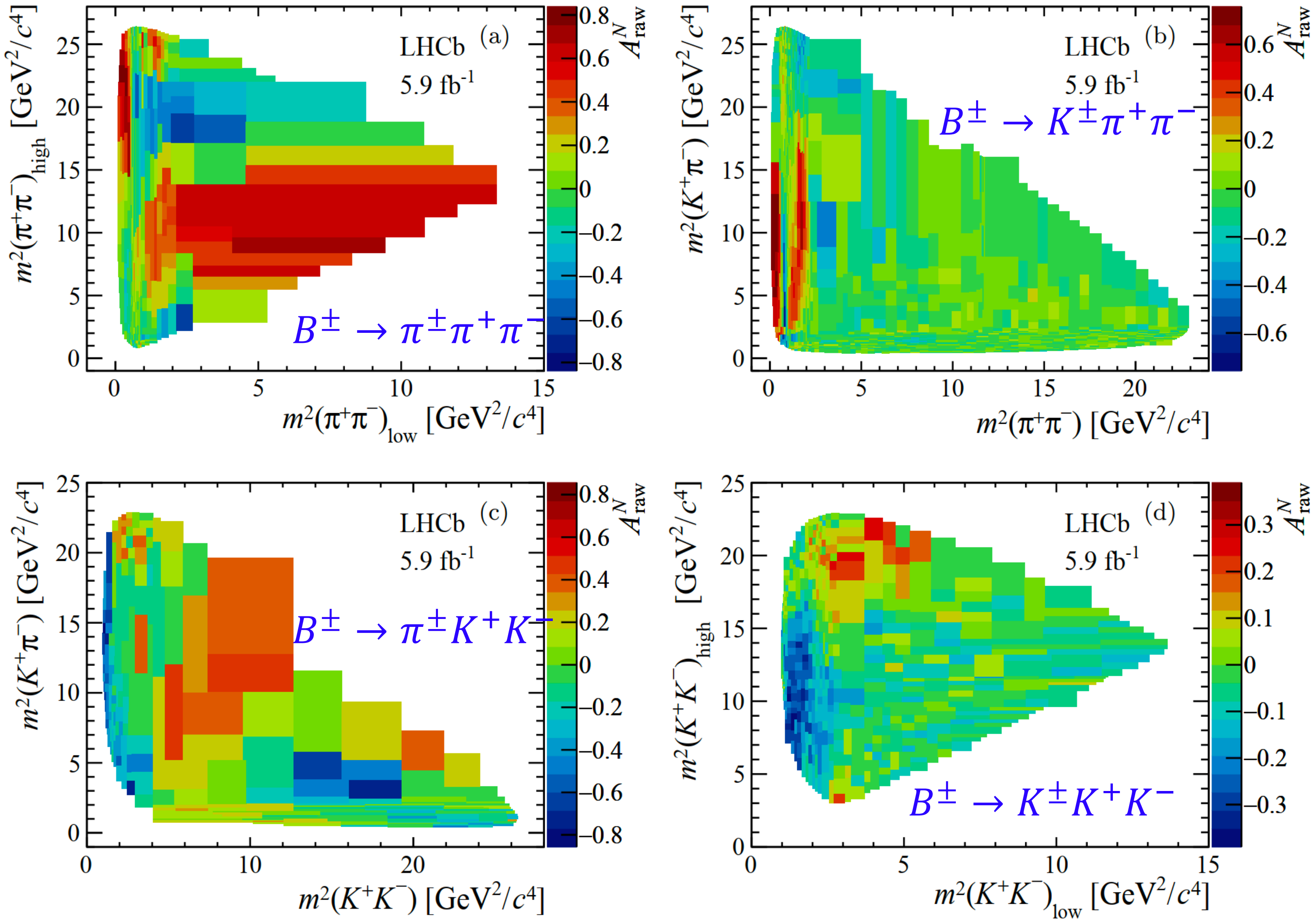
PRD98 (2018) 032004

Beauty: CPV pattern for N-body charmless decays

PRD108(2023)012008

Varying strong phases and resonance compositions

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



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- What is LHCb
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- CP violation in mesons
- **CP violation in baryons**

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, submitted to PRD
$\Lambda_b^0 \to \Lambda_c^+h^-$	Decay parameter	9 fb^{-1}	PRL 133 (2024) 261804
$\Lambda_b^0 \to \Lambda hh'$	A_{CP}	9 fb^{-1}	PRL 134 (205) 101802
$\Lambda_b^0 \to pK^-\pi^+\pi^-$	A_{CP}	9 fb^{-1}	arXiv:2503.16954, submitted to Nature

Why and how

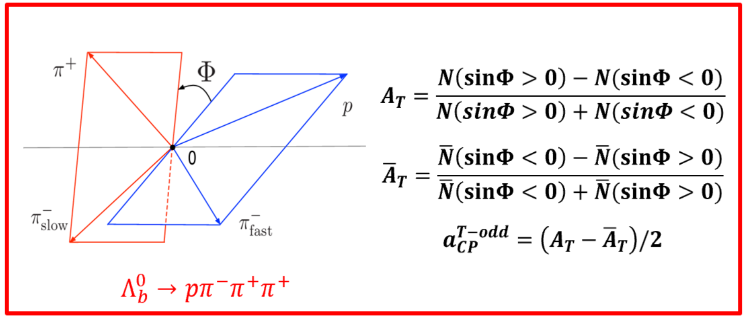
- EW-type baryogenesis requires large CP violation in baryons
- Baryons share the same decay dynamics with mesons in the SM

  ⇒ Large CP violation in b-baryons is possible

- Methods explored to search for CPV in baryons (complementarity)

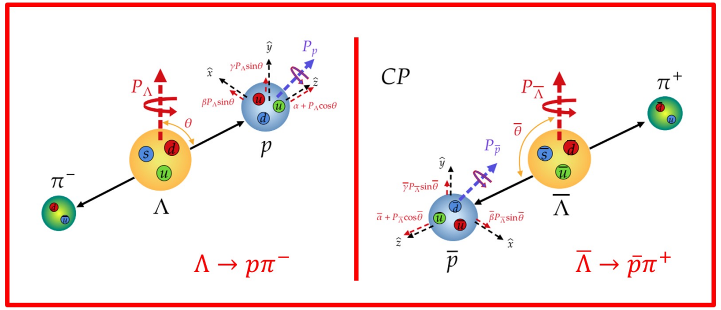
Symmetry 15 (2023) 522

Triple product asymmetry (TPA)

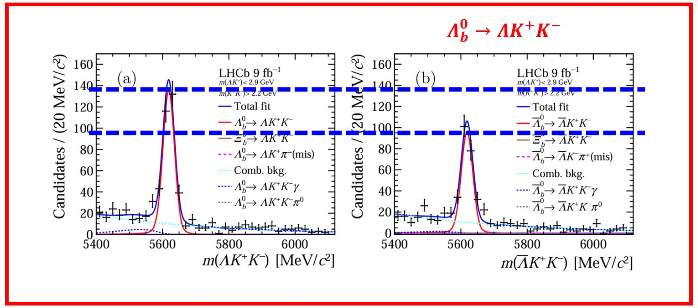


Angular/Amplitude analysis

Decay parameter



Decay rate asymmetry



$$A_{CP} = \frac{\Gamma_b - \Gamma_{\bar{b}}}{\Gamma_b + \Gamma_{\bar{b}}}$$

Precision: b baryon $\mathcal{O}(10\% \sim 0.1\%)$, c baryon $\mathcal{O}(0.1\%)$, hyperon $\mathcal{O}(1\% \sim 0.1\%)$

Triple product method

- Triple products in Λ_b^0 rest frame

$$\Lambda_b^0\text{:}\quad C_{\hat{T}} \equiv \vec{p}_p \cdot (\vec{p}_{\pi_{\text{fast}}} \times \vec{p}_{\pi^+}) \propto \sin\Phi$$

$$\bar{\Lambda}_b^0\text{:}\quad \bar{C}_{\hat{T}} \equiv \vec{p}_{\bar{p}} \cdot (\vec{p}_{\pi_{\text{fast}}} \times \vec{p}_{\pi^-}) \propto \sin\bar{\Phi}$$

- P-odd asymmetries

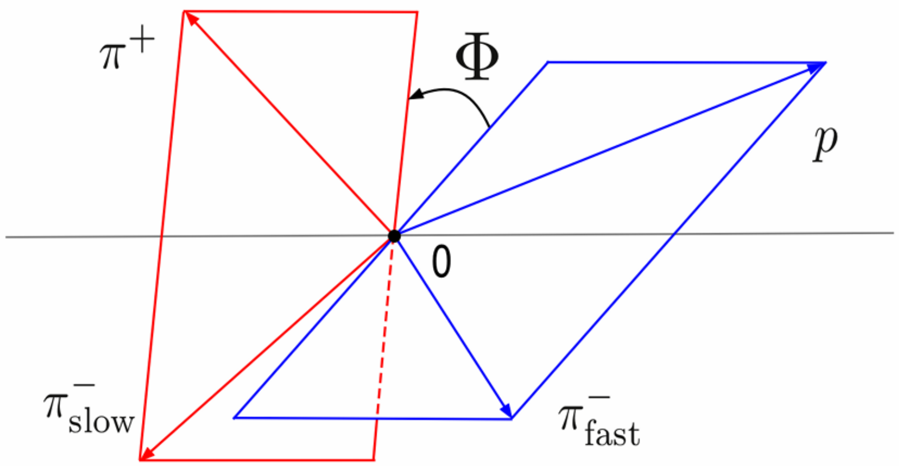
$$\Lambda_b^0\text{:}\quad A_{\hat{T}} = \frac{N_{\Lambda_b^0}(C_{\hat{T}} > 0) - N_{\Lambda_b^0}(C_{\hat{T}} < 0)}{N_{\Lambda_b^0}(C_{\hat{T}} > 0) + N_{\Lambda_b^0}(C_{\hat{T}} < 0)},$$

$$\bar{\Lambda}_b^0\text{:}\quad \bar{A}_{\hat{T}} = \frac{N_{\bar{\Lambda}_b^0}(-\bar{C}_{\hat{T}} > 0) - N_{\bar{\Lambda}_b^0}(-\bar{C}_{\hat{T}} < 0)}{N_{\bar{\Lambda}_b^0}(-\bar{C}_{\hat{T}} > 0) + N_{\bar{\Lambda}_b^0}(-\bar{C}_{\hat{T}} < 0)}$$

- CP-violating observable: $\boxed{a_{CP}^{\hat{T}\text{-odd}} = \frac{1}{2}\left(A_{\hat{T}} - \bar{A}_{\hat{T}}\right)}$

- P-violating observable: $\boxed{a_{P}^{\hat{T}\text{-odd}} = \frac{1}{2}\left(A_{\hat{T}} + \bar{A}_{\hat{T}}\right)}$

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

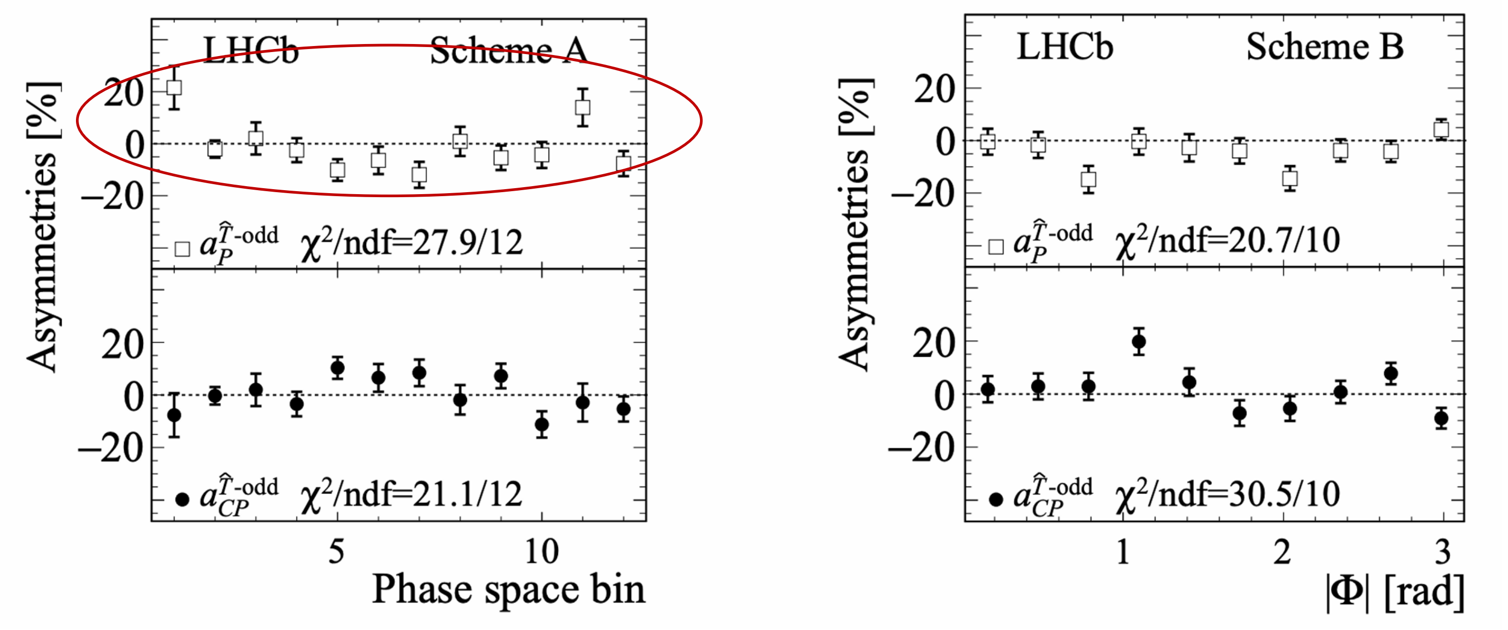


J.-P. Wang, Q. Qin, F.-.S. Yu, *Complementary CP violation induced by T-odd and T-even correlations* arXiv:2211.07332

$\boxed{a_{CP}^{\hat{T}-\text{odd}} \propto \sin\Delta\phi\cos\Delta\delta}$

CPV of $\Lambda_b^0 \to ph^-h^+h^-$ with TPA

- Evidence of CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decay (3.3σ) in Run 1 data



Nature Phys. 13 (2017) 391

However, not confirmed including 2015-2017 data

PRD 102 (2020) 051101

- No significant CP violation found in $\Lambda_b^0 \to pK^-\pi^+\pi^-$, $\Lambda_b^0 \to pK^-K^+K^-$ and $\Xi_b^0 \to pK^-K^-\pi^+$ using Run 1 data (~1% precision)

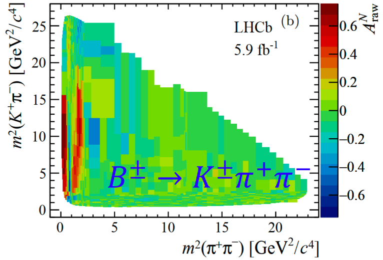
JHEP 08 (2018) 039

CPV with amplitude/angular analysis

CPV in $\Xi_b^- \to pK^-K^-$ decays

PRD 104 (2021) 052010

- Three body charmless $b \to u\bar{u}s$ transition, analogy to $B \to K\pi\pi$ decays



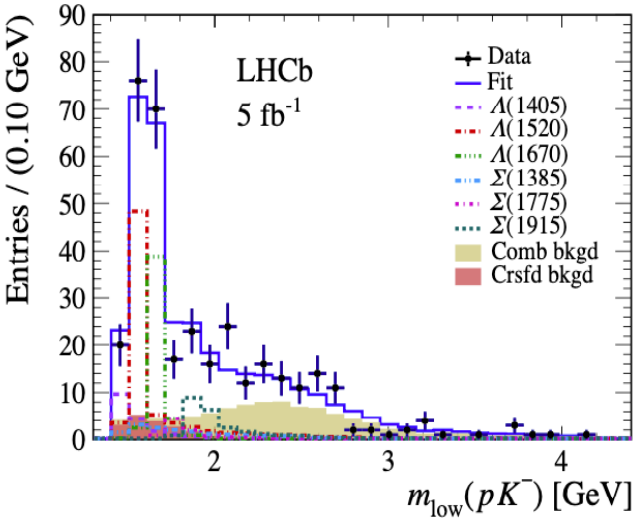
Branching fraction similar to $\mathcal{B}(B \to K\pi\pi)$ decays

$$\mathcal{B}\left(\Xi_b^- \to pK^-K^-\right) = (2.3 \pm 0.9) \times 10^{-6}$$

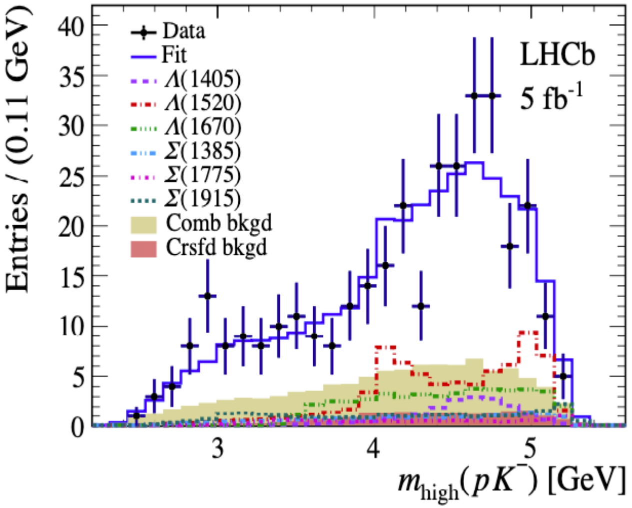
- Amplitude analysis with 6 Λ/Σ resonances

Component	A^{CP} (10^{-2})
$\Sigma(1385)$	-27 ± 34 (stat) ± 73 (syst)
$\Lambda(1405)$	-1 ± 24 (stat) ± 32 (syst)
$\Lambda(1520)$	-5 ± 9 (stat) ± 8 (syst)
$\Lambda(1670)$	3 ± 14 (stat) ± 10 (syst)
$\Sigma(1775)$	-47 ± 26 (stat) ± 14 (syst)
$\Sigma(1915)$	11 ± 26 (stat) ± 22 (syst)

$m_{\rm low}(pK^-)$



$m_{\rm high}(pK^-)$



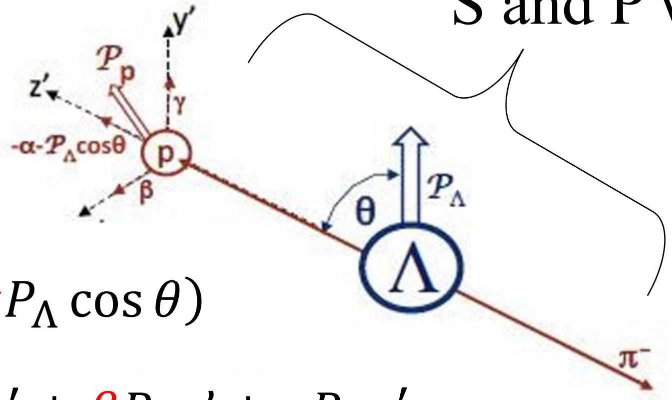
No evidence of CPV

Multiple solutions,
CPC 48 (2024) 053001

Baryon decay parameters

- Proposed by Lee & Yang to study parity (P) violation in hyperon decay $\Lambda \to p\pi^+$
- Clean observables, less polluted by experimental effects

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

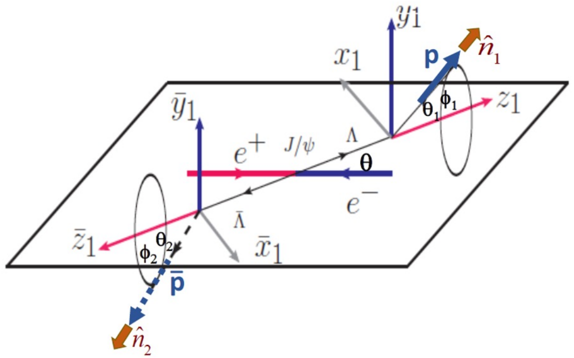
Complementary to decay rate asymmetry

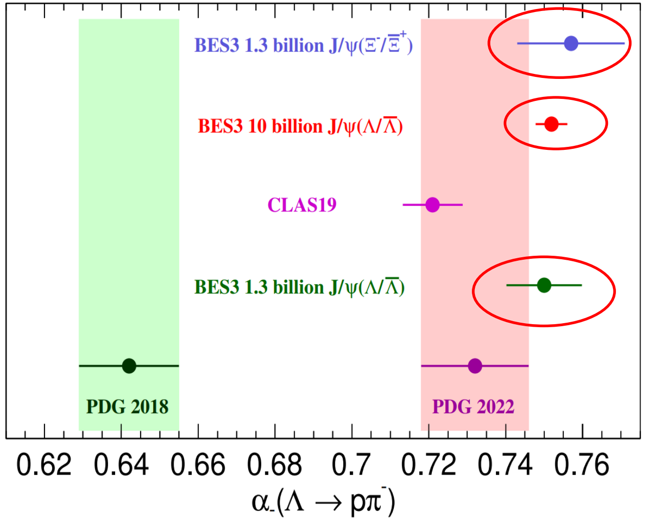
Decay parameters and CPV in hyperons

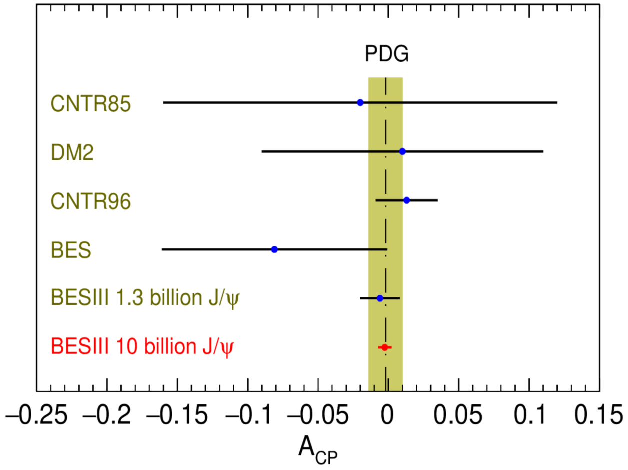
- Pioneering work to probe CPV in $J/\psi \to \Lambda\bar{\Lambda}$

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

Entangled Λ and $\bar{\Lambda}$





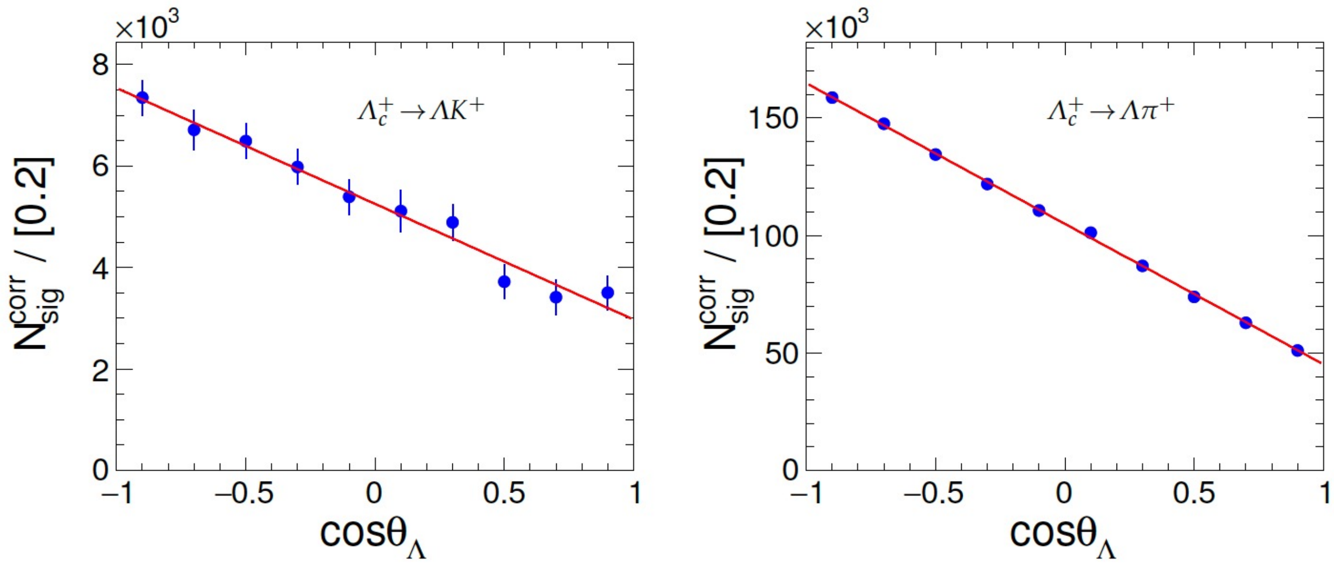


- Many other ψ to hyperon channels explored, no sign of CP violation

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

Decay parameters and CPV in charm baryons

Decay	$\alpha_{\Lambda_c^+}\alpha_-$	$\alpha_{\bar{\Lambda}_c^-}\alpha_+$	$\alpha_{\Lambda_c^+}$	$\alpha_{\bar{\Lambda}_c^-}$	$\mathcal{A}_{CP}^{\alpha}$
$\Lambda_c^+ \to \Lambda\pi^+$	-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

Beauty and charm baryon decay parameters

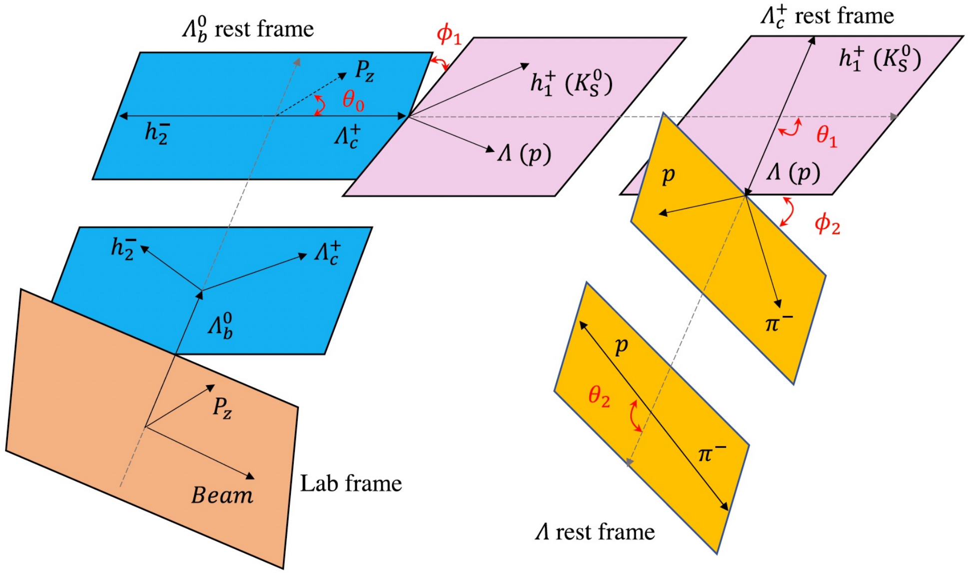
- Simultaneous angular analysis of 6 decays

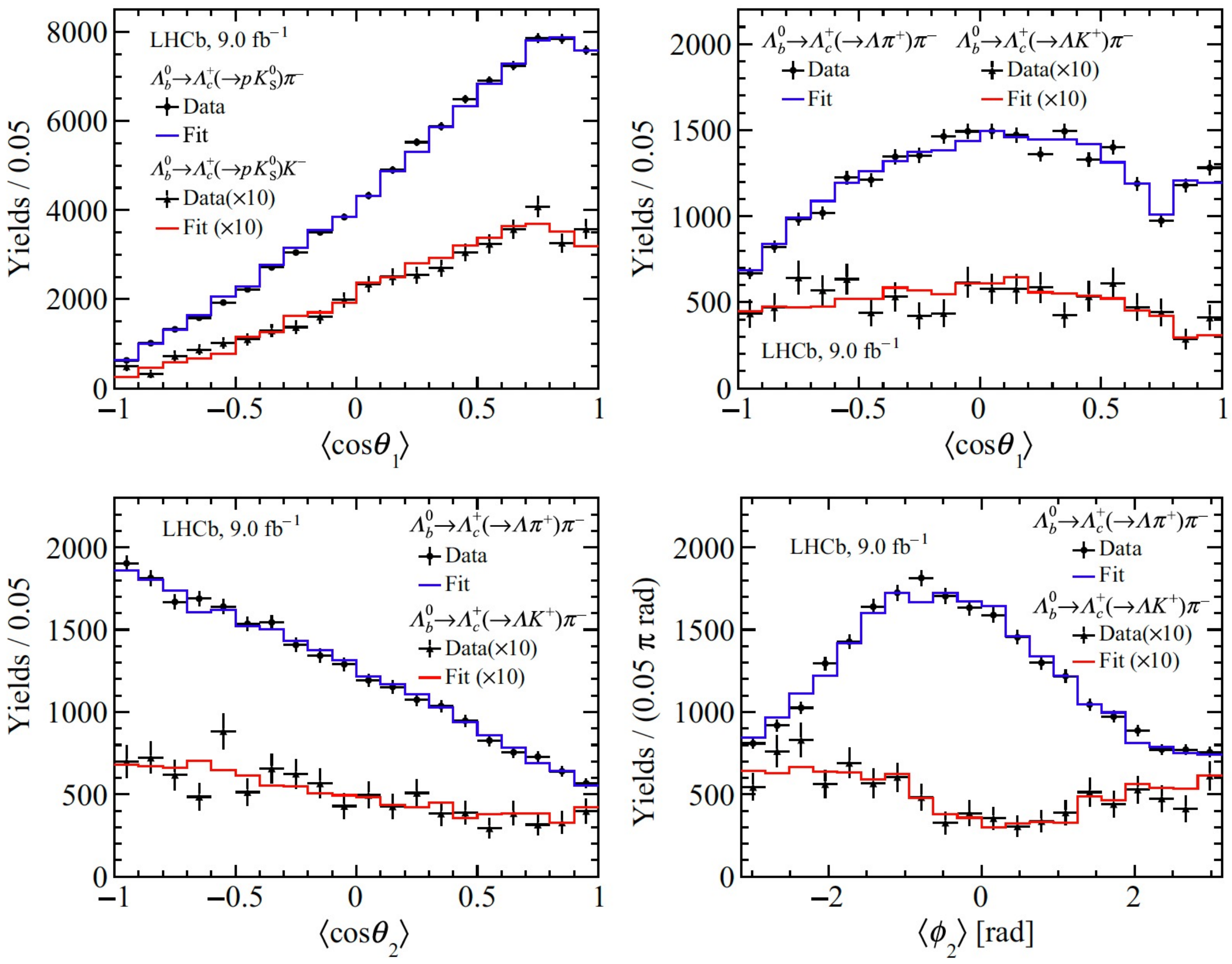
PRL 133 (2024) 261804

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

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

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





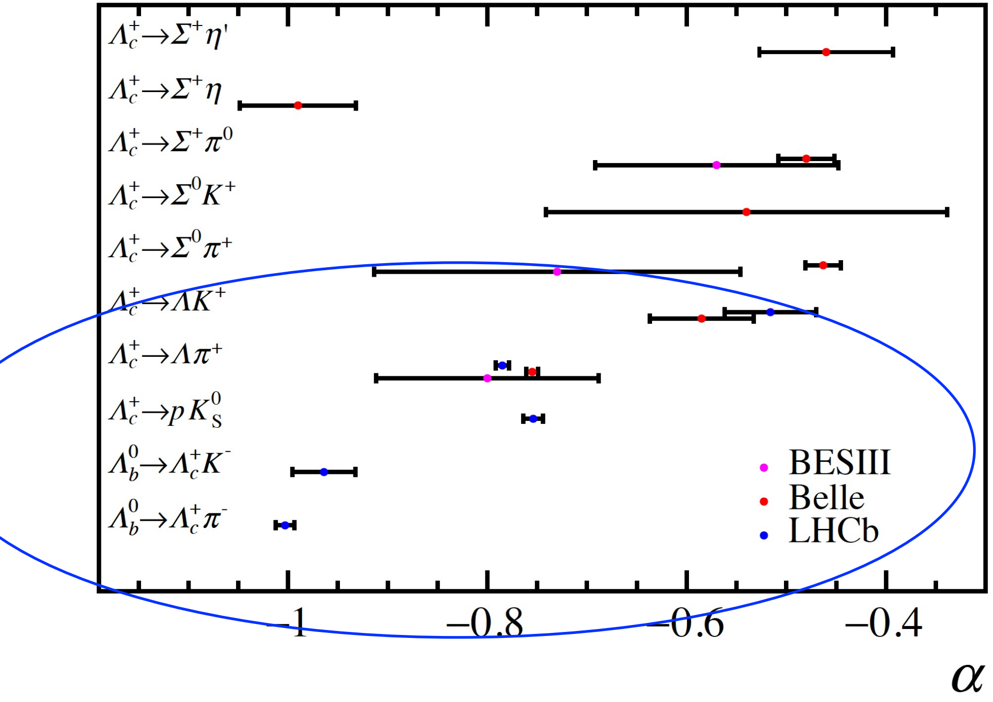
P and CP violation

PRL 133 (2024) 261804

P violating α parameters

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

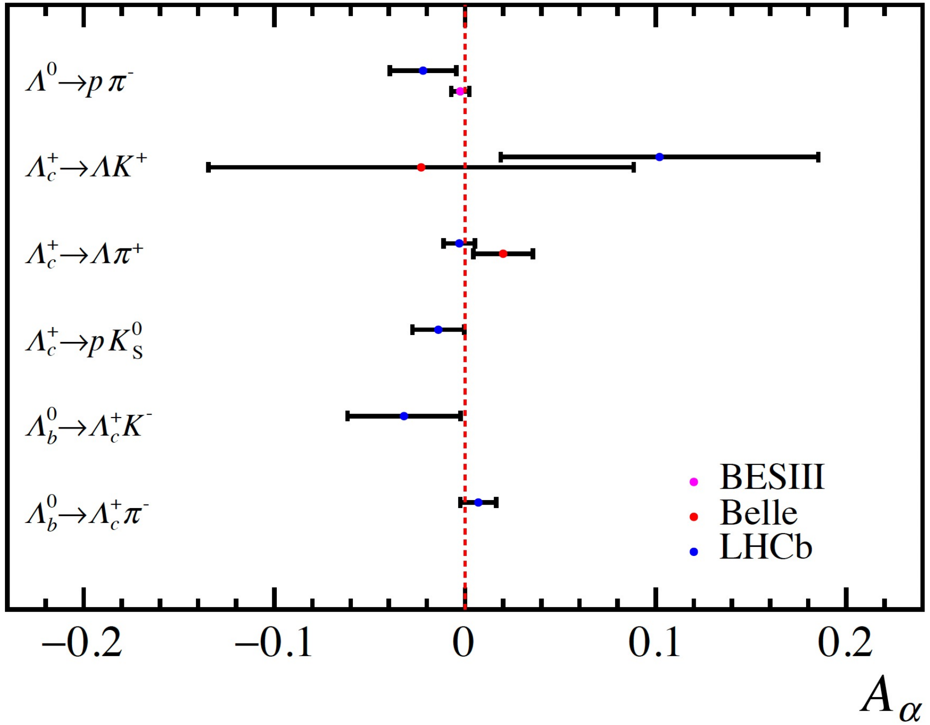
Consistent with Belle and BESIII



CP violating A_{CP}^{α} parameters

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

Consistent with CP symmetry



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

PRL 133 (2024) 261804

- No CP violation in β, γ or 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)	2.693 ± 0.017	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

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

CPV with decay rate

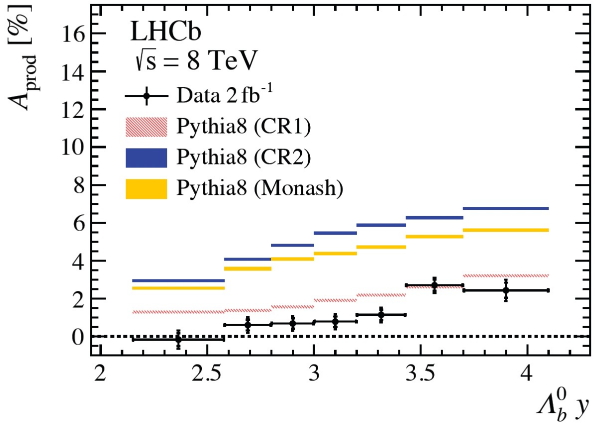
$$A_{CP} = \frac{\Gamma_b - \Gamma_{\overline{b}}}{\Gamma_b + \Gamma_{\overline{b}}}$$

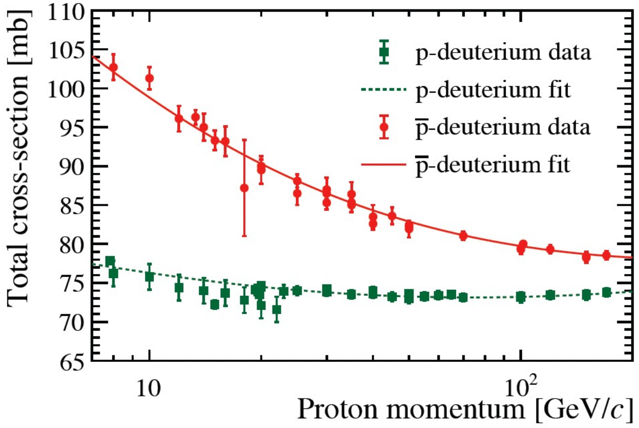
Crucial to control systematics

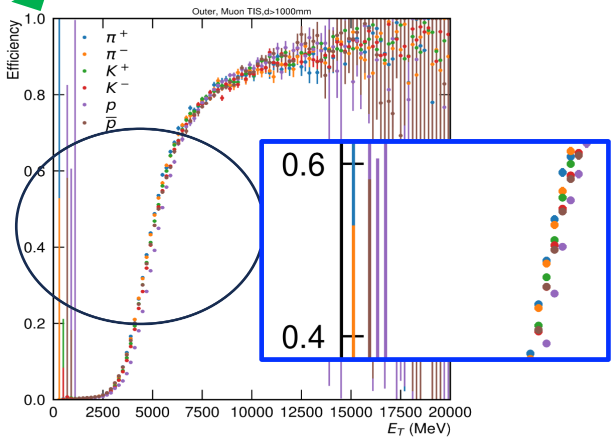
- Subtraction of experiment induced asymmetries (~ 1%, similar to/larger than CPV itself)

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

JHEP 10 (2021) 060







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

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

Usually good cancellation, only limited by $\Lambda_b^0 \to \Lambda_c^+\pi^-$ sample size

CPV for charm decay $\Lambda_c^+ \to ph^+h^-$

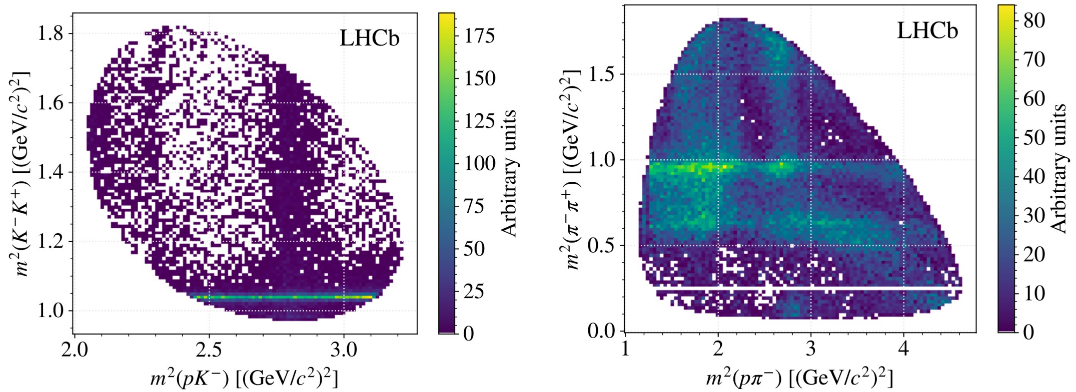
JHEP 03 (2018) 182

- Charm baryon CPV expected to be small, ~0.1%

I. I. Bigi, arXiv:1206.4554

Golden channel: $\Lambda_c^+ \to pK^+K^-, p\pi^+\pi^-$

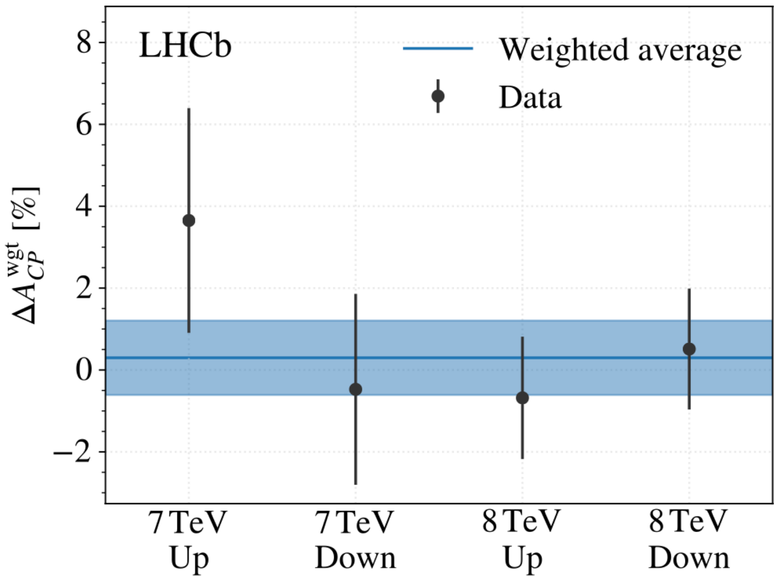
- ➢ Singly Cabibbo-suppressed ($D^0 \to KK, \pi\pi$)
- ➢ Large yields and high S/B ratio
- ➢ Rich resonances



Challenging to control systematics

Measurement with Run 1 data (3 fb^{-1})

$$\Delta A_{CP}^{\text{wgt}} = A_{CP}(pK^-K^+) - A_{CP}^{\text{wgt}}(p\pi^-\pi^+) = (0.30 \pm 0.91 \pm 0.61)\,\%,$$



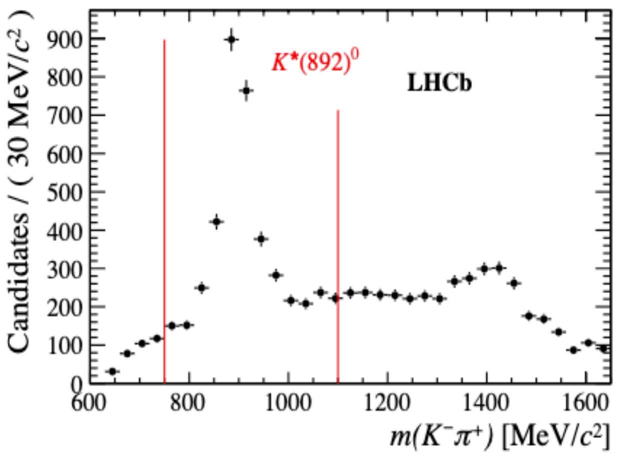
CP asymmetry for $\Lambda_b^0, \Xi_b^0 \to phhh$ decays

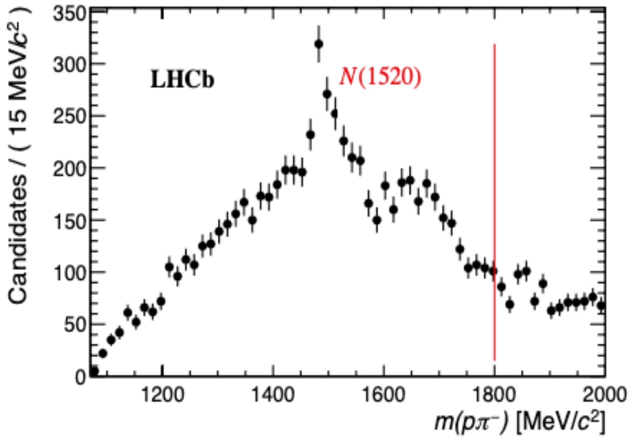
EPJC 79 (2019) 745

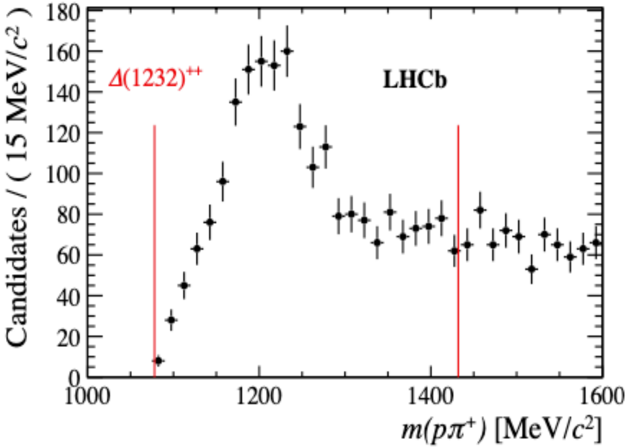
- Six decay modes, with yields of 0.5-10K (3 fb^{-1})
- Abundant resonant structures

$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$
$\Xi_b^0 \to pK^-\pi^+\pi^-$ $\Lambda_b^0 \to pK^-\pi^+\pi^-$
$\Xi_b^0 \to pK^-\pi^+K^-$ $\Lambda_b^0 \to pK^-K^+\pi^-$
$\Lambda_b^0 \to pK^-K^+K^-$

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







- Global and local A_{CP} around resonances studied, difference to $\Lambda_b^0 \to \Lambda_c^+\pi^-$ decay

$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) = (+1.1 \pm 2.5 \pm 0.6)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (+3.2 \pm 1.1 \pm 0.6)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-K^+\pi^-) = (-6.9 \pm 4.9 \pm 0.8)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-K^+K^-) = (+0.2 \pm 1.8 \pm 0.6)\,\%$$

- No evidence of CPV (~1% precision)
- CPV hint for $\Lambda_b^0 \to pK^-\pi^+\pi^-$ decay
- Rule out global CPV $\gg$ 5%

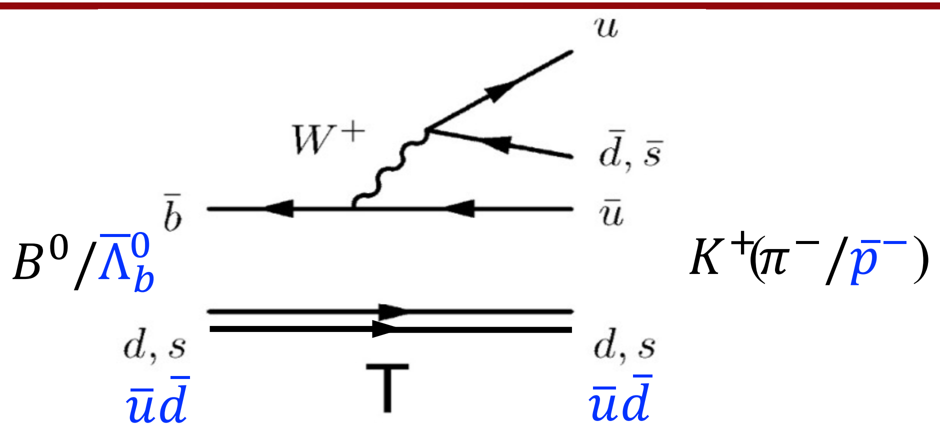
CP violation in $\Lambda_b^0 \to p h^-$ decays

arXiv:2412.13958

- Dynamics analogy to $B^0 \to h^+ h^-$ decays
- Large yield and high purity
- CP violation predicted: ~5%

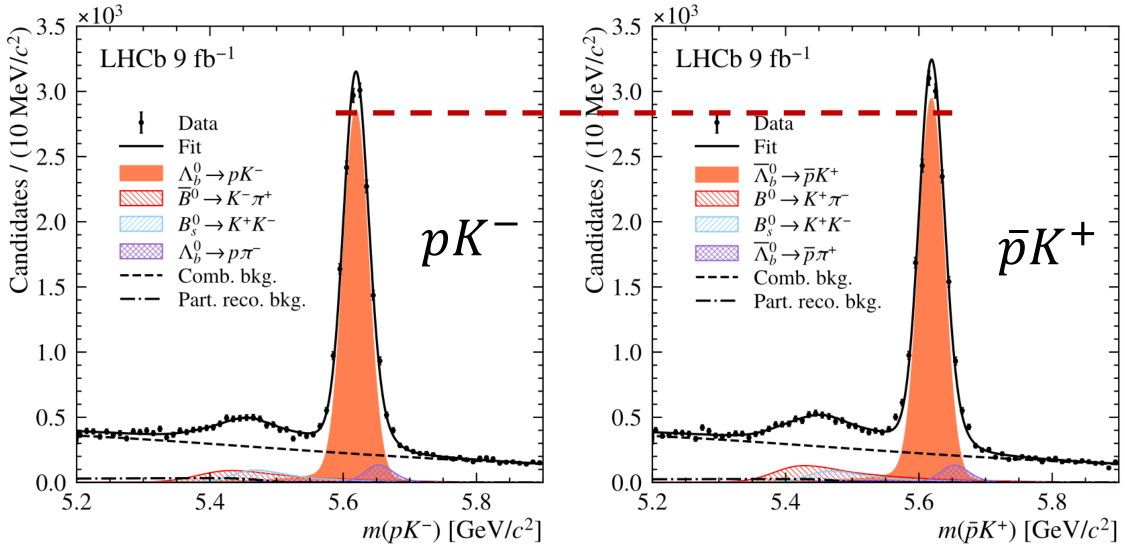
PRD 102 (2012) 034033
PRD 95 (2017) 093001

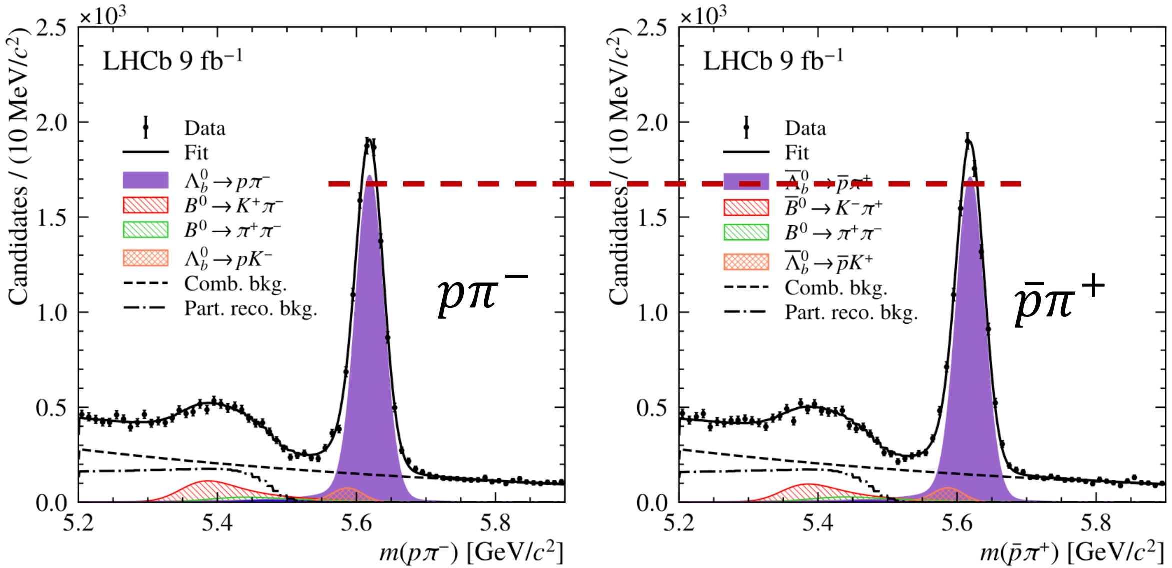
- Sizable CP violation ruled out



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

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

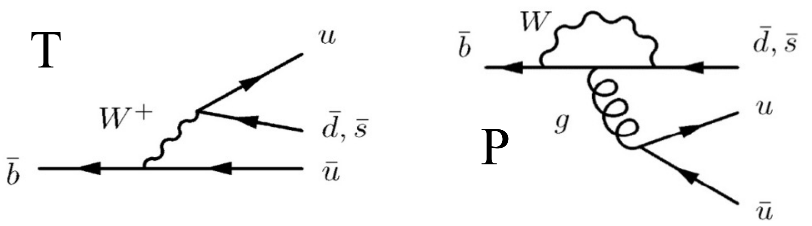




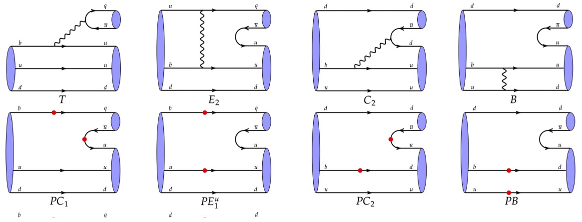
Why CP violation so small

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

  One diagram overwhelming? small strong phase difference?



- Dynamics more complex than mesons



韩佳杰、余纪新、李亚等，arXiv:2409.02821

➢ Tree amplitude dominating

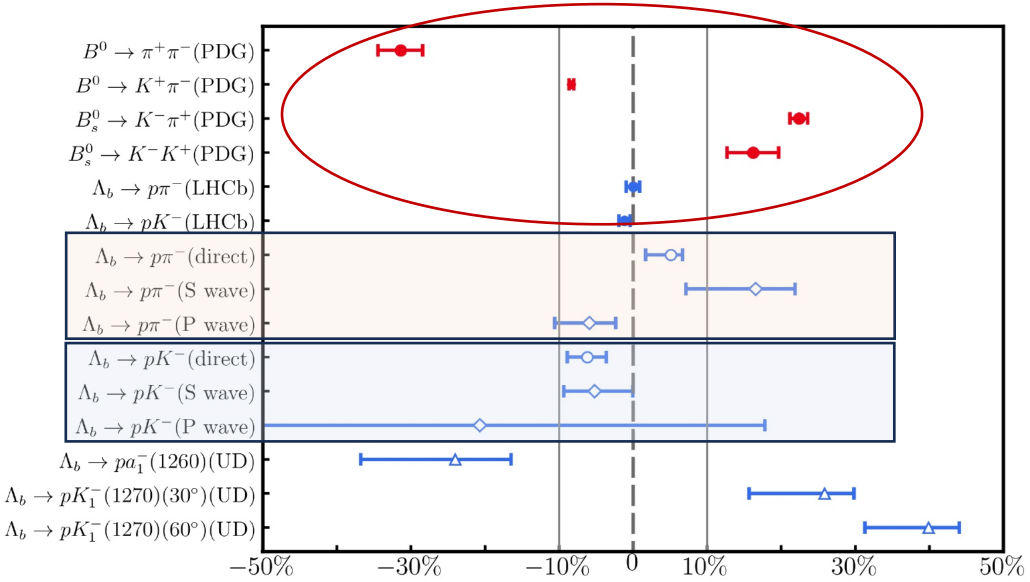
$\Lambda_b^0 \to p\pi^-$

Amplitudes	Real(S)	Imag(S)	Real(P)	Imag(P)
		$\Lambda_b \to p\pi^-$		
T	701.19	−51.38	967.54	−265.17
C_2	−26.61	12.43	−41.51	0.14
E_2	−55.01	−38.14	−36.23	62.89
B	−4.00	9.60	−12.73	−19.93
Tree $\mathcal{T}$	615.57	−67.49	877.08	−222.06
PC_1	57.90	−1.12	1.88	−11.11
PC_2	−5.88	−12.00	4.62	14.20
PE_1^u	0.39	−9.47	−3.65	8.04
PB	0.85	−1.06	−1.46	−0.53
$PE_1^d + PE_2$	−0.55	−3.83	1.37	-0.31
Penguin $\mathcal{P}$	52.71	−27.49	2.77	10.28

S P

➢ 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

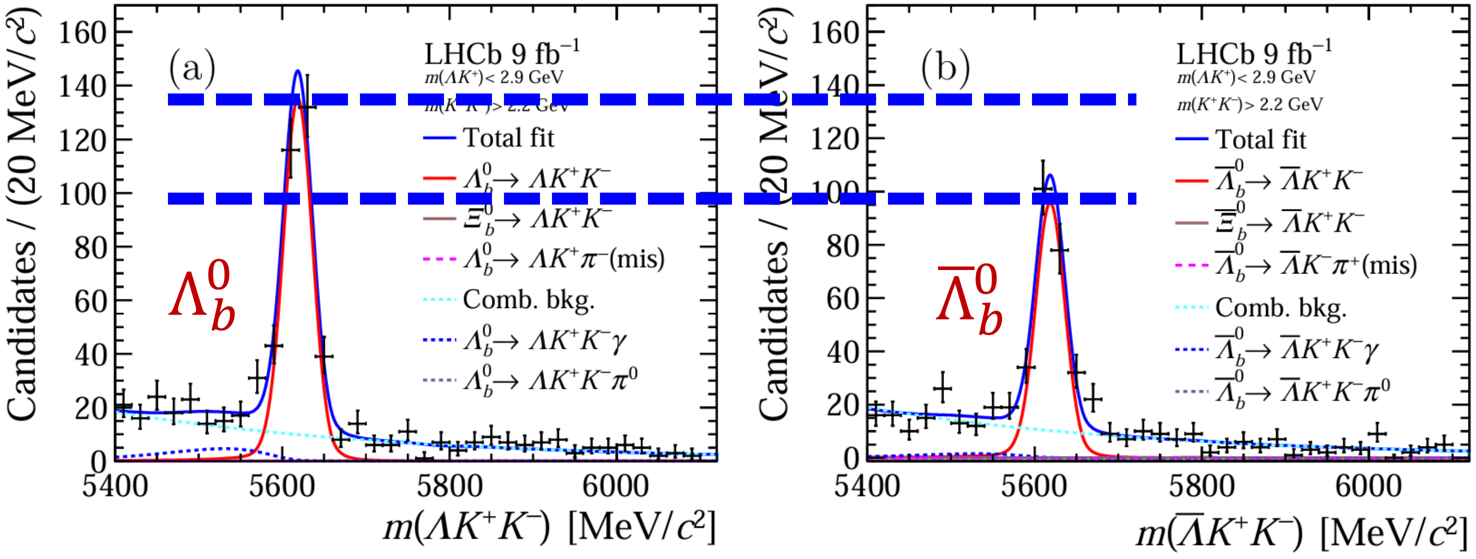
PRL 134 (2025) 101802

- 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

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

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)

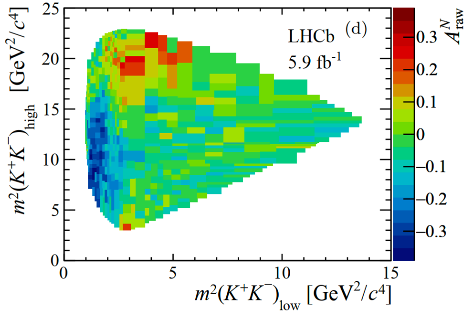
- Many N^{*+} contributing to $\Lambda_b^0 \to N^{*+}K^-$

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

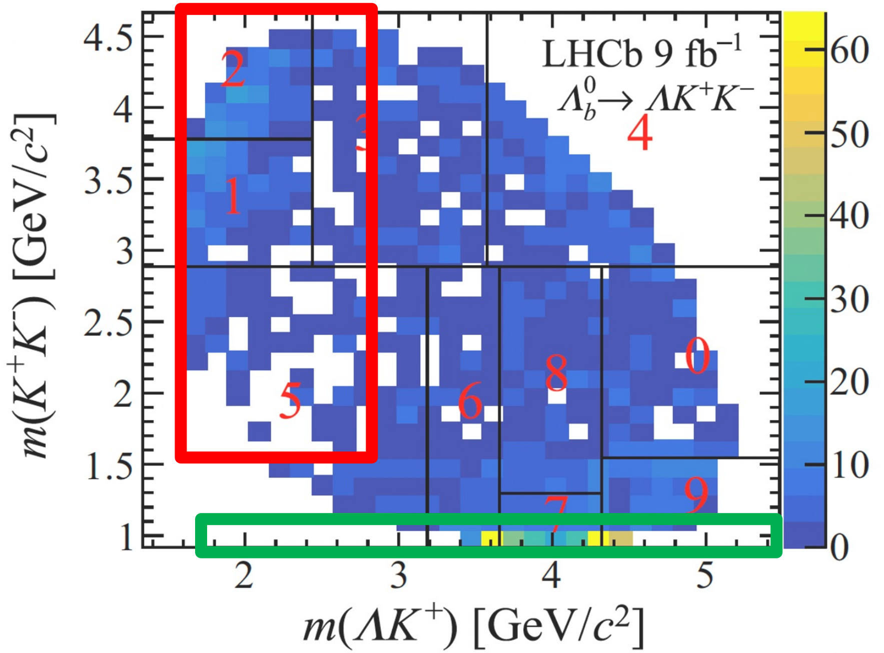
$N^{*+} \to \Lambda K^+ \quad \Rightarrow \Lambda_b^0 \to N^{*+}(\Lambda K^+)K^-$

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

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



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



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More local CP asymmetries

PRL 134 (2025) 101802

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

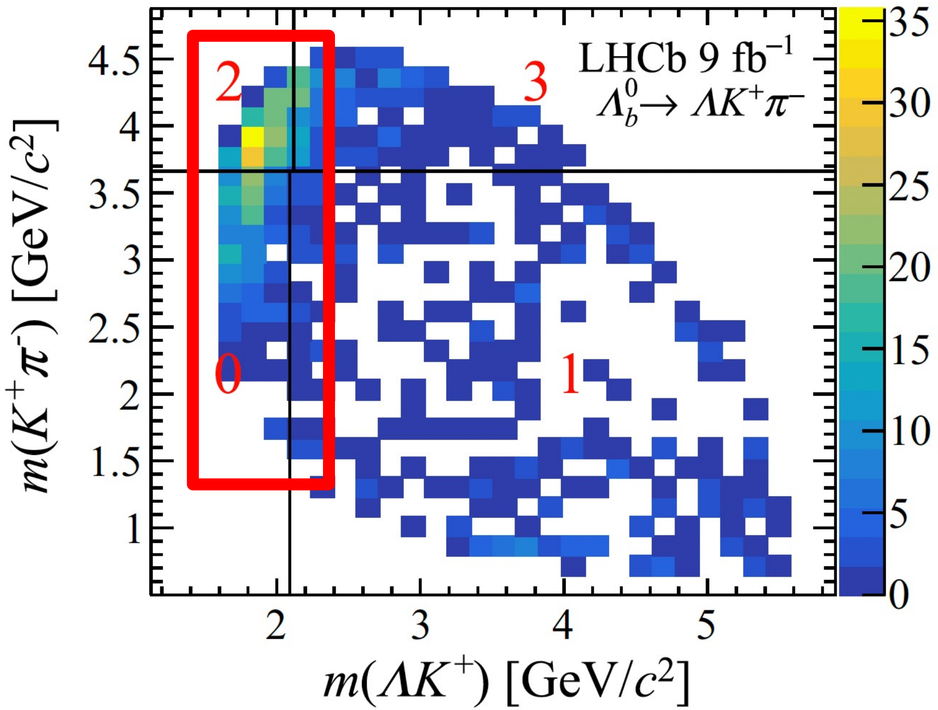
$\Lambda_b^0 \to N^{*+}(\to \Lambda K^+)\pi^-$

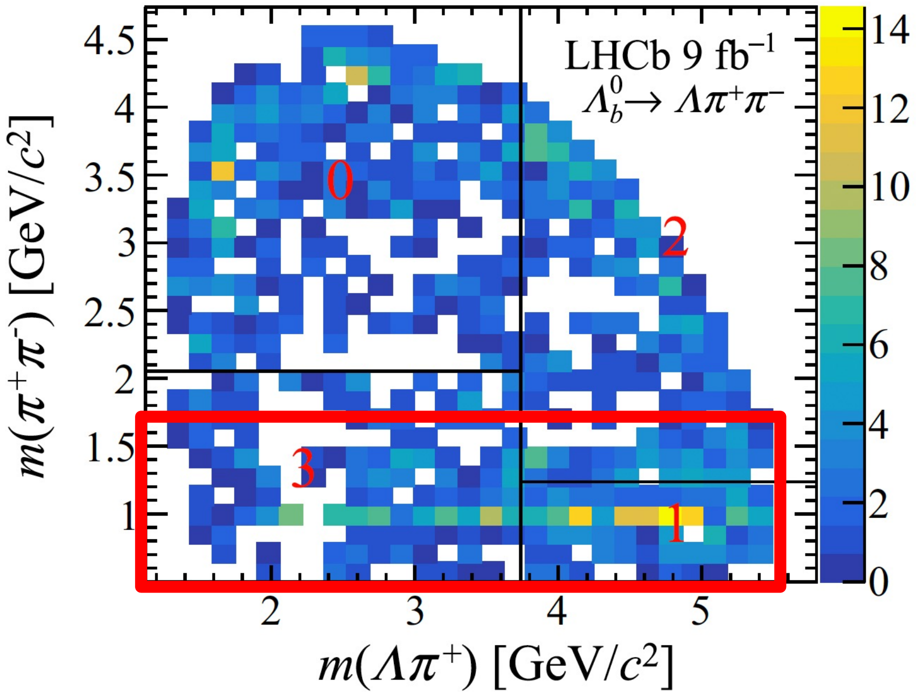
$\Delta A_{CP}(N^{*+}\pi^-) = -0.078 \pm 0.051 \pm 0.027$

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

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

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

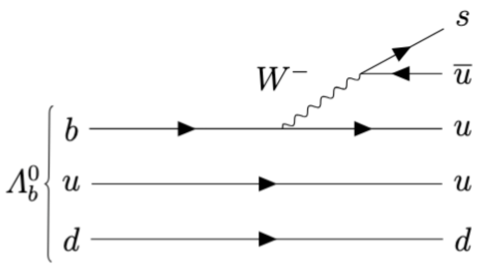


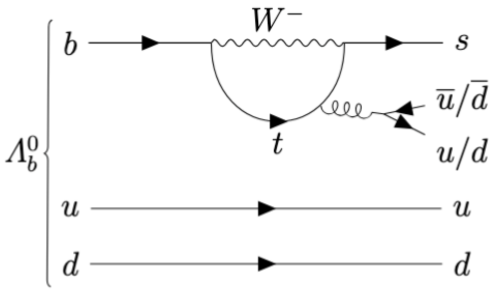


Study of $\Lambda_b^0 \to pK^-\pi^+\pi^-$ decays with Run 1+2

arXiv:2503.14954

- Contributed by tree and loop diagrams





- Rich resonances

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

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

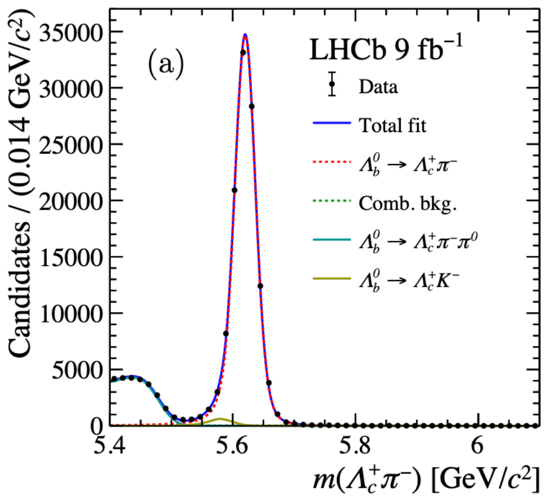
- Cancelling production and detection asymmetries

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

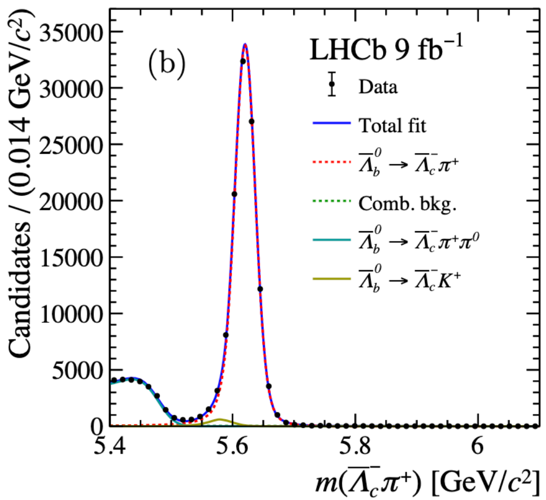
$$A_{CP} = \Delta A_{\text{yield}} - \Delta A_{\text{prod}} - \Delta A_{\text{exp}}$$

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

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



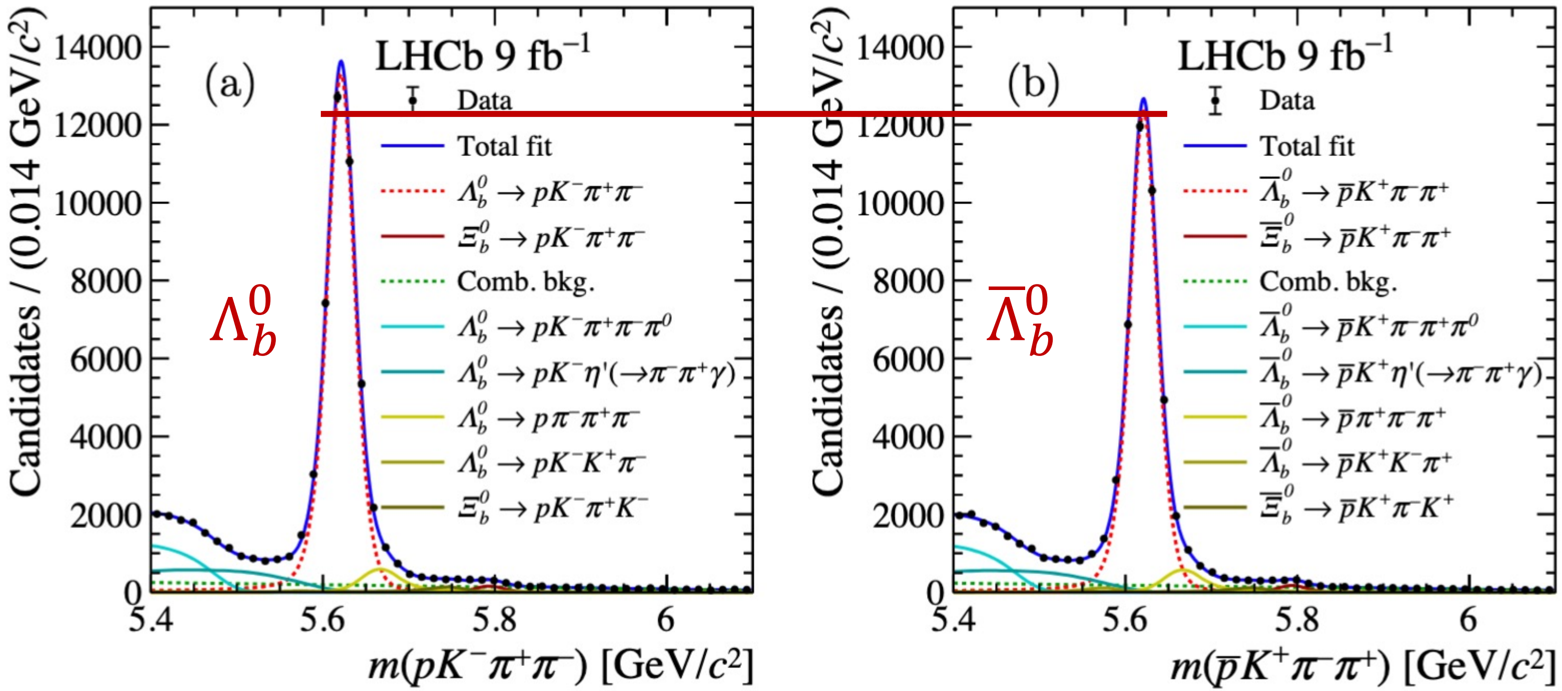
$\overline{\Lambda}_b^0 \to \overline{\Lambda}_c^-\pi^+$



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

arXiv:2503.14954

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



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

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

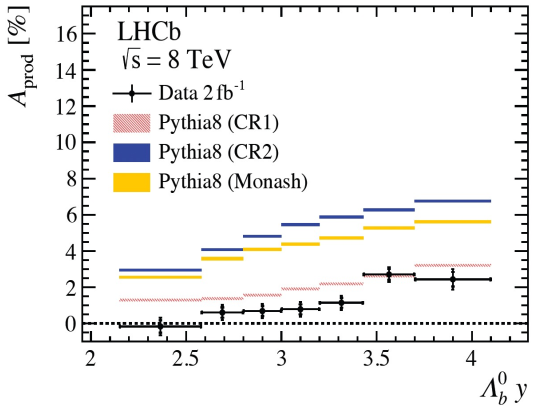
$\overline{N}_{\text{yield}} =$
$(3.885 \pm 0.023)\times 10^4$

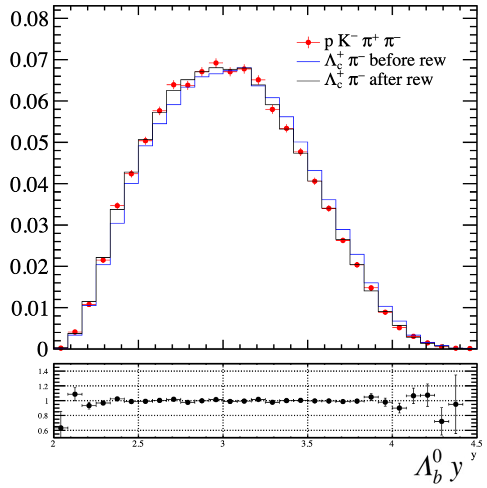
Corrections for experimental bias

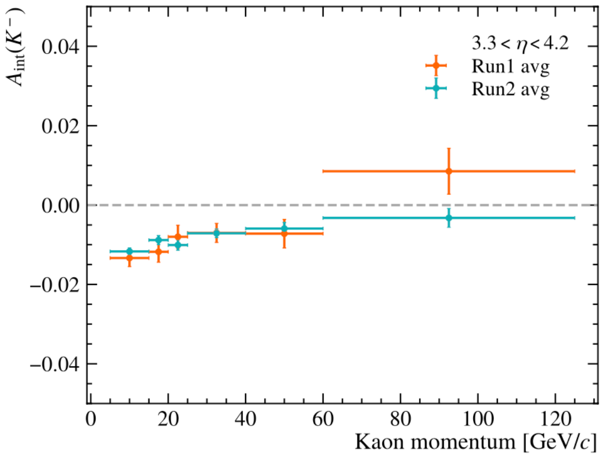
$$A_{CP} = \Delta A_{\text{yield}} - \Delta A_{\text{prod}} - \Delta A_{\text{exp}}$$

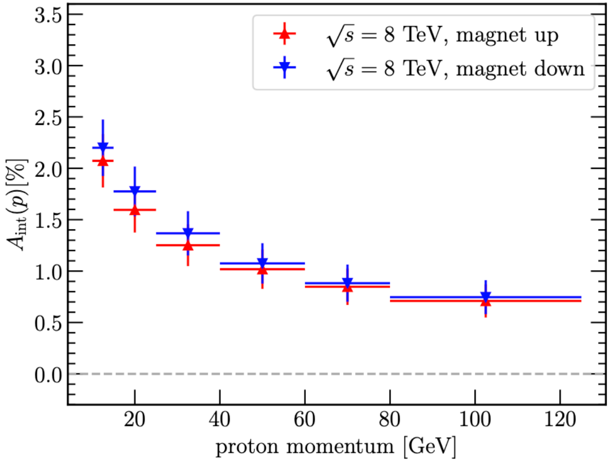
- Production asymmetry: cancelled by matching Λ_b^0 kinematics of control to signal mode

- 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

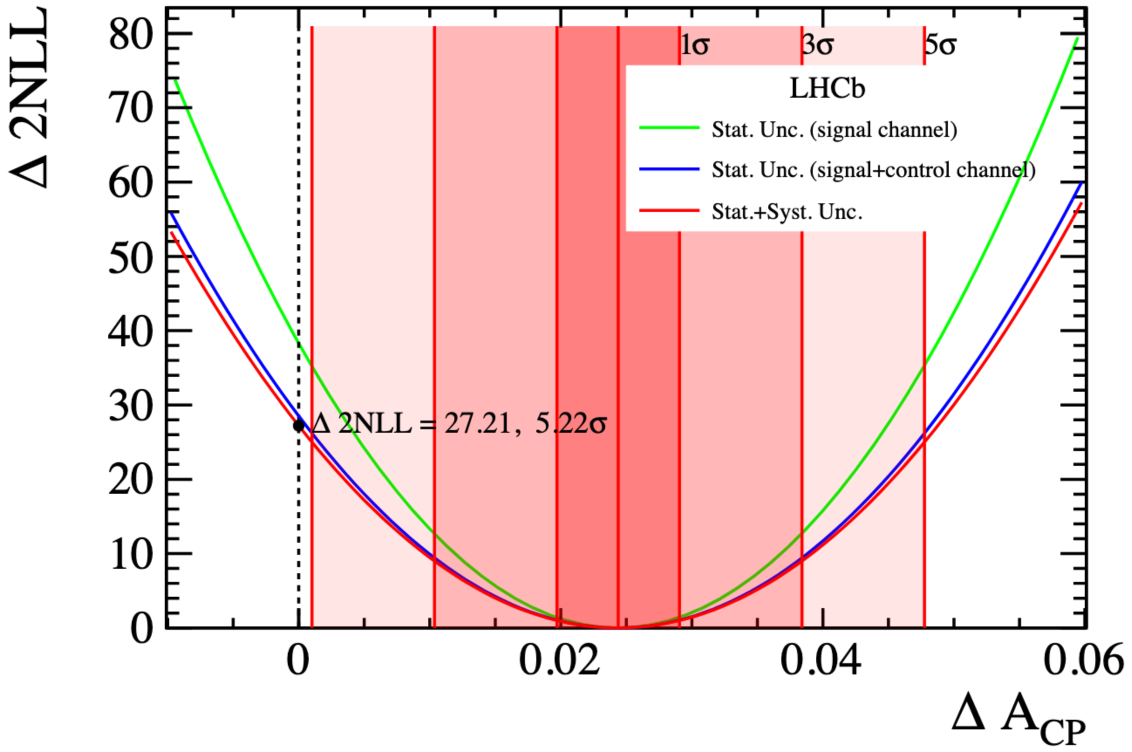
Contribution	Run 1	Run 2
Nuisance asymmetry difference	0.193%	0.051%
Mass fit	0.044%	0.067%
Total systematic uncertainty	0.198%	0.084%

0.10%

First observation of CP violation

arXiv:2503.14954

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



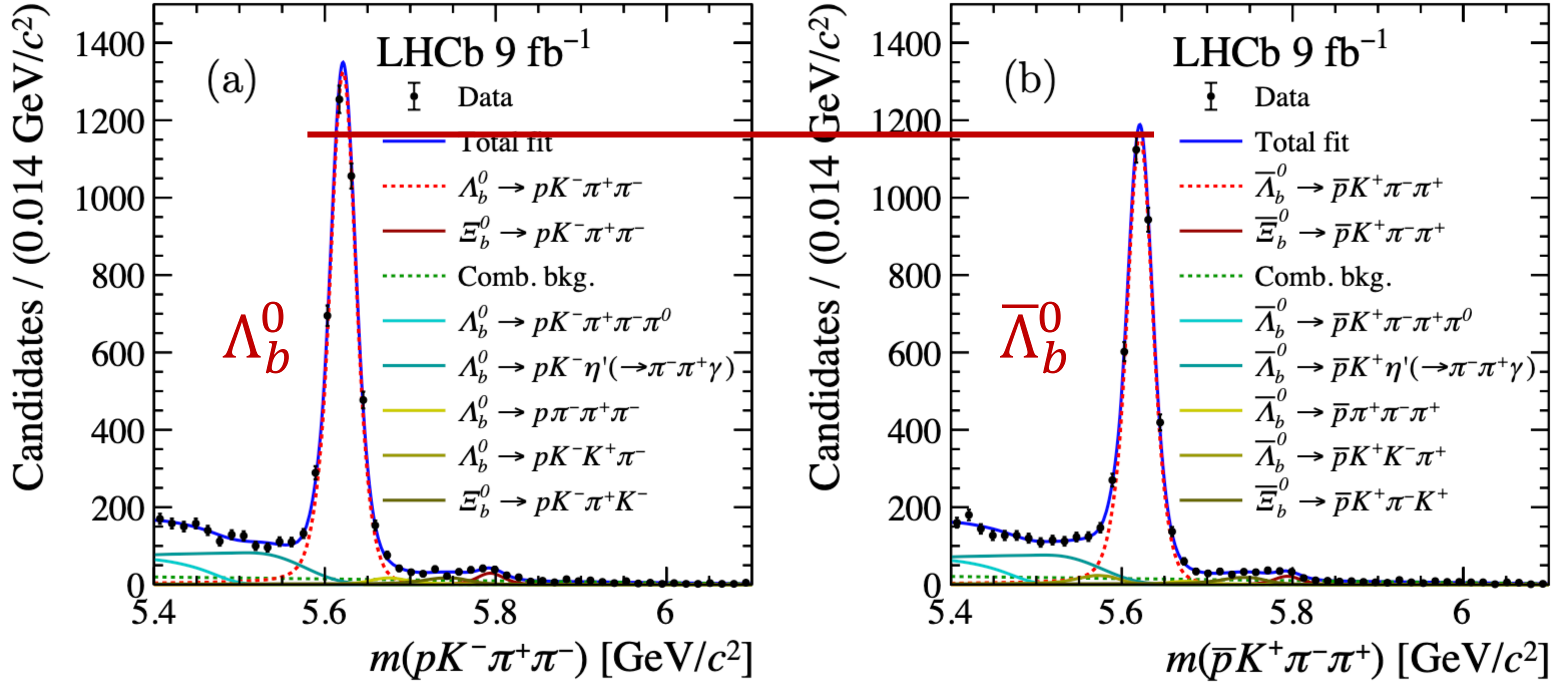
Rule out CP symmetry at 5.2σ, and large CP violation

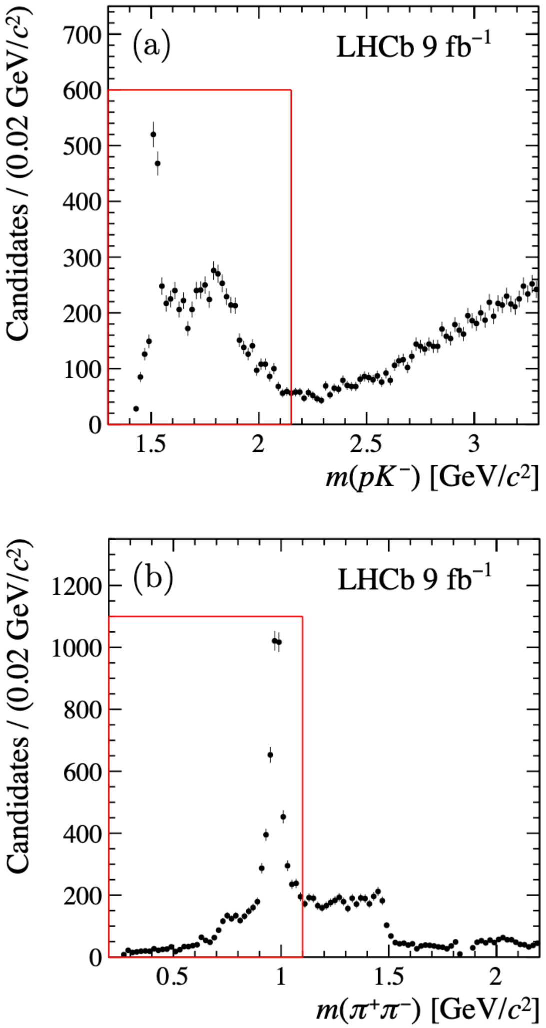
CP asymmetry in resonance regions 1

arXiv:2503.14954

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

$> 3\sigma$

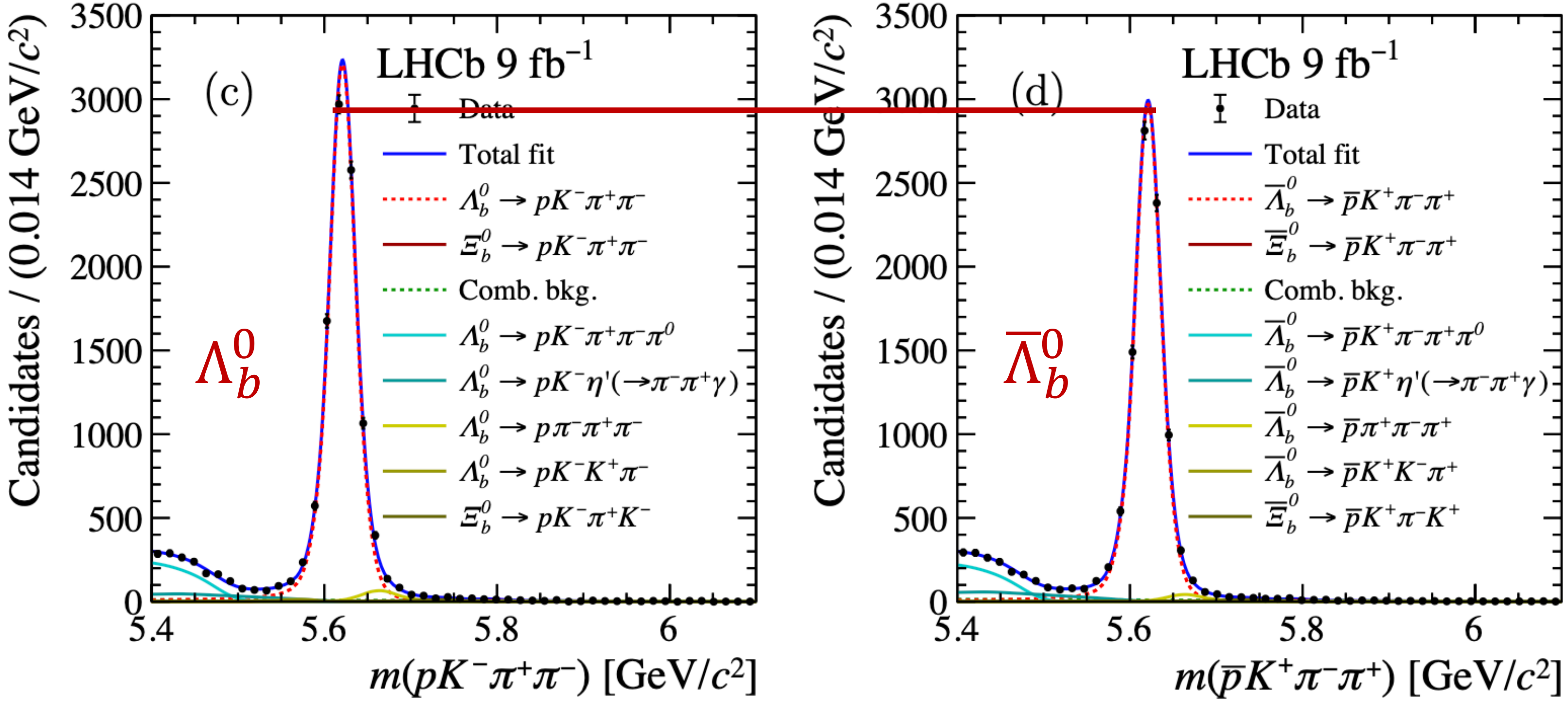


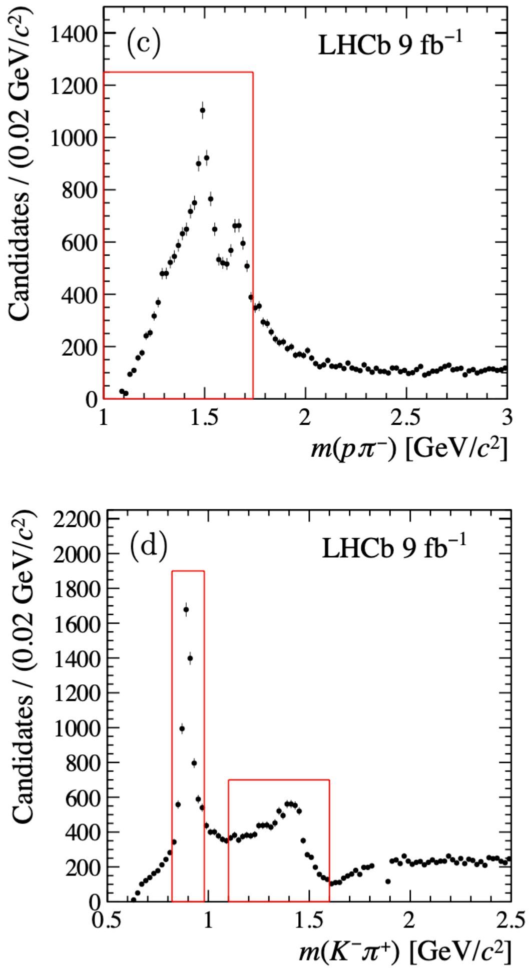


CP asymmetry in resonance regions 2

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 $1.1 < m_{\pi^+K^-} < 1.6$	$(2.7 \pm 0.8 \pm 0.1)\%$

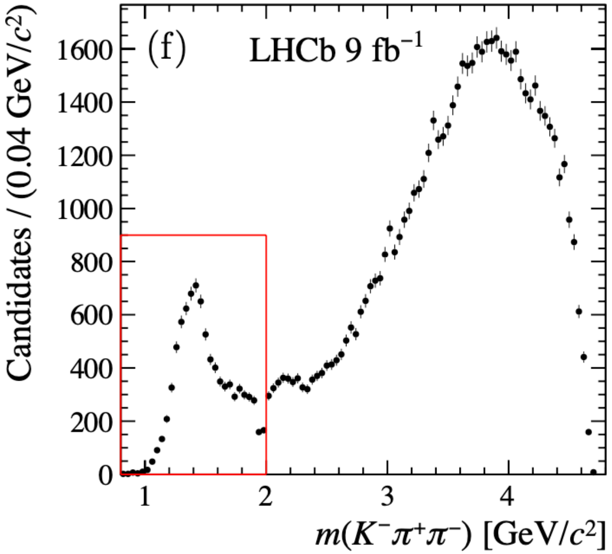


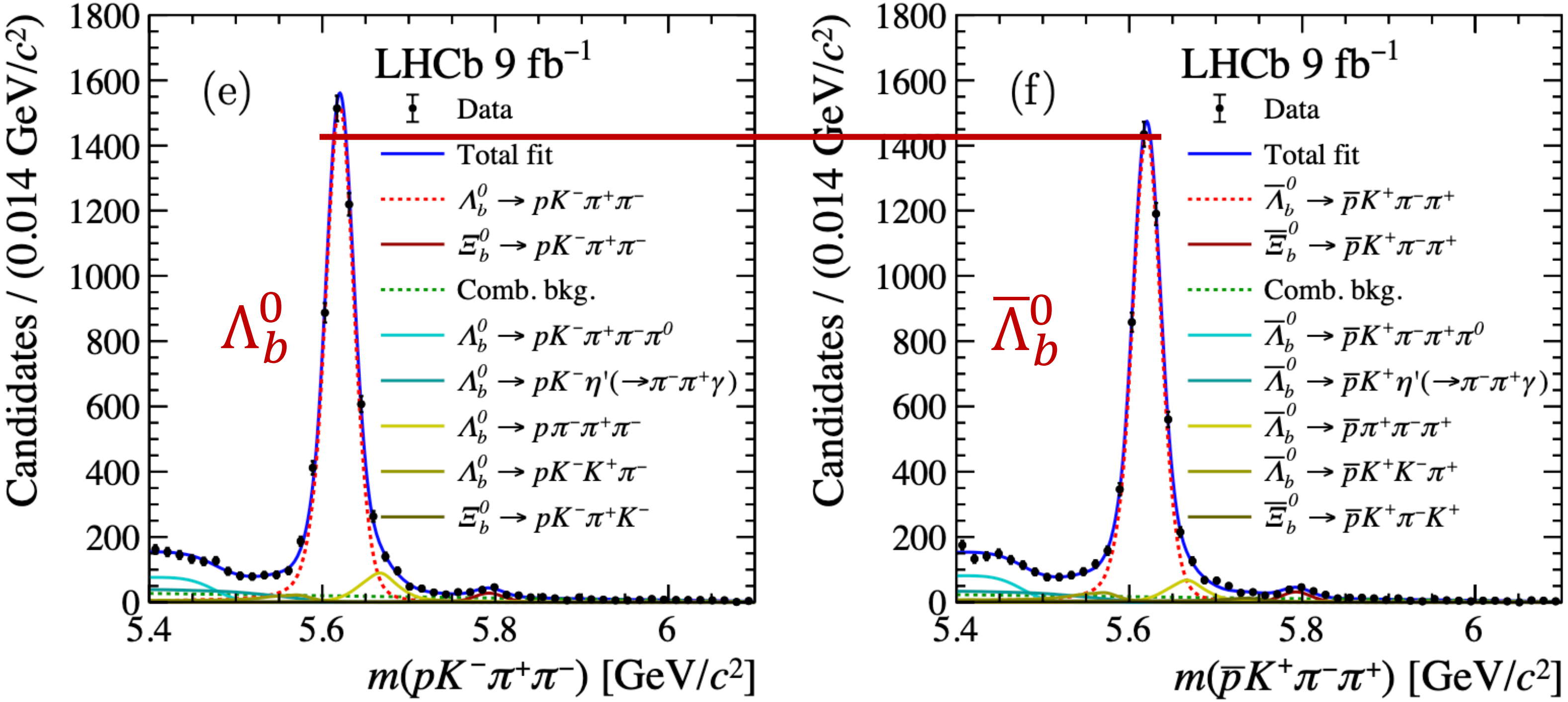


CP asymmetry in resonance regions 3

arXiv:2503.14954

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



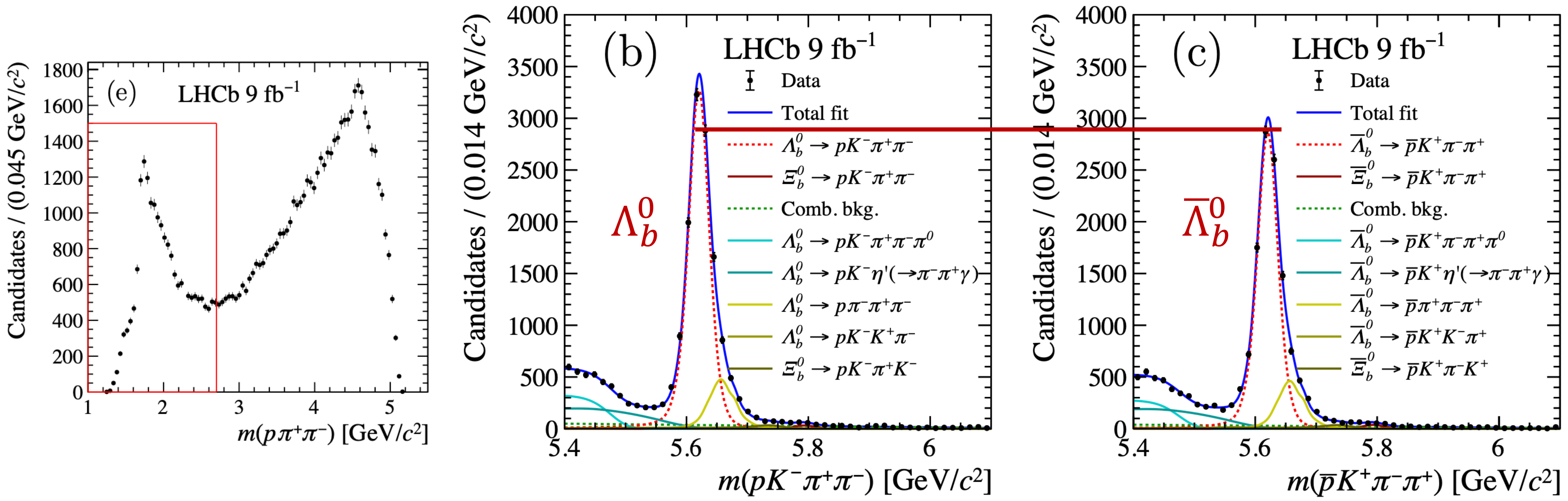


CP asymmetry in resonance regions 4

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



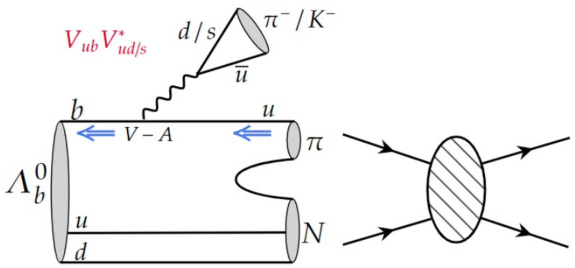
Predictions?

- CP violation in $\Lambda_b^0 \to N^{*+}(\to p\pi^+\pi^-)K^-$ similar to $\Lambda_b^0 \to N^{*+}(\to \Lambda K^+)K^-$

  $A_{CP} = (5.4 \pm 0.9)\%$ $\qquad$ $A_{CP} = (16.5 \pm 5.1)\%$

- Generally difficult to calculate for multiple body decays
- Complicated by many resonances
- **Predictions exploiting $N\pi$ scattering data compatible with LHCb**

decay processes	Scenarios	global CPV	CPV of $\cos\theta < 0$	CPV of $\cos\theta > 0$
$\Lambda_b^0 \to (\Delta^{++}\pi^-)K^-$	S1	5.9%	8.0%	3.6%
	S2	5.8%	6.3%	5.3%
	S3	5.6%	4.3%	7.0%
$\Lambda_b^0 \to (\Delta^{++}\pi^-)\pi^-$	S1	−4.1%	−5.4%	−2.4%
	S2	−3.9%	−3.9%	−3.9%
	S3	−3.6%	−2.3%	−5.3%
$\Lambda_b^0 \to (p\pi^0)K^-$	S1	5.8%	8.2%	2.7%
	S2	5.8%	8.0%	3.0%
	S3	5.8%	7.8%	3.3%
$\Lambda_b^0 \to (p\pi^0)\pi^-$	S1	−3.9%	−3.9%	−3.7%
	S2	−3.9%	−3.8%	−4.3%
	S3	−3.8%	−3.6%	−4.8%



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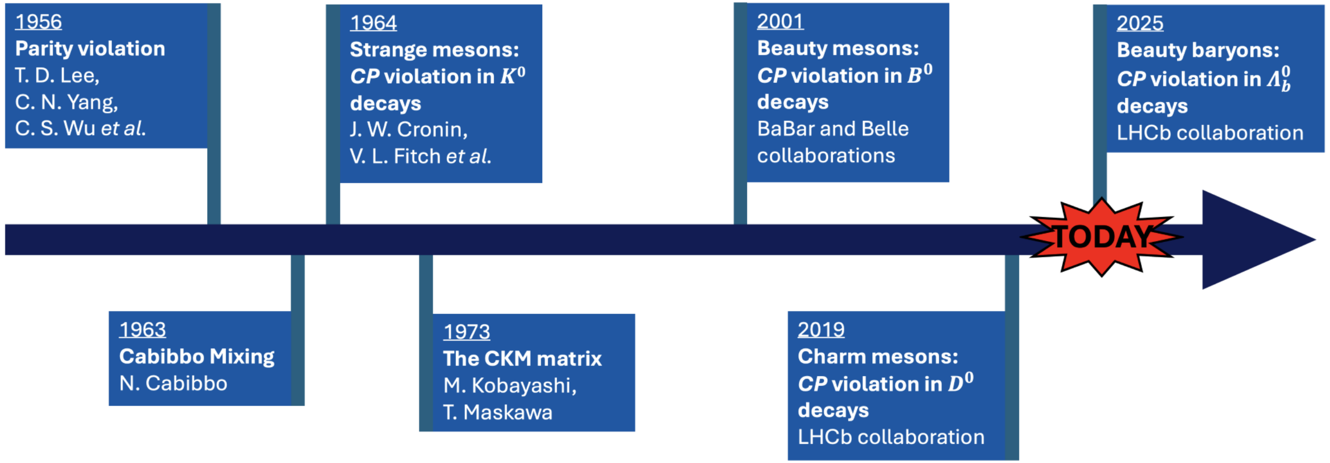
CPC 48 (2024) 101002

What does it tell us

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



- **CP violation unexpectedly small for baryons**

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

- **Baryon dynamics more complex than mesons.** New ideas needed?

Observation of charge-parity symmetry breaking in baryon decays

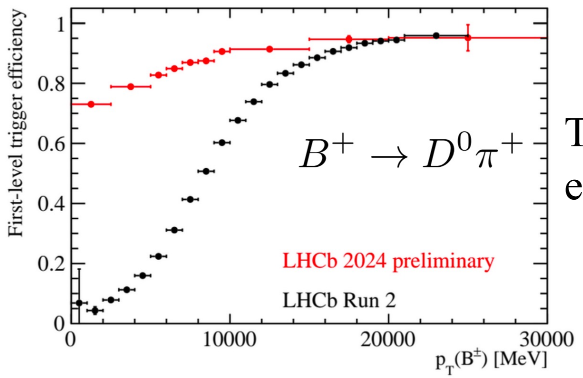
LHCb Collaboration • Roel Aaij (Nikhef, Amsterdam) Show All(1156)
Mar 21, 2025

29 pages
e-Print: 2503.16954 [hep-ex]
Report number: LHCb-PAPER-2024-054, CERN-EP-2025-031
Experiments: CERN-LHC-LHCb
View in: CERN Document Server, HAL Science Ouverte, ADS Abstract Service

pdf links cite claim reference search 5 citations

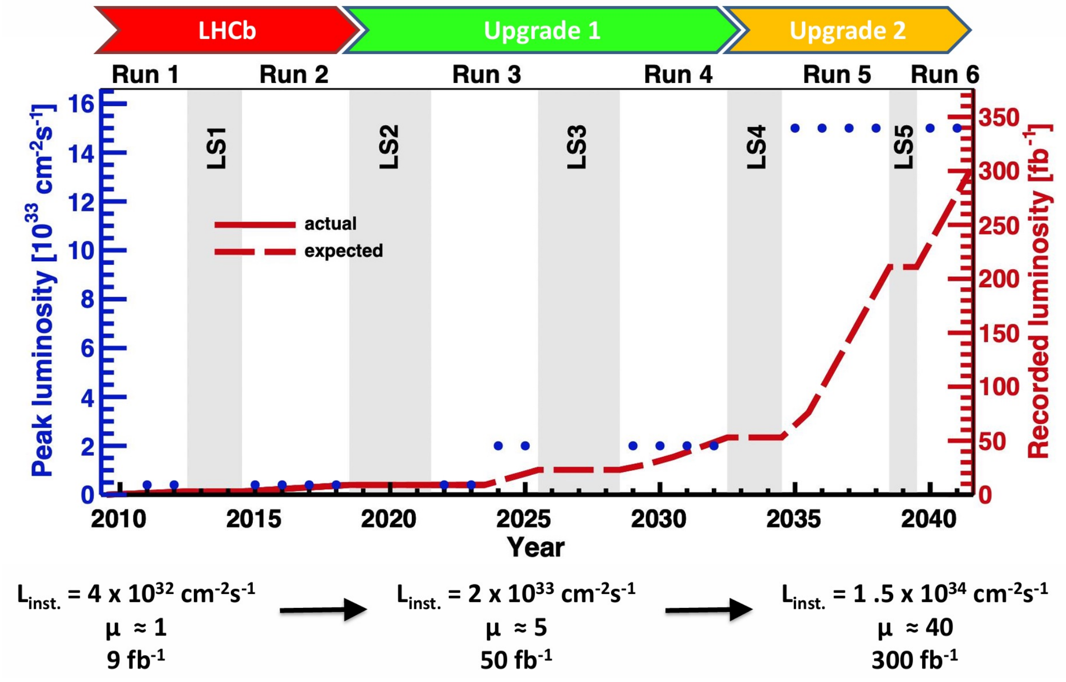
Baryon CP violation in (near) future

- LHCb will take data with Upgrade I detector for 50 fb^{-1}
  - ➢ Run3 (→2026): > 20 fb^{-1} data and 2× better trigger efficiency



Trigger efficiency

Era of 0.1% precision



Opportunities for baryon CPV

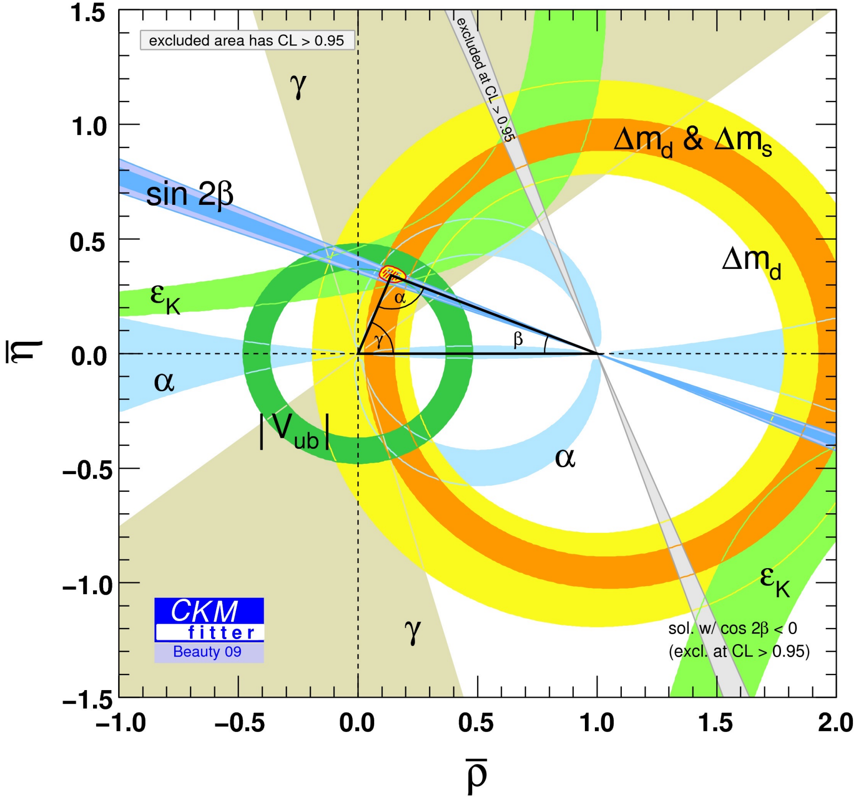
- ➢ Confirmation
- ➢ More decays
- ➢ More dynamics
- ➢ Charm baryon
- ➢ Unexpected observations ?

谢谢！

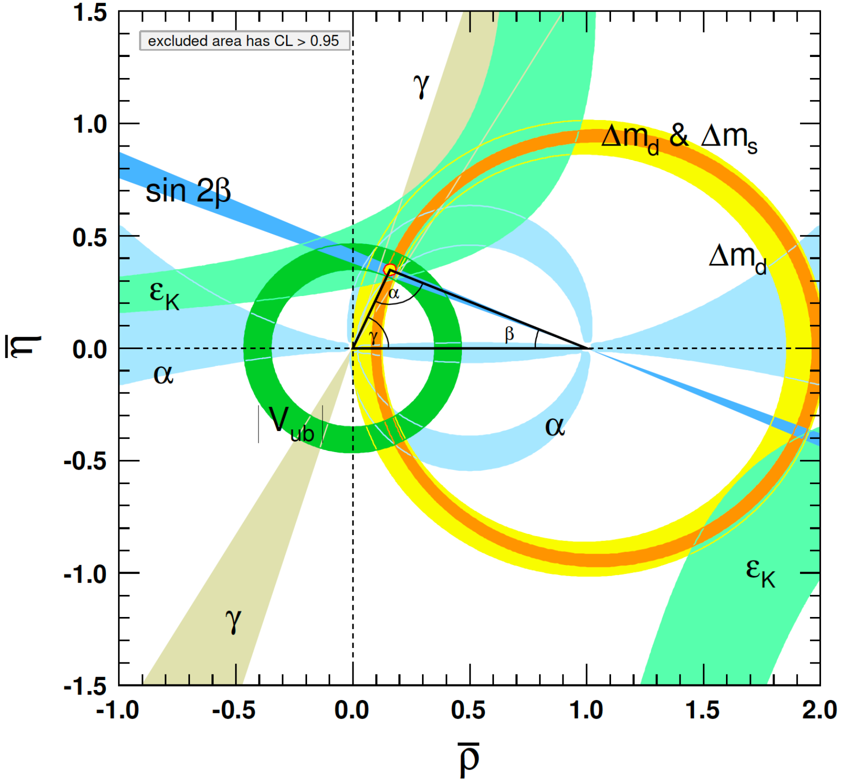
Backup slides

Global analysis of CKM mechanism (4 parameters)

When LHC started



Current status



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

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

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 $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [255]	0.022	0.036	0.006	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	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

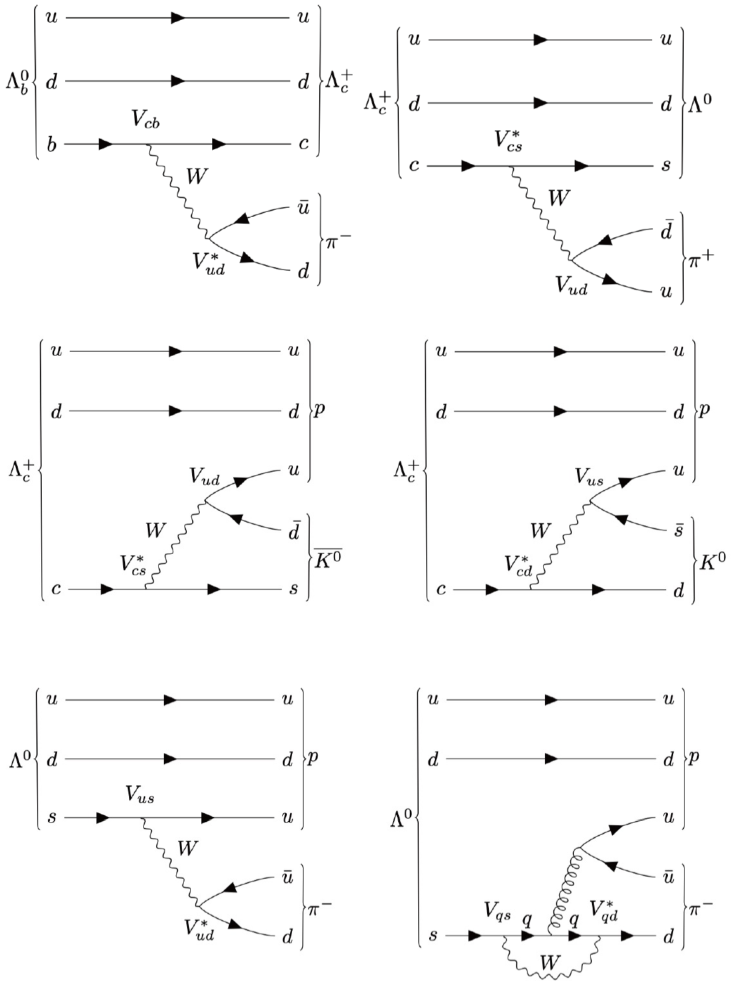
1% level precision

High precision charm physics

More information for decay paramerters

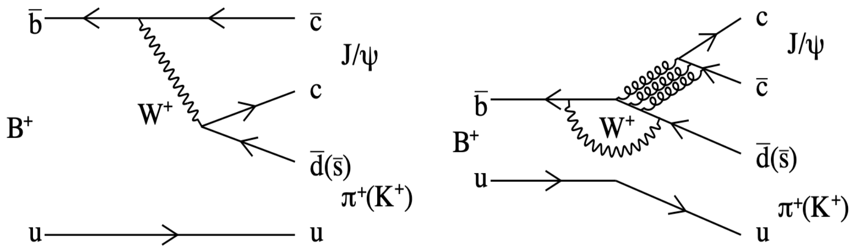
$$\frac{\mathrm{d}^3\Gamma}{\mathrm{d}\cos\theta_0 \mathrm{d}\cos\theta_1 \mathrm{d}\phi_1} \propto 1 + \alpha_{\Lambda_b^0}\alpha_{\Lambda_c^+}\cos\theta_1 + P_z \cdot (\alpha_{\Lambda_b^0}\cos\theta_0 + \alpha_{\Lambda_c^+}\cos\theta_0\cos\theta_1 - \gamma_{\Lambda_b^0}\alpha_{\Lambda_c^+}\sin\theta_0\sin\theta_1\cos\phi_1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

$$\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}$$



Beauty: evince of CPV in b to charmonium

CPV in $b \to c\bar{c}s$ sensitive to charm loop (heavily suppressed)



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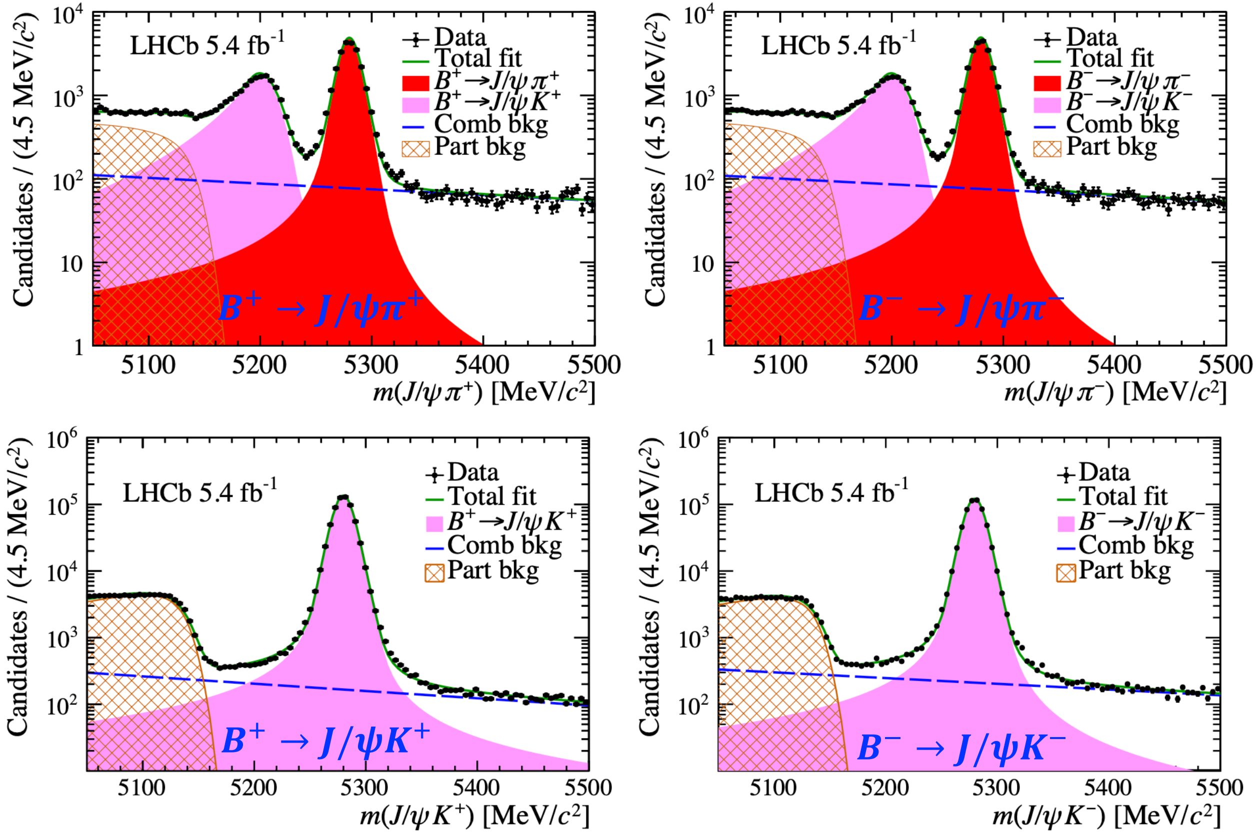


$A_{CP}(B^+ \to J/\psi\pi^+)$

$A_{CP}(B^+ \to J/\psi K^+)$

$$\Delta A^{CP} = (1.42 \pm 0.44)\times 10^{-2}$$

(3.2σ)

CP asymmetry for $\Lambda_b^0 \to DpK^-$

PRD104 (2021) 112008

- Sensitive to measure γ with in baryon decays $r_B \sim \left|\frac{V_{ub}V_{cs}^*}{V_{cb}V_{us}^*}\right| \sim 0.4$

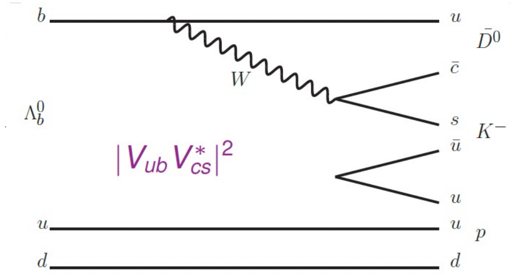
  Possibly large interference $A_{CP} \propto r_B/r_D \sin\gamma \sin\delta$

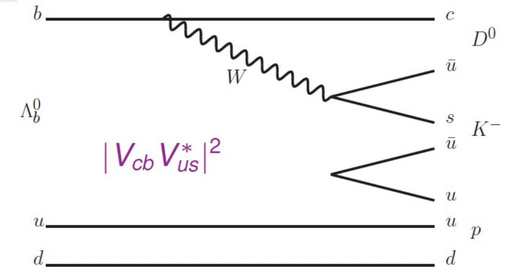
- CPV studied for DCS decay $D^0 \to K^+\pi^-$

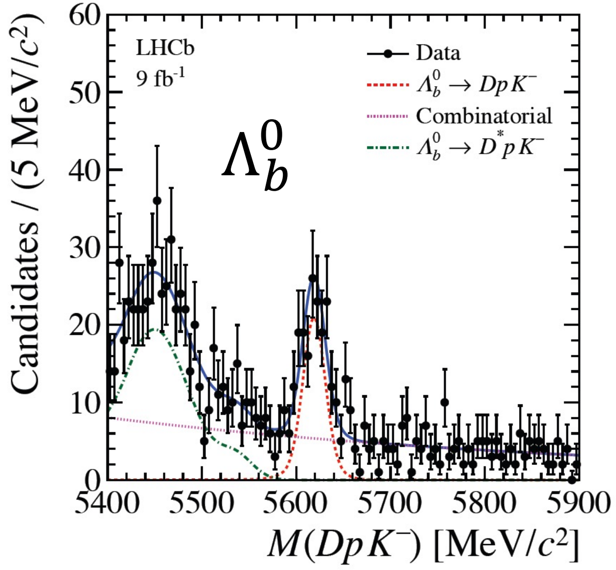
  Interference between $\Lambda_b^0 \to (K^+\pi^-)_{D^0}pK^-$ and $\Lambda_b^0 \to (K^+\pi^-)_{\bar{D}^0}pK^-$

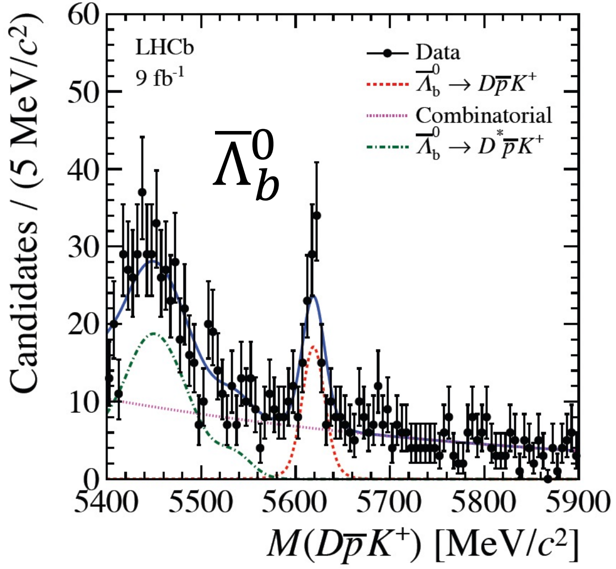
$A_{CP} = 0.12 \pm 0.09^{+0.02}_{-0.03}$ (full phase space)

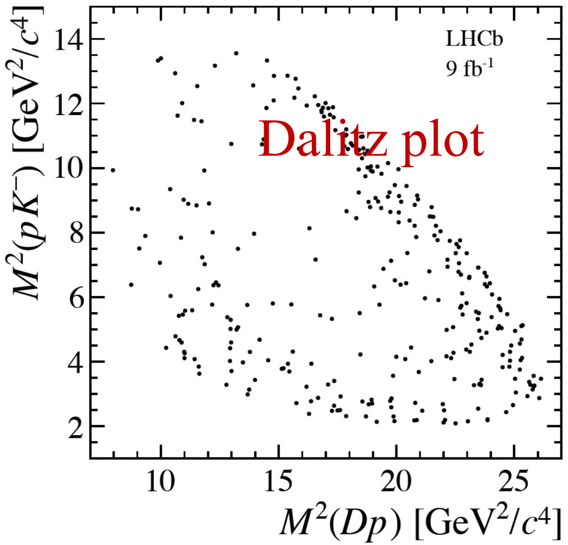
$A_{CP} = 0.01 \pm 0.16^{+0.03}_{-0.02}$ ($M(pK^-) < 2.2$ GeV)











Beauty: phase γ

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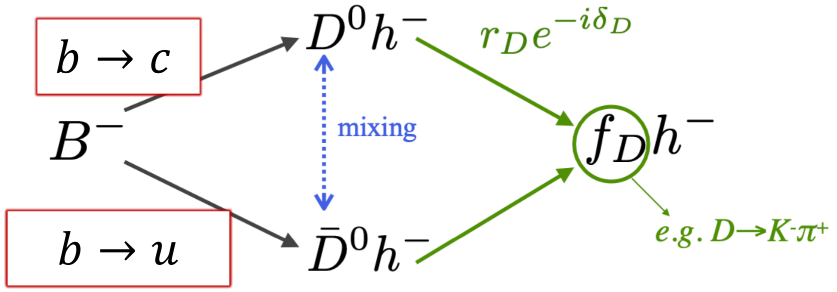
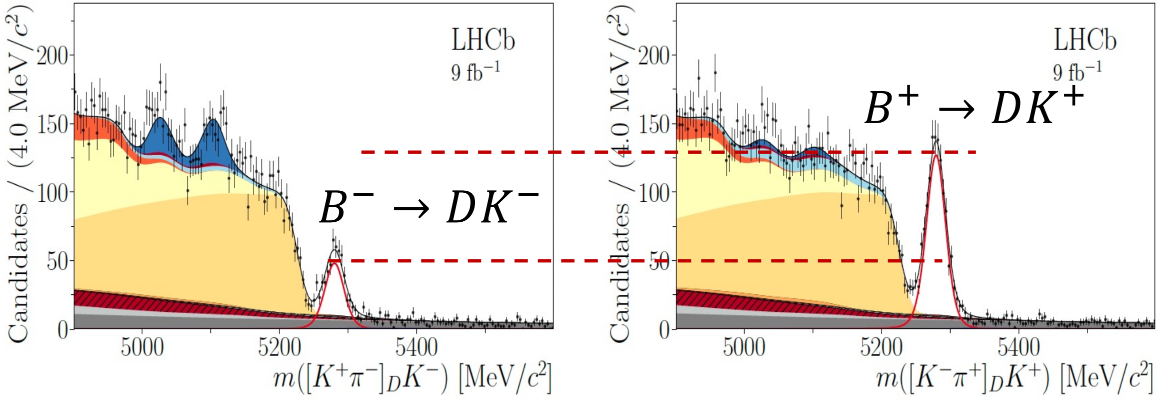
Interference between $b \to u$ and $b \to c$, theoretically clean



$$A_{CP} \propto \sin\gamma \sin\delta$$



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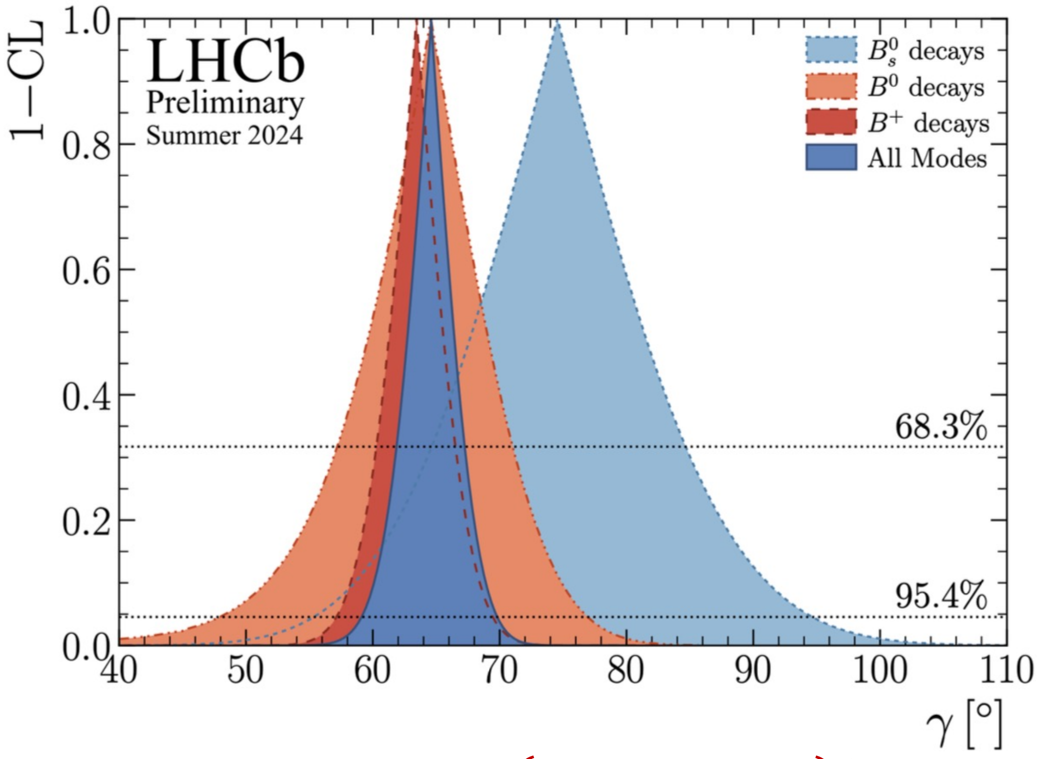
γ combination



$$\gamma_{\text{LHCb}} = (64.6 \pm 2.8)^\circ$$

21/Mar/2025

实验上是否在重子衰变中发现了CP破坏?

是的，LHCb实验在重子衰变中首次观测到了**CP破坏**现象。这一重要发现于2017年公布，标志着粒子物理学领域的一个重大突破。

背景：

- **CP破坏**（电荷共轭–宇称破坏）是粒子物理学中的一个重要现象，它解释了宇宙中物质与反物质的不对称性。
- 此前，CP破坏主要在介子（如K介子和B介子）的衰变中被观测到，但在重子（由三个夸克组成的粒子，如质子、中子等）衰变中尚未被发现。

LHCb的发现：

提问方式（时间）不对?

- LHCb实验通过研究Λb^0重子的衰变过程，首次在重子系统中观测到了CP破坏。
- 具体来说，实验分析了Λb^0重子衰变为质子、π^-和K^+的过程，发现其衰变率与对应的反粒子衰变率存在显著差异，这是CP破坏的直接证据。

意义：

- 这一发现填补了粒子物理学中的一个重要空白，进一步验证了标准模型的预测。