Baryonic CP violation at LHCb

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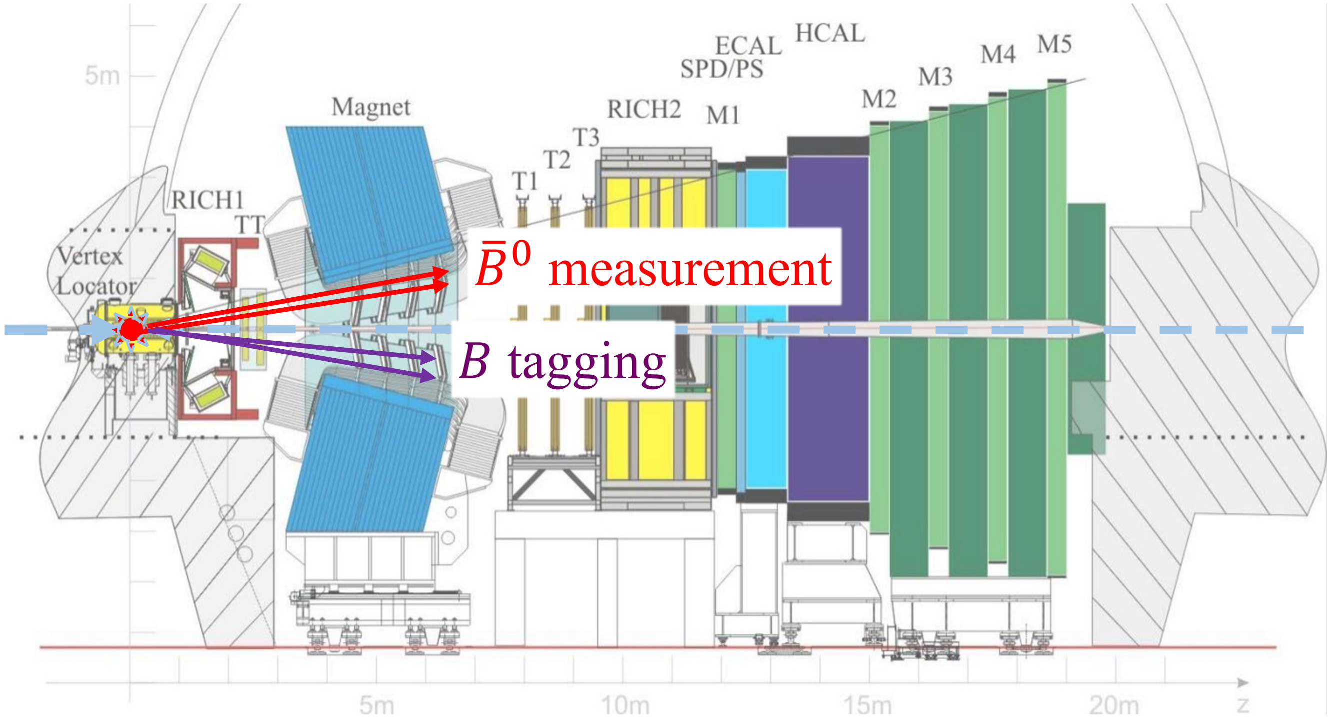
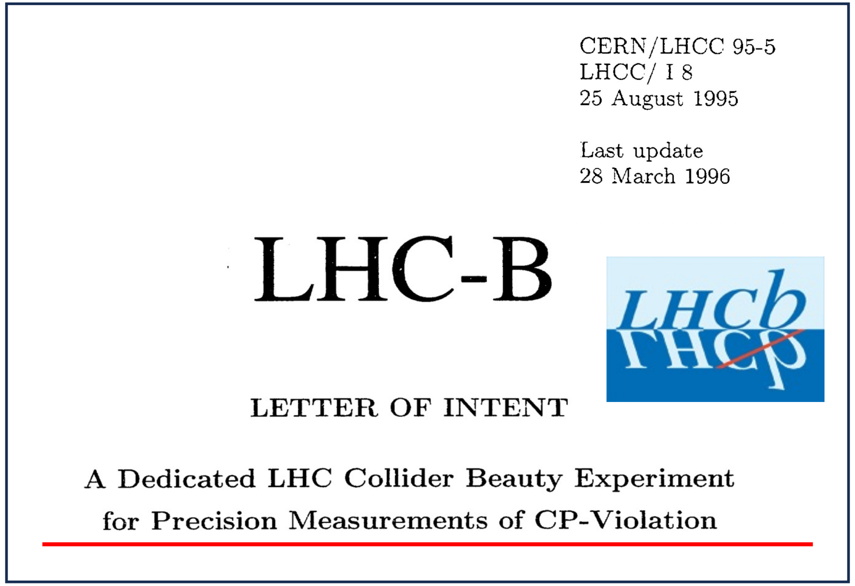
LHCb

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

- Dedicated flavor experiment at CERN for *b*, *c* hadrons




CERN/LHCC 95-5
LHCC/ I 8
25 August 1995

Last update
28 March 1996

LHC-B

LETTER OF INTENT

A Dedicated LHC Collider Beauty Experiment
for Precision Measurements of CP-Violation

Excellent vertexing, hadron PID, momentum; flexible trigger …

LHCb合作组：22个国家，102家单位，1700多名成员

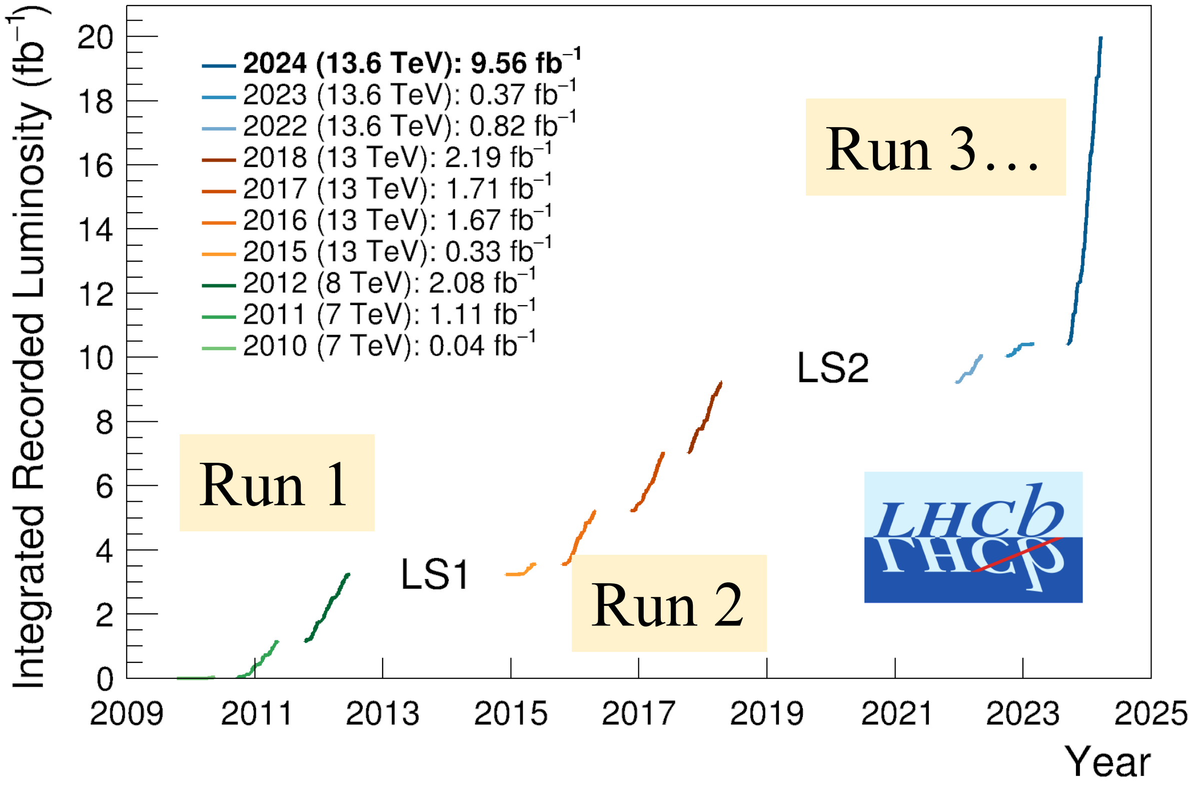
LHCb中国组：清华大学、华中师范大学、高能物理研究所、中国科学院大学、武汉大学、湖南大学、华南师范大学、北京大学、兰州大学、中国科学技术大学、西北工业大学、河南师范大学

LHCb 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)

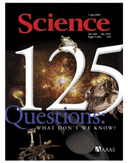
$\sigma(pp \to b\bar{b}X, 13\ \text{TeV}) \approx 0.5\ \text{mb}$ $B^+: B^0: B_s^0: \Lambda_b^0 \approx 4:4:1:2$



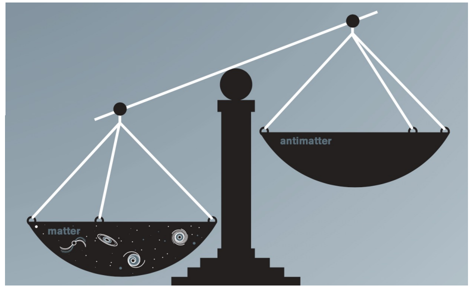
Why CP violation

- Matter and antimatter asymmetry in Universe (BAU)

Sakharov:
- Baryon-violation
- C and CP violation
- Out of thermal equilibrium



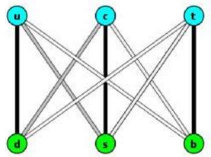
$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$$



Matter Anti-matter

- CKM mechanism

➢ Quark mixing matrix

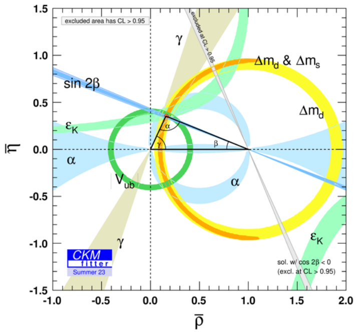


$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} + \mathcal{O}(10^{-3})$$

A single phase parameter gives rise to quark CPV

✓ Unitarity: four independent parameters

✓ CP violation: phases and dynamics



➢ Established and tested through precision data

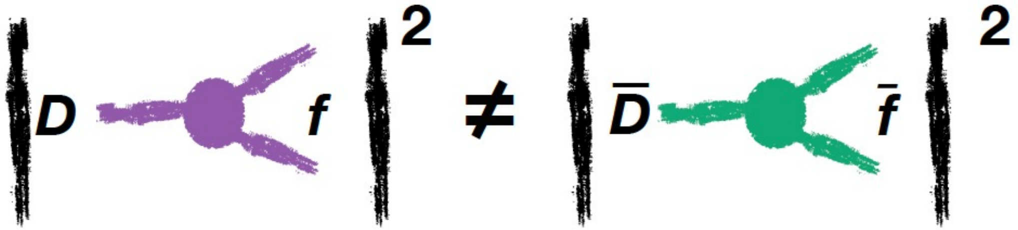
➢ But insufficient to explain BAU

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

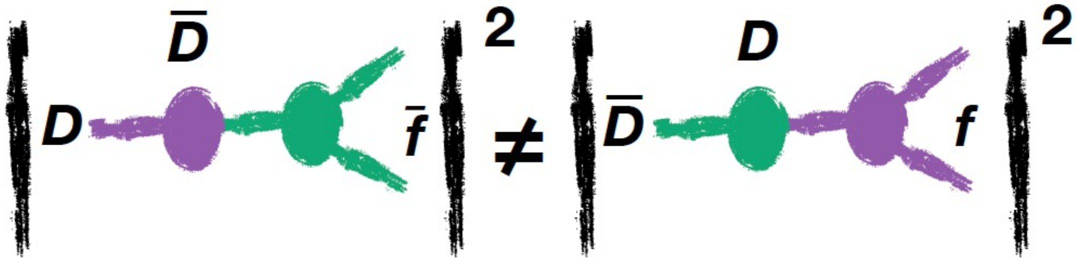
BSM CP violation needed !

Three types of CP violation

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



Diract CP violation



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

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

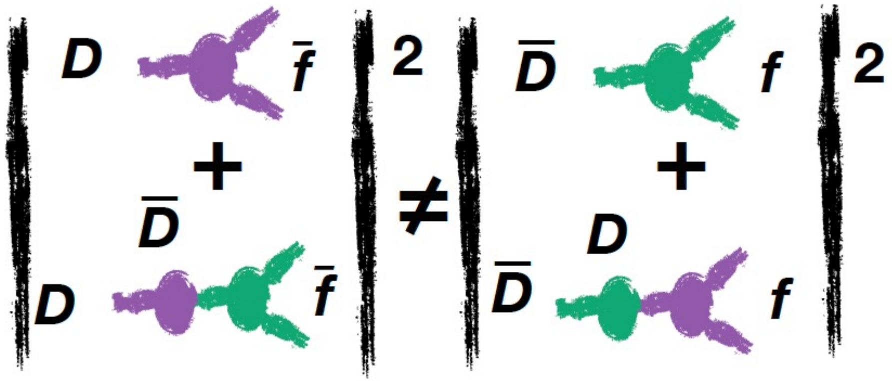


Figure by Serena Maccolini

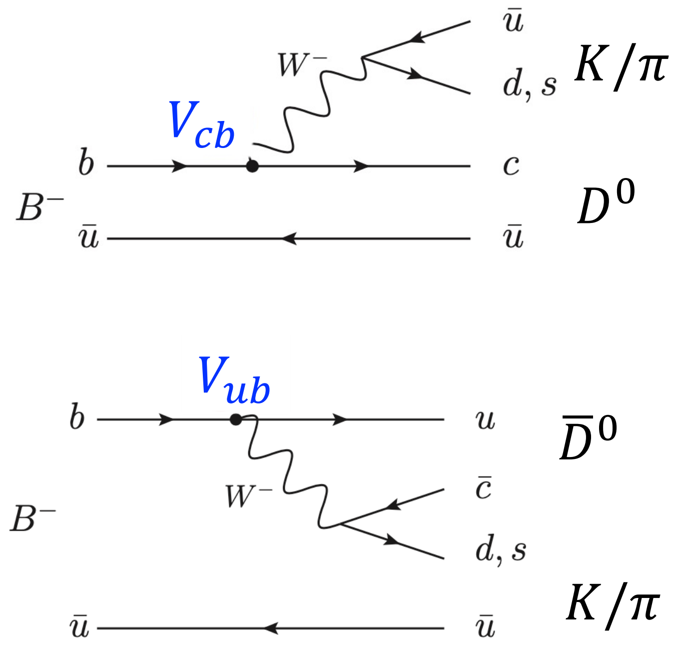
Direct CP violation

- Interference between decay paths

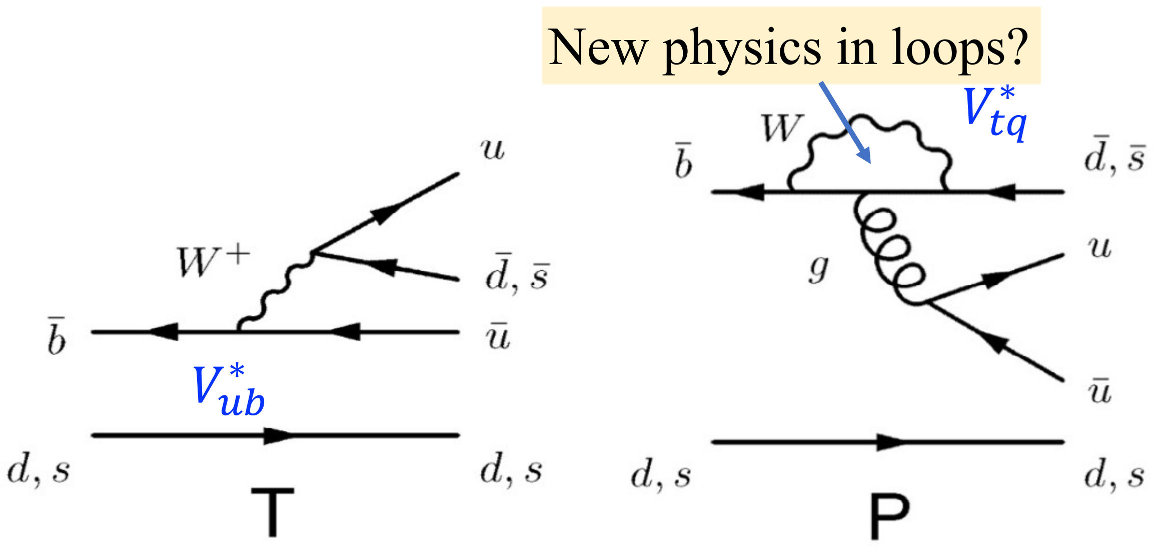
Strong phase difference — Weak phase difference

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

➢ Tree diagrams (measuing γ)



➢ Tree and loop diagram



CPV for mesons

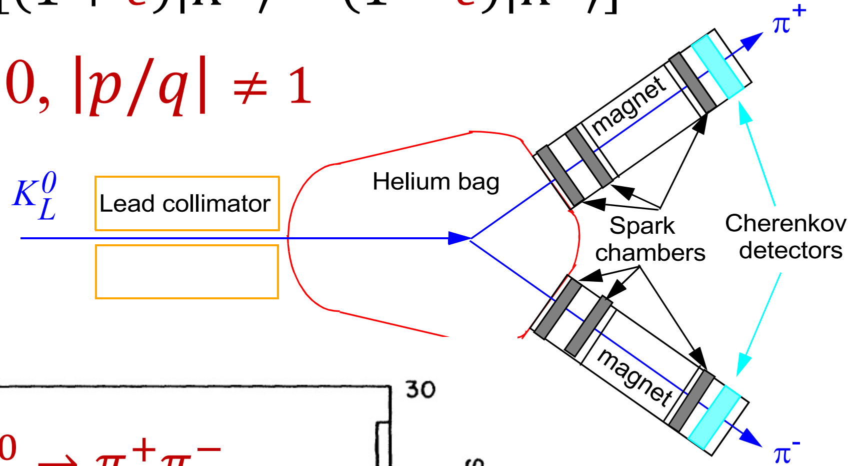
CPV in K mesons

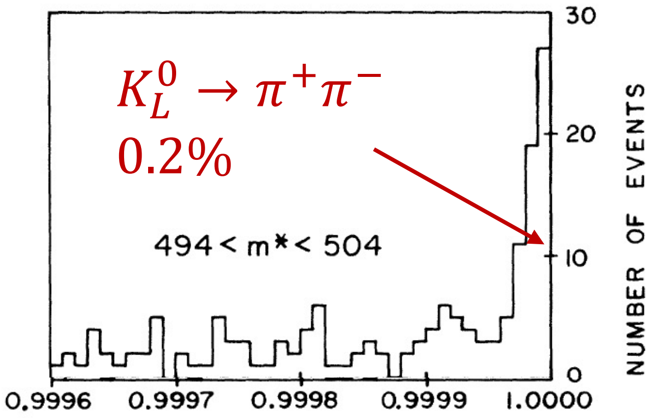
CPV in K^0- $\bar{K}^0$ mixing

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

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

$$\bar{\epsilon} \neq 0, \ |p/q| \neq 1$$

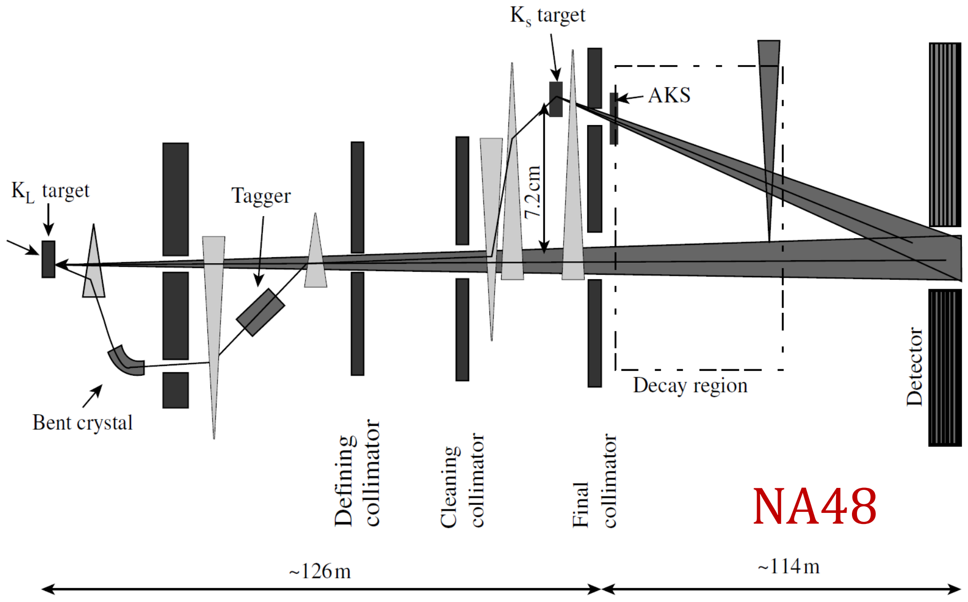




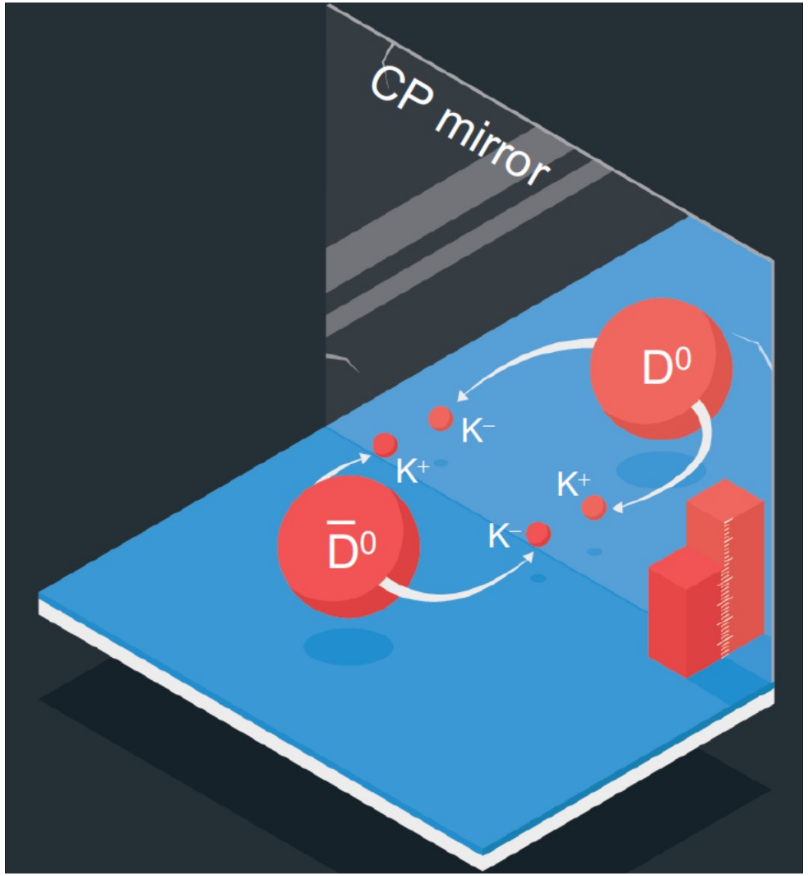
Direct CPV

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

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



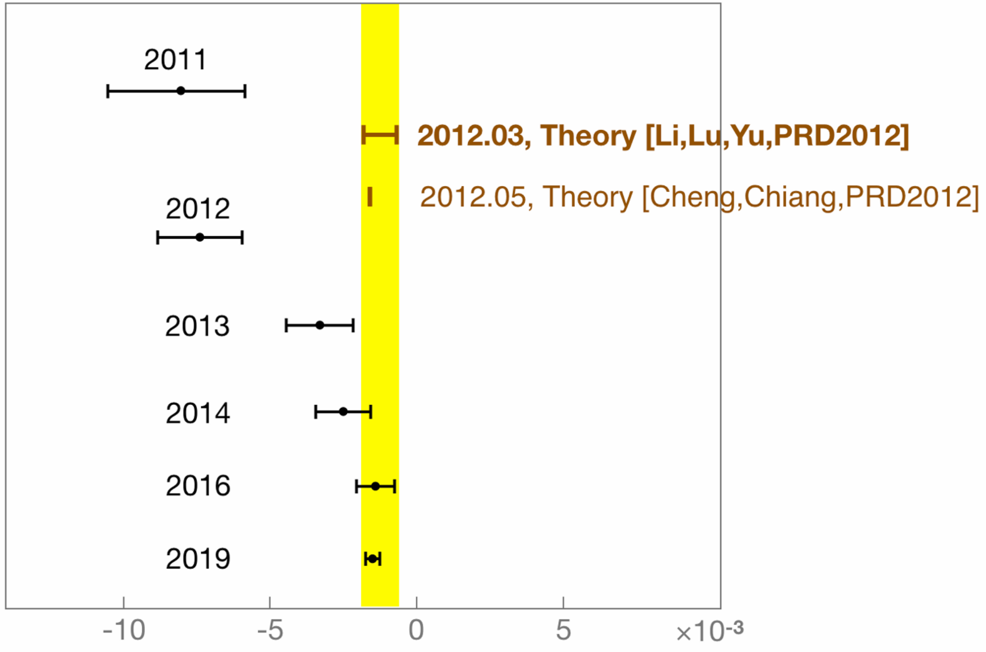
Direct CPV in charm



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

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$
$$= (-15.4 \pm 2.9)\times 10^{-4}$$

PRL 122 (2019) 211803

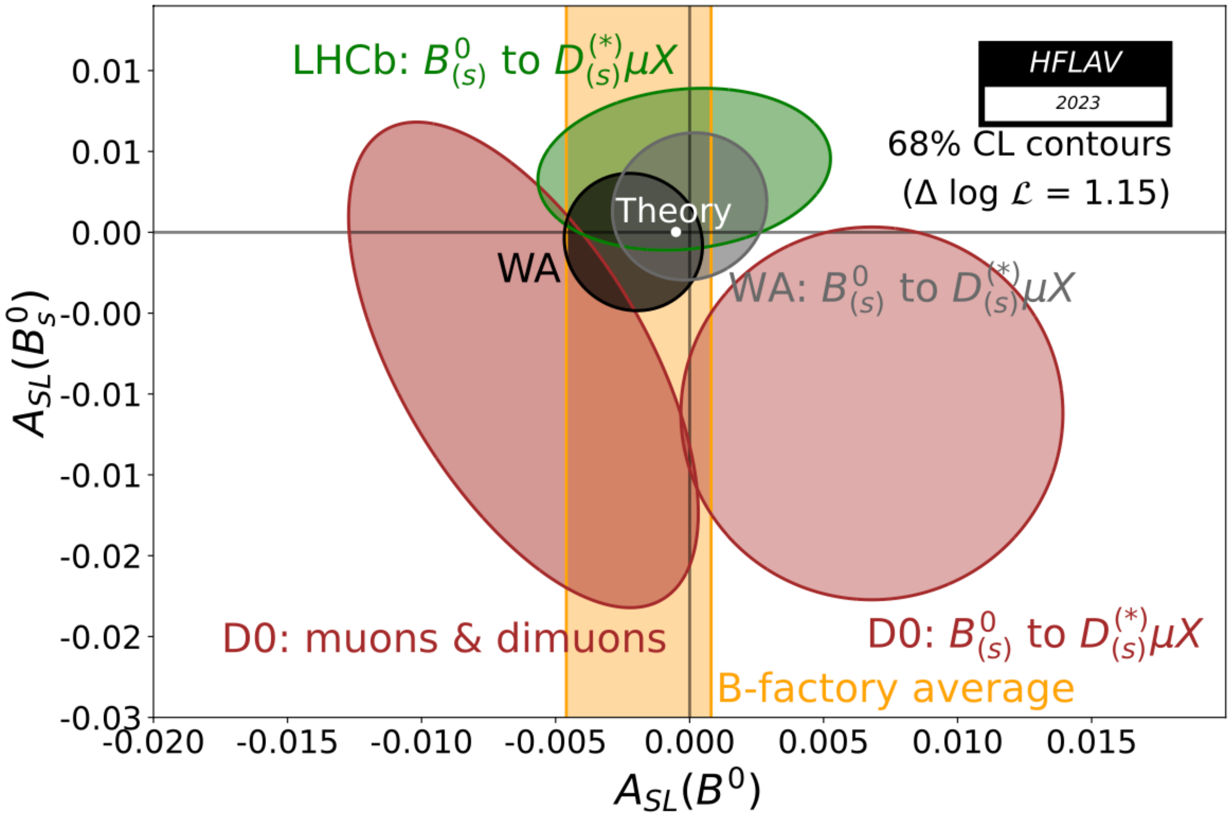


Beauty: CPV in mixing

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

Oscillation asymmetry

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



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

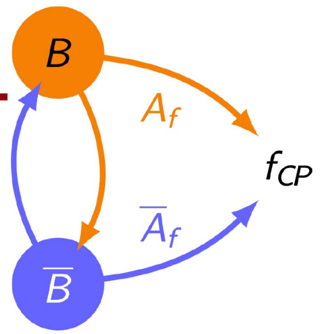
$$\Longleftrightarrow \quad |q_d/p_d| = 1.0010 \pm 0.0008$$
$$\Longleftrightarrow \quad |q_s/p_s| = 1.0003 \pm 0.0014$$

SM: $\sim 10^{-4}$ (B^0), $\sim 10^{-5}$ (B^0_s)

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

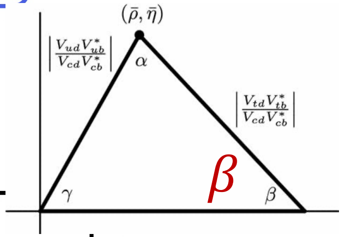
No hint of CPV in mixing

Beauty: mixing induced CPV

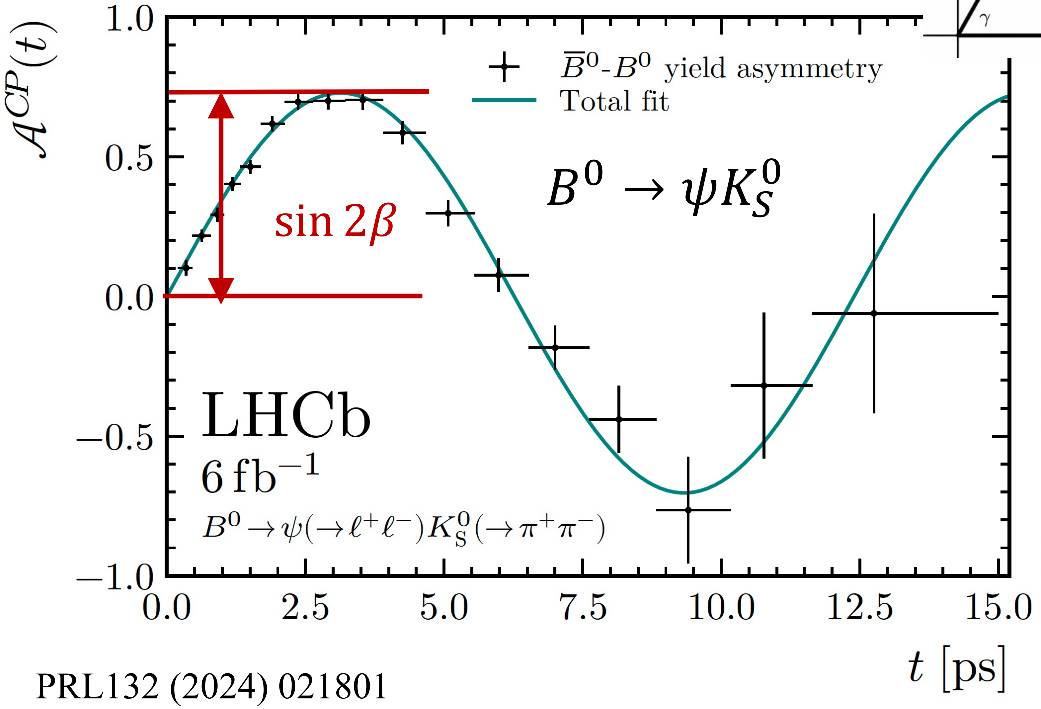


$\sin 2\beta$ in $B^0 \to \psi K_S^0$ decay

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



$$S_{\psi K_S^0}^{\text{Run 2}} = 0.716 \pm 0.013 \pm 0.008$$
$$C_{\psi K_S^0}^{\text{Run 2}} = 0.012 \pm 0.012 \pm 0.003$$



PRL132 (2024) 021801

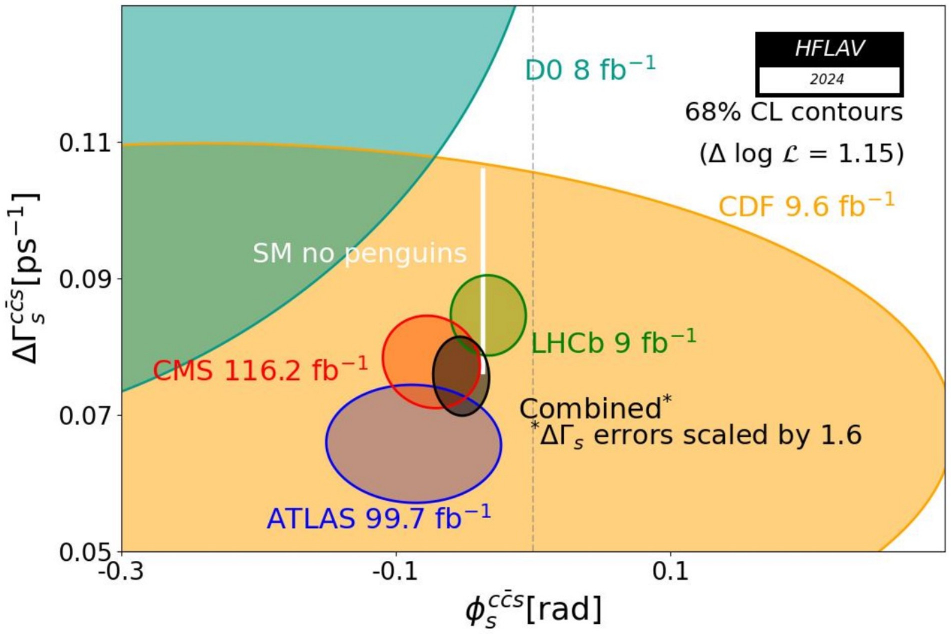
$\phi_s^{c\bar{c}s}$ in $B_s^0 \to c\bar{c}s$ decay

Comb. $\phi_s^{c\bar{c}s} = -0.052 \pm 0.013$ rad

Evidence of non-zero CPV

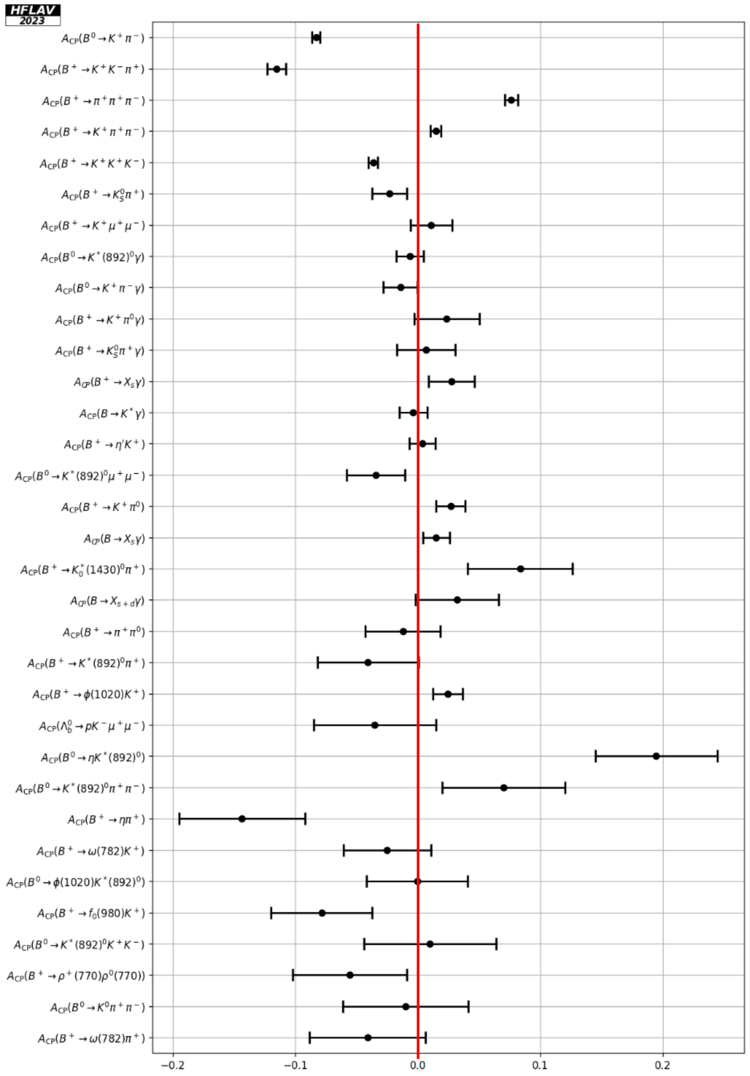
Consistent with global fit [CKMFitter]

$\phi_s^{\text{SM}} = -2\beta_s = -0.037 \pm 0.001$ rad

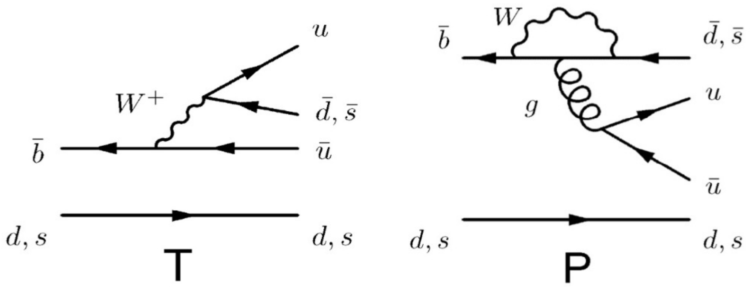


Beauty: direct CPV

Charmless decays



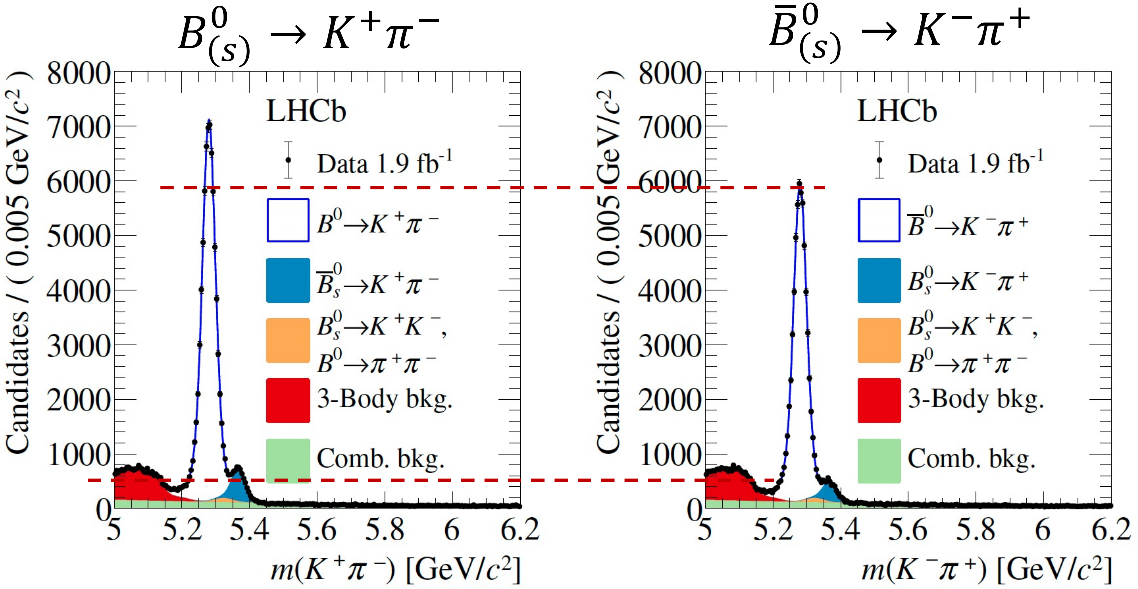
Interference tween tree and penguin diagrams



Possibly large CPV

$$A_{CP}^{B^0} = -0.083 \pm 0.005$$

$$A_{CP}^{B_s^0} = 0.236 \pm 0.017$$

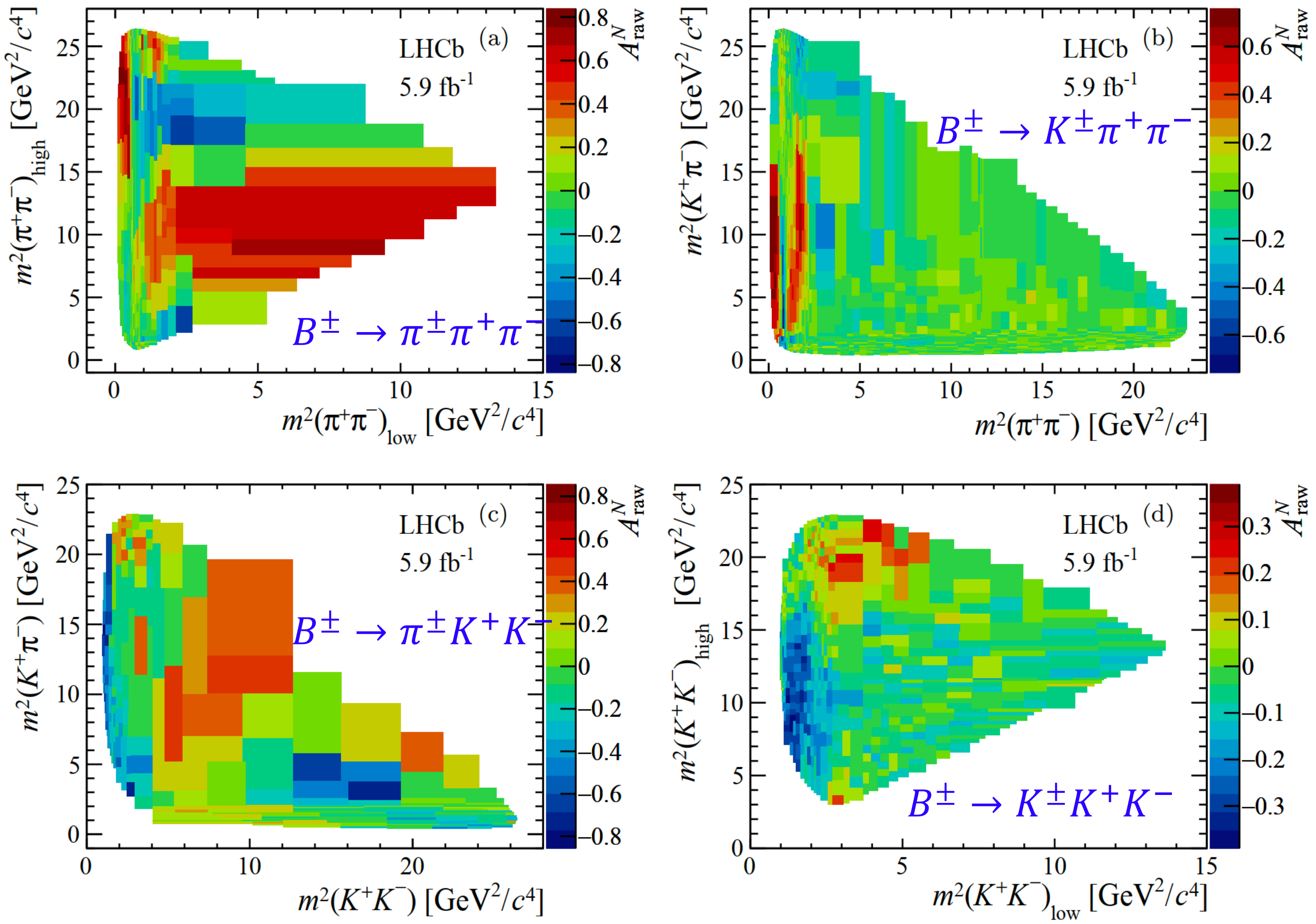


PRD98 (2018) 032004

Beauty: CPV pattern for n-body charmless decays

PRD108(2023)012008

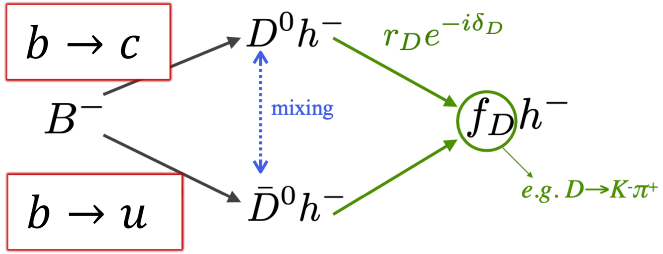
Varying strong phases and resonance compositions



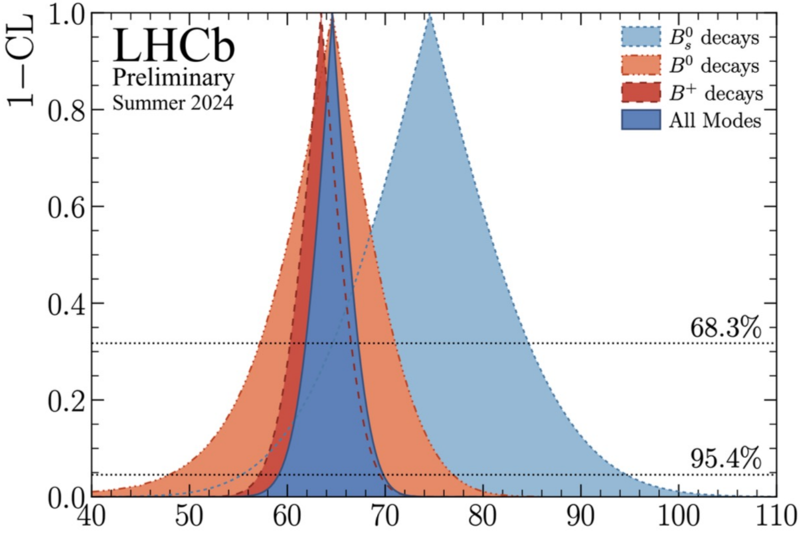
Beauty: direct CPV for b to charm decays

γ measurement

Interference between $b \to u$ and $b \to c$



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



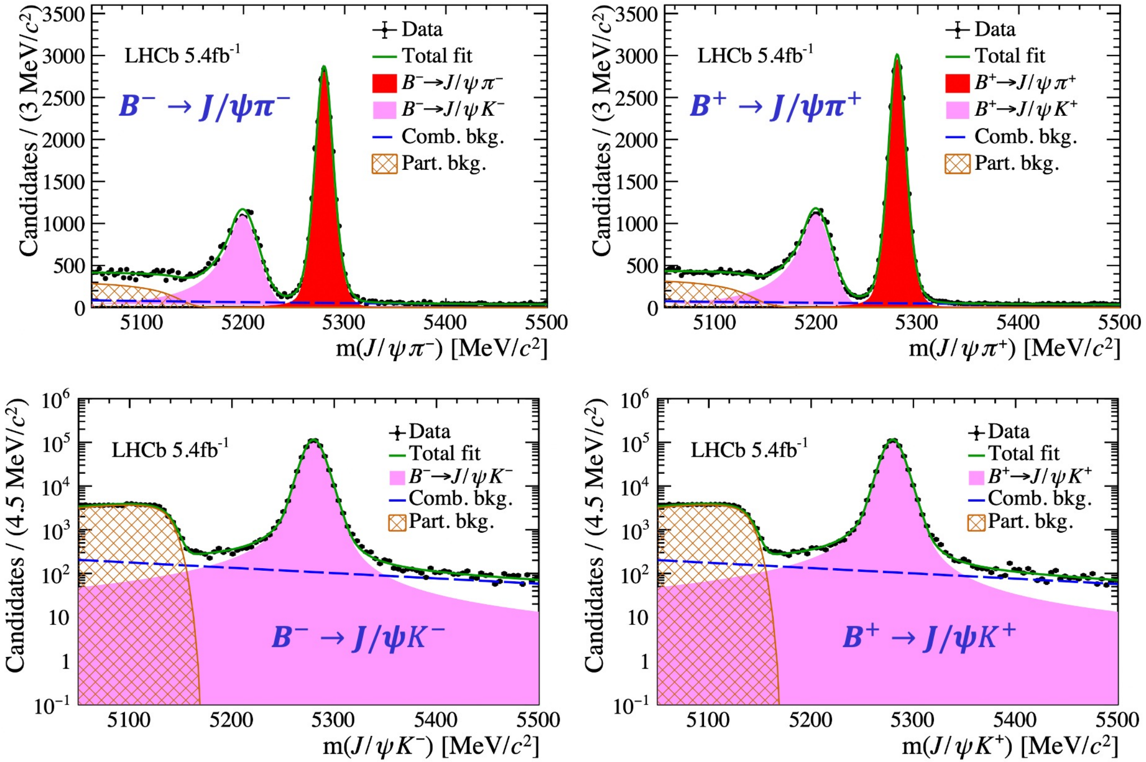
LHCb-CONF-2024-004

Evince of direct CPV in b to charmonium

$B^+ \to J/\psi K^+$ v.s. $B^+ \to J/\psi \pi^+$

$$\Delta A^{CP} = (1.42 \pm 0.43 \pm 0.08) \times 10^{-2}$$

PRL 134 (2025) 101801



CPV in beauty baryons

Long list of efforts by 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

Why and how

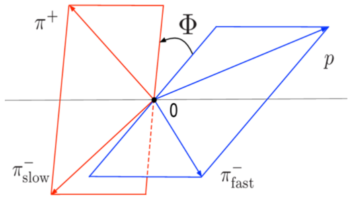
- EW-type baryogenesis requires large CP violation in baryons
- Baryons share the same decay dynamics with mesons in the SM

  ⇒ 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)



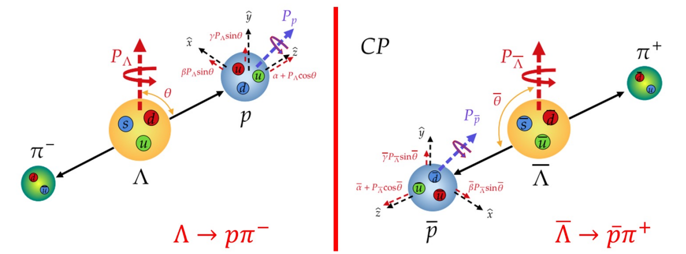
$$A_T = \frac{N(\sin\Phi > 0) - N(\sin\Phi < 0)}{N(\sin\Phi > 0) + N(\sin\Phi < 0)}$$

$$\bar{A}_T = \frac{\bar{N}(\sin\Phi < 0) - \bar{N}(\sin\Phi > 0)}{\bar{N}(\sin\Phi < 0) + \bar{N}(\sin\Phi > 0)}$$

$$a_{CP}^{T\text{-}odd} = (A_T - \bar{A}_T)/2$$

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

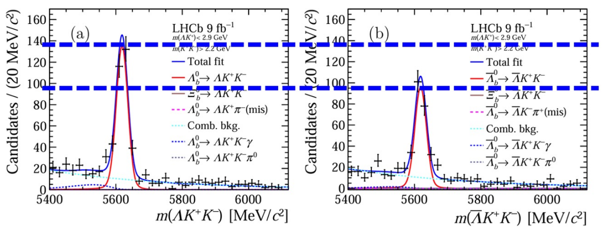
Angular/Amplitude analysis
Decay parameter



Decay rate asymmetry

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

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



Current precision: *b* baryon $\mathcal{O}(1 \sim 10\%)$, *c* baryon $\mathcal{O}(0.1\%)$, hyperon $\mathcal{O}(0.001 \sim 0.01\%)$

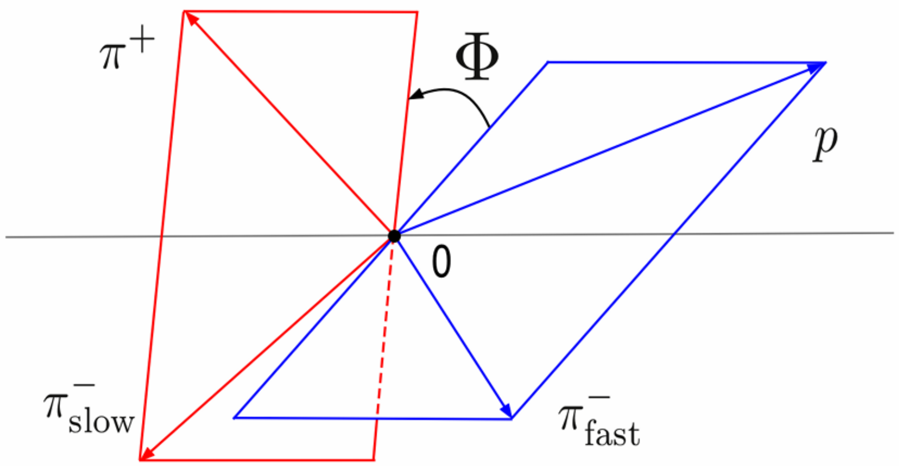
So far (22/Mar/2025), baryon CPV not established, despite some indications

Triple product method for $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

- Triple products in Λ_b^0 rest frame

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

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



- P-odd asymmetries

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

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

- CP-violating observable:

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

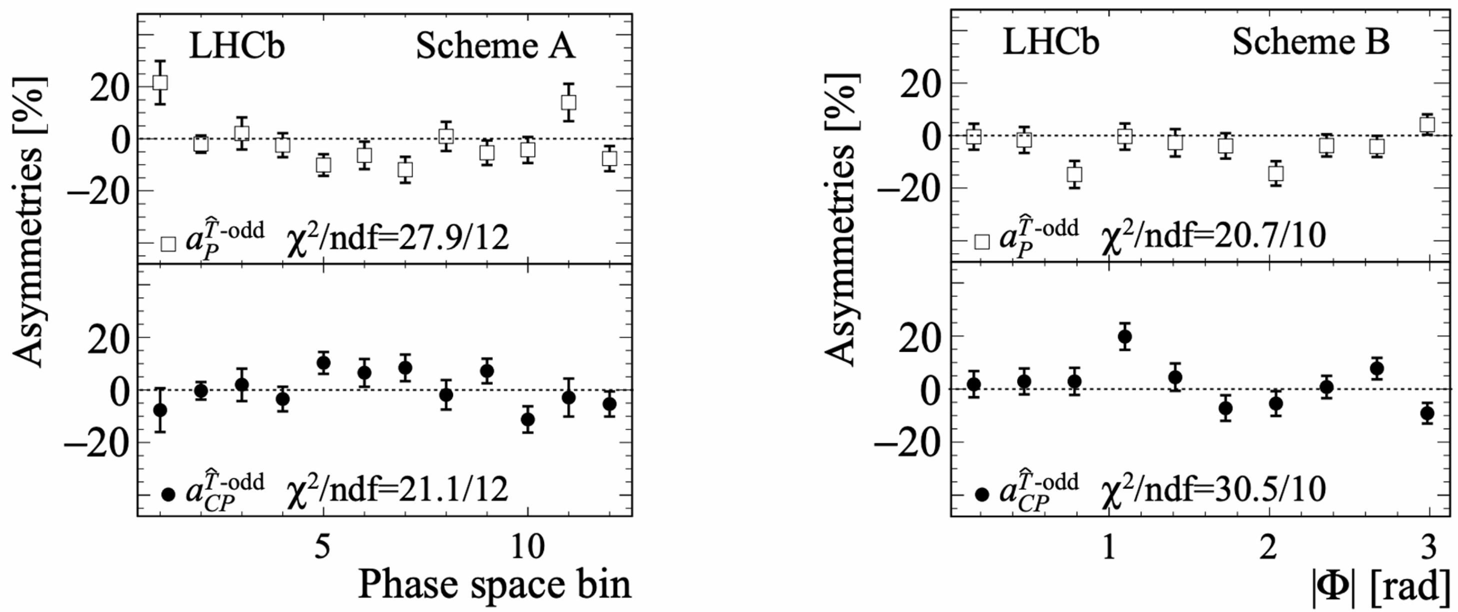
- P-violating observable:

$$a_{P}^{\hat{T}\text{-odd}} = \frac{1}{2}(A_{\hat{T}} + \bar{A}_{\hat{T}})$$

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

CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ with TPA

- Evidence of of CPV (3.3σ) by with Run 1 data



Nature Phys. 13 (2017) 391

However, not confirmed by study with 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

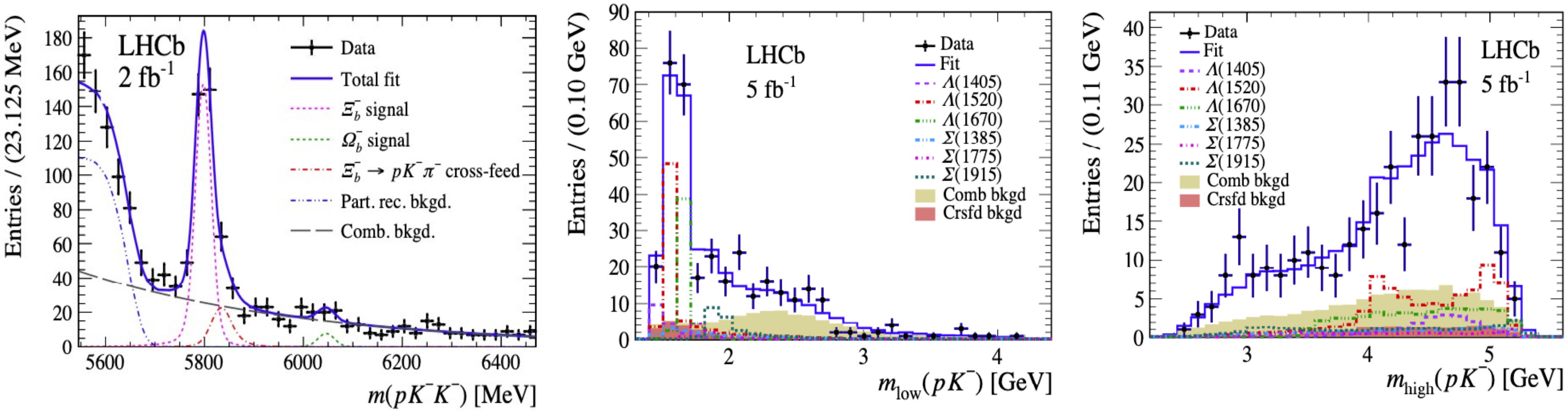
JHEP 08 (2018) 039

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

PRD 104 (2021) 052010

- Three body charmless $b \to s$ transition, analogy to $B \to K\pi\pi$ decays
- Amplitude analysis with 6 resonances

$m_{\text{low}}(pK^-)$ $m_{\text{high}}(pK^-)$



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

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

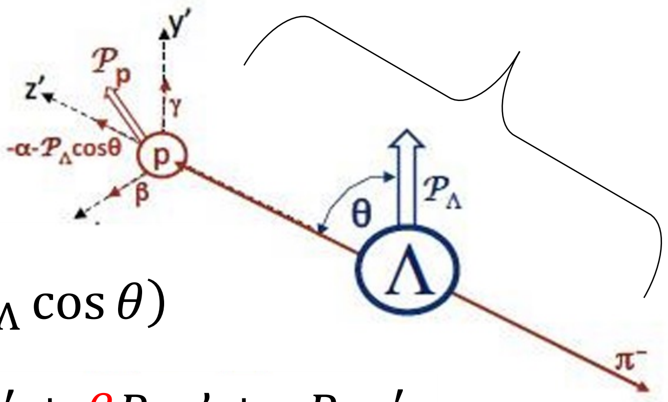
Component	A^{CP} (10^{-2})
$\Sigma(1385)$	-27 ± 34 (stat) ± 73 (syst)
$\Lambda(1405)$	-1 ± 24 (stat) ± 32 (syst)
$\Lambda(1520)$	-5 ± 9 (stat) ± 8 (syst)
$\Lambda(1670)$	3 ± 14 (stat) ± 10 (syst)
$\Sigma(1775)$	-47 ± 26 (stat) ± 14 (syst)
$\Sigma(1915)$	11 ± 26 (stat) ± 22 (syst)

No evidence of CPV

Baryon decay parameters

- Proposed by Lee & Yang to study parity (P) violation in hyperon decay $\Lambda \to p\pi^+$

S and P waves



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

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

$$\alpha \equiv \frac{2\mathrm{Re}(S^* P)}{|S|^2 + |P|^2},$$
$$\beta \equiv \frac{2\mathrm{Im}(S^* P)}{|S|^2 + |P|^2},$$
$$\gamma \equiv \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2},$$
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: $A_{CP}^{\alpha} = \frac{\alpha(\Lambda)+\alpha(\bar{\Lambda})}{\alpha(\Lambda)-\alpha(\bar{\Lambda})}$ …

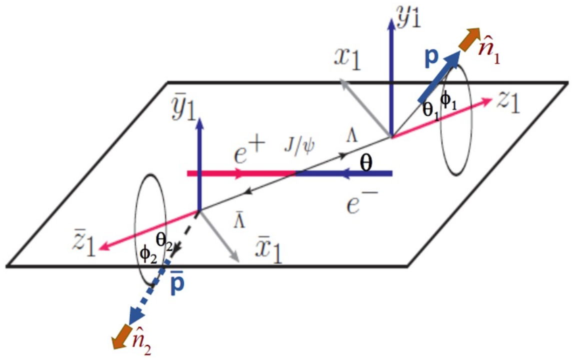
Complementary to decay rate asymmetry

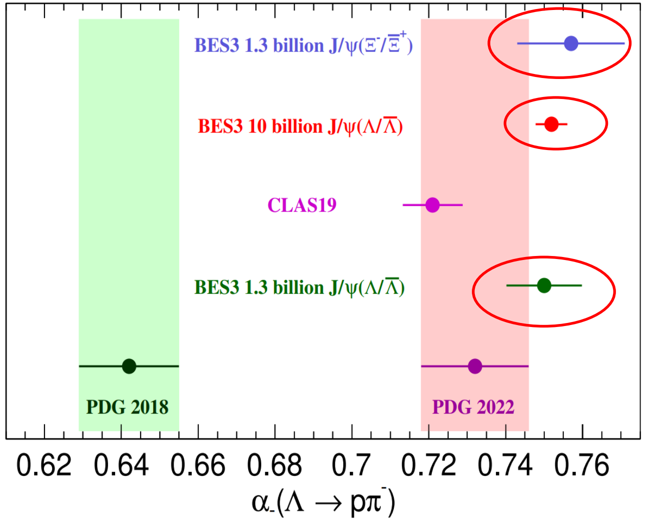
BESIII Decay parameters and CPV in hyperons

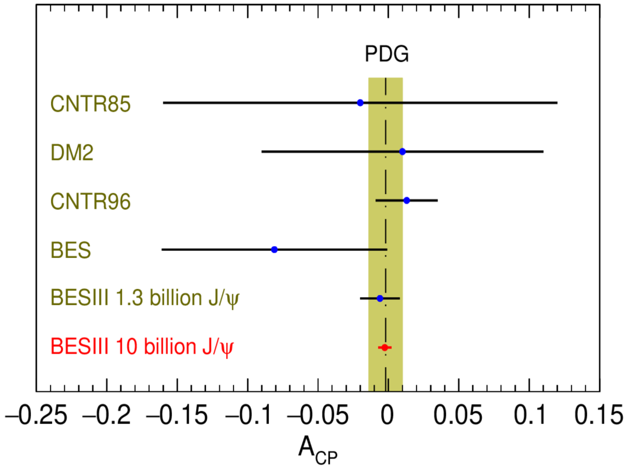
- Pioneering work to probe CPV in $J/\psi \to \Lambda\bar{\Lambda}$

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

Entangled Λ and $\bar{\Lambda}$





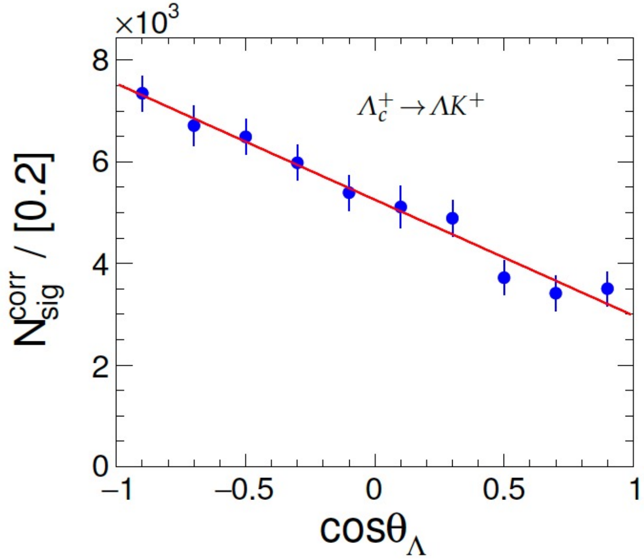


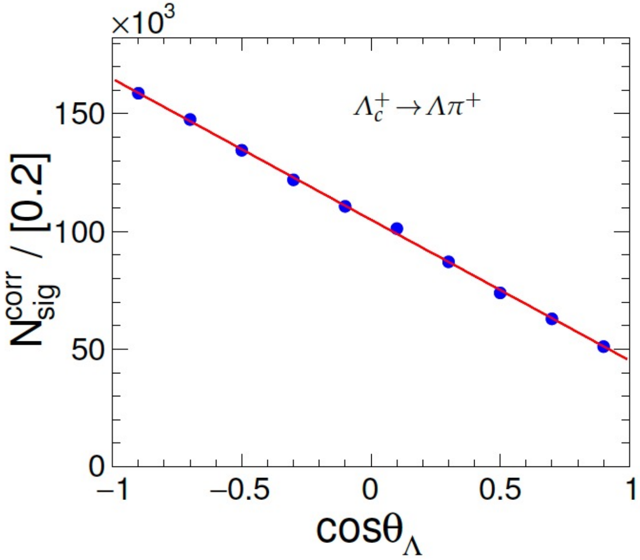
- Many other ψ to hyperon channels explored, no sign of CP violation

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

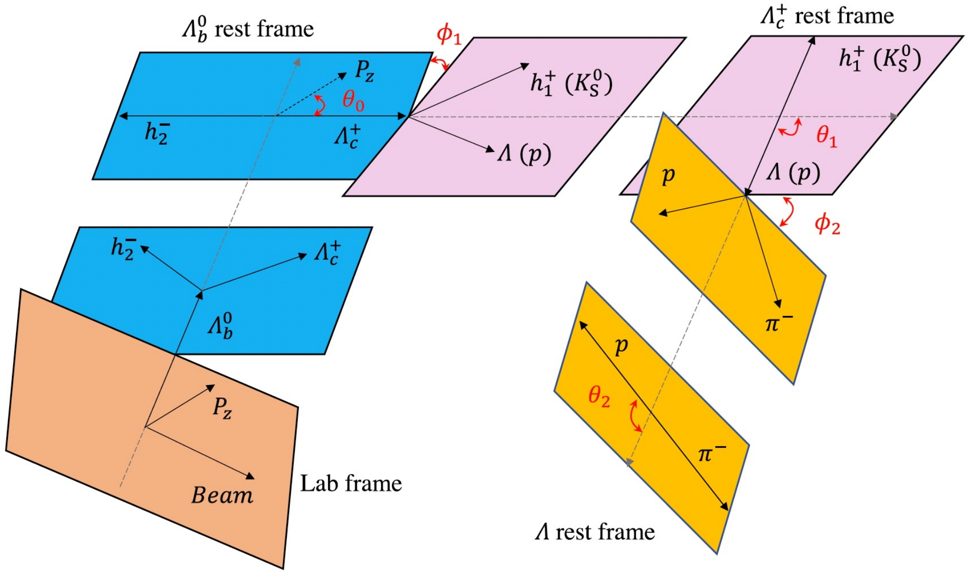
- Simultaneous angular analysis of 6 decays

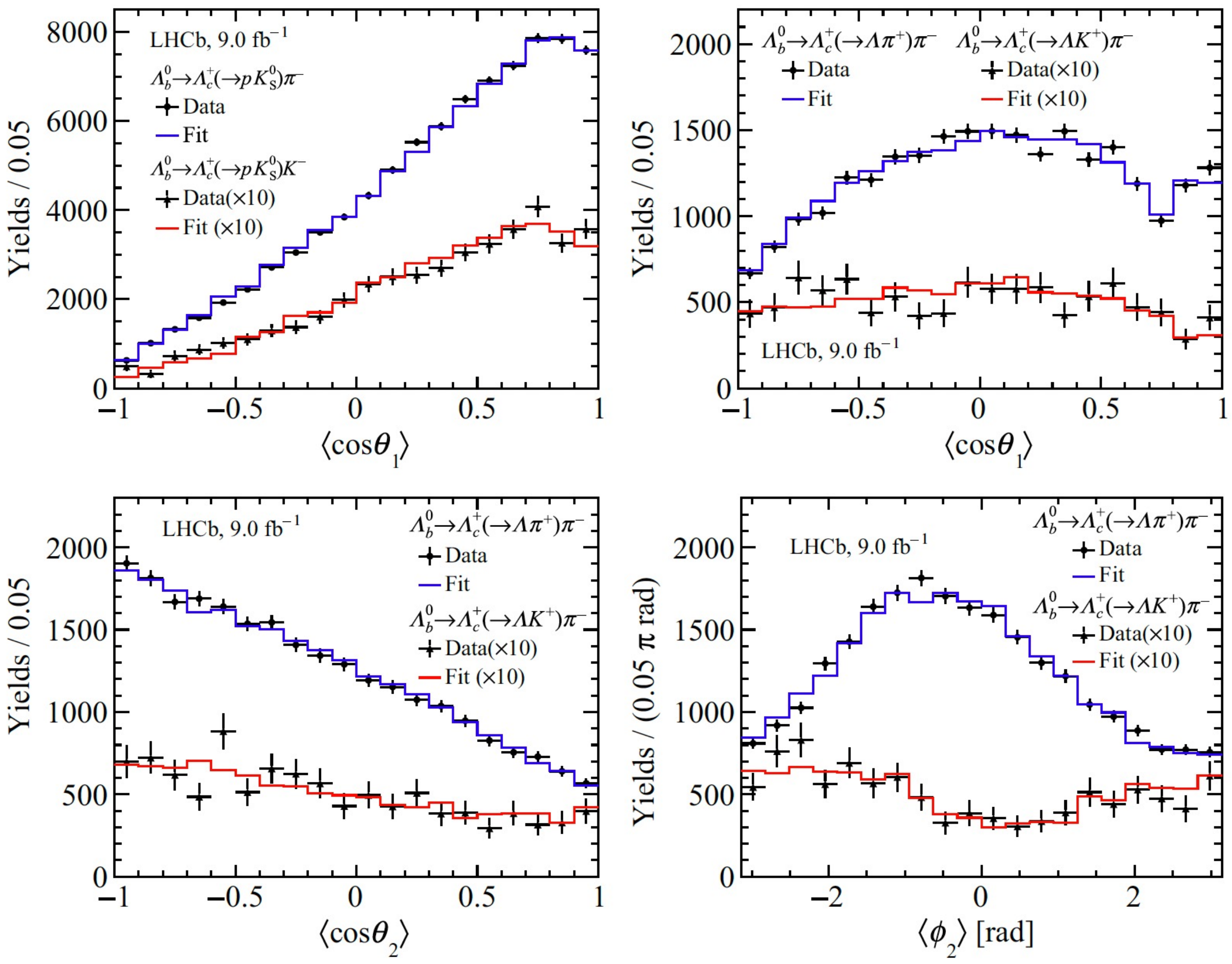
$\Lambda_b^0 \to \Lambda_c^+ h^- \ (h = \pi, K)$

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

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

PRL 133 (2024) 261804





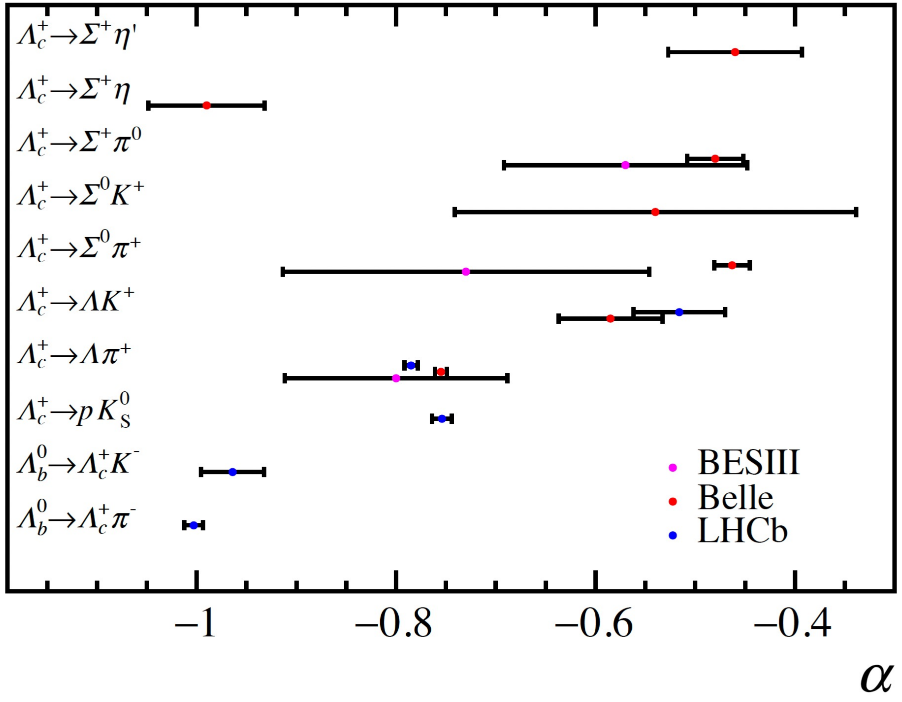
P and CP violation

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 $\alpha(\Lambda \to p\pi^-)$

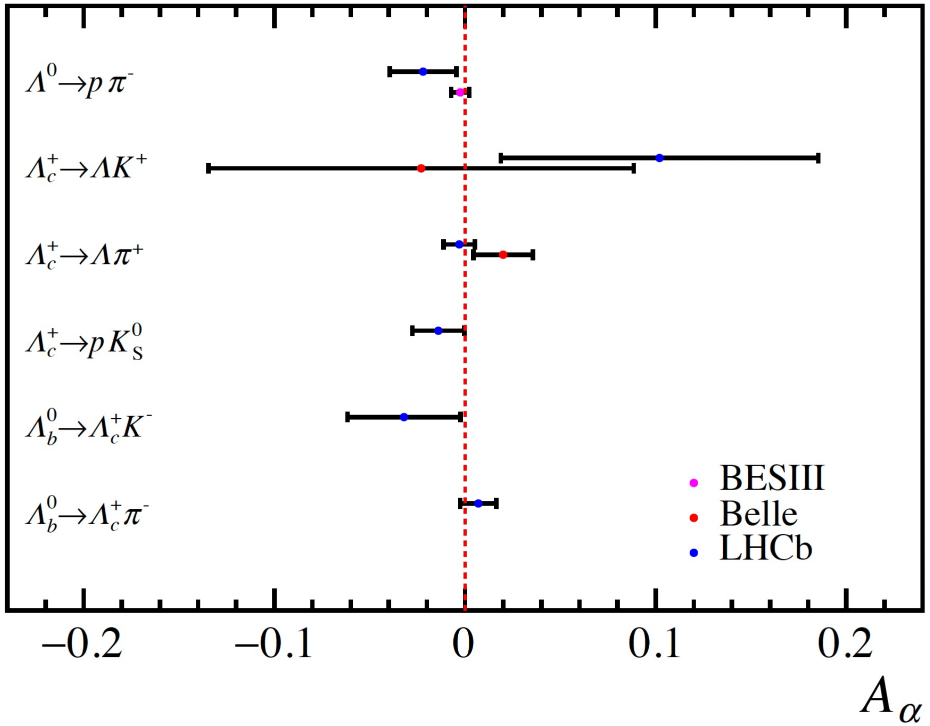
Consistent with Belle and BESIII



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

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

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

CPV with decay rate

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

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

EPJC 79 (2019) 745

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

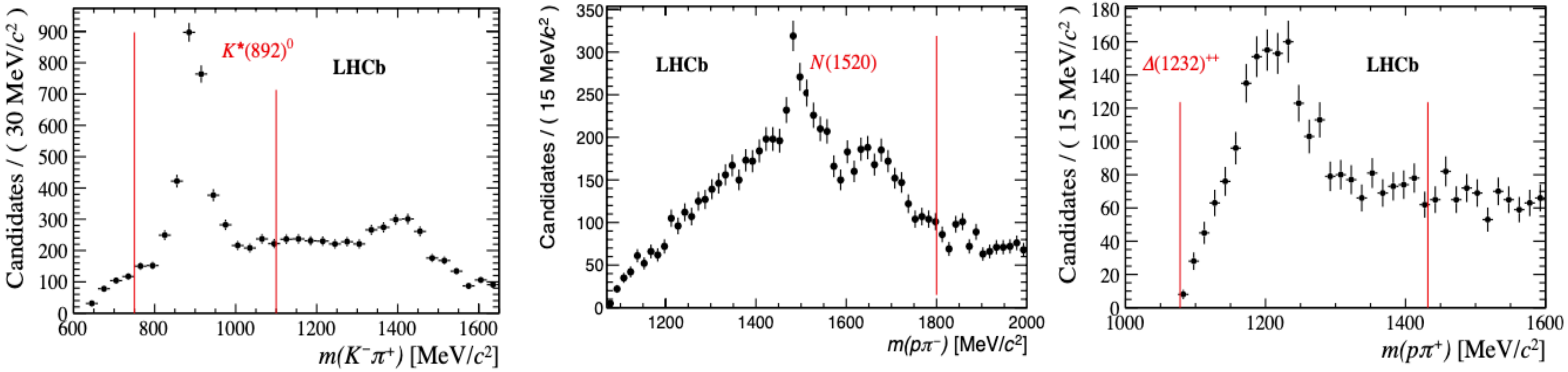
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

$\Xi_b^0 \to pK^-\pi^+\pi^-$ $\quad \Lambda_b^0 \to pK^-\pi^+\pi^-$

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

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

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

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

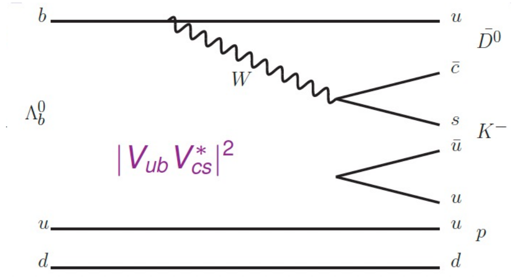
No evidence of A_{CP} with ~1% precision
Rule out global CP violation ≫ 5%

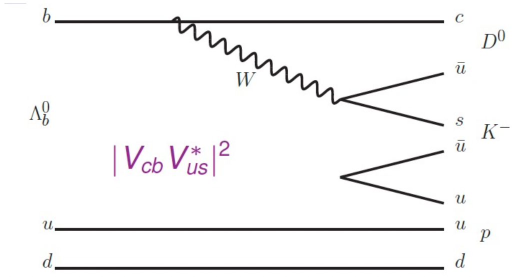
CP asymmetry for $\Lambda_b^0 \to DpK^-$

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



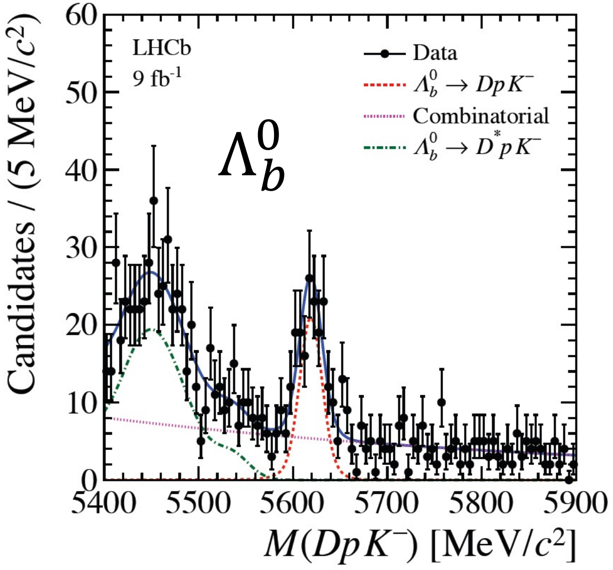


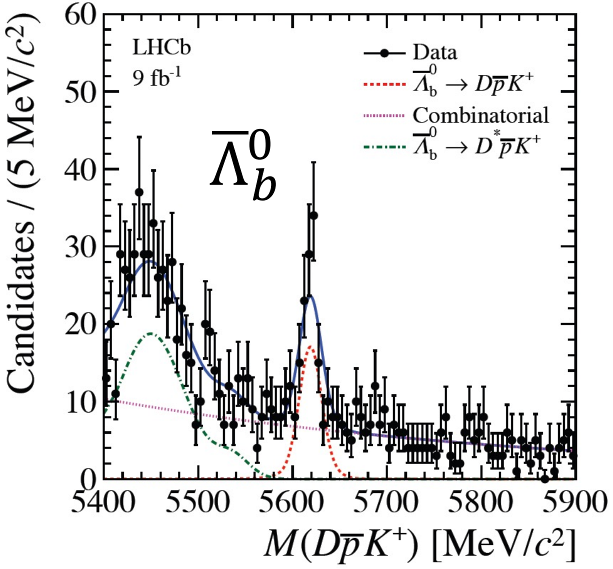
- CPV studied for DCS decay $D^0 \to K^+\pi^-$

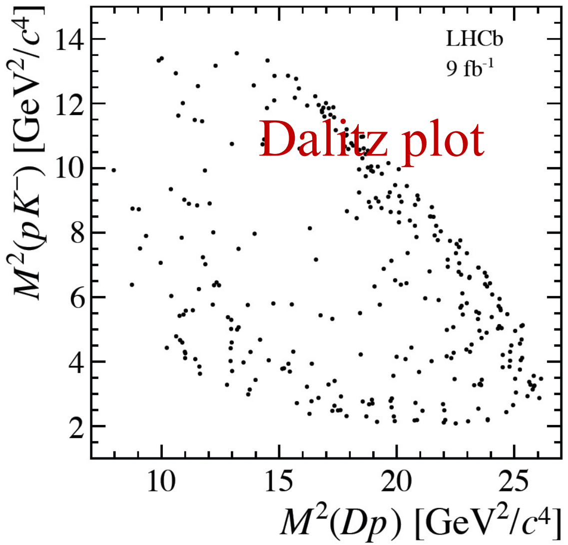
  Interference between $\Lambda_b^0 \to (K^+\pi^-)_{D^0}pK^-$ and $\Lambda_b^0 \to (K^+\pi^-)_{\bar{D}^0}pK^-$

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

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







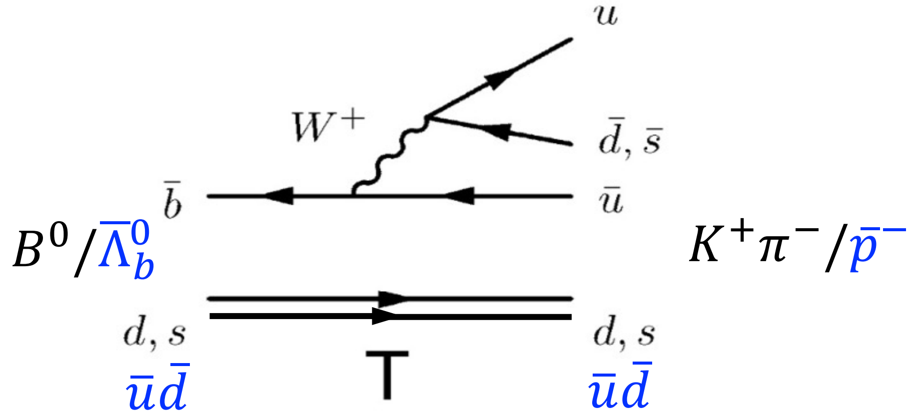
CP violation in $\Lambda_b^0 \to p h^-$ decays

arXiv:2412.13958

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

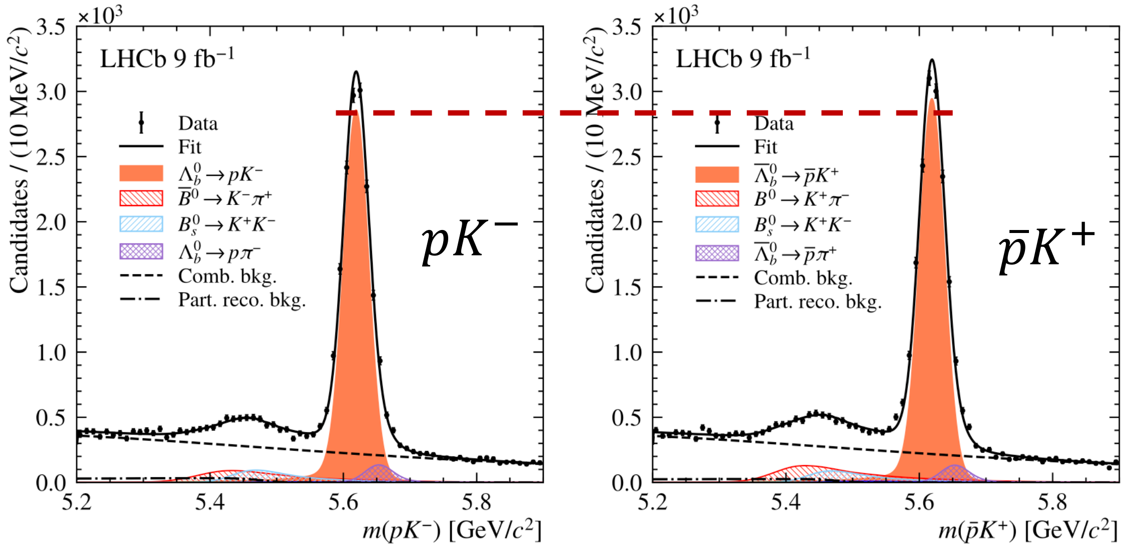
PRD 102 (2012) 034033
PRD 95 (2017) 093001

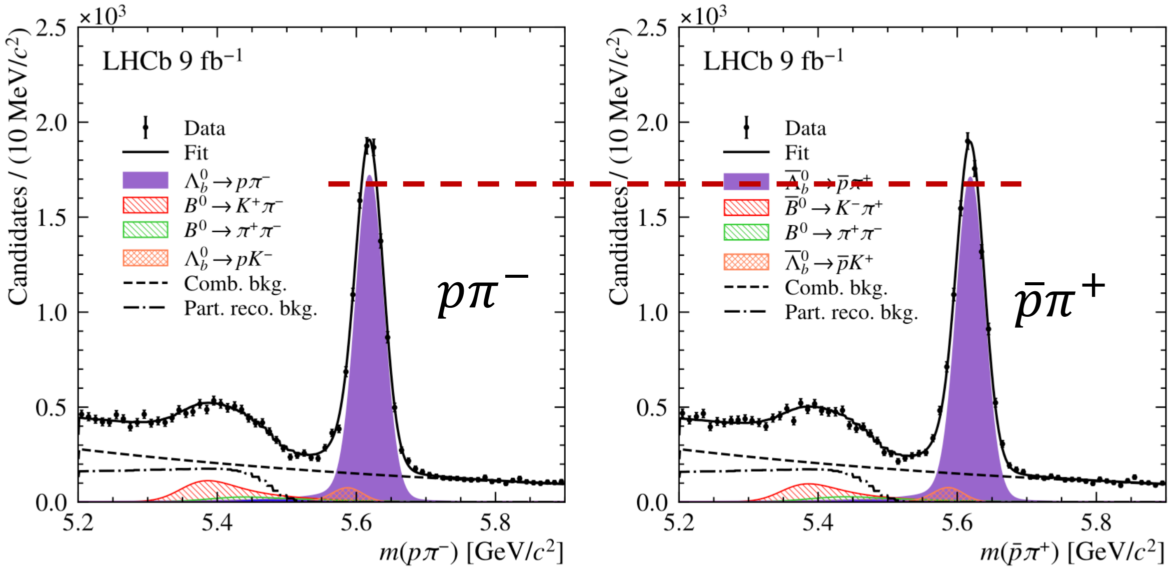
- Sizable CP violation not confirmed



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

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





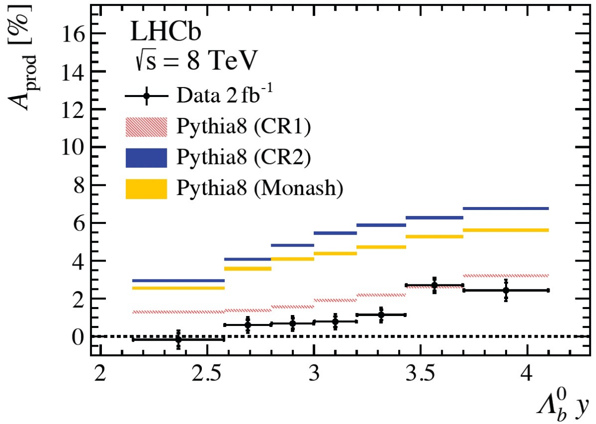
Crucial to control systematics

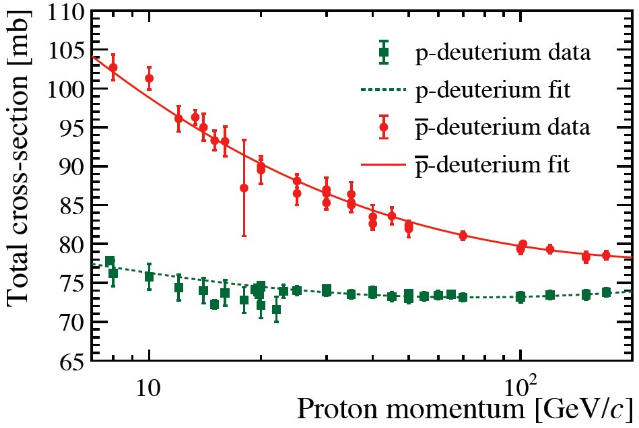
arXiv:2412.13958

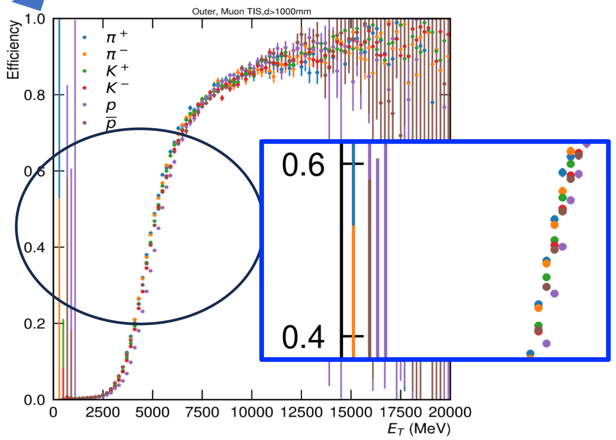
- Subtraction of experiment induced asymmetries (~ 1%)

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

JHEP 10 (2021) 060







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

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

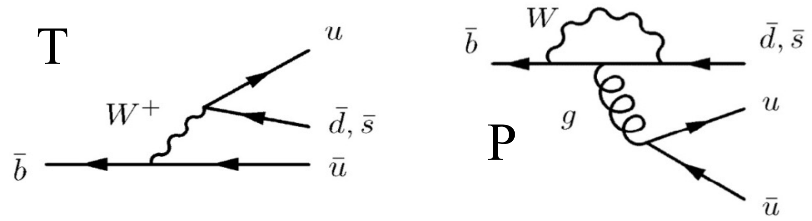
$$A_{CP}^{p\pi^-} = \Delta A_{\text{raw}} - \Delta A_{\text{D}}^{p} - \Delta A_{\text{D}}^{\pi^-} - \Delta A_{\text{PID}} - \Delta A_{\text{P}}^{\Lambda_b^0} - \Delta A_{\text{T}} - A_{\text{D}}^{K^-} - A_{\text{D}}^{\pi^+} + A_{CP}^{\Lambda_c^+\pi^-}$$

Good cancellation, eventually limited by $\Lambda_b^0 \to \Lambda_c^+\pi^-$ sample size

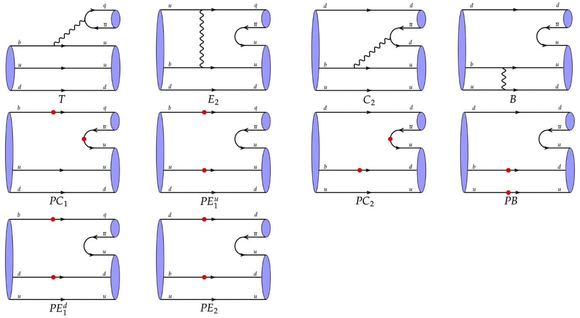
Why CP violation so small

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

  One diagram overwhelming? small strong phase difference?



- Dynamics more complex than mesons



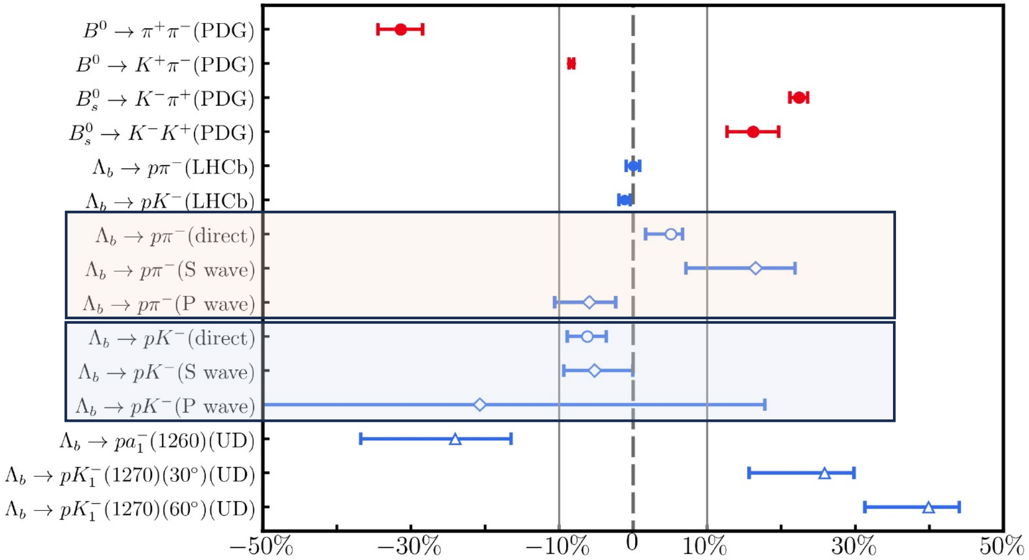
韩佳杰、余纪新、李亚等，arXiv:2409.02821

➤ Tree amplitude dominating

$\Lambda_b \to pK^-$				
T	853.60	−52.08	1190.21	−340.84
E_2	−66.28	−59.48	−50.31	79.56
Tree $\mathcal{T}$	787.31	−111.55	1139.90	−261.28
PC_1	75.64	−0.82	−4.35	−13.81
PE_1^u	0.10	−11.80	−4.76	9.93
PE_1^d	−1.50	−7.38	1.66	2.09
Penguin $\mathcal{P}$	74.23	−20.00	−7.45	−1.79

➤ 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

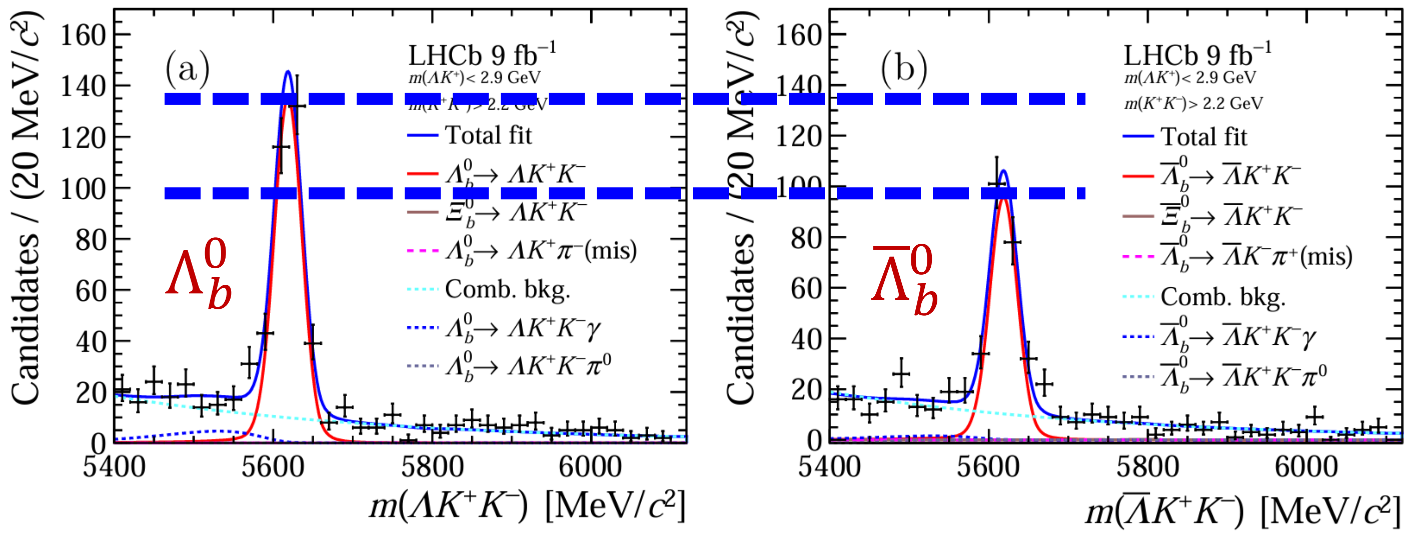
CP asymmetry in $\Lambda_b^0 \to \Lambda h_1^+ h_2^-$ decays

PRL 134 (2025) 101802

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

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

3.1σ, evidence for CPV



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

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

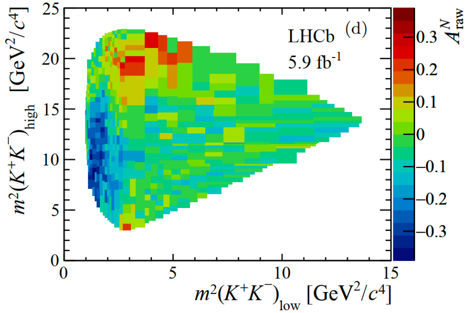
Several related N^{*+} channels to cross-check

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

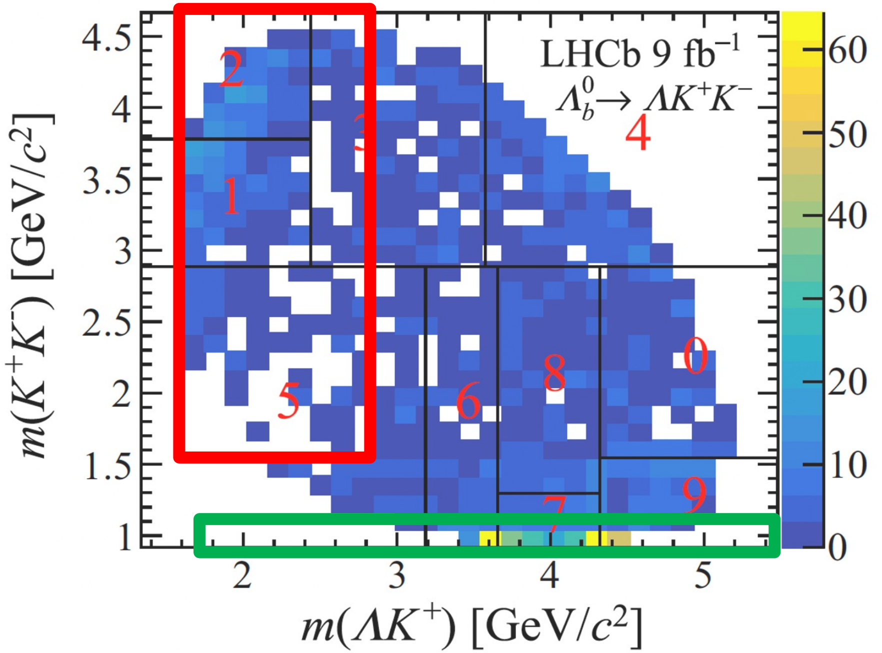
$N^{*+} \to p\pi^+\pi^- \quad \Rightarrow \Lambda_b^0 \to N^{*+}(p\pi^+\pi^-)K^-$

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

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



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

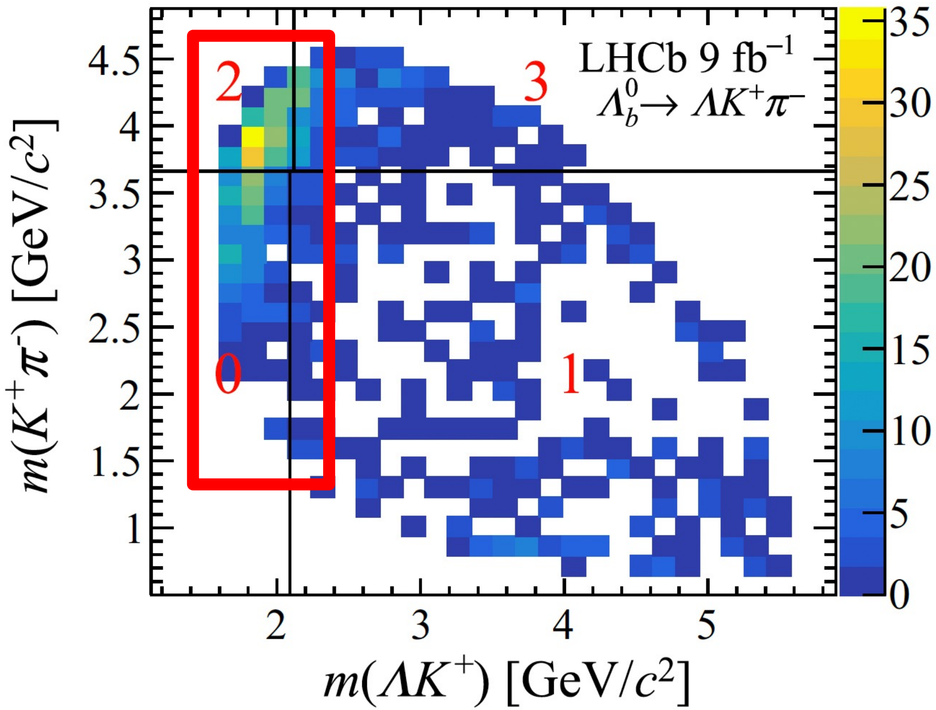


More local CP asymmetries

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

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

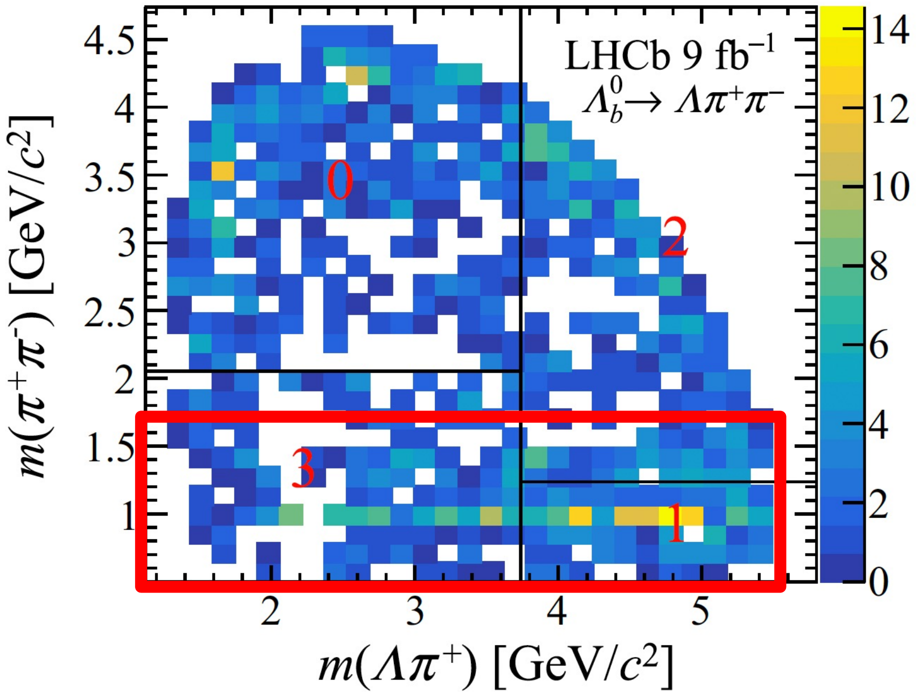
$\Delta A_{CP}(N^{*+}\pi^-) = -0.078 \pm 0.051 \pm 0.027$



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

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

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



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

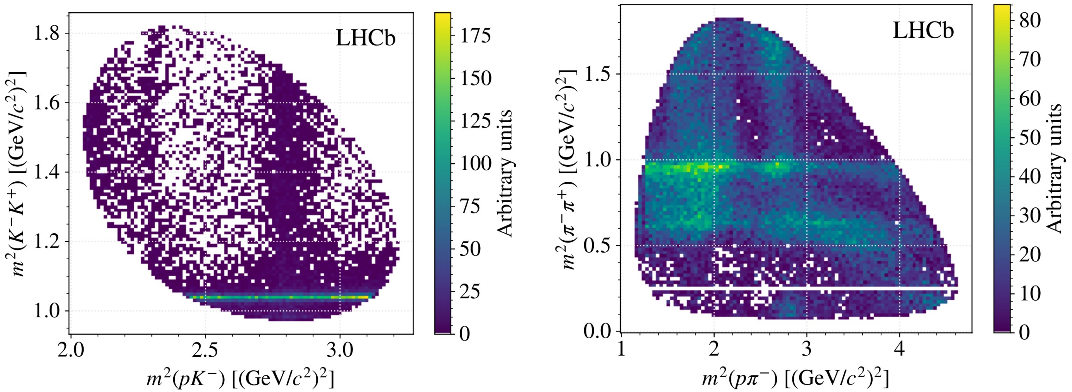
JHEP 03 (2018) 182

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

I. I. Bigi, arXiv:1206.4554

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

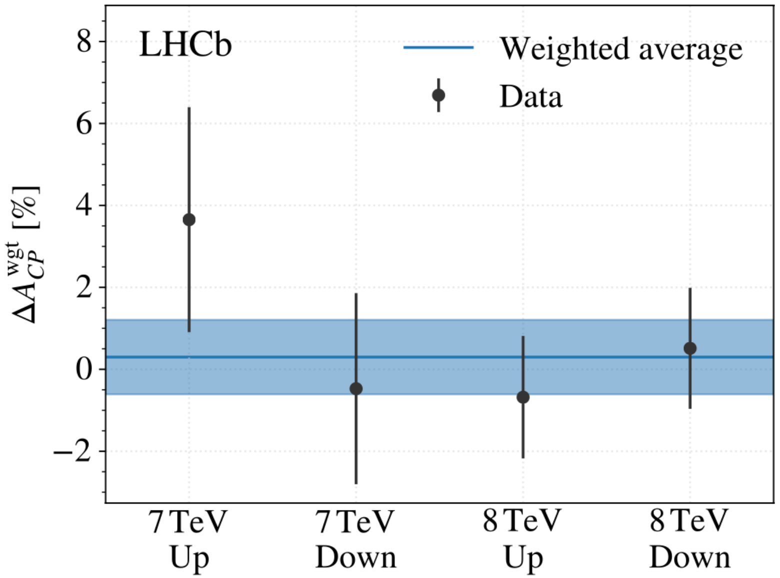
- ➢ Singly Cabibbo-suppressed ($D^0 \to KK, \pi\pi$)
- ➢ Large yields and high S/B ratio
- ➢ Rich resonances



Challenging to control systematics

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

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



?

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。

提问方式（时间）不对?

LHCb的发现：

- 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。

From P violation to CP violation: a summary

1956 李、杨提出P破坏

1963 Cabibbo提出两代夸克混合

1970 GIM预言粲夸克

1973 KM提出三代夸克混合机制

理论？

新的CP破坏源？

1957 吴健雄发现P破坏

1958 Goldhaber发现C破坏

1964 Cronin、Fitch发现K^0介子CP破坏

1974 丁肇中、里奇特发现粲夸克

1977 莱德曼发现底夸克

1995 费米实验室发现顶夸克

2001 BaBar、Belle发现B^0介子CP破坏

2013 LHCb发现B_s^0介子CP破坏

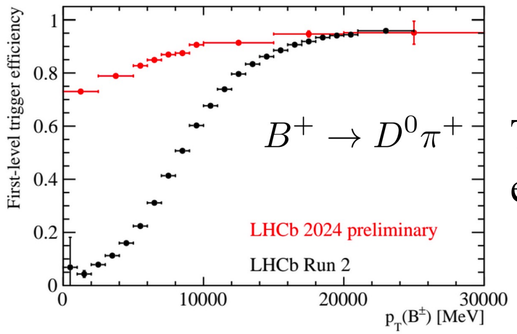
2019 LHCb发现D^0介子CP破坏

重子CP破坏呼之欲出

实验？

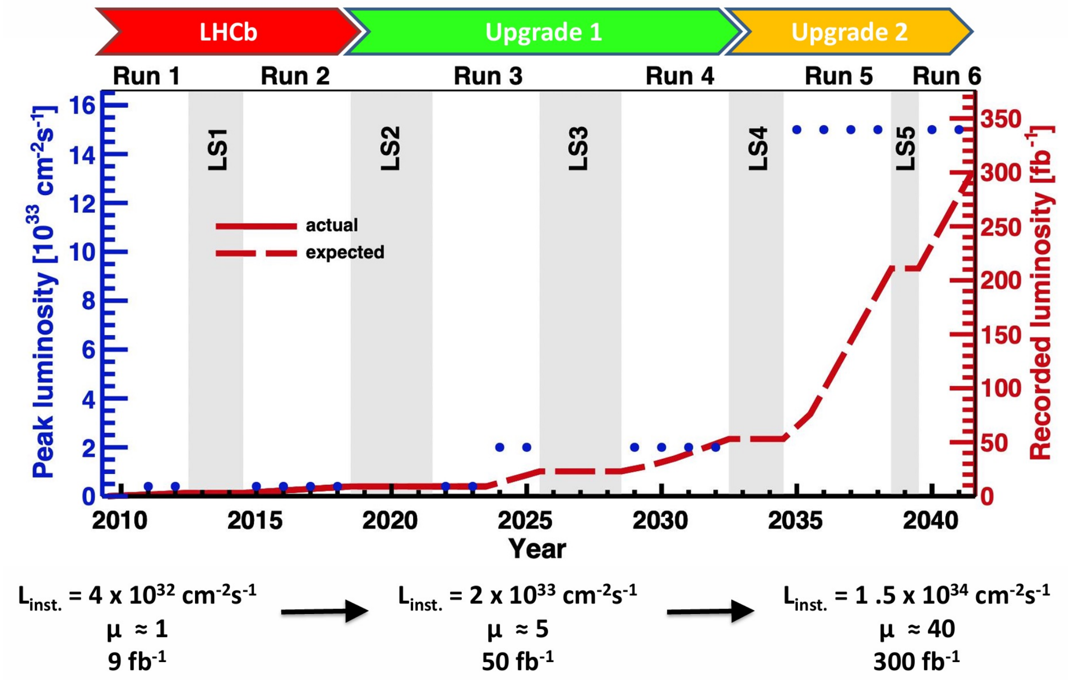
LHCb (near) upgrade plan

- 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

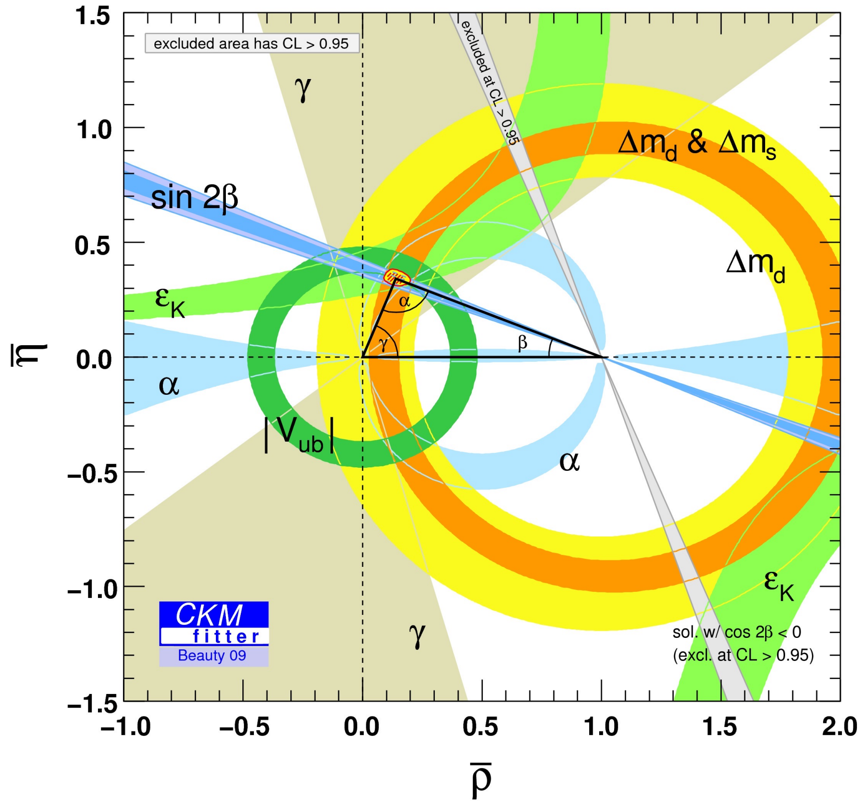
- ➢ Confirmation
- ➢ More decays
- ➢ More dynamics
- ➢ Charm baryon
- ➢ Unexpected observations ?

谢谢！

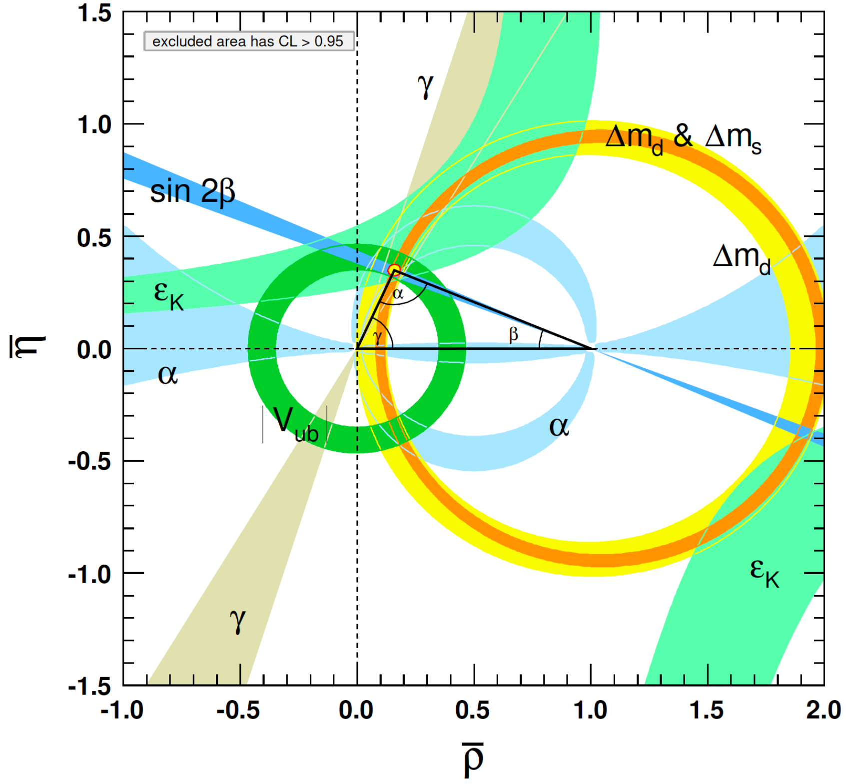
Backup slides

Global analysis of CKM mechanism (4 parameters)

When LHC started



Current status



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

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

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}$$