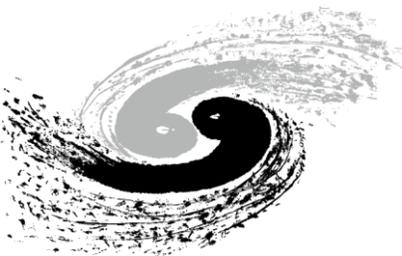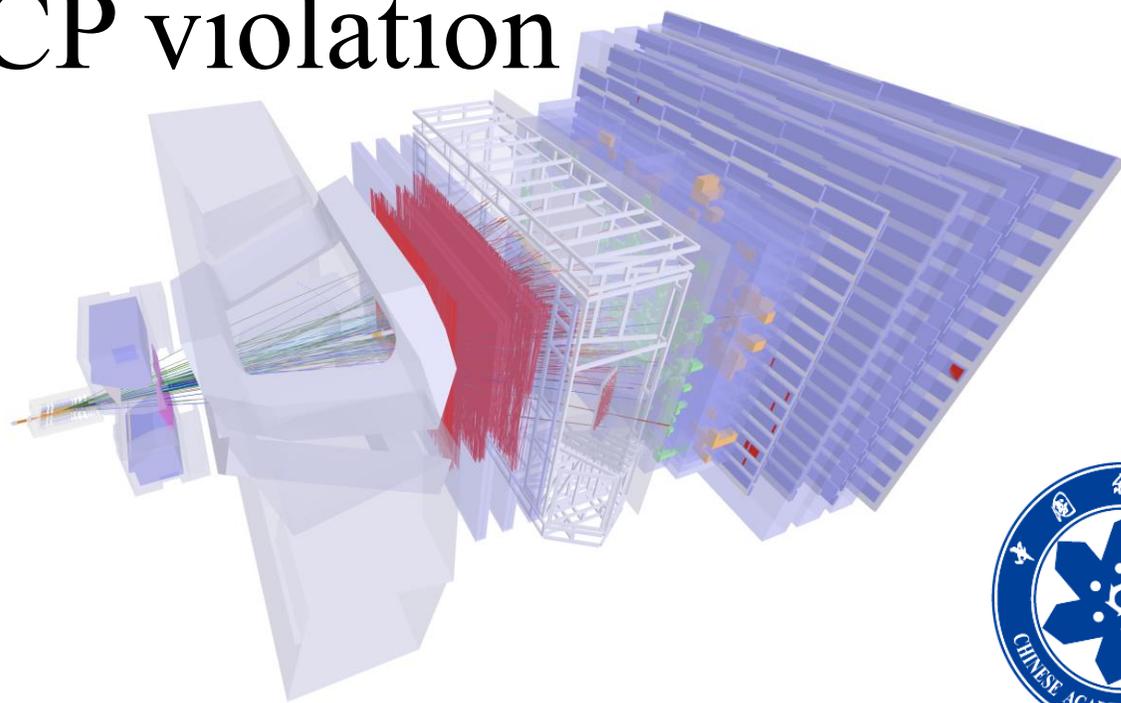# Experimental searches of CP violation
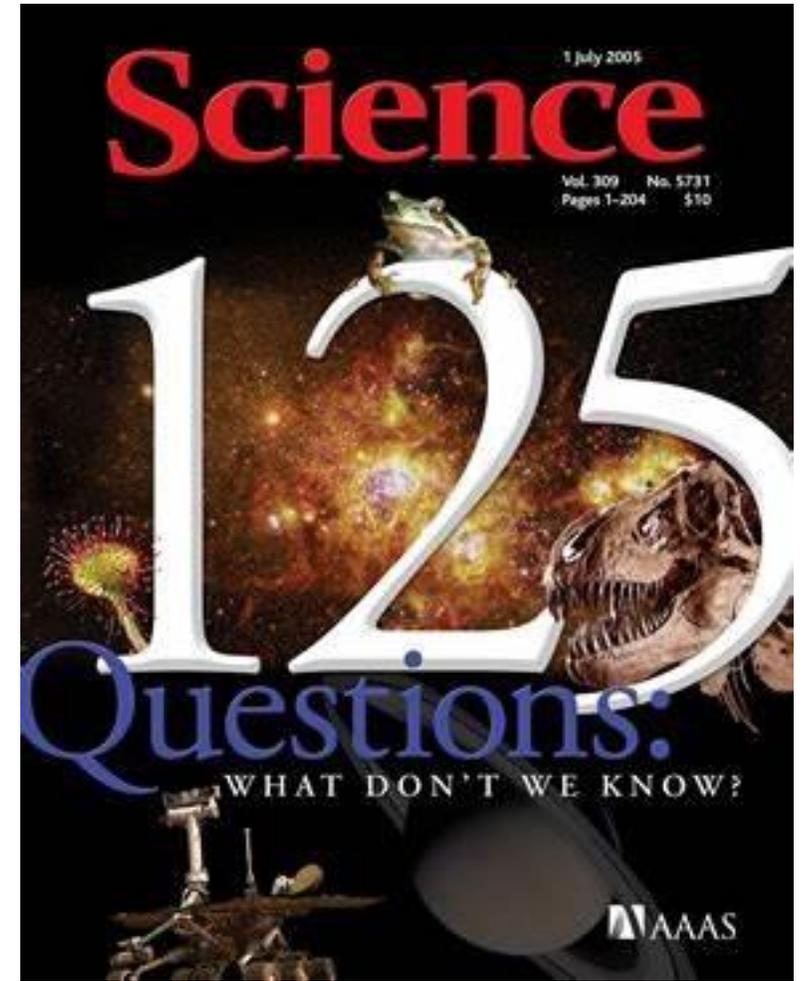
Shanzhen Chen

IHEP, CAS

2 February 2026

Baryogenesis in the Universe

- "Why is there more matter than antimatter?"
  - "baryogenesis"
  - One of the 125 questions listed by *Sciences* in 2005

- Sakharov conditions for baryogenesis:
  - Baryon number violation
  - C and CP violation
  - Out of thermal equilibrium

- CP violation

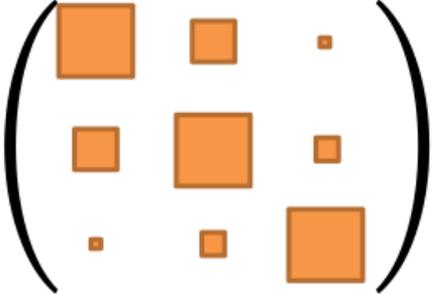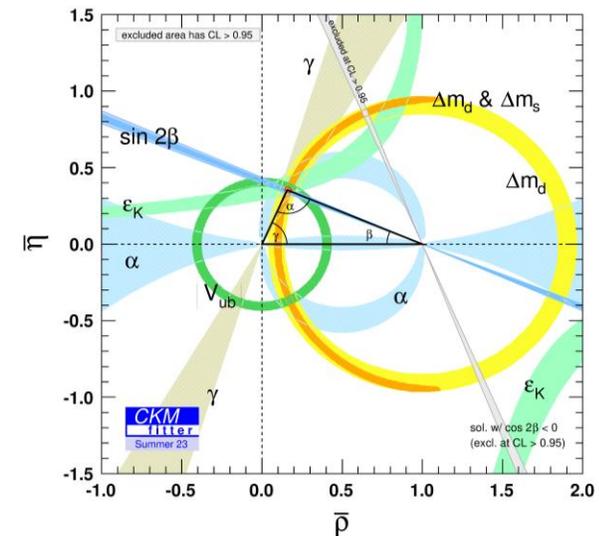 Has been widely studied by flavor factories

CP violation

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

$$V = \left\{ \begin{array}{ccc} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-l\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{l\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{l\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{l\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{l\delta_{13}} & c_{23}c_{13} \end{array} \right\},$$

- Quark mixing matrix
- A single phase parameter gives rise to quark CPV
- Well tested

- But not sufficient to explain matter and antimatter asymmetry in Universe

Source of CP violation in SM

$$A_j = |A_j|e^{i\left(+\phi_j^{\text{weak}}+\kappa_j\right)}$$

CP

$$\bar{A}_j = |A_j|e^{i\left(-\phi_j^{\text{weak}}+\kappa_j\right)}$$

$$P(i \to f) = |A_1 + A_2|^2$$

$$P(\bar{i} \to \bar{f}) = |\bar{A}_1 + \bar{A}_2|^2$$
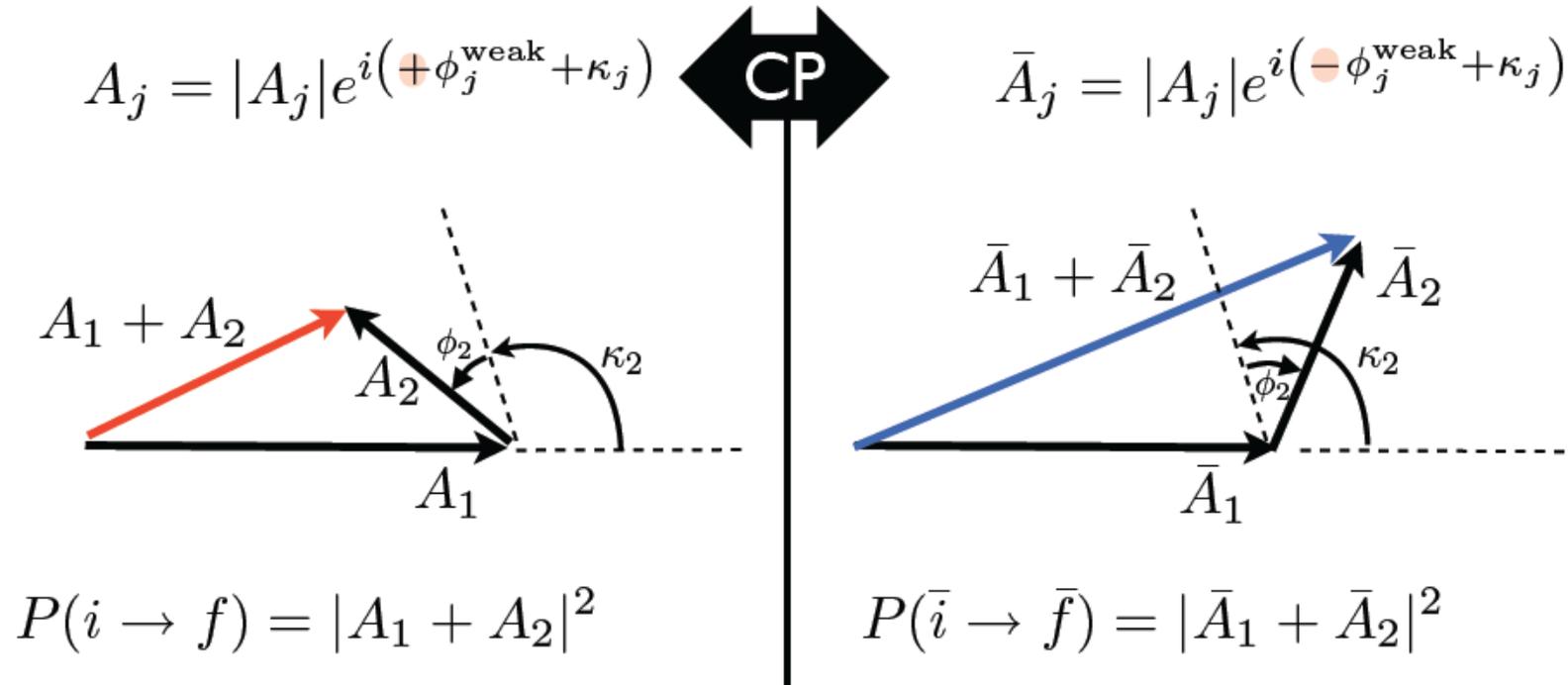
$$= |A_1|^2 + 2|A_1||A_2|\cos(\phi_2 \pm \kappa_2) + |A_2|^2$$
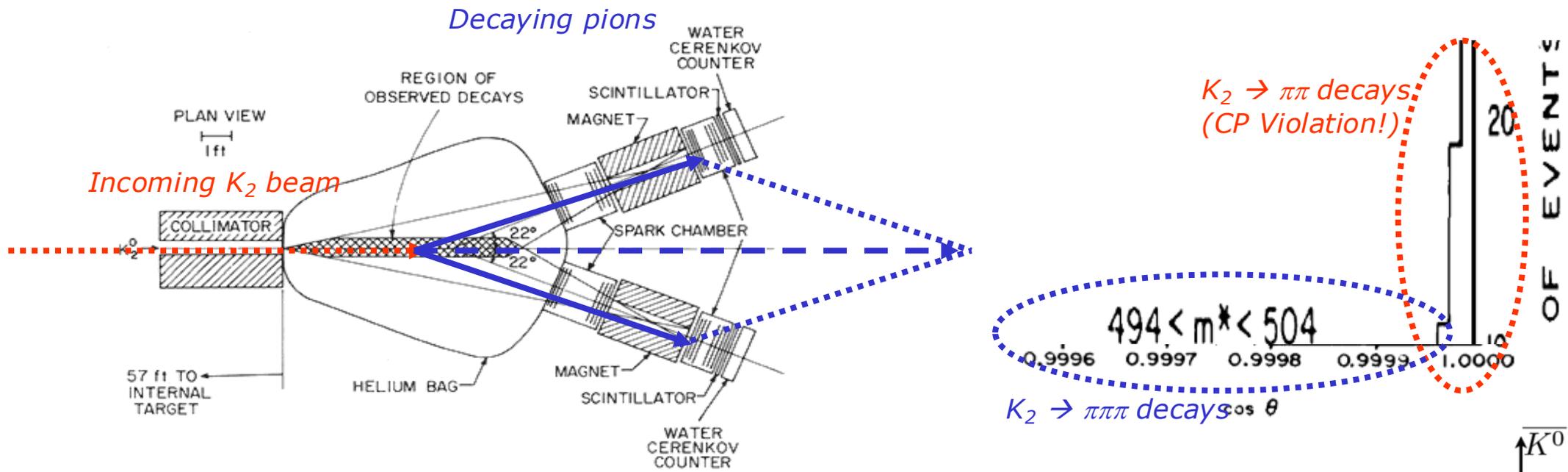
$$P(i \to f) - P(\bar{i} \to \bar{f}) = -4|A_1||A_2|\sin(\phi_2)\sin(\kappa_2)$$

Strong phase difference

Weak phase difference

Requires a strong phase difference does not flip sign under CP operation, a weak phase difference flips sign under CP operation, and interference between at least two decay amplitudes

CP violation in K mesons: Cronin-Fitch experiment

- Measure CP quantum number by measuring faction of $K_L \to \pi\pi$ decays

- $|K_1\rangle = 1/\sqrt{2}(|K^0\rangle + |\overline{K}^0\rangle)$, $|K_2\rangle = 1/\sqrt{2}(|K^0\rangle - |\overline{K}^0\rangle)$
- $CP|K_1\rangle = +1|K_1\rangle$, $CP|K_2\rangle = -1|K_2\rangle$, K_1, K_2 are CP eigenstates in the case of no CPV, all K_L should decays to $\pi\pi\pi^0$
- 0.2% K_L decays to $\pi\pi$, $(K_1、K_2) \neq (K_S、K_L) \to$ CP violation
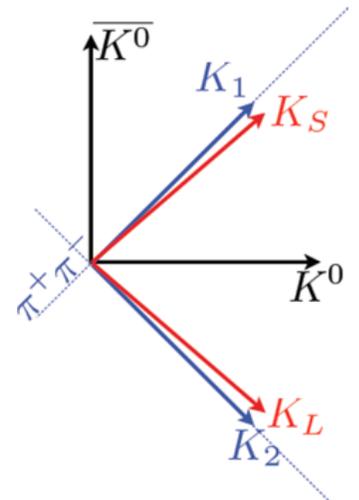
CP violation in B mesons: B-factories

- Using $B^0 \to charmonium + K^0$ channels
  - $B^0 \to J/\psi K_S^0$, $B^0 \to \psi(2S)K_S^0$, $B^0 \to \chi_{c1}K_S^0$, etc.

- $A_{CP}(\Delta t) = \dfrac{f^+(\Delta t) - f^-(\Delta t)}{f^+(\Delta t) + f^-(\Delta t)}$

$$= -\eta_f \sin 2\beta \sin(\Delta m_{B^0} \Delta t)$$

- Fit time-dependent distribution, got non-zero $\sin 2\beta$ $\to$ CP violation

BaBar

Belle

PRL **87**, 091801 (2001) , PRL **87**, 091802 (2001)
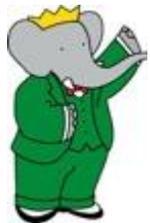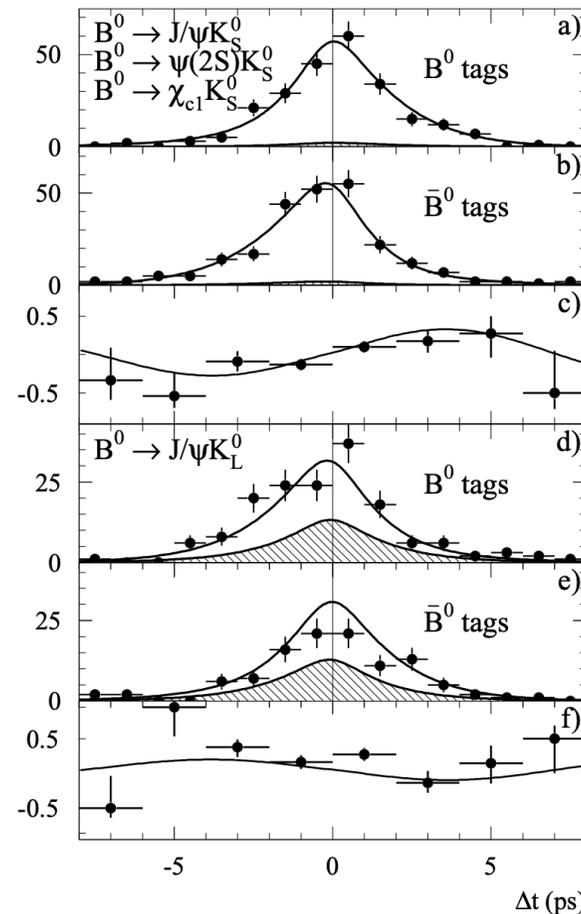
CP violation in D mesons: LHCb experiment
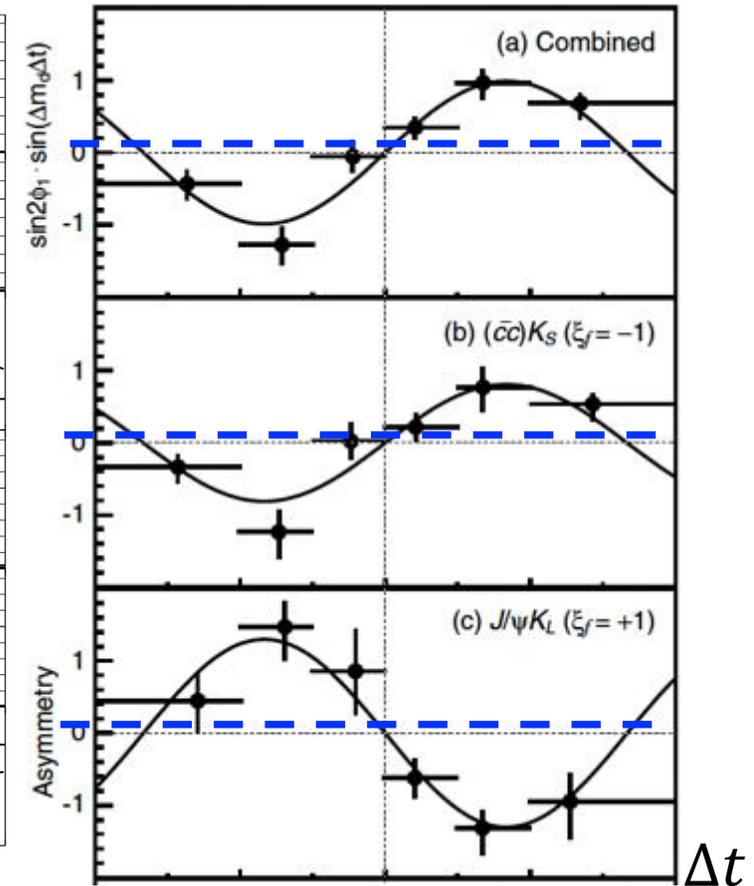
- Measure $\Delta A_{CP} = A_{CP}(D^0 \to KK) - A_{CP}(D^0 \to \pi\pi)$
  - where $A_{CP}(KK) = A_{raw}(KK) - A_{prod}(D) - A_{det}(\pi_s^+)$
    $$A_{CP}(\pi\pi) = A_{raw}(\pi\pi) - A_{prod}(D) - A_{det}(\pi_s^+)$$

  - $A_{prod}(D)$, $A_{det}(\pi_s^+)$ cancels in ΔA_{CP}

$K^+ K^-$ sample

$\pi^+ \pi^-$ sample

44×10^6

14×10^6
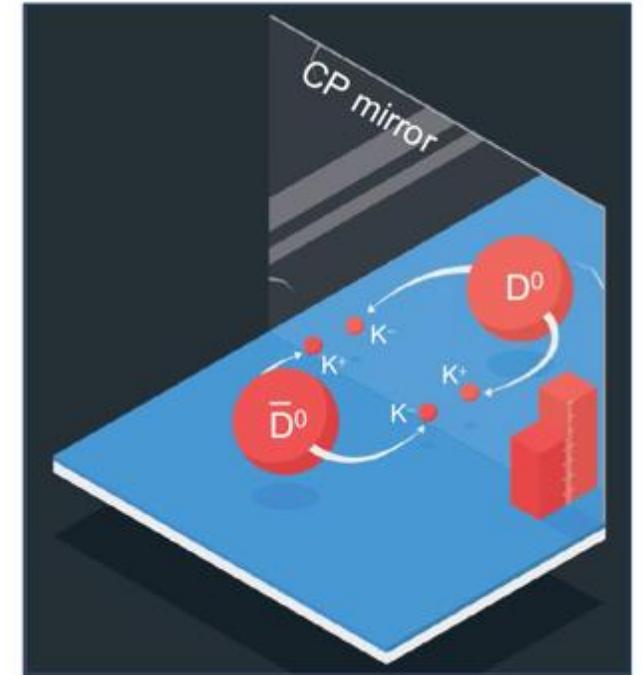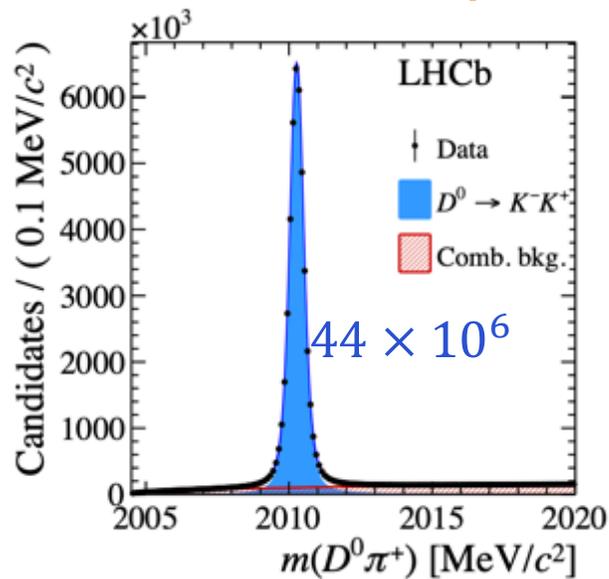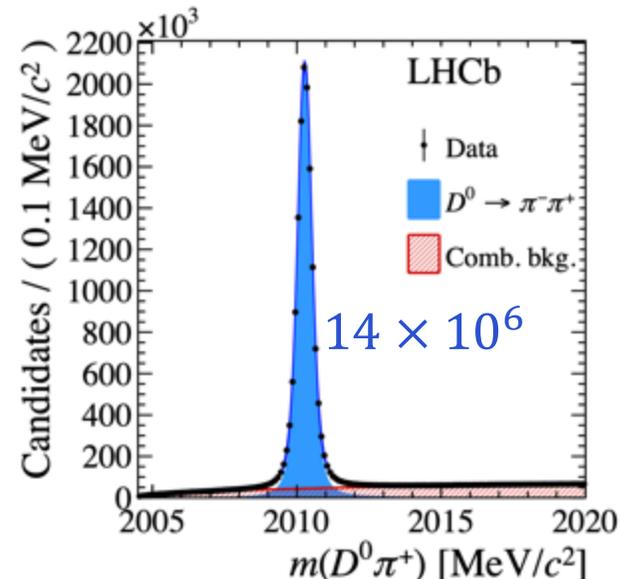
$$A_{CP}(D^0 \to K^+K^-)$$
$$-A_{CP}(D^0 \to \pi^+\pi^-)$$
$$= (\mathbf{-15.4 \pm 2.9}) \times \mathbf{10^{-4}}$$

CP violation study milstones

- Experimentally found in Strange, Bottom, and Charm sectors

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

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

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

1963
Cabibbo Mixing
N. Cabibbo

1973
The CKM matrix
M. Kobayashi,
T. Maskawa

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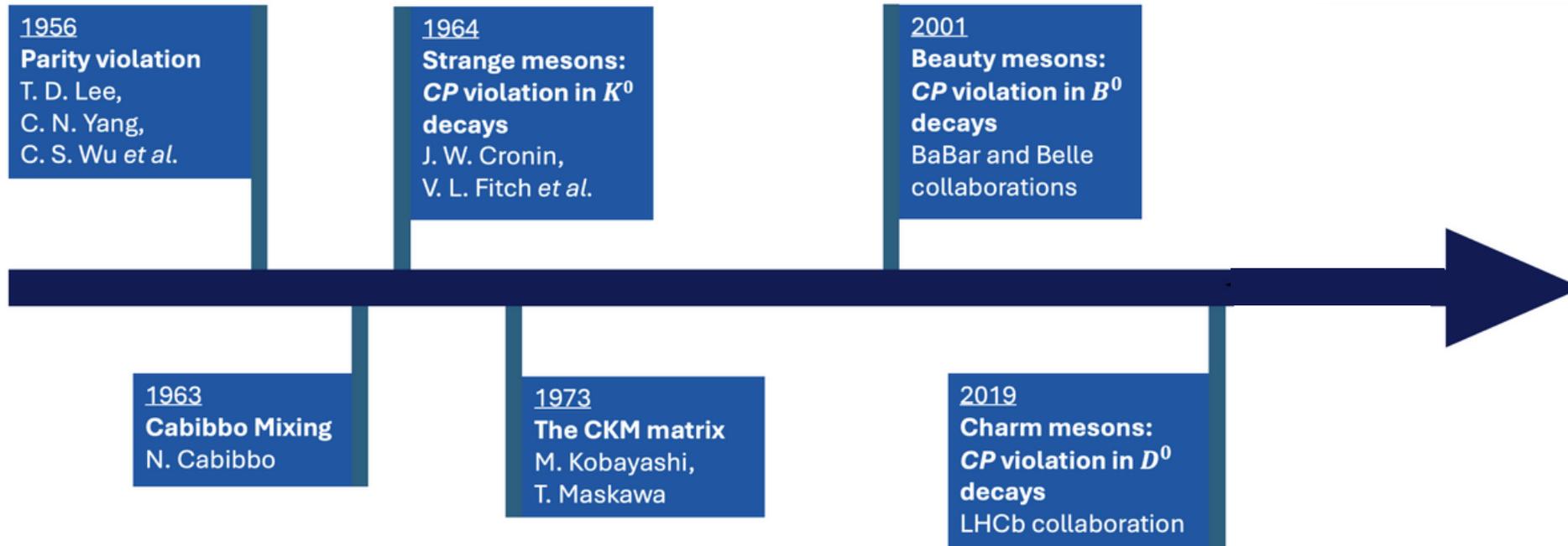
Strange sector

Hyperon studies @ BESIII

- With 10 billion J/ψ and 3 billion $\psi(3686)$ collected at BESIII, $\sim 10^7$ entangled hyperon pairs can be produced which enables precise studies of the hyperons

- More $\psi(3686)$ data will be taken after the upgrade of BEPCII and BESIII inner tracker

Table 2 Hyperon production from the J/ψ or $\psi(2S)$ two-body decays with 10^{10} events on the J/ψ peak and 3×10^9 events on the $\psi(2S)$ peak. N_B 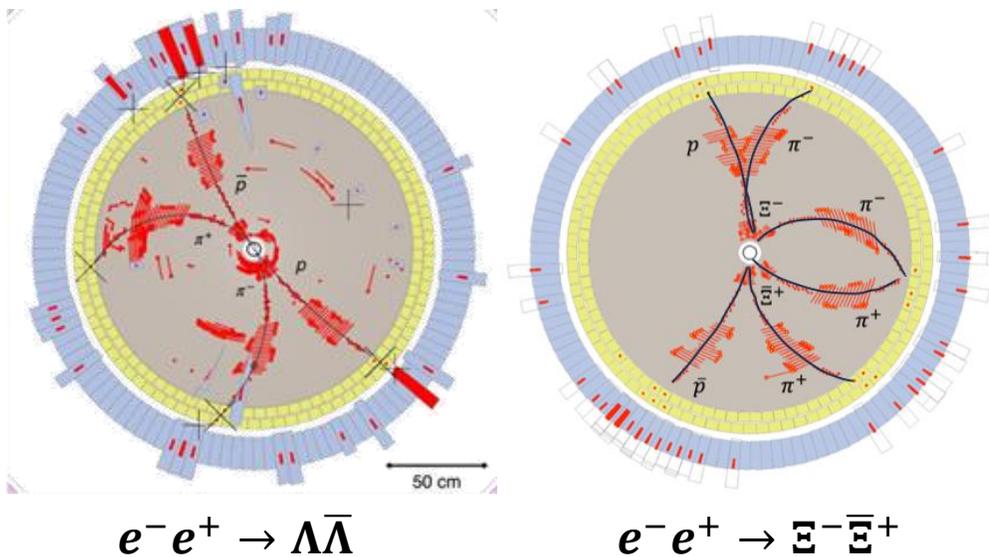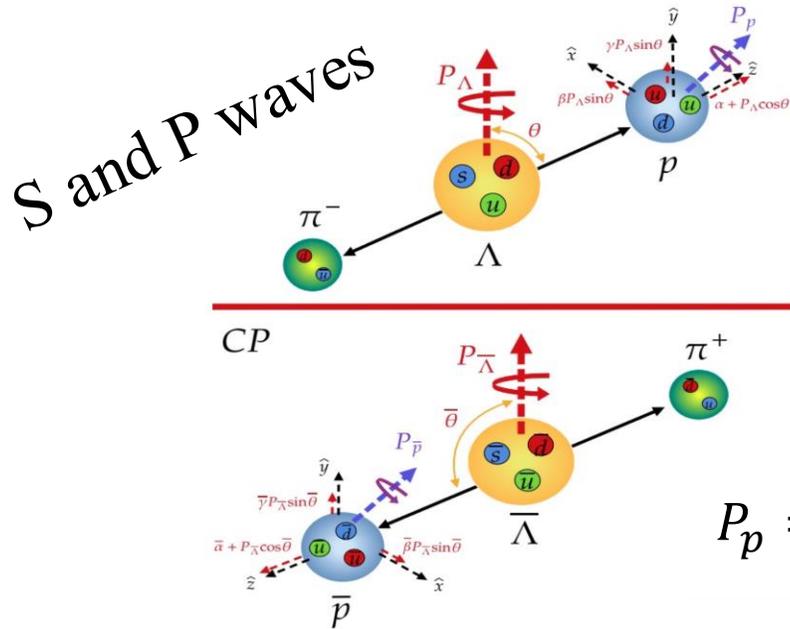is the number of the expected hyperon events. Data are from the Particle Data Group (PDG2016) [3]. [Front. Phys. 12(5), 121301 (2017)]

Decay mode	$\mathcal{B}(\times 10^{-3})$	N_B $(\times 10^6)$
$J/\psi \to \Lambda\bar{\Lambda}$	1.61 ± 0.15	16.1 ± 1.5
$J/\psi \to \Sigma^0\bar{\Sigma}^0$	1.29 ± 0.09	12.9 ± 0.9
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	1.50 ± 0.24	15.0 ± 2.4
$J/\psi \to \Sigma(1385)^-\bar{\Sigma}^+$ (or c.c.)	0.31 ± 0.05	3.1 ± 0.5
$J/\psi \to \Sigma(1385)^-\bar{\Sigma}(1385)^+$ (or c.c.)	1.10 ± 0.12	11.0 ± 1.2
$J/\psi \to \Xi^0\bar{\Xi}^0$	1.20 ± 0.24	12.0 ± 2.4
$J/\psi \to \Xi^-\bar{\Xi}^+$	0.86 ± 0.11	8.6 ± 1.0
$J/\psi \to \Xi(1530)^0\bar{\Xi}^0$	0.32 ± 0.14	3.2 ± 1.4
$J/\psi \to \Xi(1530)^-\bar{\Xi}^+$	0.59 ± 0.15	5.9 ± 1.5
$\psi(2S) \to \Omega^-\bar{\Omega}^+$	0.05 ± 0.01	0.15 ± 0.03

$e^-e^+ \to \Lambda\bar{\Lambda}$

$e^-e^+ \to \Xi^-\bar{\Xi}^+$

Baryon decay parameters

- Proposed by Lee & Yang to study parity (P) violation in hyperon decay
  $\Lambda \rightarrow p\pi^+$ [Phys. Rev. 108, 1645 (1957)]

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

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

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

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

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

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

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

CP violating observables: $A_{CP}^\alpha = \frac{\alpha(\Lambda)+\alpha(\overline{\Lambda})}{\alpha(\Lambda)-\alpha(\overline{\Lambda})}$ ...
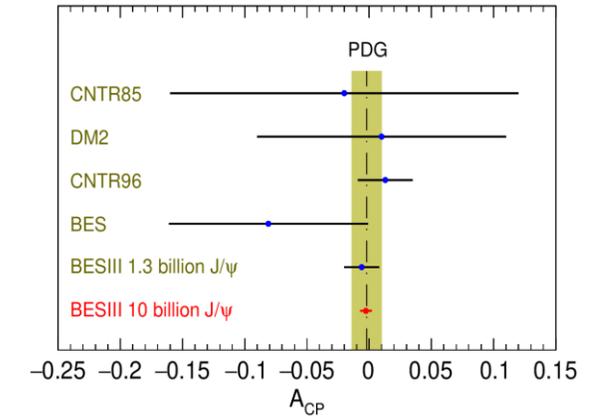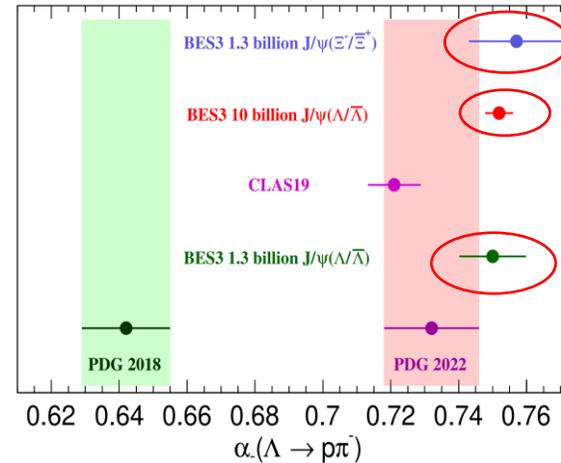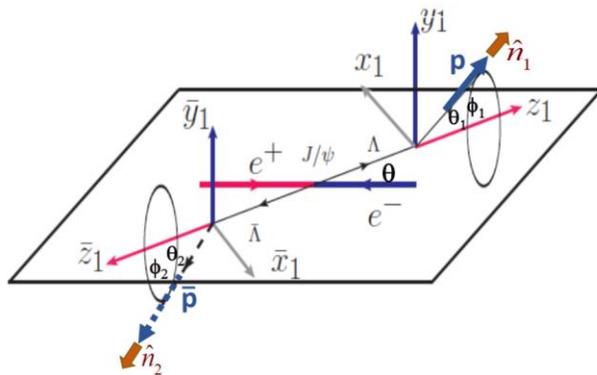
Complementary to decay rate asymmetry

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	$J/\psi \to \Lambda\bar{\Lambda}$	$\psi \to \Sigma^+\bar{\Sigma}^-$	$J/\psi \to \Sigma^+\bar{\Sigma}^-$	$J/\psi \to \Xi^-\bar{\Xi}^+$	$\psi(2S) \to \Xi^-\bar{\Xi}^+$	$J/\psi \to \Xi^0\bar{\Xi}^0$
A_{CP}	-0.0025 ±0.0046 ±0.0012	-0.004 ±0.037 ±0.010	-0.080 ±0.052 ±0.028	-0.006 ± 0.013 ± 0.006	-0.015 ±0.051 ±0.010	-0.0054 ±0.0065 ± 0.0031
	PRL129 (2022) 131801	PRL125 (2020) 052004	PRL131(2023) 191802	Nature 606 (2022) 64	PRD106(2022) L091101	PRD108 (2023) L031106

Charm sector

Asymmetries & techniques

	global CPV	Localised in phase space
Decay-time integrated	A_{CP}, ΔA_{CP}, ...	Dalitz plot, binned χ^2, energy test, ...
Decay-time dependent	y_{CP}, A_{Γ}, ...	D^0->$K_S hh$ ......

$\mathbf{A_{CP}}$

- Take $D^0 \to K^- K^+$ A_{CP} analysis as example

- Full decay chain $D^{*+} \to D^0 (\to K^- K^+) \pi_s^+$

- $A_{raw}(i \to f) = \dfrac{N(i \to f) - N(\bar{\imath} \to \bar{f})}{N(i \to f) + N(\bar{\imath} \to \bar{f})}$

- $A_{CP}(D \to K^- K^+) = A_{raw}(D \to K^- K^+) - A_{prod}(D) - A_{det}(\pi_s^+)$

- Use control modes to cancel production and detection asymmetries
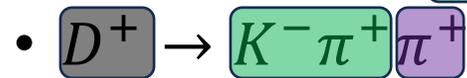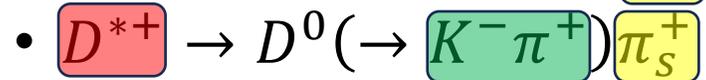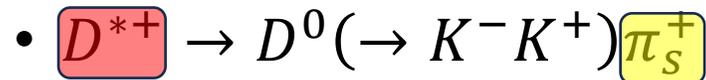
  - $\boxed{D^{*+}} \to D^0 (\to K^- K^+) \boxed{\pi_s^+}$ ⌐Nuisance asymmetries⌐
  - $\boxed{D^{*+}} \to D^0 (\to \boxed{K^- \pi^+}) \boxed{\pi_s^+}$
  - $\boxed{D^+} \to \boxed{K^- \pi^+} \boxed{\pi^+}$
  - $\boxed{D^+} \to \overline{K}^0 \boxed{\pi^+}$
  - $\overline{K}^0$ detection asymmetry known

$$
\begin{aligned}
& A_{\text{CP}}(D^0 \to K^- K^+) \\
&= A_{\text{raw}}(D^0 \to K^- K^+) - A_{raw}(D^0 \to K^- \pi^+) \\
&+ A_{raw}(D^+ \to K^- \pi^+ \pi^+) - A_{raw}(D^+ \to \overline{K}^0 \pi^+) \\
&+ A_{\text{det}}(\overline{K}^0)
\end{aligned}
$$

Summary of LHCb results

Table 1: Summary of LHCb direct CP violation searches in two-body charm decays.

Decay channel	Data sample	A_{CP}
$D^+ \to \phi\pi^+$ [1]	$1\,\mathrm{fb}^{-1}$	$(-0.04 \pm 0.14 \pm 0.14)\%$
$D_s^+ \to K_S^0\pi^+$ [1]	$1\,\mathrm{fb}^{-1}$	$(0.61 \pm 0.83 \pm 0.14)\%$
$D^0 \to K^-K^+$ [2]	$3\,\mathrm{fb}^{-1}$	$(-0.06 \pm 0.15 \pm 0.10)\%$
$D^\pm \to K_S^0 K^\pm$ [3]	$3\,\mathrm{fb}^{-1}$	$(0.03 \pm 0.17 \pm 0.14)\%$
$D_s^\pm \to K_S^0\pi^\pm$ [3]	$3\,\mathrm{fb}^{-1}$	$(0.38 \pm 0.46 \pm 0.17)\%$
$D^0 \to K_S^0 K_S^0$ [4]	$3\,\mathrm{fb}^{-1}$	$(-0.029 \pm 0.052 \pm 0.022)\%$
$D^0 \to K^-K^+$ [2]	$3\,\mathrm{fb}^{-1}$	$(0.14 \pm 0.15 \pm 0.10)\%$
$D^\pm \to \eta'\pi^\pm$ [5]	$3\,\mathrm{fb}^{-1}$	$(-0.61 \pm 0.72 \pm 0.53 \pm 0.12)\%$
$D_s^\pm \to \eta'\pi^\pm$ [5]	$3\,\mathrm{fb}^{-1}$	$(-0.82 \pm 0.36 \pm 0.22 \pm 0.27)\%$
$D^0 \to K_S^0 K_S^0$ [6]	$2\,\mathrm{fb}^{-1}$	$(4.3 \pm 3.4 \pm 1.0)\%$
$D^0 \to K_S^0 K_S^0$ [7]	$6\,\mathrm{fb}^{-1}$	$(-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$
$D^+ \to \eta\pi^+$ [8]	$6\,\mathrm{fb}^{-1}$	$(0.34 \pm 0.66 \pm 0.16 \pm 0.05)\%$
$D_s^+ \to \eta'\pi^+$ [8]	$6\,\mathrm{fb}^{-1}$	$(0.32 \pm 0.51 \pm 0.12)\%$
$D^+ \to \eta\pi^+$ [8]	$6\,\mathrm{fb}^{-1}$	$(0.49 \pm 0.18 \pm 0.06 \pm 0.05)\%$
$D_s^+ \to \eta'\pi^+$ [8]	$6\,\mathrm{fb}^{-1}$	$(0.01 \pm 0.12 \pm 0.08)\%$
$D^+ \to \pi^+\pi^0$ [9]	$9\,\mathrm{fb}^{-1}$	$(-1.3 \pm 0.9 \pm 0.6)\%$
$D^+ \to K^+\pi^0$ [9]	$9\,\mathrm{fb}^{-1}$	$(-3.2 \pm 4.7 \pm 2.1)\%$
$D^+ \to \pi^+\eta$ [9]	$6\,\mathrm{fb}^{-1}$	$(-0.2 \pm 0.8 \pm 0.4)\%$
$D^+ \to K^+\eta$ [9]	$6\,\mathrm{fb}^{-1}$	$(-6 \pm 10 \pm 4)\%$
$D_s^+ \to K^+\pi^0$ [9]	$9\,\mathrm{fb}^{-1}$	$(-0.8 \pm 3.9 \pm 1.2)\%$
$D_s^+ \to \pi^+\eta$ [9]	$6\,\mathrm{fb}^{-1}$	$(0.8 \pm 0.7 \pm 0.5)\%$
$D_s^+ \to K^+\eta$ [9]	$6\,\mathrm{fb}^{-1}$	$(0.9 \pm 3.7 \pm 1.1)\%$
$D^0 \to K^-K^+$ [10]	$5.7\,\mathrm{fb}^{-1}$	$(0.068 \pm 0.054 \pm 0.016)\%$

[1] JHEP 06 (2013) 112
[2] Phys. Lett. B767 (2017) 177
[3] JHEP 10 (2014) 025
[4] JHEP 10 (2015) 055
[5] Phys. Lett. B771 (2017) 21
[6] JHEP 11 (2018) 048
[7] Phys. Rev. D104 (2021) L031102
[8] JHEP 04 (2023) 081
[9] JHEP 06 (2021) 019
[10] Phys. Rev. Lett. 131 (2023) 091802

$\Delta \mathbf{A_{CP}}$

- $A_{CP}(KK) = A_{raw}(KK) - A_{prod}(D) - A_{det}(\pi_s^+)$

- $A_{CP}(\pi\pi) = A_{raw}(\pi\pi) - A_{prod}(D) - A_{det}(\pi_s^+)$

- ΔA_{CP} is the difference between these two A_{CP}

- Advantage 1:
  - Cancel production and detection asymmetries
  - $A_{CP}(KK) - A_{CP}(\pi\pi) \approx A_{raw}(KK) - A_{raw}(\pi\pi)$

- Advantage 2:
  - $A_{CP}(KK)$ and $A_{CP}(\pi\pi)$ has similar amplitude but opposite sign
  - $A_{CP}(KK) - A_{CP}(\pi\pi) \approx 2|A_{CP}(KK)| \approx 2|A_{CP}(\pi\pi)|$

- The discovery of CP violation in charm sector in 2019 uses ΔA_{CP}

Summary of LHCb results

Table 2: Summary of the $\Delta\mathcal{A}_{CP}$ results from the LHCb two-body D^0 decay measurements in the charm sector.

Data sample	$\Delta\mathcal{A}_{CP}$ ($\times 10^{-3}$)
0.62 fb^{-1}, D^* tag [11]	$-8.2 \pm 4.1 \pm 0.6$
1.0 fb^{-1}, B tag [12]	$4.9 \pm 3.0 \pm 1.4$
3.0 fb^{-1}, B tag [13]	$1.4 \pm 1.6 \pm 0.8$
3.0 fb^{-1}, D^* tag [14]	$-1.0 \pm 0.8 \pm 0.3$
5.9 fb^{-1}, B or D^* tag [15]	-1.54 ± 0.29

CP violation found!

[11] Phys. Rev. Lett. 108 (2012) 111602
[12] Phys. Lett. B723 (2013) 33
[13] JHEP 07 (2014) 041
[14] Phys. Rev. Lett. 116 (2016) 191601
[15] Phys. Rev. Lett. 122 (2019) 211803

Asymmetries & techniques

|	global CPV	Localised in phase space
Decay-time integrated	A_{CP}, ΔA_{CP}, ……	Dalitz plot, binned χ^2, energy test, ……
Decay-time dependent	y_{CP}, A_Γ, ……	$D^0 \rightarrow K_S hh$ ……

Binned χ^2 method

- Simplest and most used method in CPV searches in multi-body decays
- Divide phase space (usually Dalitz plot) into bins, calculate S_{CP}^i in each bin
- $S_{CP}^i = \dfrac{N^i(X) - \alpha N^i(\overline{X})}{\sqrt{N^i(X) - \alpha^2 N^i(\overline{X})}}$

- α is global asymmetry $\alpha = \dfrac{N_{tot}(X)}{\overline{N}_{tot}(\overline{X})}$, compare S_{CP}^i and normal distribution
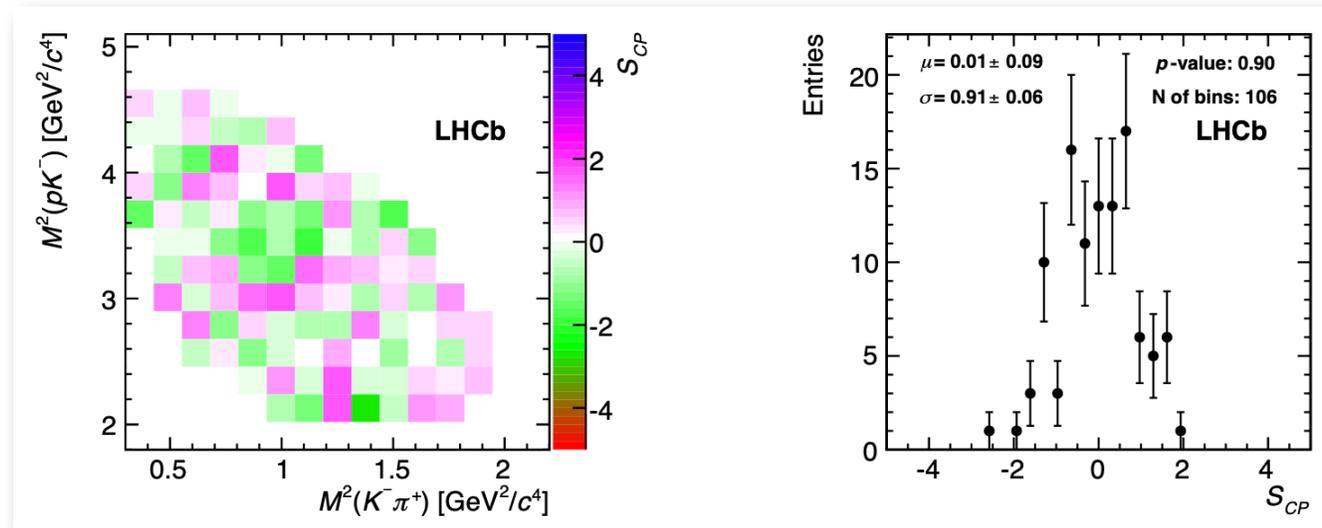
Energy test method
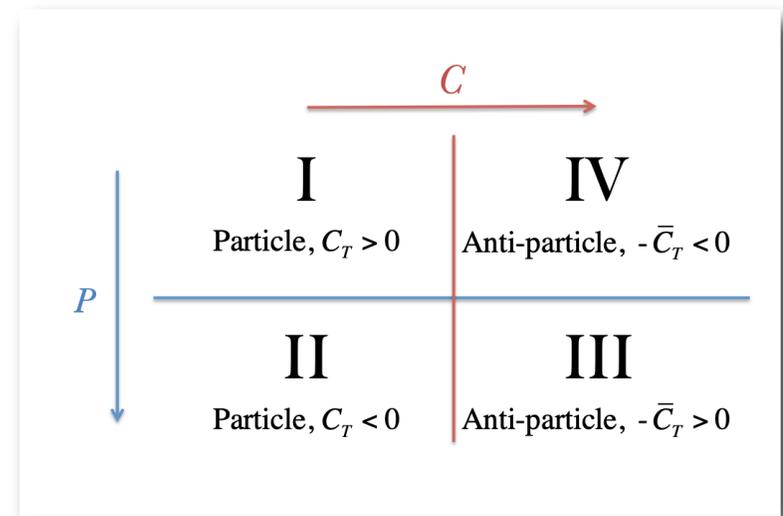
- Compare two distributions statistically
- Idea comes from the calculation of electric potential energy
- +q and −q equally distributed, electric potential energy = 0
- +q and −q distributions different, electric potential energy > 0
- System → phase space
  +q /−q → opposite flavoured decays
- Form test statistics T
- $T = \frac{1}{n(n-1)} \Sigma_{i,j>i}^{n} \psi(d_{ij}) + \frac{1}{\bar{n}(\bar{n}-1)} \Sigma_{i,j>i}^{\bar{n}} \psi(d_{ij}) - \frac{1}{n\bar{n}} \Sigma_{i,j}^{n,\bar{n}} \psi(d_{ij})$
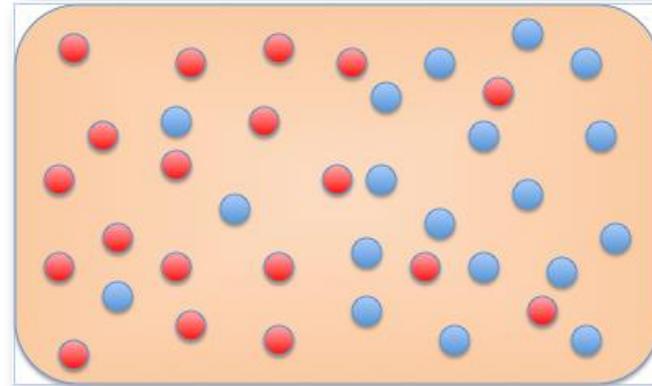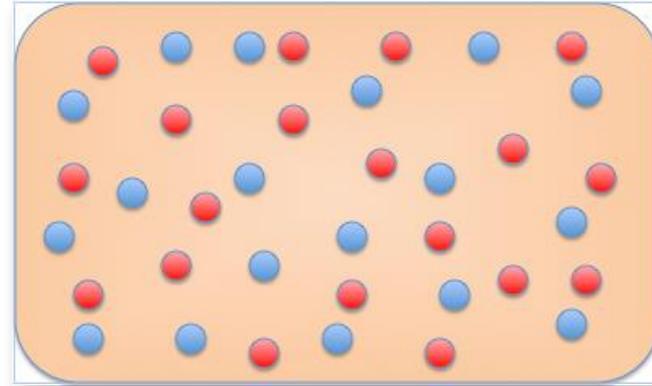
Three-body decays and Four-body decays

- Multibody pseudo-scalar decays, Independent Variables: 3n-7
- Three-body decays → 2 independent variables → Dalitz plot analysis
- Four-body decays → 5 independent variables → No preferred choice (unlike 3-body Dalitz plot): mass combinations, helicity angles, triple product
- Binned method: limited statistics in each bin
- Four-body decays: Can test P-even and P-odd contributions to CP violation separately using sign of Triple p product
- $C_T = \vec{p}_3 \cdot (\vec{p}_1 \times \vec{p}_2)$, where $CP(C_T) = -C(C_T) = -\bar{C}_T$

- P-even: I+II vs. III+IV
- P-odd: I+IV vs. II+III

	C
I	**IV**
Particle, $C_T > 0$	Anti-particle, $-\bar{C}_T < 0$
II	**III**
Particle, $C_T < 0$	Anti-particle, $-\bar{C}_T > 0$

P

Summary of LHCb results

Table 3: Summary of LHCb direct CP violation searches in phase space of charm decays.

Decay channel	Data sample	Method
$D^+ \to K^- K^+ \pi^+$ [16]	$35\,\mathrm{pb}^{-1}$	binned χ^2
$D^0 \to K^- K^+ \pi^- \pi^+$ [17]	$1.0\,\mathrm{fb}^{-1}$, D^* tag	binned χ^2
$D^0 \to \pi^- \pi^+ \pi^- \pi^+$ [17]	$1.0\,\mathrm{fb}^{-1}$, D^* tag	binned χ^2
$D^+ \to \pi^- \pi^+ \pi^+$ [18]	$1.0\,\mathrm{fb}^{-1}$	binned χ^2
$D^0 \to K^- K^+ \pi^- \pi^+$ [19]	$3.0\,\mathrm{fb}^{-1}$, B tag	binned χ^2
$D^0 \to \pi^- \pi^+ \pi^0$ [20]	$2.0\,\mathrm{fb}^{-1}$, D^* tag	energy test
$D^0 \to \pi^- \pi^+ \pi^- \pi^+$ [21]	$3.0\,\mathrm{fb}^{-1}$, D^* tag	energy test
$\Lambda_c^+ \to p h^- h^+$ [22]	$3.0\,\mathrm{fb}^{-1}$	$\Delta \mathcal{A}_{CP}$
$D^0 \to K^- K^+ \pi^- \pi^+$ [23]	$3.0\,\mathrm{fb}^{-1}$, B tag	amplitude analysis
$\Xi_c^+ \to p K^- \pi^+$ [24]	$3.0\,\mathrm{fb}^{-1}$	binned χ^2
$D^0 \to K_S^0 K^\pm \pi^\mp$ [25]	$5.4\,\mathrm{fb}^{-1}$, D^* tag	energy test
$D^0 \to \pi^- \pi^+ \pi^0$ [26]	$7.7\,\mathrm{fb}^{-1}$, D^* tag	energy test
$D^+_{(s)} \to K^- K^+ K^+$ [27]	$5.6\,\mathrm{fb}^{-1}$, D^* tag	binned χ^2
$D^+ \to K^- K^+ \pi^+$ [28]	$5.4\,\mathrm{fb}^{-1}$, D^* tag	binned χ^2
$\Lambda_c^+ \to p \mu^+ \mu^-$ [29]	$5.4\,\mathrm{fb}^{-1}$	$\mathcal{A}_{CP}$

No CP violation found in the phase space yet

[16] Phys. Rev. D84 (2011) 112008
[17] Phys. Lett. B726 (2013) 623
[18] Phys. Lett. B728 (2014) 585
[19] JHEP 10 (2014) 005
[20] Phys. Lett. B740 (2015) 158
[21] Phys. Lett. B769 (2017) 345
[22] JHEP 03 (2018) 182
[23] JHEP 02 (2019) 126
[24] Eur. Phys. J. C80 (2020) 986
[25] JHEP 03 (2024) 107
[26] Phys. Rev. Lett. 133 (2024) 101803
[27] JHEP 07 (2023) 067
[28] Phys. Rev. Lett. 133 (2024) 251801
[29] Phys. Rev. D111 (2025) L091102

Asymmetries & techniques

	global CPV	Localised in phase space
Decay-time integrated	A_{CP}, ΔA_{CP}, ...	Dalitz plot, binned χ^2, energy test, ...
Decay-time dependent	y_{CP}, A_{Γ}, ...	$D^0 \rightarrow K_S hh$ ......

y_{CP}

- Due to the existence of mixing, the decay widths of D^0 decays to CP eigenstates (KK or $\pi\pi$) Γ_{CP+} and to other final states (i.e. CF decay $K\pi$) Γ can be different

- Define $y_{CP} = \Gamma_{CP+}/\Gamma - 1$

$$y_{CP} \approx \frac{1}{2}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) y \cos\phi - \frac{1}{2}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x \sin\phi$$

- is related to $x, y, |q/p|, \phi$, and if no CP violation, $y_{CP} = y$

- Experimental measures: $y_{CP} = \dfrac{2\tau(D^0 \to f_{CF})}{\tau(\overline{D}^0 \to f_{CP}) + \tau(D^0 \to f_{CP})} - 1$

- $f_{CF} = K\pi$ final states, $f_{CP} = KK$ or $\pi\pi$ final states

A_Γ

- The lifetime asymmetry of D^0 and $\bar{D}^0$ decays to CP eigenstates (KK or $\pi\pi$)

- $A_\Gamma = -A_{CP}^{indirect}$, and satisfy

$$A_\Gamma \approx \frac{1}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y \cos\phi - \frac{1}{2}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x \sin\phi$$

- Experimental measures: $A_\Gamma = \dfrac{\tau(\bar{D}^0 \to f_{CP}) - \tau(D^0 \to f_{CP})}{\tau(\bar{D}^0 \to f_{CP}) + \tau(D^0 \to f_{CP})}$

- So far no experimental evidence of CP violation in mixing found in y_{CP} and A_Γ measurements

Summary of LHCb results

Table 4: Summary of LHCb y_{CP} and A_Γ measurements.

Data sample	Final state(s)	y_{CP} (%)	A_Γ ($\times 10^{-3}$)
29 pb^{-1}, D^* tag [30]	K^+K^-	$0.55 \pm 0.63 \pm 0.41$	$-5.9 \pm 5.9 \pm 2.1$
1.0 fb^{-1}, D^* tag [31]	$\pi^+\pi^-$	-	$0.33 \pm 1.06 \pm 0.14$
1.0 fb^{-1}, D^* tag [31]	K^+K^-	-	$-0.35 \pm 0.62 \pm 0.12$
3.0 fb^{-1}, B tag [32]	$\pi^+\pi^-$	-	$-0.92 \pm 2.6^{+0.25}_{-0.33}$
3.0 fb^{-1}, B tag [32]	K^+K^-	-	$-1.34 \pm 0.77^{+0.26}_{-0.34}$
3.0 fb^{-1}, B tag [32]	$\pi^+\pi^-$ & K^+K^-	-	-1.25 ± 0.73
3.0 fb^{-1}, B tag [33]	$\pi^+\pi^-$ & K^+K^-	$0.57 \pm 0.13 \pm 0.09$	-
3.0 fb^{-1}, D^* tag [34]	$\pi^+\pi^-$	-	$0.46 \pm 0,58 \pm 0.12$
3.0 fb^{-1}, D^* tag [34]	K^+K^-	-	$-0.30 \pm 0.32 \pm 0.10$
3.0 fb^{-1}, D^* tag [34]	$\pi^+\pi^-$ & K^+K^-	-	$-0.13 \pm 2.0 \pm 0.7$
5.4 fb^{-1}, B tag [35]	$\pi^+\pi^-$	-	$0.22 \pm 0.70 \pm 0.08$
5.4 fb^{-1}, B tag [35]	K^+K^-	-	$-0.43 \pm 0.36 \pm 0.05$
6 fb^{-1}, D^* tag [36]	$\pi^+\pi^-$	-	$0.4 \pm 0.28 \pm 0.04$
6 fb^{-1}, D^* tag [36]	K^+K^-	-	$0.23 \pm 0.15 \pm 0.03$
8.4 fb^{-1}, D^* or B tag [36]	$\pi^+\pi^-$	-	$0.36 \pm 0.24 \pm 0.04$
8.4 fb^{-1}, D^* or B tag [36]	K^+K^-	-	$0.03 \pm 0.13 \pm 0.03$
8.4 fb^{-1}, D^* or B tag [36]	$\pi^+\pi^-$ & K^+K^-	-	$0.10 \pm 0.11 \pm 0.03$
6 fb^{-1}, D^* tag [37]	$\pi^+\pi^-$	$0.657 \pm 0.053 \pm 0.016$ [1]	-
6 fb^{-1}, D^* tag [37]	K^+K^-	$0.708 \pm 0.030 \pm 0.014$ [2]	-
6 fb^{-1}, D^* tag [37]	$\pi^+\pi^-$ & K^+K^-	$0.696 \pm 0.026 \pm 0.013$ [3]	-

1. $y_{CP}^{\pi\pi} - y_{CP}^{K\pi}$ is measured in this analysis.
2. $y_{CP}^{KK} - y_{CP}^{K\pi}$ is measured in this analysis.
3. $y_{CP} - y_{CP}^{K\pi}$ is measured in this analysis.

[30] JHEP 04 (2012) 129
[31] Phys. Rev. Lett. 112 (2014) 041801
[32] JHEP 04 (2015) 043
[33] Phys. Rev. Lett. 122 (2019) 011802
[34] Phys. Rev. Lett. 118 (2017) 261803
[35] Phys. Rev. D101 (2020) 012005
[36] Phys. Rev. D104 (2021) 072010
[37] Phys. Rev. D105 (2022) 092013

Asymmetries & techniques

|	global CPV	Localised in phase space
Decay-time integrated	A_{CP}, ΔA_{CP}, ...	Dalitz plot, binned χ^2, energy test, ...
Decay-time dependent	y_{CP}, A_Γ, ...	$D^0 -> K_S h h$ ......

Mixing parameters measurements using $D^0 \to K_S \pi \pi$

- 'Golden channel' for mixing parameter measurements
  - Many interfering amplitudes in the phase space
  - CF and DCS decays to same phase space

- 'bin-flip' method
  - Oscillation mainly contribute to the upper region in the Dalitz plot
  - Ratio between upper and bottom parts as function of time sensitive to mixing
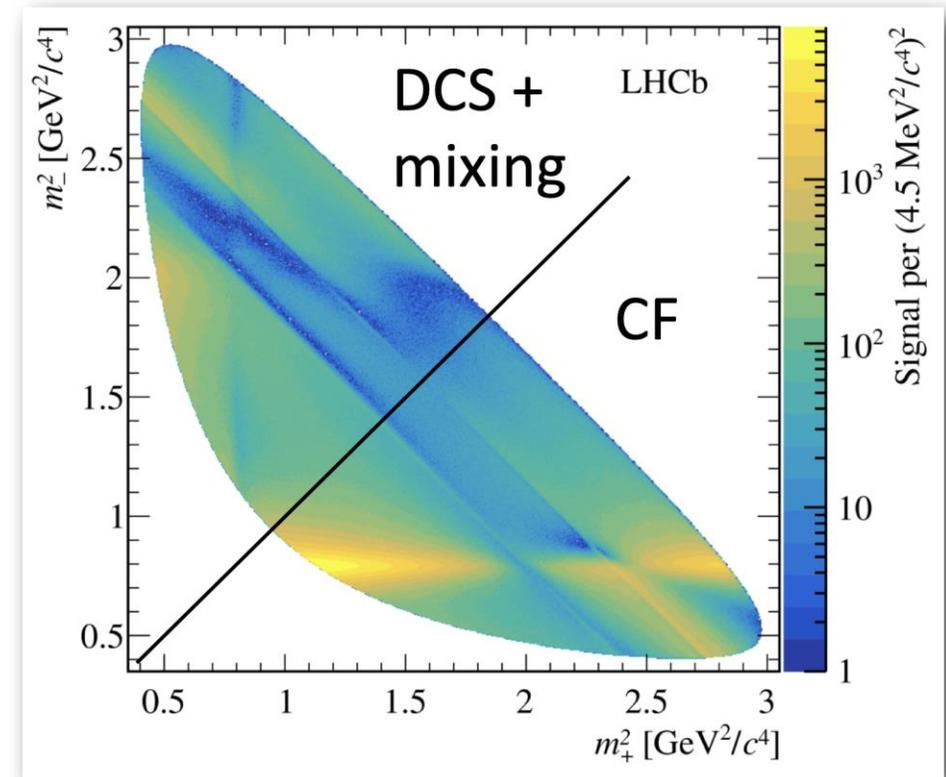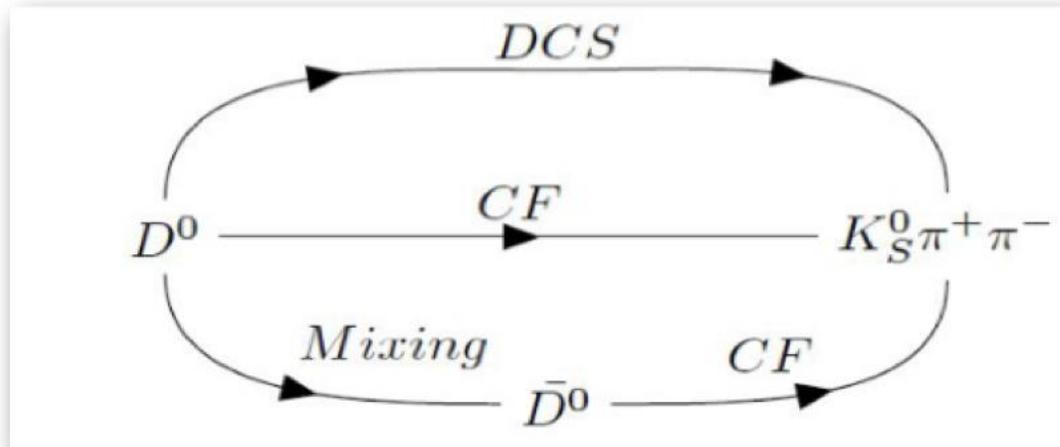
Mixing parameters measurements using $D^0 \to K_S \pi \pi$

- Bins: Strong phase measured by CLEO or BESIII
  - Reduce cancellation of different strong phase to the result

- Fit to the time dependent ratios, extract x and y from the fit function

- y > 0: lifetime of CP-even eigenstate is shorter lived than CP-odd

- x > 0: mass splitting
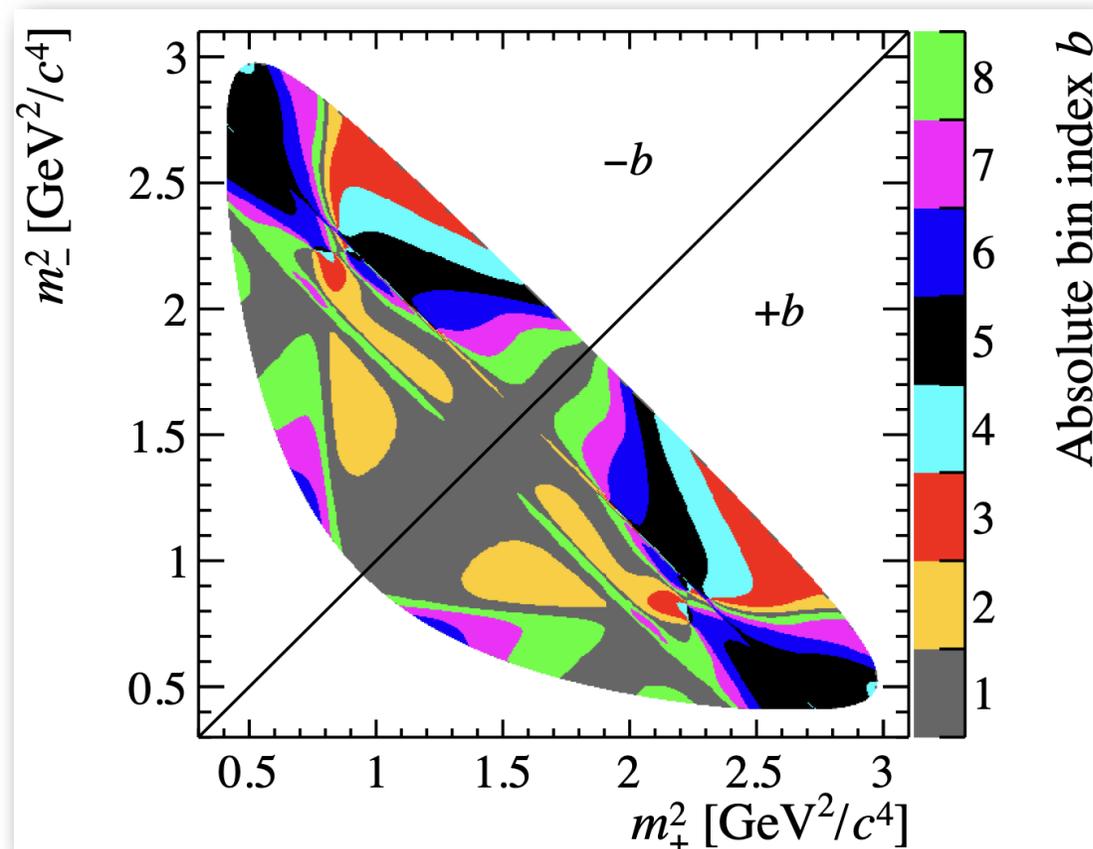
Mixing parameters measurements using $D^0 \to K_S \pi\pi$

- Fit results:
- $x = \left(3.98^{+0.56}_{-0.54}\right) \times 10^{-3}$
- $y = \left(4.6^{+1.5}_{-1.4}\right) \times 10^{-3}$
- First observation of non-zero x with significance $> 7\sigma$
  - non-zero difference between two D^0 mass eigenstates

- No CP violation found
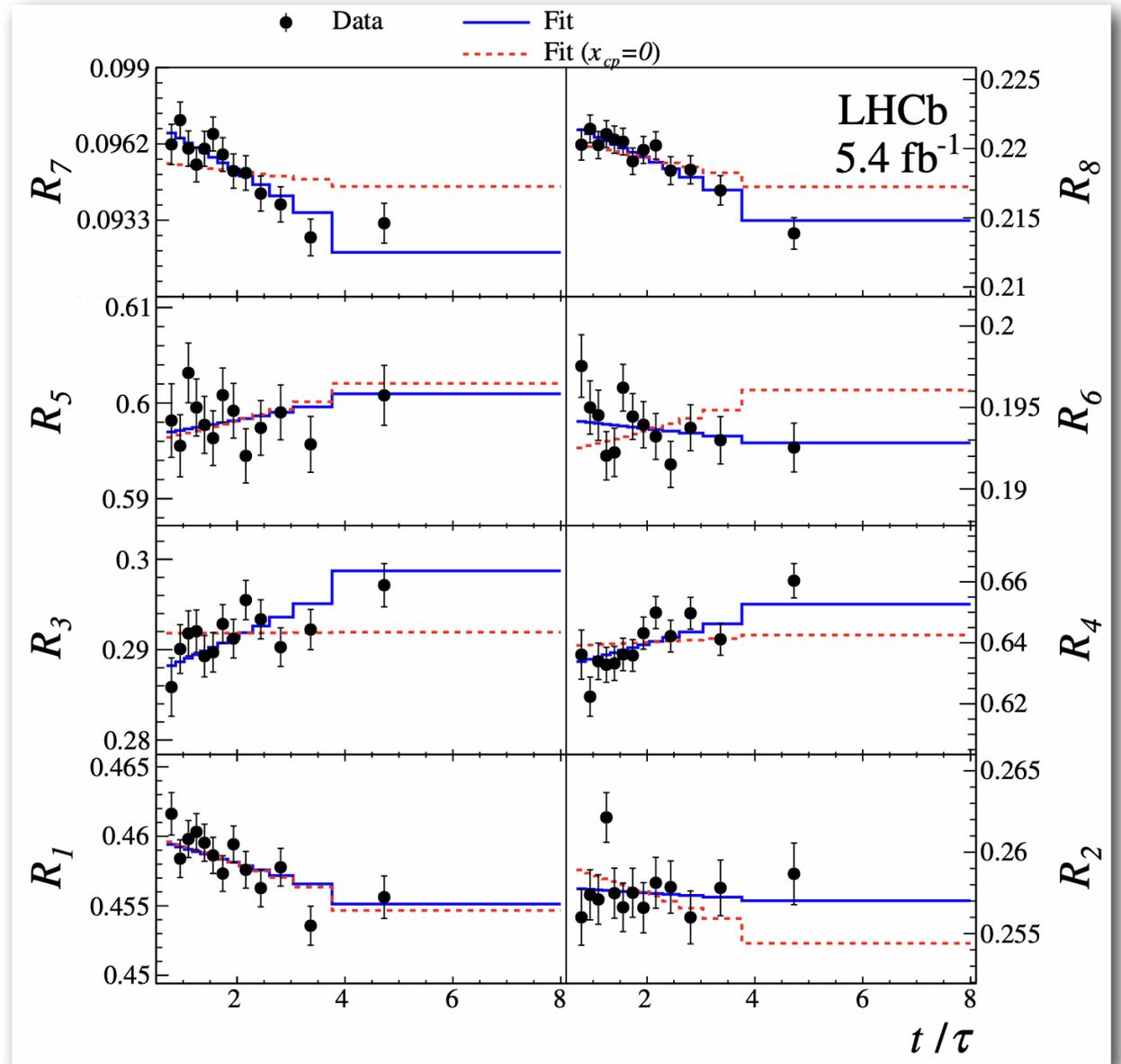
Summary of LHCb results

Table 5: Summary of the charm mixing parameters measured by LHCb using $D^0 \to K_S^0 \pi^+ \pi^-$ decays.

	CP-averaged parameters	
Data sample	x $(\times 10^{-3})$	y $(\times 10^{-3})$
1.0 fb^{-1}, D^* tag [38]	$-8.6 \pm 5.3 \pm 1.7$	$0.3 \pm 4.6 \pm 1.3$
3.0 fb^{-1}, B tag [39]	$2.7 \pm 1.6 \pm 0.4$	$7.4 \pm 3.6 \pm 1.1$
5.4 fb^{-1}, D^* tag [40]	$3.97 \pm 0.46 \pm 0.29$	$4.59 \pm 1.20 \pm 0.85$
	CP-violating parameters	
Data sample	Δx $(\times 10^{-3})$	Δy $(\times 10^{-3})$
3.0 fb^{-1}, B tag [39]	$-0.53 \pm 0.70 \pm 0.22$	$0.6 \pm 1.6 \pm 0.3$
5.4 fb^{-1}, D^* tag [40]	$-0.27 \pm 0.18 \pm 0.01$	$0.20 \pm 0.36 \pm 0.13$

First non-zero x!

[38] JHEP 04 (2016) 033
[39] Phys. Rev. Lett. 122 (2019) 231802
[40] Phys. Rev. Lett. 127 (2021) 111801

Bottom sector

CP violation via CKM unitarity triangle

- Amount of CP violation proportional to area of CKM unitarity triangles

- Measurements of parameters of CKM unitarity triangle are studies of CP violation

- "db" triangle: well established
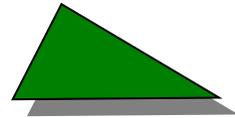
- "sb" triangle: challenging small ϕ_s

- See talks in the afternoon

$$V_{\text{CKM}} = \begin{bmatrix} & & \\ & & \\ & & \end{bmatrix}$$

Direct CP violation: b-meson studies

Decay Channel	Measured A_{CP}	Ref.
$B^+ \to \rho(770)^0 K^*(892)^+$	$0.507 \pm 0.062 \pm 0.0248$	[1]
$B^+ \to J/\psi \pi^+$	$(1.29 \pm 0.49 \pm 0.08) \times 10^{-2}$	[2]
$B^- \to DD$	$-0.5\% \sim 3.3\%$, no evidence	[3]
$B^\pm \to K^\pm \pi^+ \pi^-$	$+0.011 \pm 0.002 \pm 0.003 \pm 0.003$	[4]
$B^\pm \to K^\pm K^+ K^-$	$0.037 \pm 0.002 \pm 0.002 \pm 0.003$	[4]
$B^\pm \to \pi^\pm \pi^+ \pi^-$	$+0.080 \pm 0.004 \pm 0.003 \pm 0.003$	[4]
$B^\pm \to \pi^\pm K^+ K^-$	$0.114 \pm 0.007 \pm 0.003 \pm 0.003$	[4]
$B^\pm \to \rho(770)^0 K^\pm$	$+0.150 \pm 0.019 \pm 0.011$	[5]
$B^+ \to K^+ \pi^0$	$0.025 \pm 0.015 \pm 0.006 \pm 0.003$	[6]
$B^+ \to \pi^+ \pi^+ \pi^-$	Local $A_{CP} > 5\sigma$	[7]
$B^0 \to K^+ \pi^-$	$0.084 \pm 0.004 \pm 0.003$	[8]
$B^0_s \to \pi^+ K^-$	$0.213 \pm 0.015 \pm 0.007$	[8]
$B^- \to D^- D^0$	$(2.3 \pm 2.7 \pm 0.4)\%$	[9]
$B^- \to D^-_s D^0$	$(-0.4 \pm 0.5 \pm 0.5)\%$	[9]
$\overline{B}^0 \to K^*(892)^+$	0.308 ± 0.062	[10]
$B^\pm \to J/\psi K^\pm$	$(0.09 \pm 0.27 \pm 0.07) \times 10^2$	[11]
$B^\pm \to K^\pm \pi^+ \pi^-$	$+0.025 \pm 0.004 \pm 0.004 \pm 0.007$	[12]
$B^\pm \to K^\pm K^+ K^-$	$-0.036 \pm 0.004 \pm 0.002 \pm 0.007$	[12]
$B^\pm \to \pi^\pm \pi^+ \pi^-$	$+0.058 \pm 0.008 \pm 0.009 \pm 0.007$	[12]
$B^\pm \to \pi^\pm K^+ K^-$	$0.123 \pm 0.017 \pm 0.012 \pm 0.007$	[12]
$B^\pm \to \pi^\pm K^+ K^-$	$0.141 \pm 0.040 \pm 0.018 \pm 0.007$	[13]
$B^\pm \to \pi^\pm \pi^+ \pi^-$	$0.117 \pm 0.021 \pm 0.009 \pm 0.0077$	[13]
$B^+ \to K^+ \mu^+ \mu^-$	$0.000 \pm 0.033 \pm 0.005 \pm 0.007$	[14]
$B^\pm \to K^\pm \pi^+ \pi^-$	$0.032 \pm 0.008 \pm 0.004 \pm 0.007$	[15]
$B^\pm \to K^\pm K^+ K^-$	$0.043 \pm 0.009 \pm 0.003 \pm 0.007$	[15]
$B^0_s \to K^- \pi^+$	$0.27 \pm 0.04 \pm 0.01$	[16]
$B^\pm \to J/\psi \pi^\pm$	$0.005 \pm 0.027 \pm 0.011$	[17]
$B^\pm \to \psi(2S) \pi^\pm$	$0.048 \pm 0.090 \pm 0.011$	[17]

[1] Phys. Rev. Lett. 136, 021803 (2026)
[2] Phys. Rev. Lett. 134, 101801 (2025)
[3] JHEP 09 (2023) 202
[4] JHEP 07 (2023) 067
[5] Phys. Rev. D 108, 012013 (2023)
[6] Phys. Rev. Lett. 126, 091802 (2021)
[7] Phys. Rev. Lett. 124, 031801 (2020)
[8] Phys. Rev. D 98, 032004 (2018)
[9] JHEP 05 (2018) 160
[10] Phys. Rev. Lett. 120, 261801 (2018)
[11] Phys. Rev. D 95, 052005 (2017)
[12] Phys. Rev. D 90, 112004 (2014)
[13] Phys. Rev. Lett. 112, 011801 (2014)
[14] Phys. Rev. Lett. 111, 151801 (2013)
[15] Phys. Rev. Lett. 111, 101801 (2013)
[16] Phys. Rev. Lett. 110, 221601 (2013)
[17] Phys. Rev. D 85, 091105(R) (2012)

- CP violation found in multiple channels … but only in meson channels before 2025

# b-baryon CP violation searches @ 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
$\Lambda_b^0 \to pK^-/p\pi^-$	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
$\Lambda_b^0 \to pD^0K^-$	Miranda S_{CP}^i	9 fb^{-1}	PRD104 (2021) 112008
$\Lambda_b^0 \to \Lambda\gamma$	photon polarization	3 fb^{-1}	PRD105 (2022) L051104
$\Lambda_b^0 \to \Lambda_c^+h^-$	Decay parameter	9 fb^{-1}	PRL 133 (2024) 261804
$\Lambda_b^0 \to ph^-$	A_{CP}	9 fb^{-1}	PRD 111(2025) 092004
$\Lambda_b^0 \to \Lambda hh'$	A_{CP}	9 fb^{-1}	PRL 134 (2025) 101802
$\Lambda_b^0 \to pK^-\pi^+\pi^-$	A_{CP}	9 fb^{-1}	Nature 643 (2025) 1223
$\Lambda_b^0, \Xi_b^0 \to pK_s^0h^-$	A_{CP}	9 fb^{-1}	JHEP10(2025)169
$\Lambda_b^0 \to J/\psi ph^-$	A_{CP}, TPA	6 fb^{-1}	arXiv:2509.16103

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

- Large yield and high purity
- CP violation predicted: ~5%

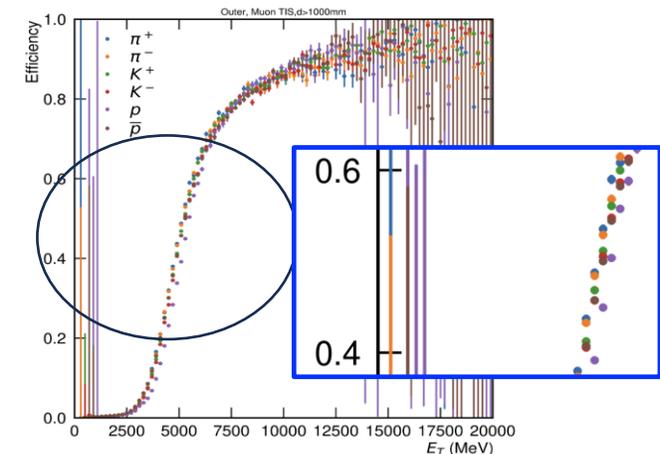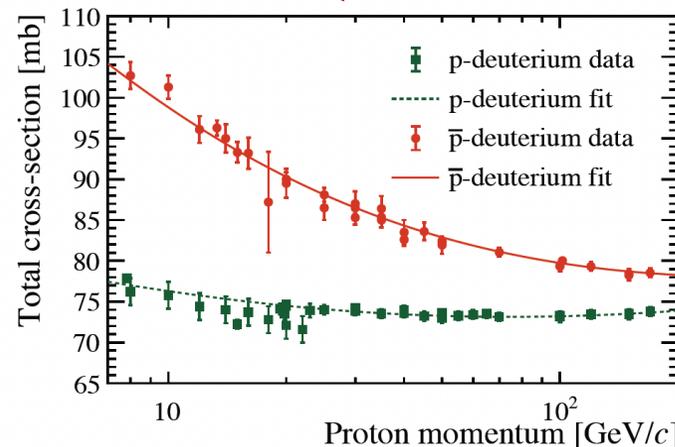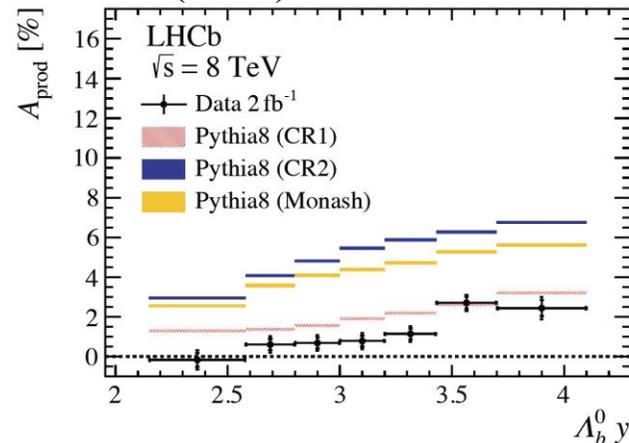 PRD 102 (2012) 034033
  PRD 95   (2017) 093001

$$B^0, B_s^0/\overline{\Lambda_b^0} \qquad\qquad K^+\pi^-/\bar{p}^-$$
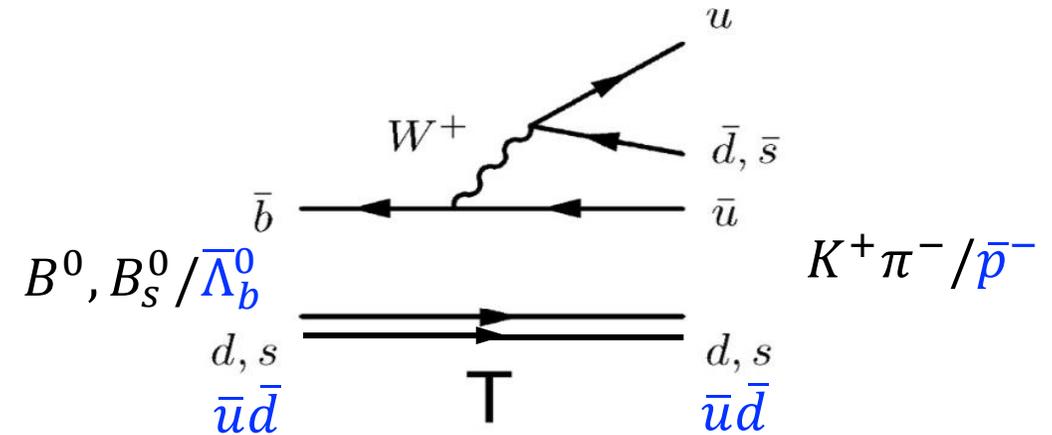
- Crucial to control systematics

- $A_{CP} = A_{raw} - A_{\text{prod}} - A_{\text{detection}} - A_{\text{PID}} - A_{\text{trigger}}$

JHEP 10 (2021) 060

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

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

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

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

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

$$A_{CP}^{p\pi^-} = (+0.2 \pm 0.8 \pm 0.4)\%$$
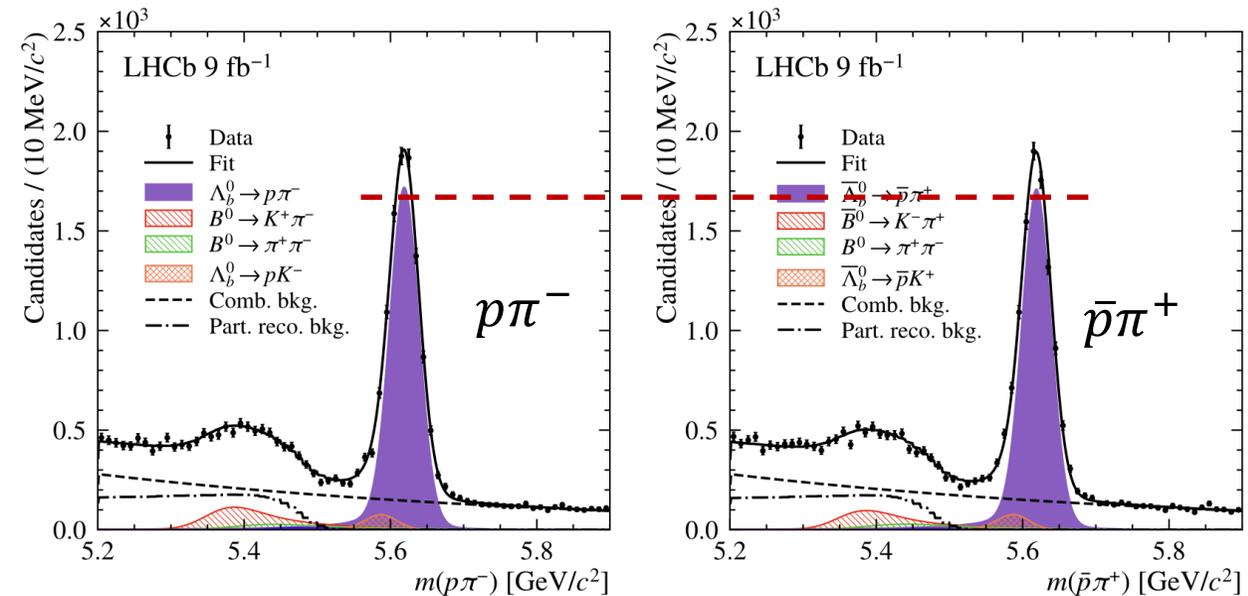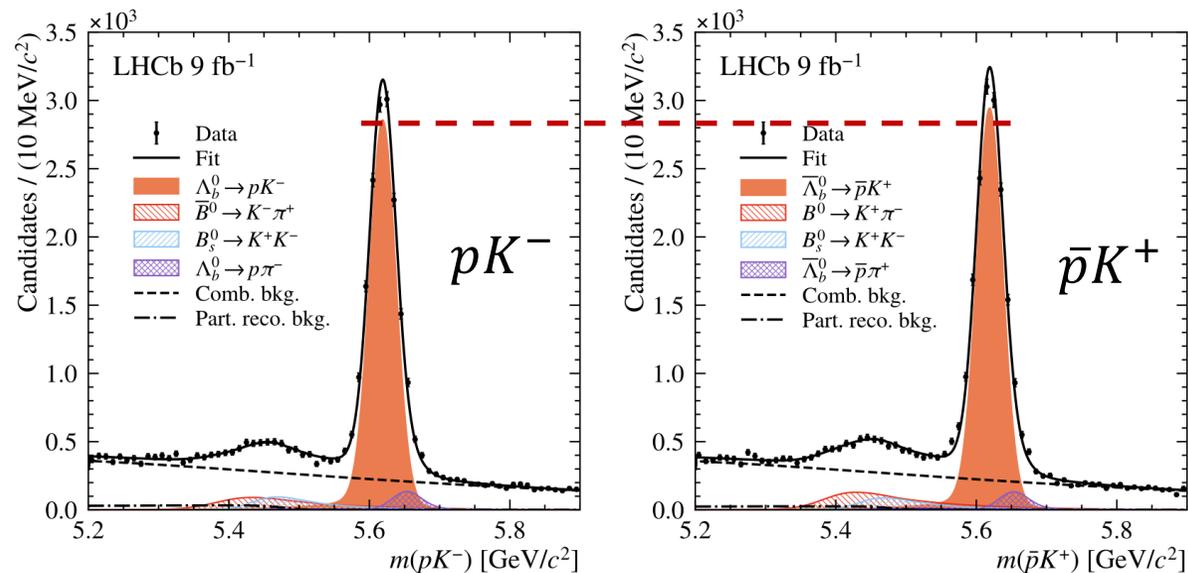
- **CP violation not found**

Why so small?

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

From CKM matrix, same for B^0 and Λ_b^0

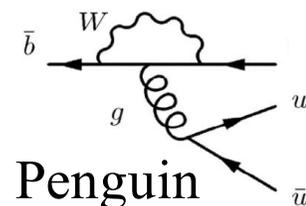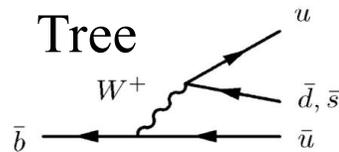- One diagram dominates? small strong phase difference?
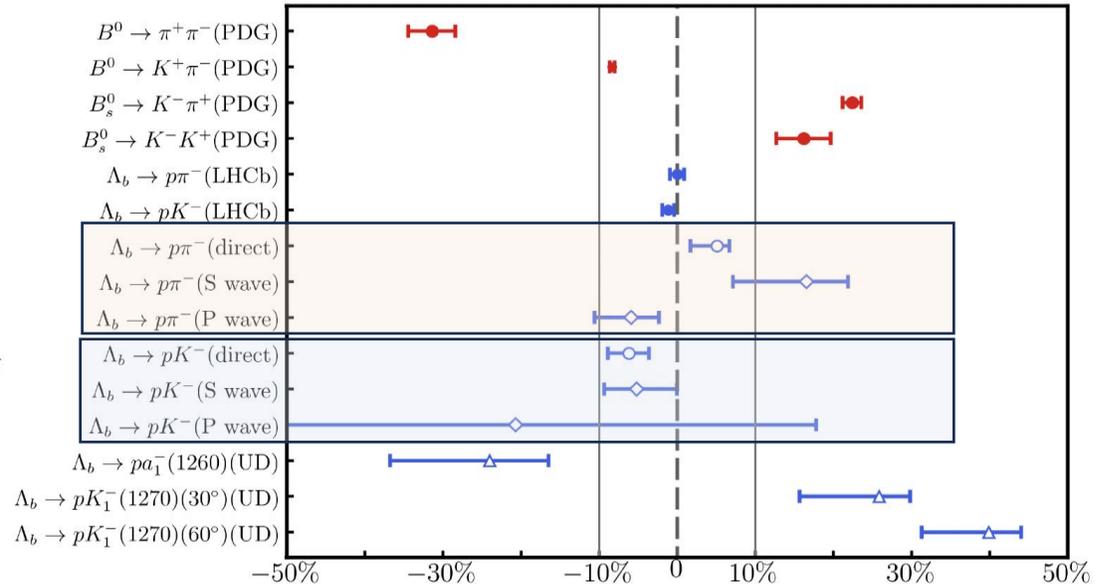
- Dynamics more complex than mesons

➢ Possible cancellation of S and P amplitudes

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

➢ Tree amplitudes may dominate

Tree

$\Lambda_b \to pK^-$				
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

Penguin

Favoring multi-body decays

39

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

- Three Λ_b^0 decays $\Lambda\pi^+\pi^-$、 $\Lambda K^+\pi^-$、 $\Lambda K^+ K^-$; one Ξ_b^0 decay

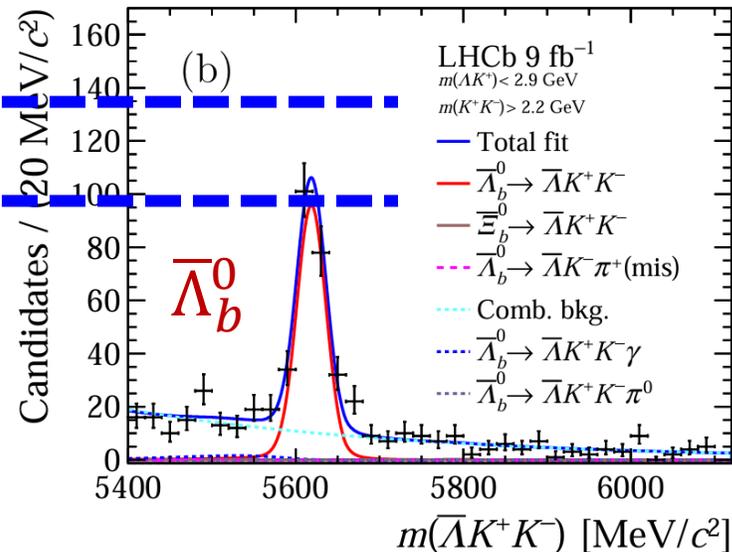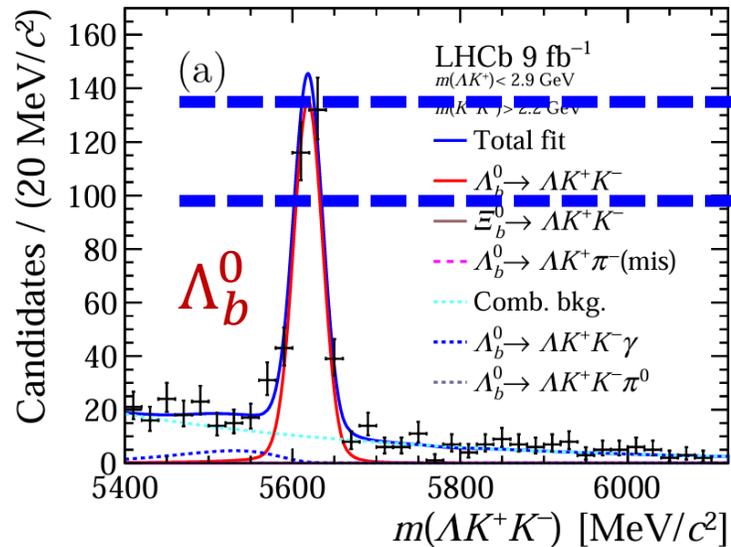- $\Lambda_b^0 \to \Lambda_c^+(\to \Lambda\pi^+)\pi^-$ as control channel

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

3.1σ, first evidence for CPV in baryon

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

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

- Two resonance-dominated regions

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

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

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

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

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

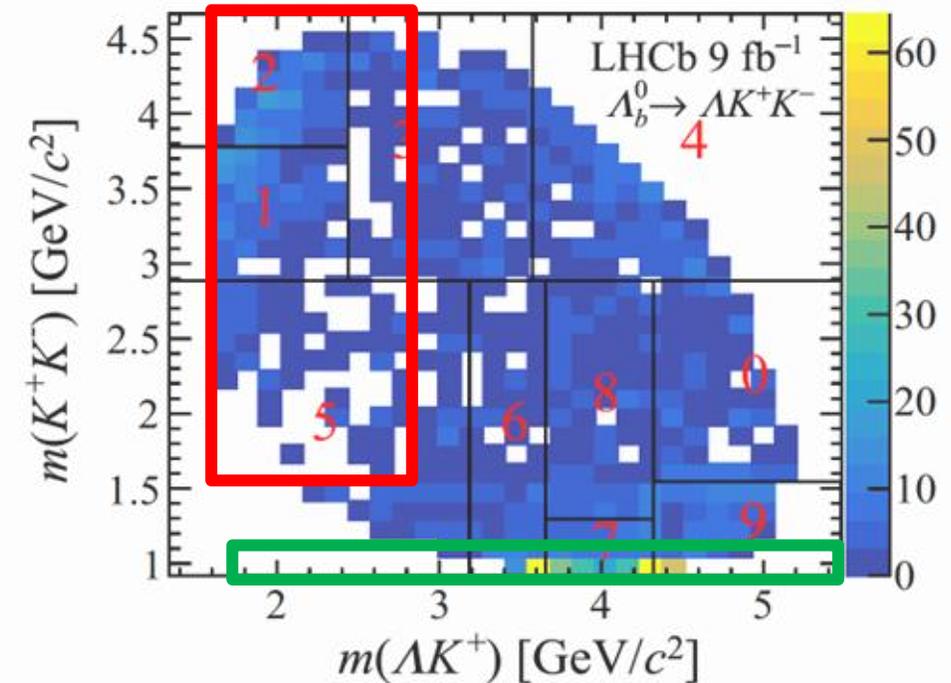$\Delta A_{CP}(N^{*+}K^-) = 0.165 \pm 0.048 \pm 0.017$ (local 3.2σ)

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

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

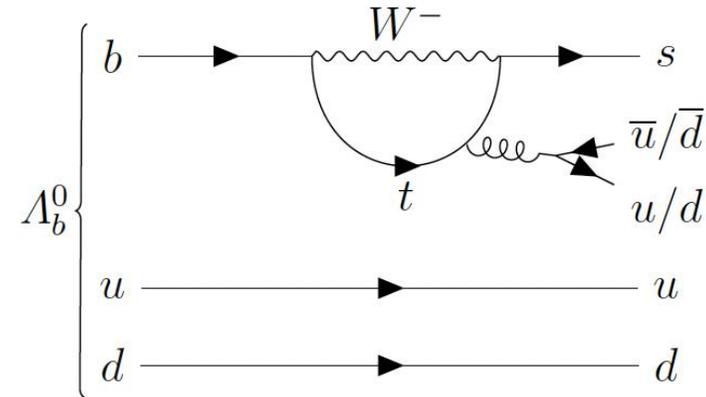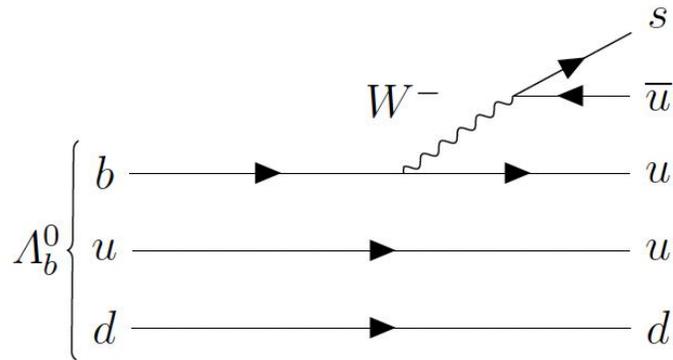 $N^{*+} \to \Lambda K^+ \quad \Rightarrow \Lambda_b^0 \to N^{*+}(\Lambda K^+)K^-$

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

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

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

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

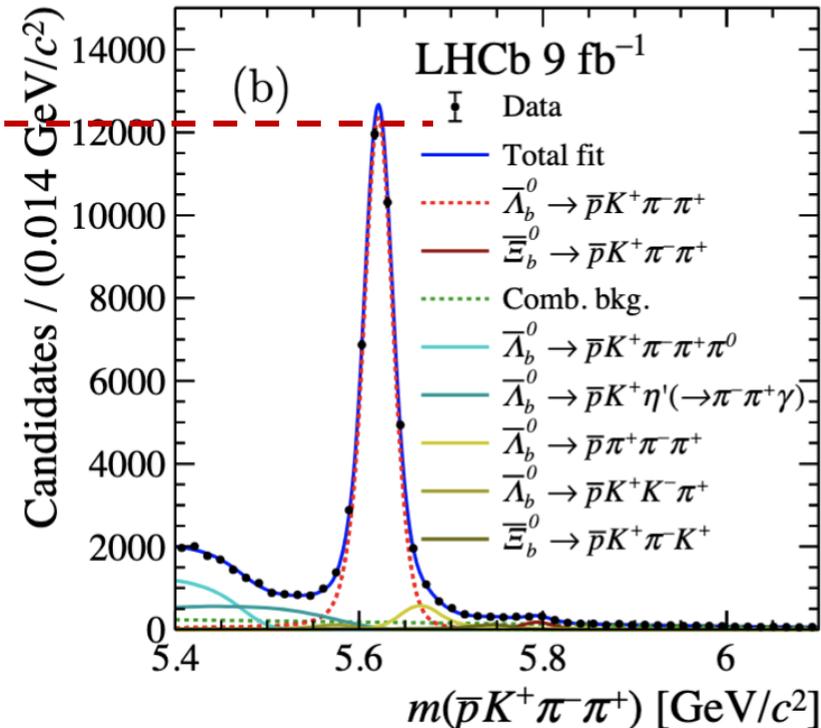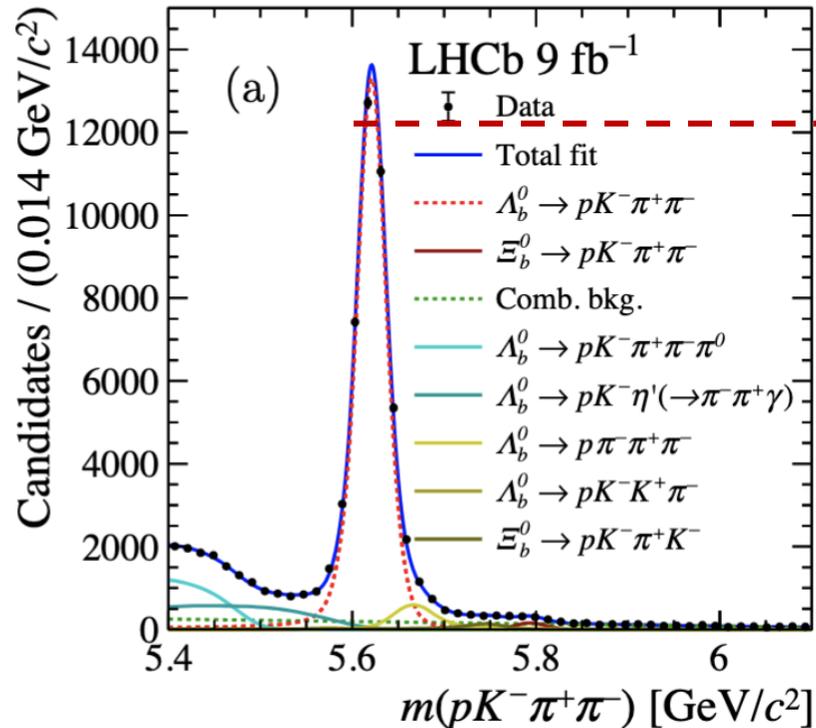- Rich resonance structures
  - $\Lambda_b^0 \to N^{*+}(p\,\pi^+\pi^-)K^-,\ p\,K^{*-}(K^-\pi^+\pi^-),\ \Lambda(p\,K^-)f(\pi^+\pi^-),\ N^{*0}(p\,\pi^-)K^{*0}(K^-\pi^+)$

- Control channel $\Lambda_b^0 \to \Lambda_c^+(p\,K^-\pi^+)\pi^-$ to subtract nuisance asymmetries

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

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

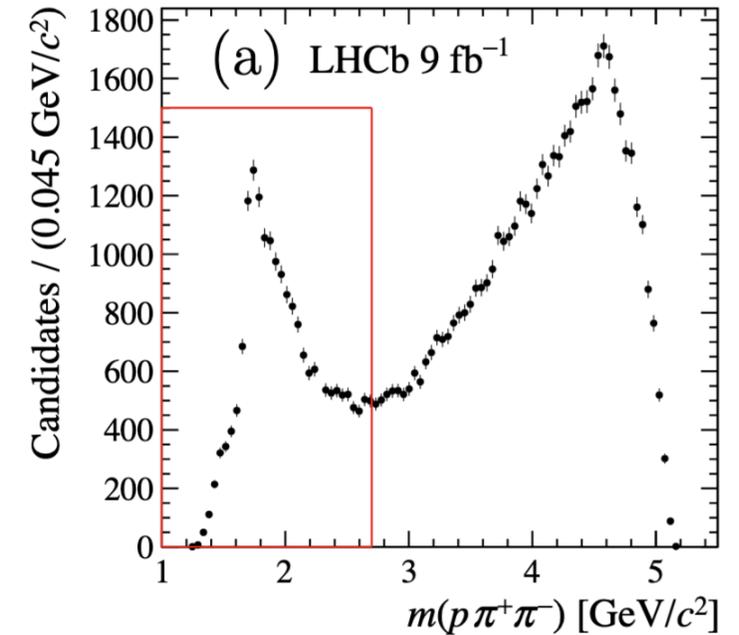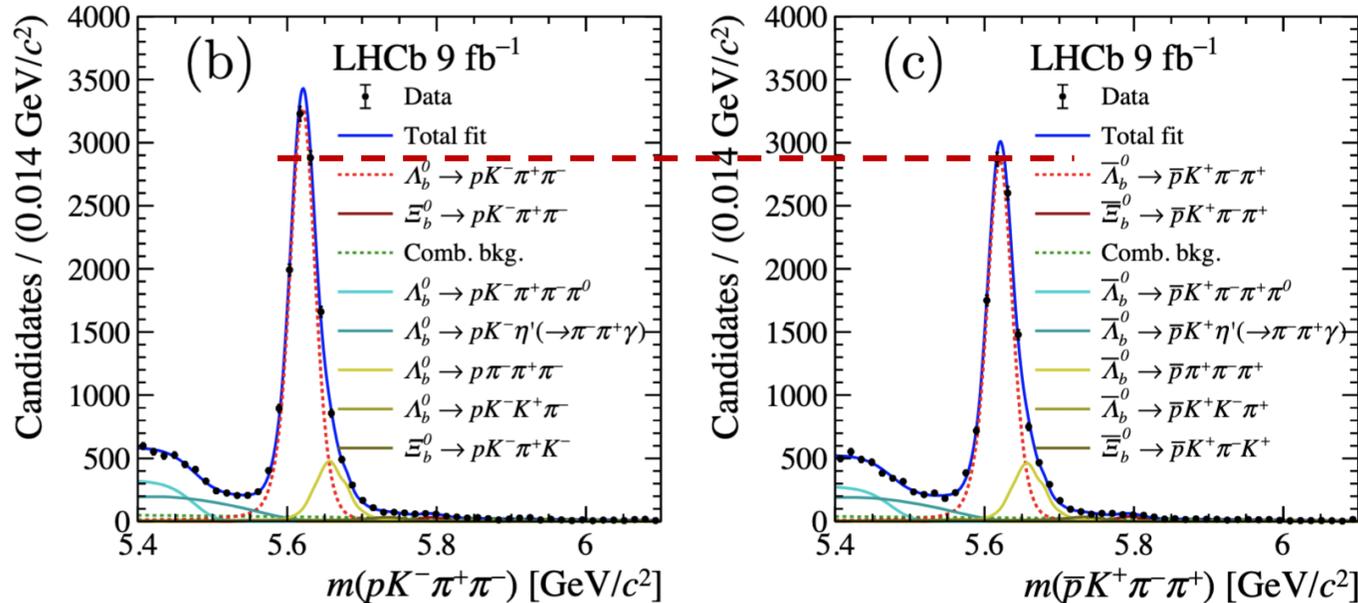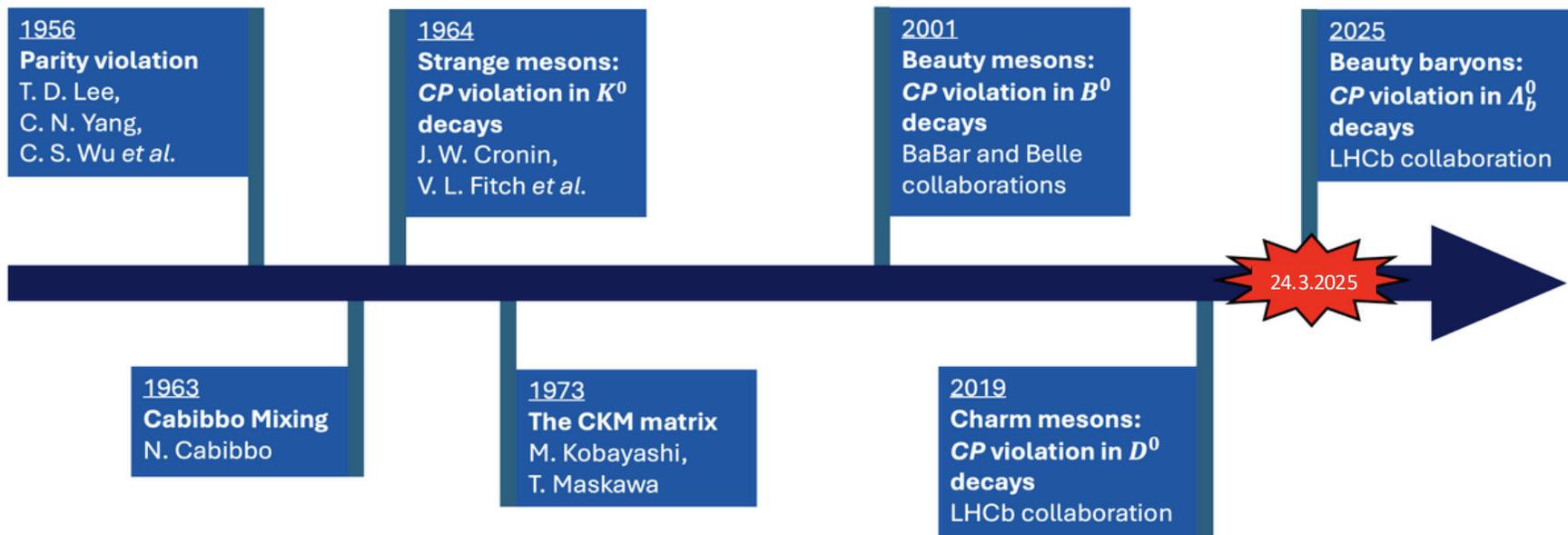(5.2σ significance)

First observation of baryon CP violation!

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

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

Local CP violation in selected regions of the phase space

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

(6.0σ)

N^{*+} resonance region

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

1963
Cabibbo Mixing
N. Cabibbo

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

1973
The CKM matrix
M. Kobayashi,
T. Maskawa

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

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

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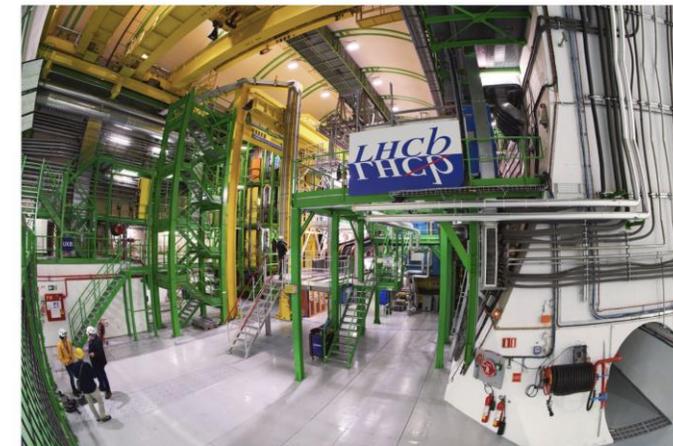*CP* violation in Λ_b^0
decays
LHCb collaboration

24.3.2025

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)

Conclusions and prospects

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

- BEPCII and BESIII inner tracker upgraded
- Belle-II expect to increase luminosity
- In LHCb Run 3, int. luminosity in 1 year comparable to the sum of Run 1&2
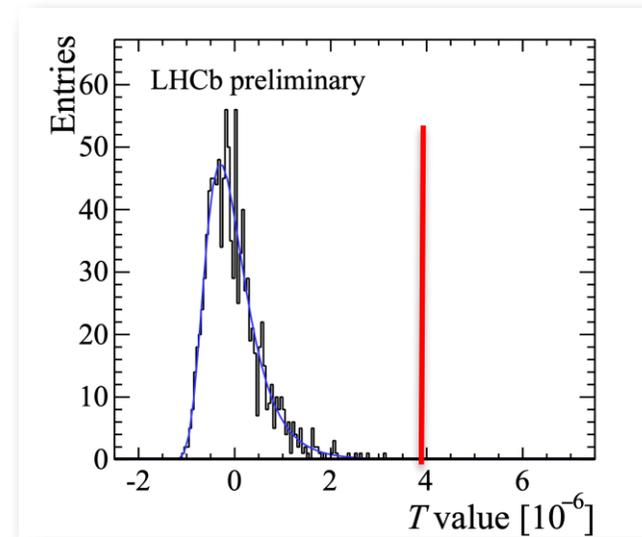
- More results are expected!
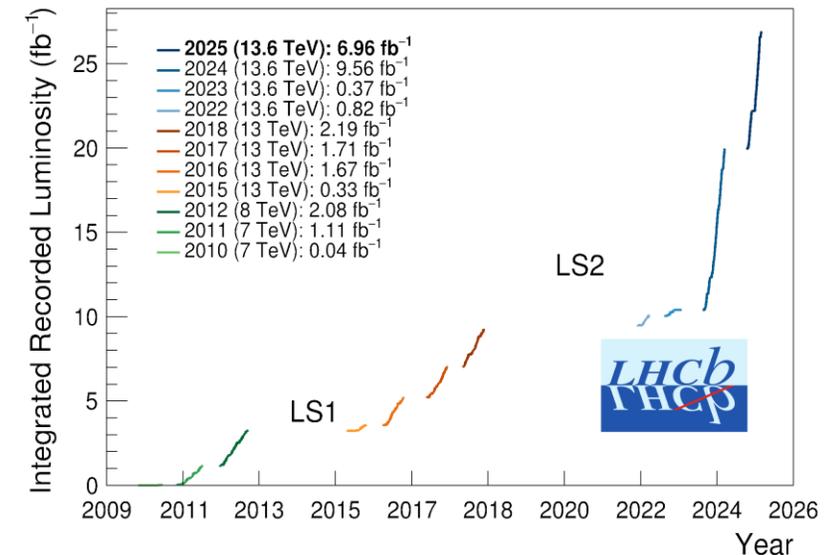
Back up

Energy test method

- Compare T-value from tested sample (T_0) with T-values from no-CPV samples
- No-CPV sample from permutation of data: randomly assign flavour tags
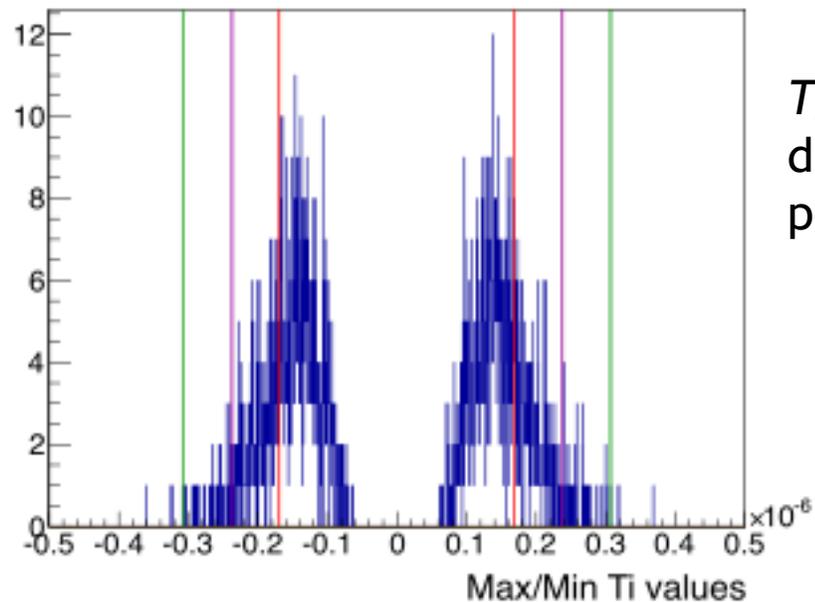- p-value: fraction of permutation T-values above T_0
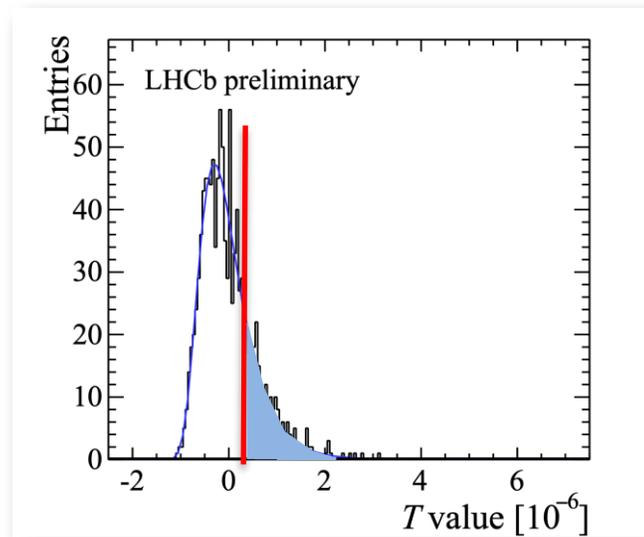

高p值——无CPV

小p值——有CPV

Energy test – Visualization

- Contribution of each event to total T -value: T_i
- Use T_i^{max} and T_i^{min} distributions from permutations to set significance levels
- Plot T_i values in terms of these significance levels $\rightarrow$ Show regions in Dalitz plot which contribute the most

T_i^{max} and T_i^{min} distributions from permutations

Visualisation of CP asymmetric MC sample
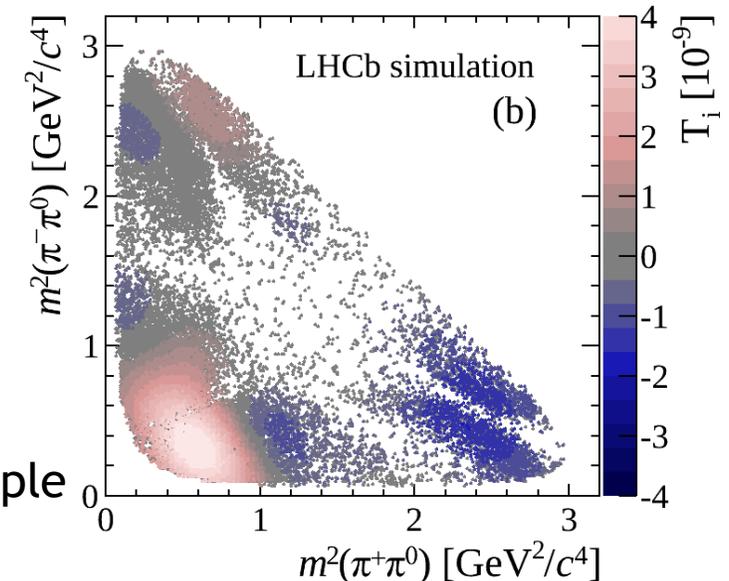
Local CP asymmetry for $\Lambda_b^0 \to \Lambda K^+ \pi^-$ / $\Lambda_b^0 \to \Lambda \pi^+ \pi^-$

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

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

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

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

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

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