CPV in $\Lambda_b^0 \to pK^-\pi^+\pi^-$ and $\Lambda_b^0 \to J/\psi p\pi^-$ decays

Xinchen Dai

on behalf of the LHCb Collaboration

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xdai@cern.ch

Introduction

- CPV is one of the necessary conditions for baryogenesis
- CPV is well established in meson decays
  - Not enough to account for the baryogenesis
  - Need contribution from New Physics
- The SM predicts similar CP violation in baryon and meson decays
  - Large CPV in (*b*-)baryons is possible
- Baryon CP violation has rarely been observed
  - Theory: Unknown underlying mechanisms
  - Experiment: Limited by statistics

Decays	Measurements	Data	References
$\Lambda_b^0 \to pK_S^0\pi^-$	A_{CP}	$1\ \mathrm{fb}^{-1}$	JHEP 04 (2014) 087
$\Lambda_b^0 \to \Lambda hh'$	A_{CP}	$3\ \mathrm{fb}^{-1}$	JHEP 05 (2016) 081
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$	TPA energy test	$3\ \mathrm{fb}^{-1}$ $6.6\ \mathrm{fb}^{-1}$	NP 13 (2017) 391 PRD 102 (2020) 051101
$\Lambda_b^0 \to pK^-\mu^+\mu^-$	A_{CP}	$3\ \mathrm{fb}^{-1}$	JHEP 06 (2017) 108
$\Lambda_c^+ \to ph^-h^+$	A_{CP}	$3\ \mathrm{fb}^{-1}$	JHEP 03 (2018) 182
$\Lambda_b^0 \to pK^-/p\pi^-$	A_{CP}	$3\ \mathrm{fb}^{-1}$	PLB 787 (2018) 124
$\Lambda_b^0 \to ph^-h^+h^-$	TPA	$3\ \mathrm{fb}^{-1}$	JHEP 08 (2018) 039
$\Lambda_b^0 \to ph^-h^+h^-$	A_{CP}	$3\ \mathrm{fb}^{-1}$	EPJC 79 (2019) 745
$\Xi_b^- \to pK^-K^-$	Amplitude	$5\ \mathrm{fb}^{-1}$	PRD 104 (2020) 052010
$\Xi_c^+ \to pK^-\pi^+$	kNN	$3\ \mathrm{fb}^{-1}$	EPJC 80 (2020) 986
$\Lambda_b^0 \to pD^0K^-$	Miranda S_{CP}^i	$9\ \mathrm{fb}^{-1}$	PRD104 (2021) 112008
$\Lambda_b^0 \to \Lambda\gamma$	Polarization	$3\ \mathrm{fb}^{-1}$	PRD105 (2022) L051104
$\Lambda_b^0 \to ph^-$	A_{CP}	$9\ \mathrm{fb}^{-1}$	PRD111 (2025) 092004
$\Lambda_b^0 \to \Lambda_c^+h^-$	Decay parameter	$9\ \mathrm{fb}^{-1}$	PRL 133 (2024) 261804
$\Lambda_b^0 \to \Lambda hh'$	A_{CP}	$9\ \mathrm{fb}^{-1}$	PRL 134 (2025) 101802
$\Lambda_b^0 \to pK^-\pi^+\pi^-$	A_{CP}	$9\ \mathrm{fb}^{-1}$	Nature 643 (2025) 1223
$\Lambda_b^0 \to pK_S^0h^-$	A_{CP}	$9\ \mathrm{fb}^{-1}$	arXiv:2508.17836
$\Lambda_b^0 \to J/\psi ph$	A_{CP} , TPA	$6\ \mathrm{fb}^{-1}$	arXiv:2509.16103

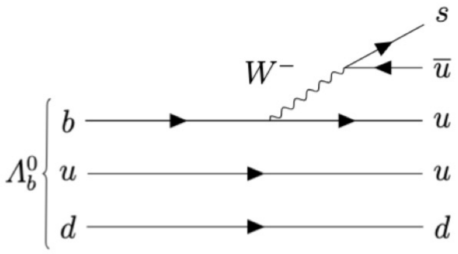
Introduction

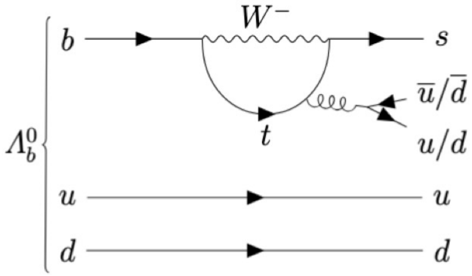
➢ The only source of CPV in SM is through CKM mechanism

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

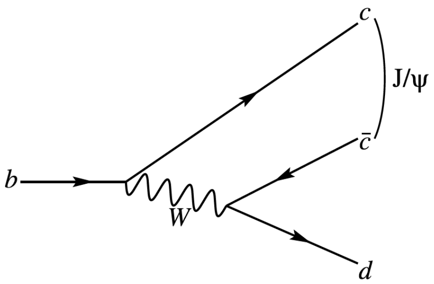
- Interference of two amplitudes (with different strong&weak phases) generates CP violation

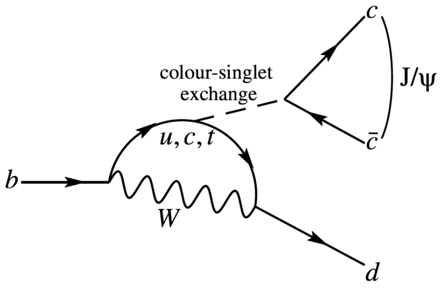
$\Lambda_b^0 \to pK^-\pi^+\pi^-$





$\Lambda_b^0 \to J/\psi p\pi^-$





$$\mathcal{A}_{CP} = \frac{|A(\Lambda_b^0)|^2 - |A(\bar{\Lambda}_b^0)|^2}{|A(\Lambda_b^0)|^2 + |A(\bar{\Lambda}_b^0)|^2} = \frac{2\sin\Delta\delta\sin\Delta\phi}{|A_{\mathrm{T}}/A_{\mathrm{L}}| + |A_{\mathrm{L}}/A_{\mathrm{T}}| + 2\cos\Delta\delta\cos\Delta\phi}$$

CP violation measurement

- CP violation appears as a difference in decay rates between particles and antiparticles
- In experiment, we measure the asymmetry in event yields instead of decay widths.

$$A_{raw} = \frac{N\left(\Lambda_b^0 \to X\right) - N\left(\bar{\Lambda}_b^0 \to \bar{X}\right)}{N(\Lambda_b^0 \to X) + N(\bar{\Lambda}_b^0 \to \bar{X})}$$

- Nuisance asymmetries from production and detection（including PID&Trigger asym.） must be accounted

$$A_{raw} = A_{CP} + A_{prod} + A_{det}$$

- A control channel is introduced to cancel the leading-order nuisance asymmetries, and the CP asymmetry difference between the two modes is given by

$$\Delta A_{CP} = A_{CP}^{signal} - A_{CP}^{control} = \Delta A_{raw} - \Delta A_{prod} - \Delta A_{det}$$

CPV in $\Lambda_b^0 \to pK^-\pi^+\pi^-$

LHCb Run I ($3\mathrm{fb}^{-1}$) ΔA_{CP}

$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) = (+1.1 \pm 2.5 \pm 0.6)\,\%,$$

$$\boxed{\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (+3.2 \pm 1.1 \pm 0.6)\,\%,}$$

$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-K^+\pi^-) = (-6.9 \pm 4.9 \pm 0.8)\,\%,$$

$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-K^+K^-) = (+0.2 \pm 1.8 \pm 0.6)\,\%,$$

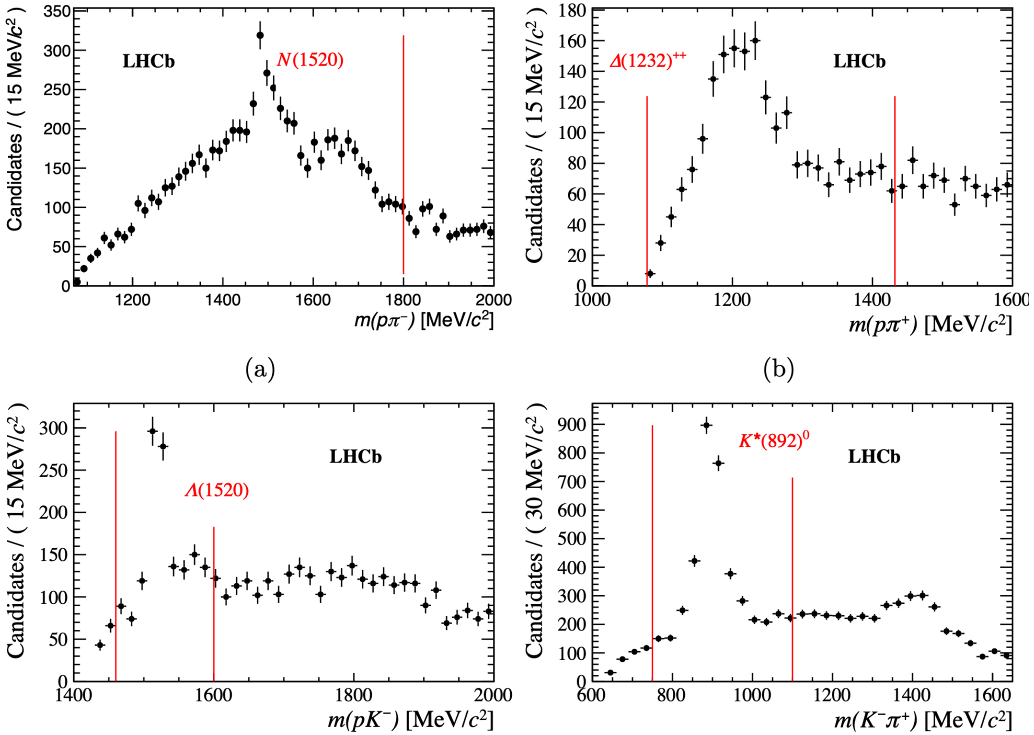
EPJC 79 (2019) 745

LHCb Run I ($3\mathrm{fb}^{-1}$) TPA

	$\Lambda_b^0 \to pK^-\pi^+\pi^-$
$a_P^{\widehat{T}\text{-odd}}$ (%)	$-0.60 \pm 0.84 \pm 0.31$
$a_{CP}^{\widehat{T}\text{-odd}}$ (%)	$-0.81 \pm 0.84 \pm 0.31$

JHEP 08 (2018) 039

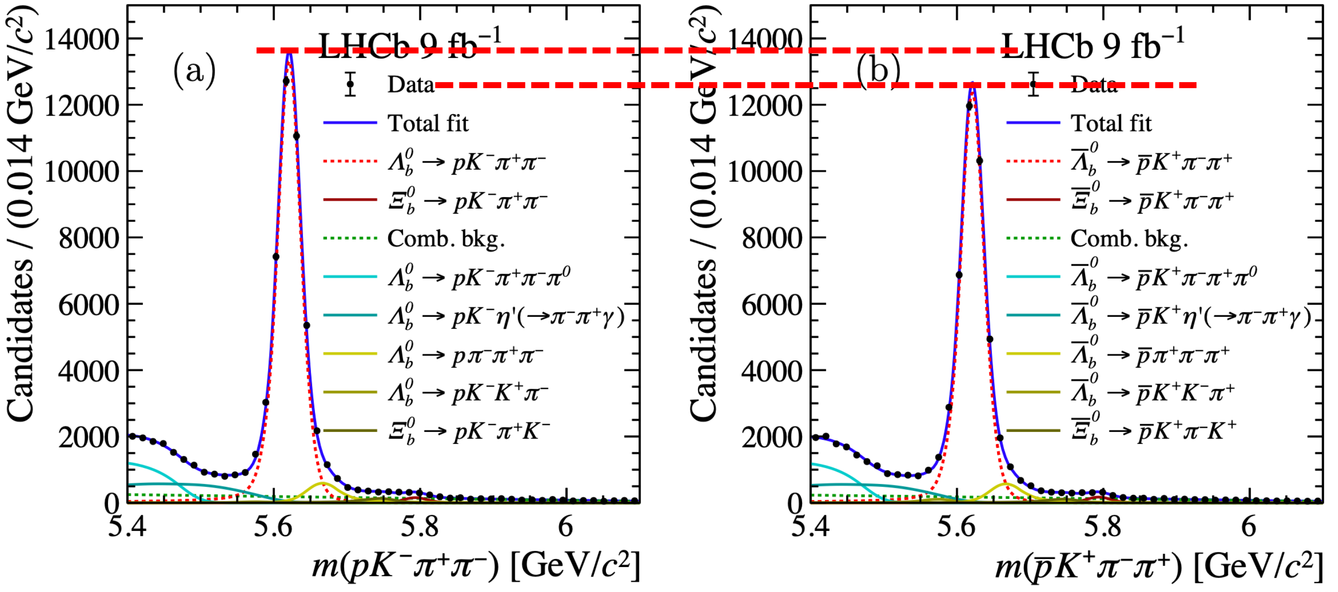
- ➢High purity
- ➢Large statistics
- ➢Rich resonances



CPV in $\Lambda_b^0 \to pK^-\pi^+\pi^-$

- Full Run1+2 data (9fb^{-1})
- Signal yields are extracted from fit to $m(\Lambda_b^0)$ and $m(\overline{\Lambda}_b^0)$
- Control channel $\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\pi^-$ is introduced to cancel nuisance asym.

$$\Delta A_{CP} = A_{CP}^{signal} - A_{CP}^{control} = \Delta A_{raw} - \Delta A_{prod} - \Delta A_{det}$$



$$\boldsymbol{A_{raw} = (3.71 \pm 0.39)\%}$$

- $\Delta A_{raw} \approx 2.46\%$
- $\Delta A_{prod} \approx 0$: Cancelled by reweighting Λ_b^0 kinematics of the control channel to match those of signal.
- $\Delta A_{det} \approx 0.01\%$: evaluated event by event according to kinematics of final-state particles.

$$\boldsymbol{\Delta A_{CP} = (2.45 \pm 0.46 \pm 0.10)\% \quad 5.2\sigma}$$

First observation!

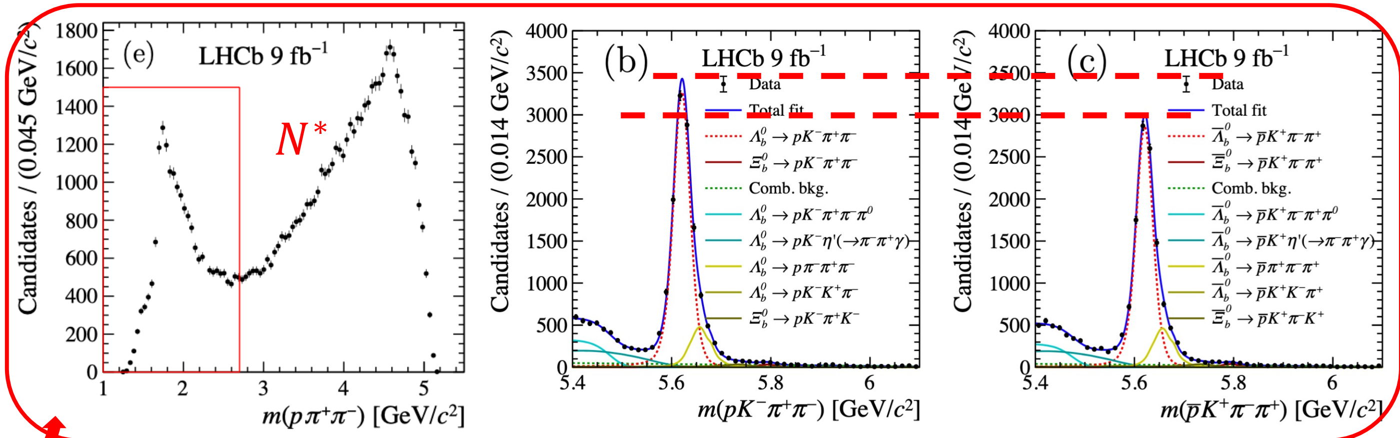
CPV in $\Lambda_b^0 \to pK^-\pi^+\pi^-$

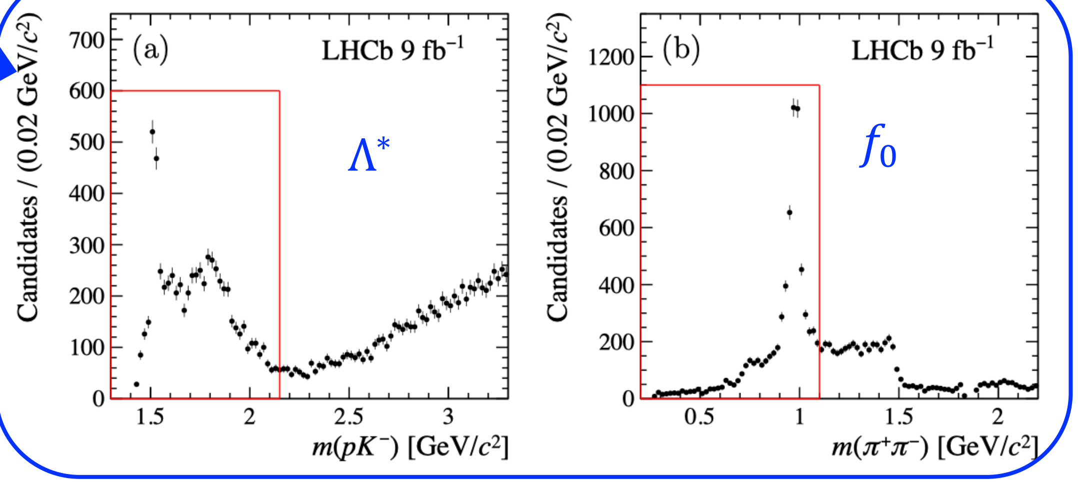
- CPV in local PHSP also investigated.

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 $1.1 < m_{\pi^+K^-} < 1.6$	$(2.7 \pm 0.8 \pm 0.1)\%$
$\Lambda_b^0 \to R(p\pi^+\pi^-)K^-$	$m_{p\pi^+\pi^-} < 2.7$	$(5.4 \pm 0.9 \pm 0.1)\%$
$\Lambda_b^0 \to R(K^-\pi^+\pi^-)p$	$m_{K^-\pi^+\pi^-} < 2.0$	$(2.0 \pm 1.2 \pm 0.3)\%$

4σ

6σ



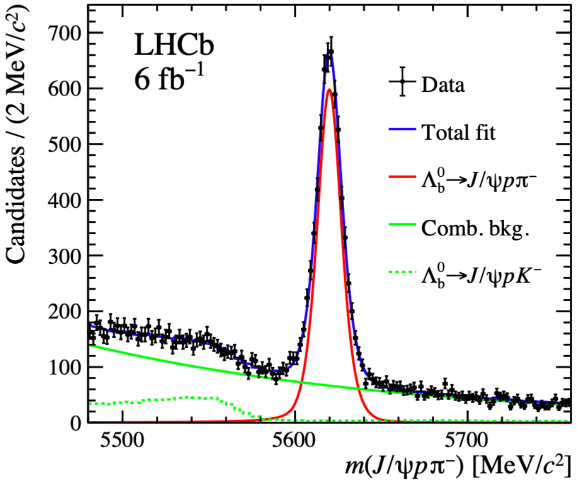


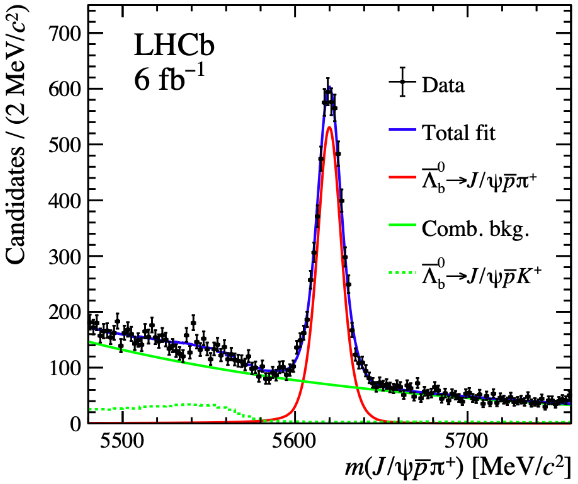
- Significant enhancement of CPV in $N^*(p\pi^+\pi^-)$ resonances
- Needed to disentangle contributions from overlapping resonances.

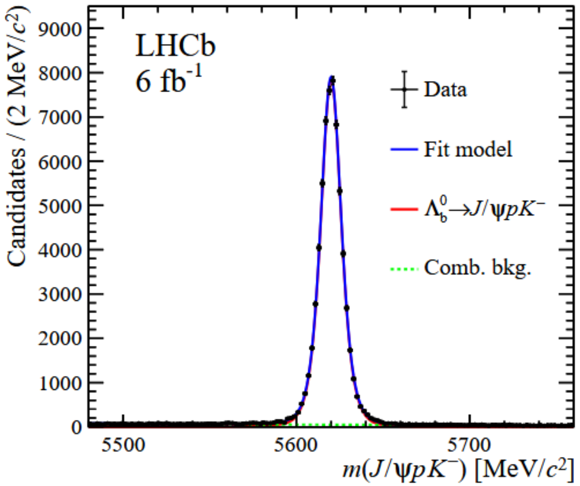
CPV in $\Lambda_b^0 \to J/\psi p \pi^-$

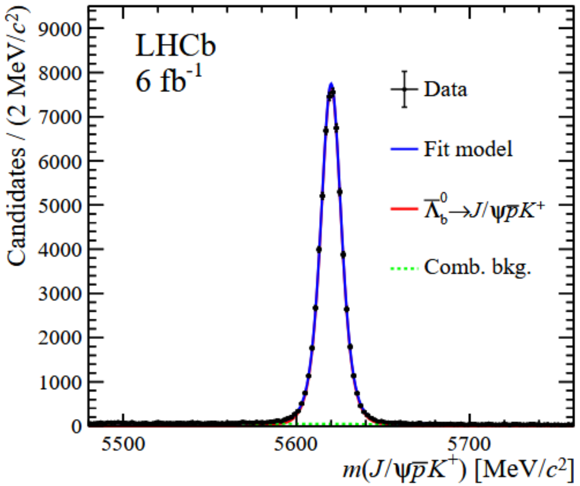
- $b \to c\bar{c}d$ process, large penguin contribution could enhance the CPV
- Full Run2 data ($6\ \mathrm{fb}^{-1}$)
- $\Delta A_{CP} = A_{\mathrm{raw}}(\Lambda_b^0 \to J/\psi p \pi^-) - A'_{\mathrm{raw}}(\Lambda_b^0 \to J/\psi p K^-) + A_{\mathrm{D}}(K^-) - A_D(\pi^-)$

Production and proton detection asym. are cancelled by reweighting the kinematics of Λ_b^0&p to match those of signal









(10853 ± 134) yields
$A_{raw}(\Lambda_b^0 \to J/\psi p \pi^-) = (5.94 \pm 1.14)\ \%$

(125380 ± 372) yields
$A_{raw}(\Lambda_b^0 \to J/\psi p K^-) = (0.98 \pm 0.30)\ \%$

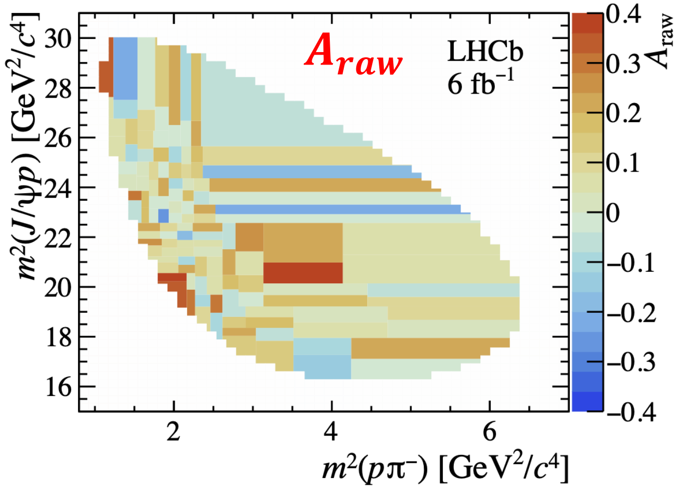
$\Delta A_{CP} = (4.03 \pm 1.18 \pm 0.23)\%$ **3.3 σ**

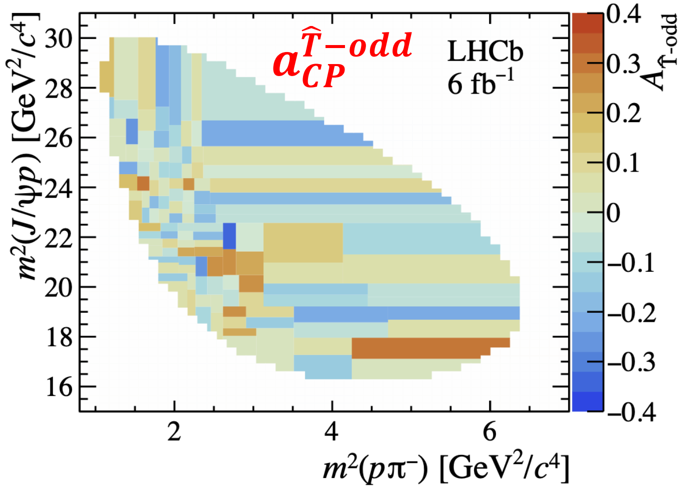
Run 1 results:
$\Delta A_{CP} = (5.7 \pm 2.4 \pm 1.2)\%$

Combined with Run 1: $\Delta A_{CP} = (4.31 \pm 1.06 \pm 0.28)\%$ **3.9 σ**

Local CPV in $\Lambda_b^0 \to J/\psi p \pi^-$

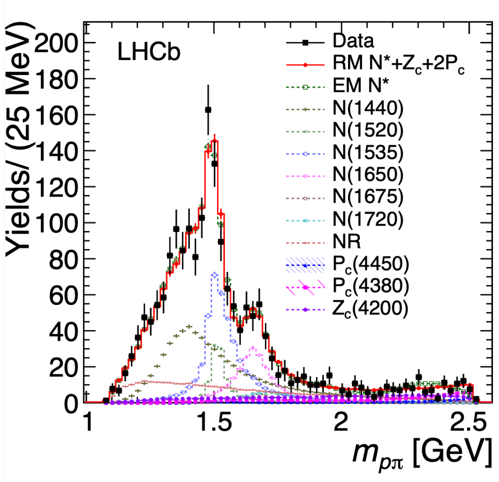
- Measurement of local CP asymmetry in 128 bins

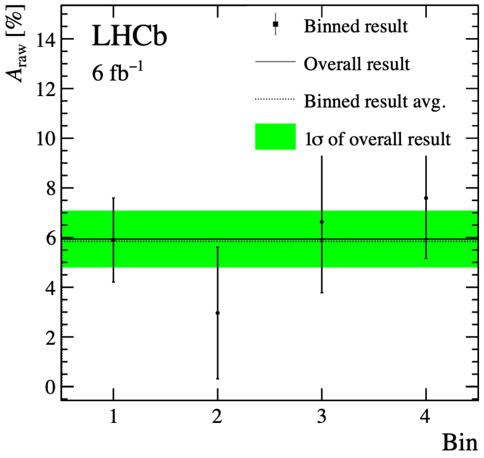


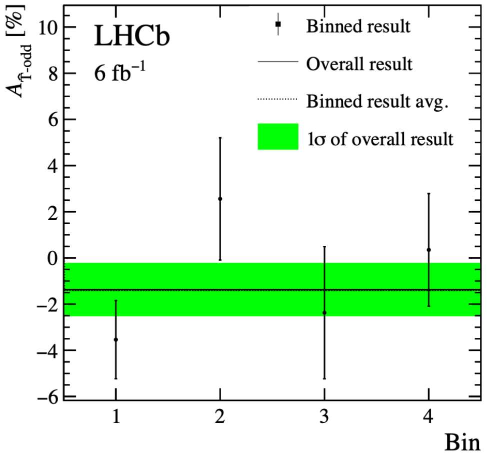


- Both raw asymmetry A_{raw} and TPA $a_{CP}^{\hat{T}-odd}$ are measured

- local CP asymmetry near $N^*(p\pi)$ resonances



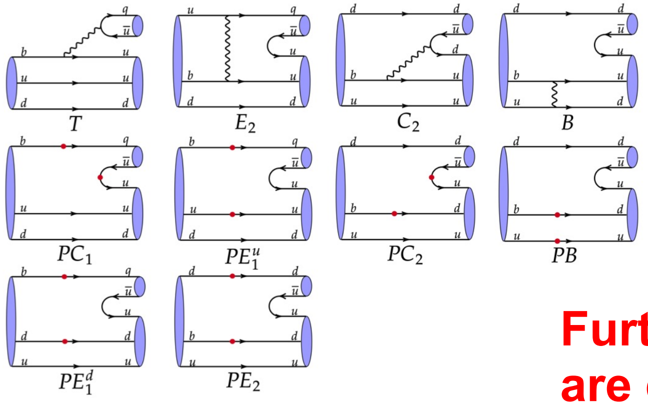




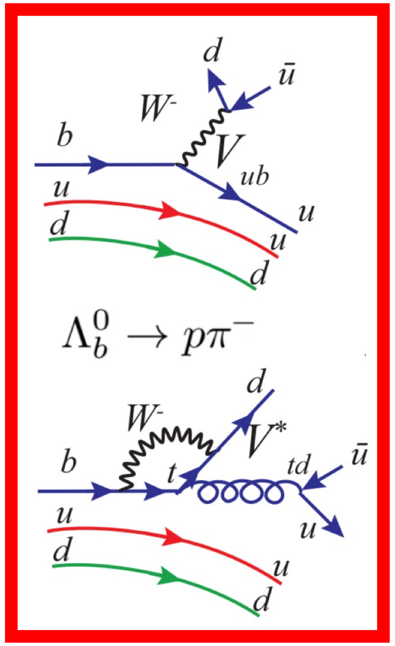
- No significant variation of asymmetries across the phase space

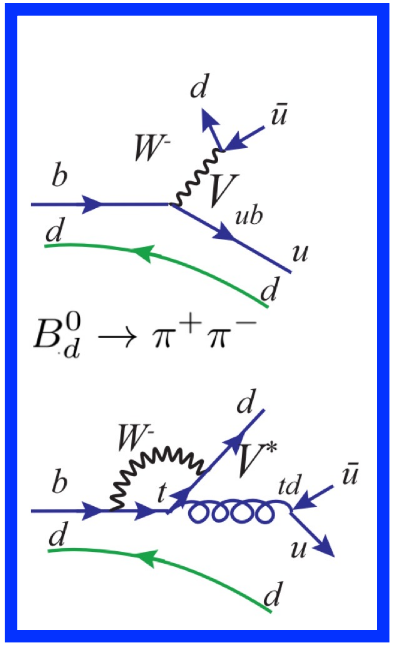
Why baryon CPV so small

- Small strong phase difference
- The cancellation between different partial wave turns in small net direct CPV
- Overlap of resonances could dilute CPV



Further measurements are essential to clarify the picture

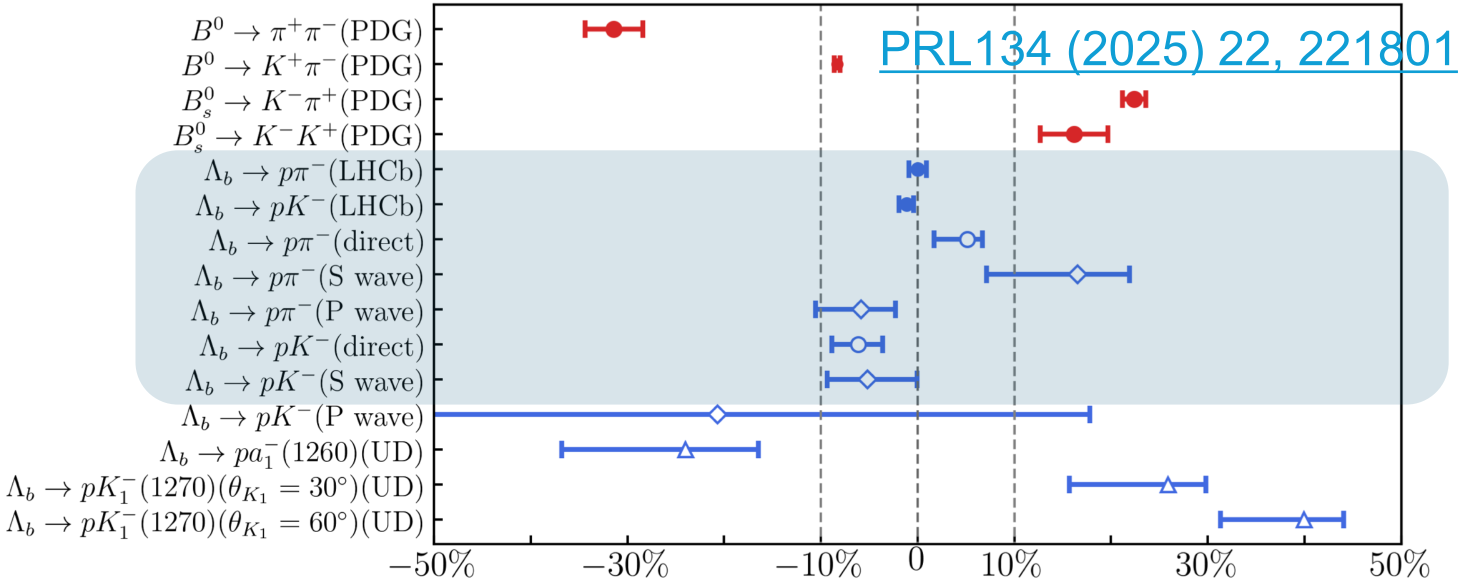




S+P wave

S wave only

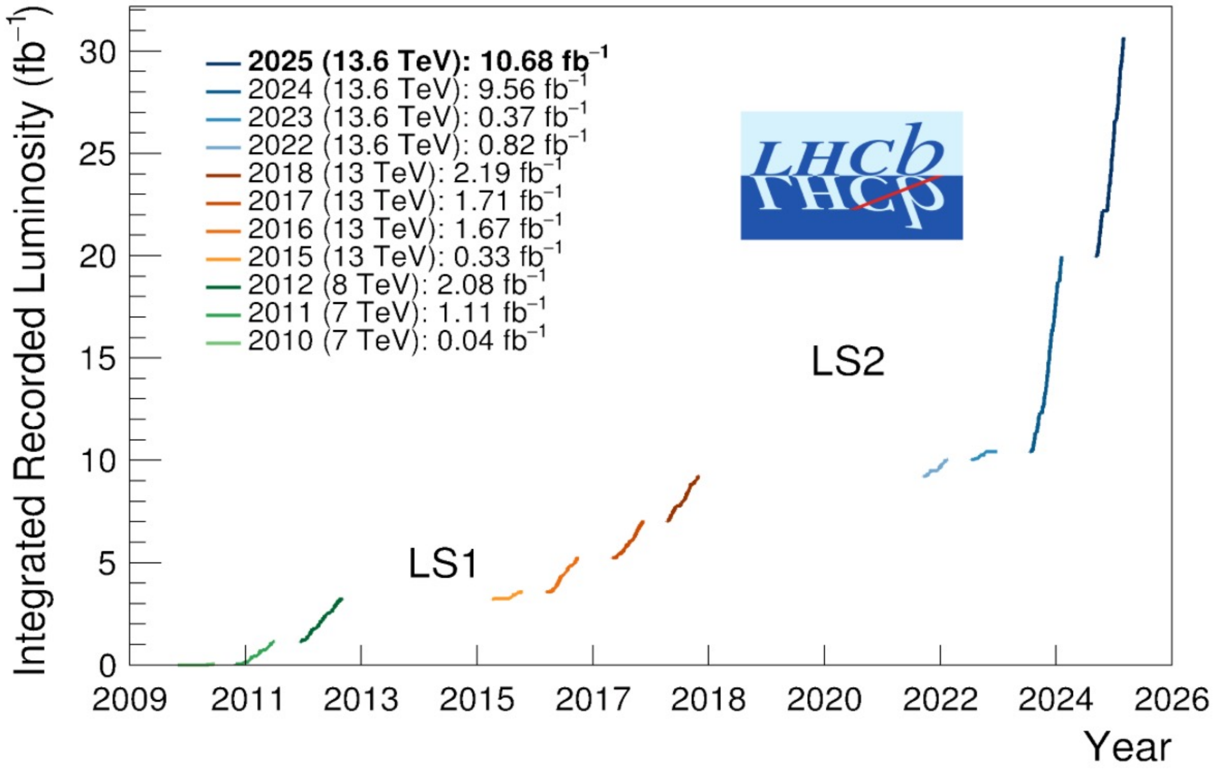
PRL134 (2025) 22, 221801



- S- and P-wave CPV are large but cancelled

Outlook

- Higher integrated luminosity in Run 3 (25–30 fb^{-1})
- Trigger efficiency for hadron final states increased by factor of 2



LHCb Run 1

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

- Current statistics enable us to reduce the uncertainty to ~0.1%

Summary

- First observation of CP violation — a milestone in CPV studies

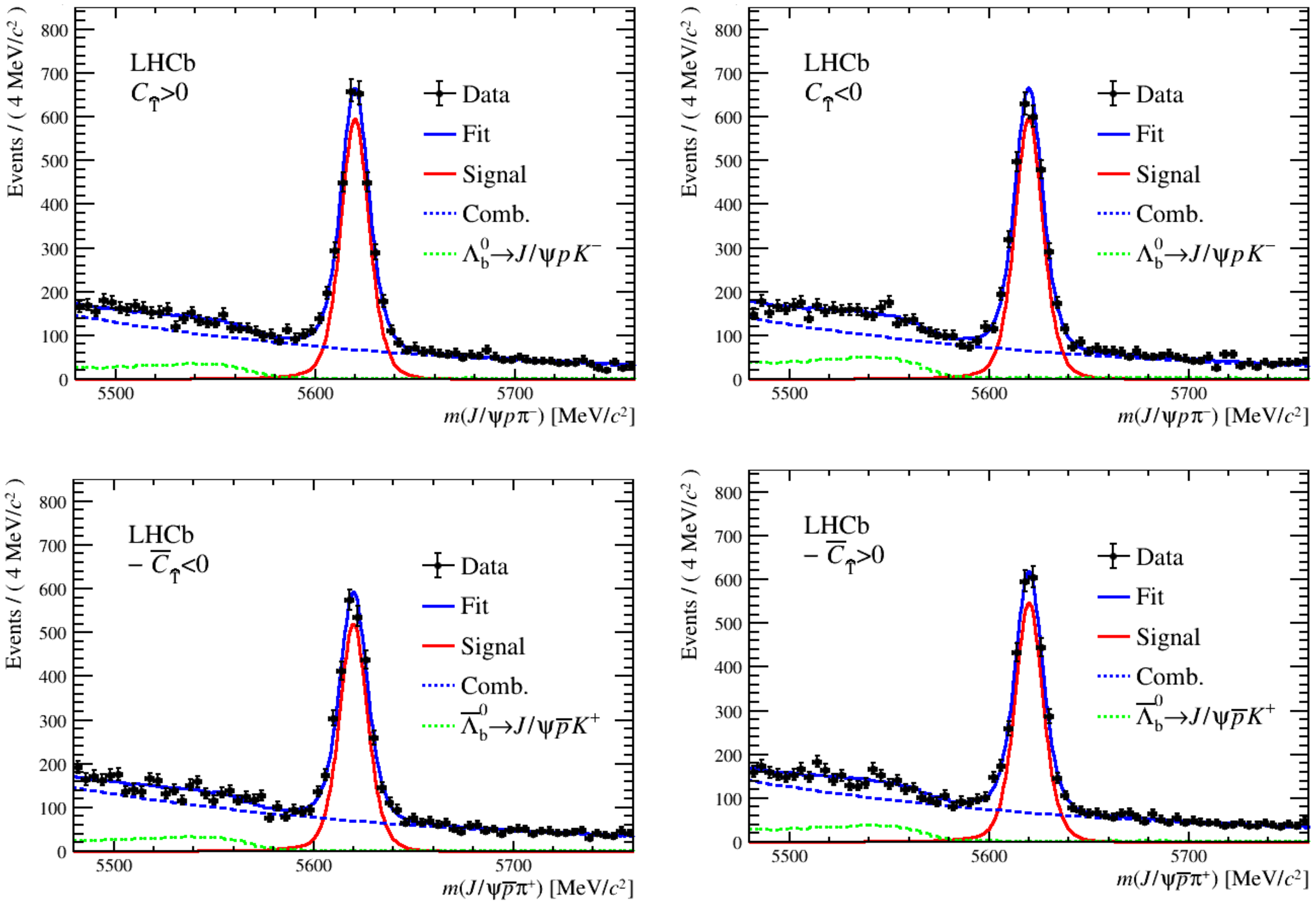
- First evidence of CP violation in b-baryon to charmonium

- With LHCb Run3 data, more precise measurement will come
  - Search for CP violation in more baryon decays.
  - Search for CP violation using more CP observables.

Backup

TPA in $\Lambda_b^0 \to J/\psi p \pi^-$

- Triple product asymmetry:
- Λ_b^0: $C_T \equiv \vec{p}_{\mu^+} \cdot (\vec{p}_p \times \vec{p}_{\pi^-})$
- $\overline{\Lambda}_b^0$: $\bar{C}_T \equiv \vec{p}_{\mu^-} \cdot (\vec{p}_{\bar{p}} \times \vec{p}_{\pi^+})$
- $A_{\hat{T}}(C_{\hat{T}}) = \frac{N(C_{\hat{T}}>0)-N(C_{\hat{T}}<0)}{N(C_{\hat{T}}>0)+N(C_{\hat{T}}<0)}$,
- $a_{CP}^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} - \bar{A}_{\hat{T}})$



- $a_{CP}^{\hat{T}-odd}$= (−1.37 ± 1.15 ± 0.21) %