

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

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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 Standard Model 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

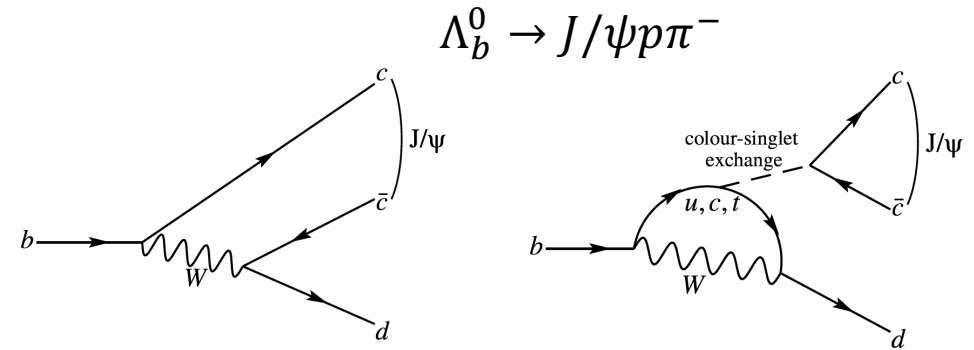
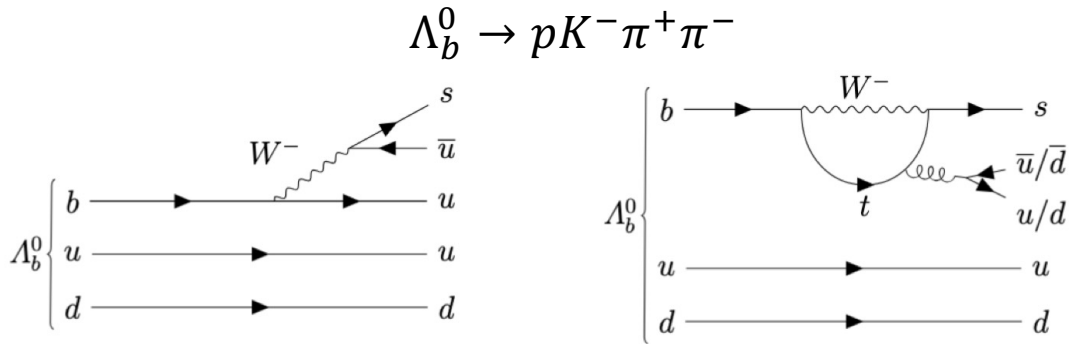
Decays	Measurements	Data	References
$\Lambda_b^0 \rightarrow p K_S^0 \pi^-$	A_{CP}	1 fb ⁻¹	JHEP 04 (2014) 087
$\Lambda_b^0 \rightarrow \Lambda h h'$	A_{CP}	3 fb ⁻¹	JHEP 05 (2016) 081
$\Lambda_b^0 \rightarrow p \pi^- \pi^+ \pi^-$	TPA energy test	3 fb ⁻¹ 6.6 fb ⁻¹	NP 13 (2017) 391 PRD 102 (2020) 051101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



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

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.

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

- 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

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

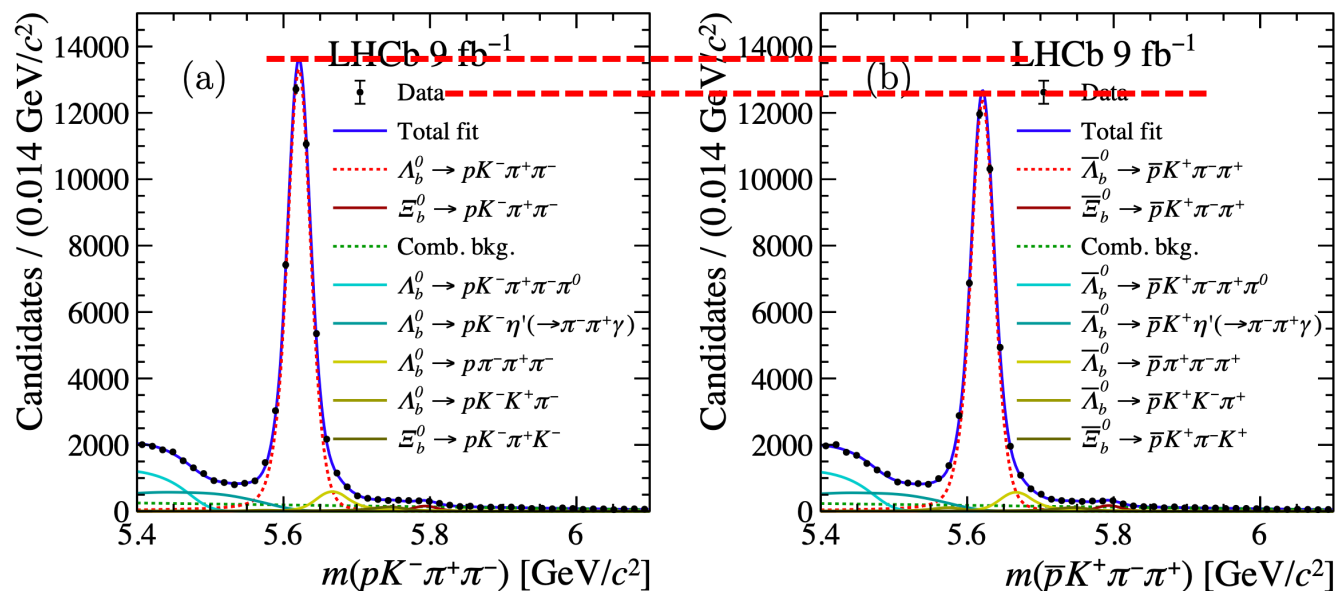
CPV in $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$

➤ Full Run1+2 data (9fb⁻¹)

➤ Signal yields are extracted from fit to $m(\Lambda_b^0)$ and $m(\bar{\Lambda}_b^0)$

➤ Control channel $\Lambda_b^0 \rightarrow \Lambda_c^+(\rightarrow pK^-\pi^+)\pi^-$ is introduced to cancel nuisance asym.

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



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

➤ $\Delta A_{raw} \approx 2.46\%$

➤ $\Delta A_{prod} \approx 0$: Cancelled by reweighting Λ_b^0 kinematics of the signal to match those of control channel.

➤ $\Delta A_{det} \approx 0.01\%$: evaluated event by event according to kinematics of final-state particles.

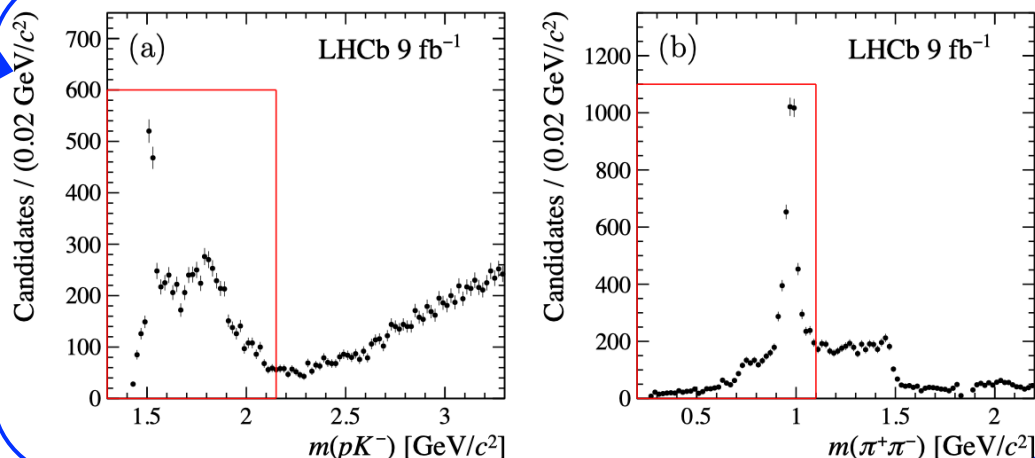
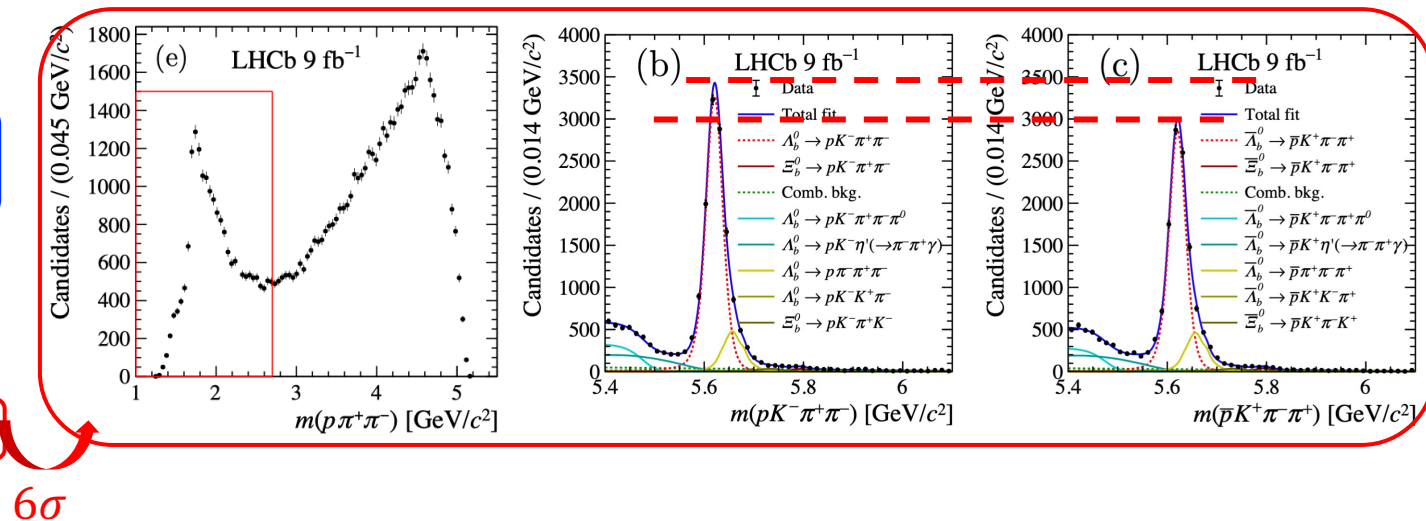
$$A_{CP} = (2.45 \pm 0.46 \pm 0.10)\% \quad 5.2\sigma$$

First observation!

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

➤ CPV in local PHSP also investigated.

Decay topology	Mass region (GeV/c^2)	$\mathcal{A}_{CP}$
$\Lambda_b^0 \rightarrow R(pK^-)R(\pi^+\pi^-)$	$m_{pK^-} < 2.2$ $m_{\pi^+\pi^-} < 1.1$ $m_{p\pi^-} < 1.7$	$(5.3 \pm 1.3 \pm 0.2)\%$ 4σ
$\Lambda_b^0 \rightarrow R(p\pi^-)R(K^-\pi^+)$	$0.8 < m_{\pi^+K^-} < 1.0$ or $1.1 < m_{\pi^+K^-} < 1.6$	$(2.7 \pm 0.8 \pm 0.1)\%$
$\Lambda_b^0 \rightarrow R(p\pi^+\pi^-)K^-$	$m_{p\pi^+\pi^-} < 2.7$	$(5.4 \pm 0.9 \pm 0.1)\%$
$\Lambda_b^0 \rightarrow R(K^-\pi^+\pi^-)p$	$m_{K^-\pi^+\pi^-} < 2.0$	$(2.0 \pm 1.2 \pm 0.3)\%$



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

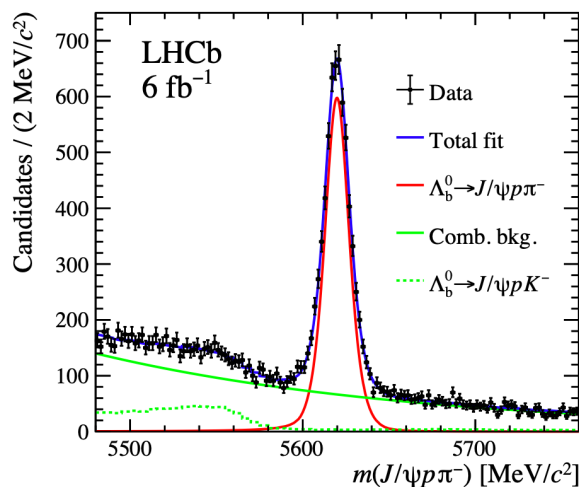
CPV in $\Lambda_b^0 \rightarrow J/\psi p \pi^-$

➤ $b \rightarrow ccd$ process, large penguin contribution could enhance the CPV

➤ Full Run2 data

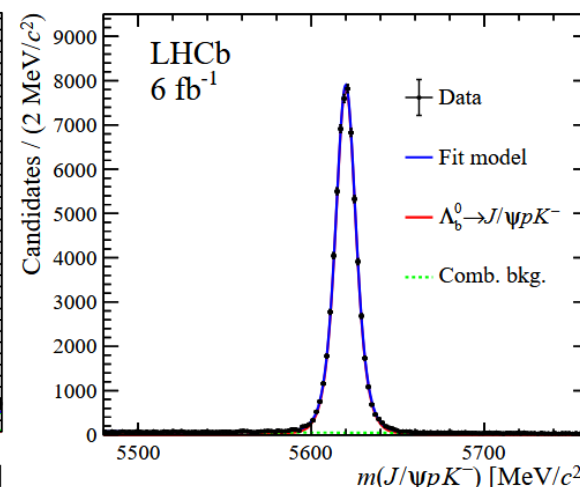
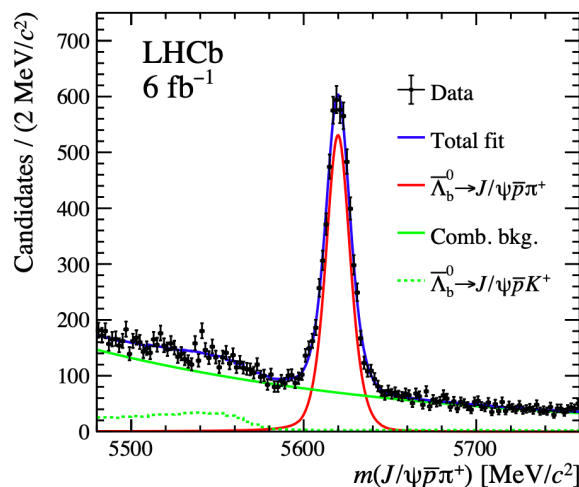
➤ $\Delta A_{CP} = A_{\text{raw}}(\Lambda_b^0 \rightarrow J/\psi p \pi^-) - A'_{\text{raw}}(\Lambda_b^0 \rightarrow J/\psi p K^-) + A_D(K^-) - A_D(\pi^-)$

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



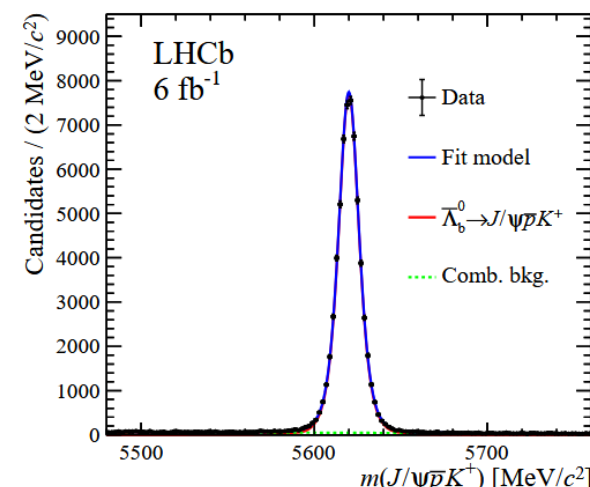
(10853 ± 134) yields

$$A_{\text{raw}}(\Lambda_b^0 \rightarrow J/\psi p \pi^-) = (5.94 \pm 1.14) \%$$



(125380 ± 372) yields

$$A_{\text{raw}}(\Lambda_b^0 \rightarrow J/\psi p K^-) = (0.98 \pm 0.30) \%$$



$$\Delta A_{CP} = (4.03 \pm 1.18 \pm 0.23) \% \quad \mathbf{3.3 \sigma}$$

Run 1 results:

$$\Delta A_{CP} = (5.7 \pm 2.4 \pm 1.2) \%$$

Combined with Run 1: $\Delta \mathcal{A}_{CP} = (4.31 \pm 1.06 \pm 0.28) \% \quad \mathbf{3.9 \sigma}$

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

➤ Triple product asymmetry:

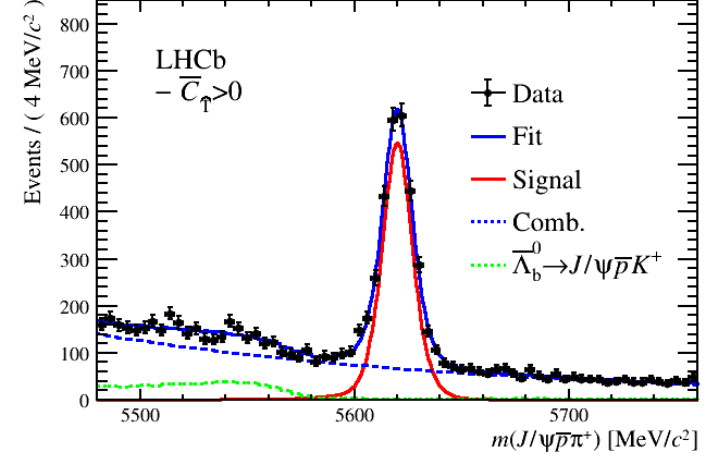
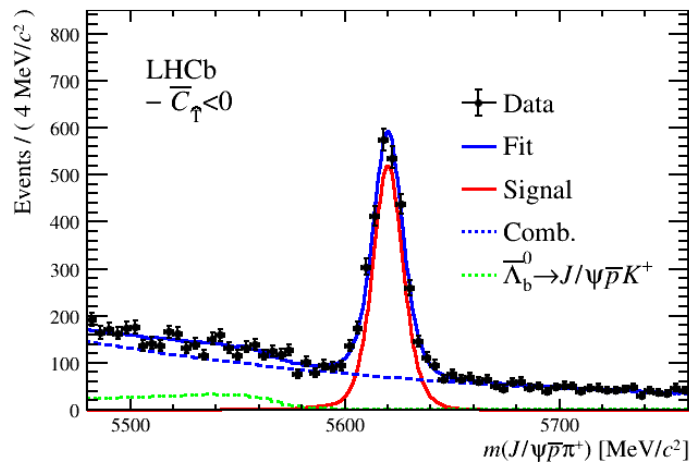
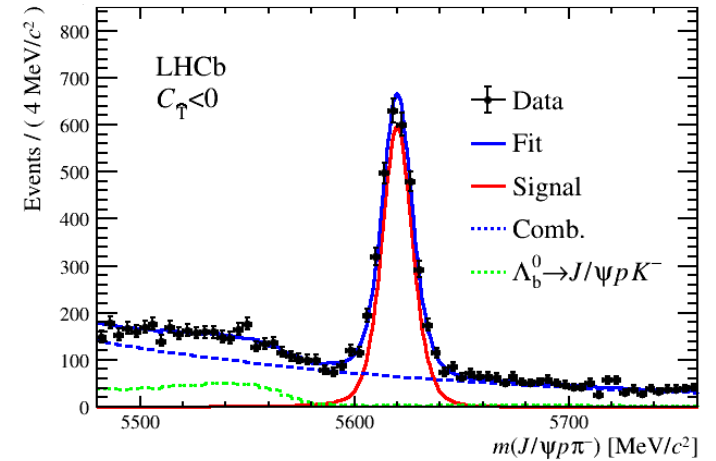
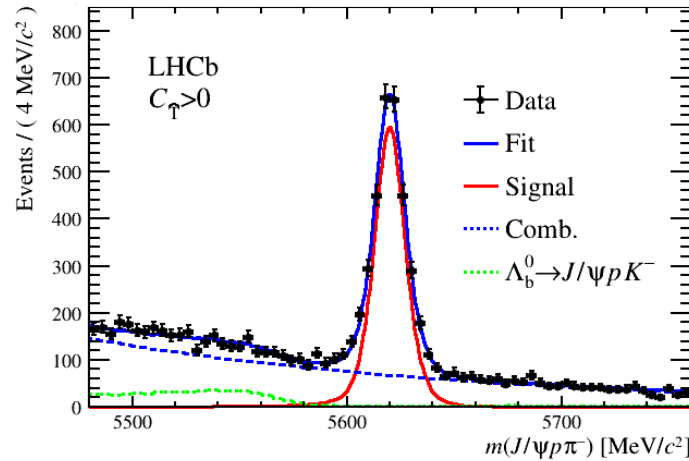
➤ Λ_b^0 : $C_T \equiv \vec{p}_{\mu^+} \cdot (\vec{p}_p \times \vec{p}_{\pi^-})$

➤ $\bar{\Lambda}_b^0$: $\bar{C}_T \equiv \vec{p}_{\mu^-} \cdot (\vec{p}_{\bar{p}} \times \vec{p}_{\pi^+})$

➤ $A_{\hat{T}}(C_{\hat{T}}) = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}$

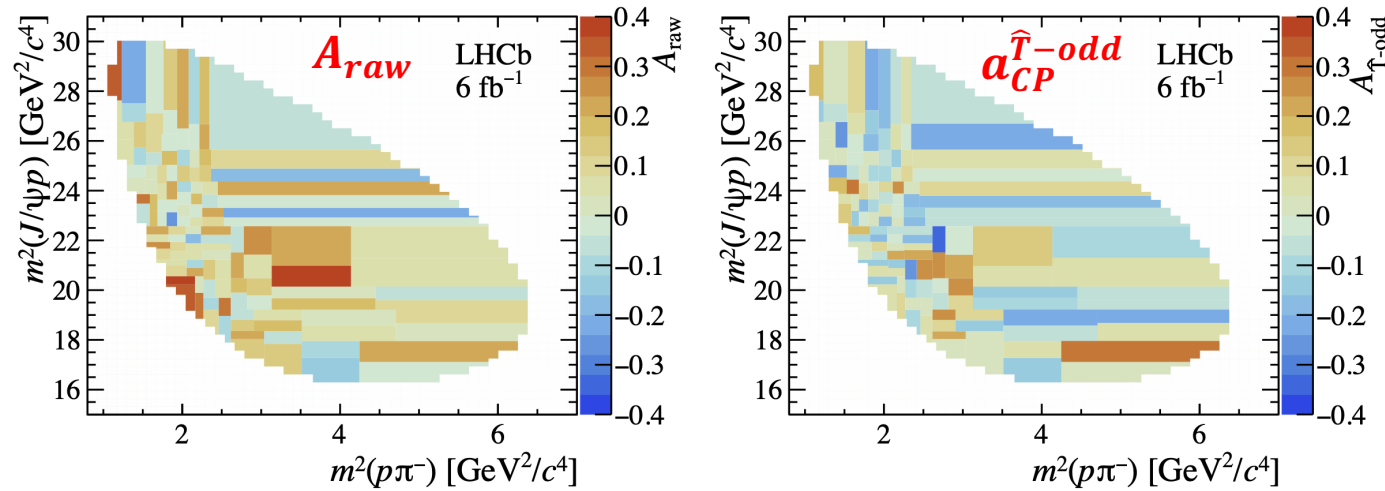
➤ $a_{CP}^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} - \bar{A}_{\hat{T}})$

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



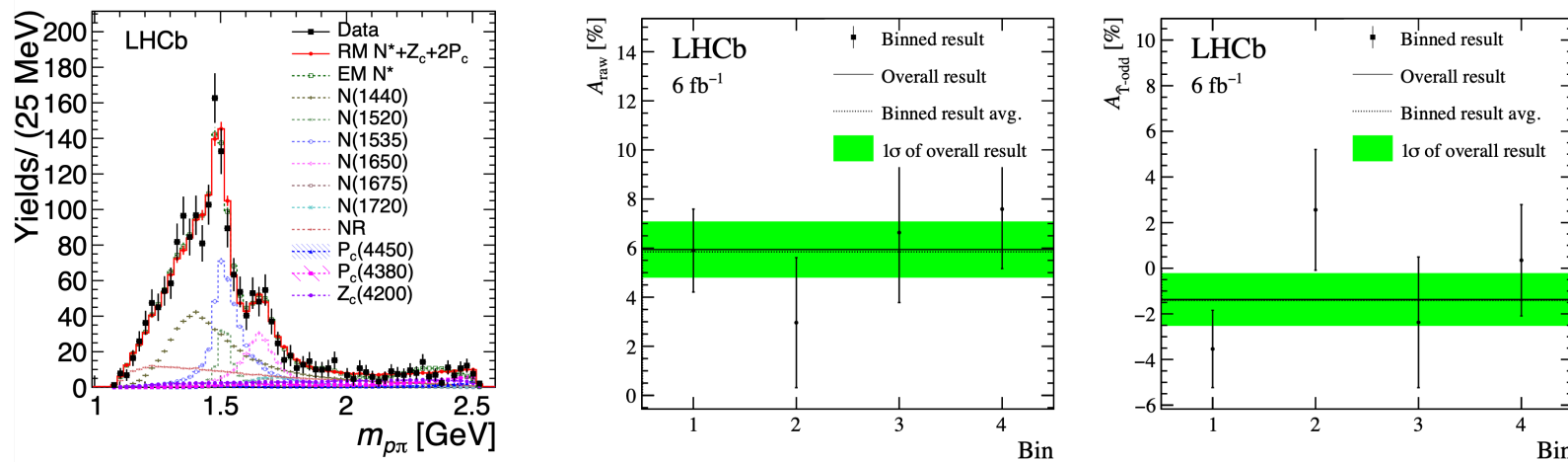
Local CPV in $\Lambda_b^0 \rightarrow J/\psi p \pi^-$

➤ Measurement of local CP asymmetry in 128 bins



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

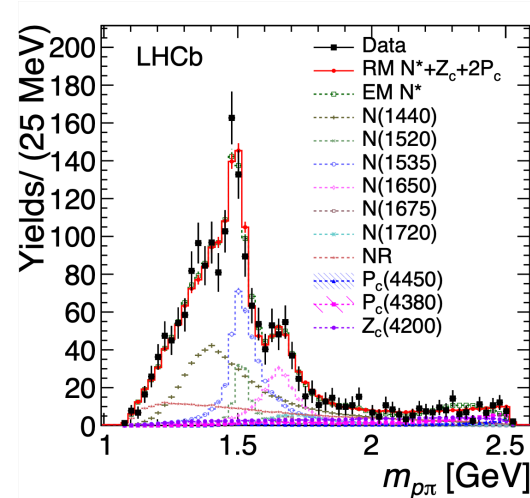
➤ local CP asymmetry near $N^*(p\pi)$ resonances



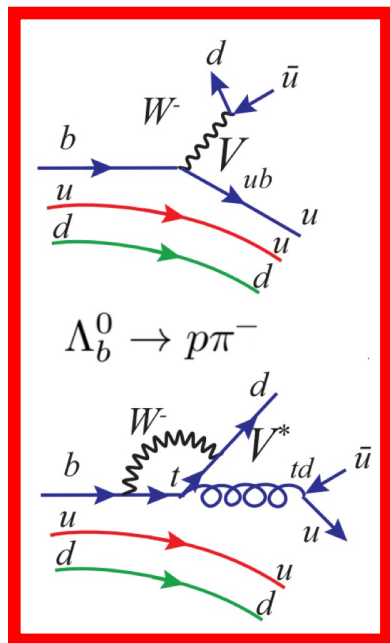
➤ No significant variation of asymmetries across the phase space

Why baryon CPV so small

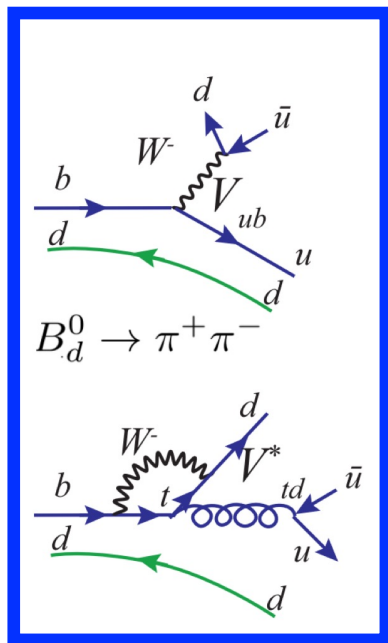
- Small strong phase difference
- The cancellation between different partial wave turns in small net direct CPV
- Overlap of resonances could dilute CPV



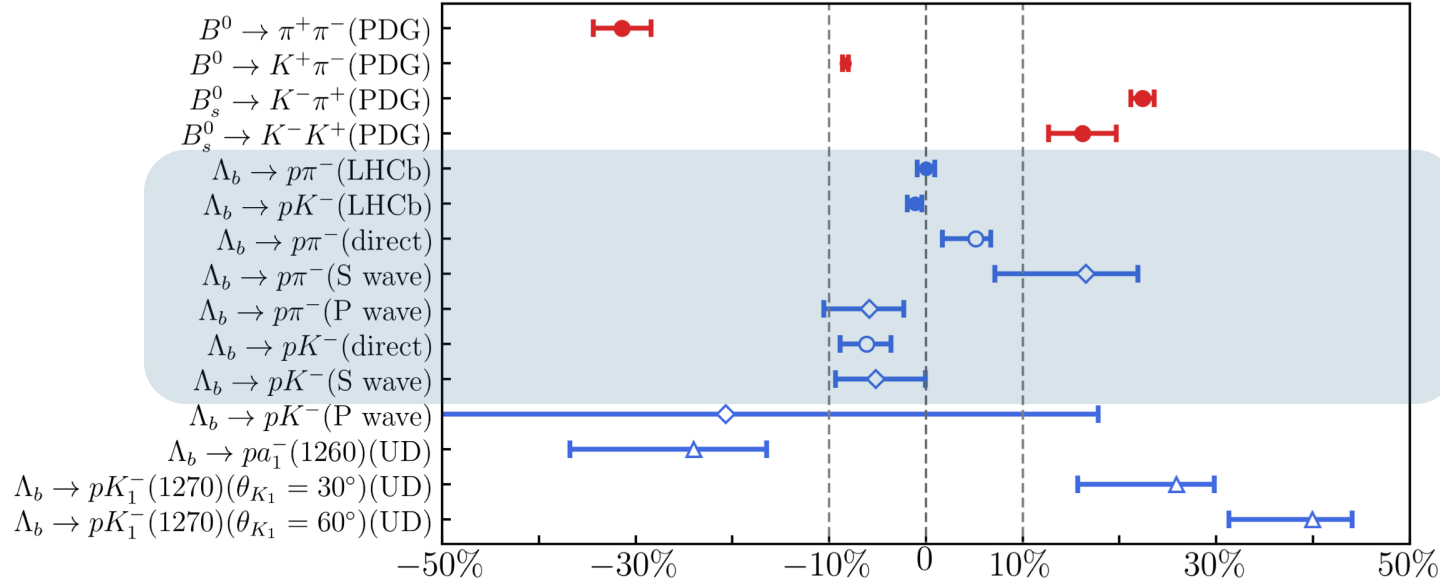
Further measurements are essential to clarify the picture



S+P wave



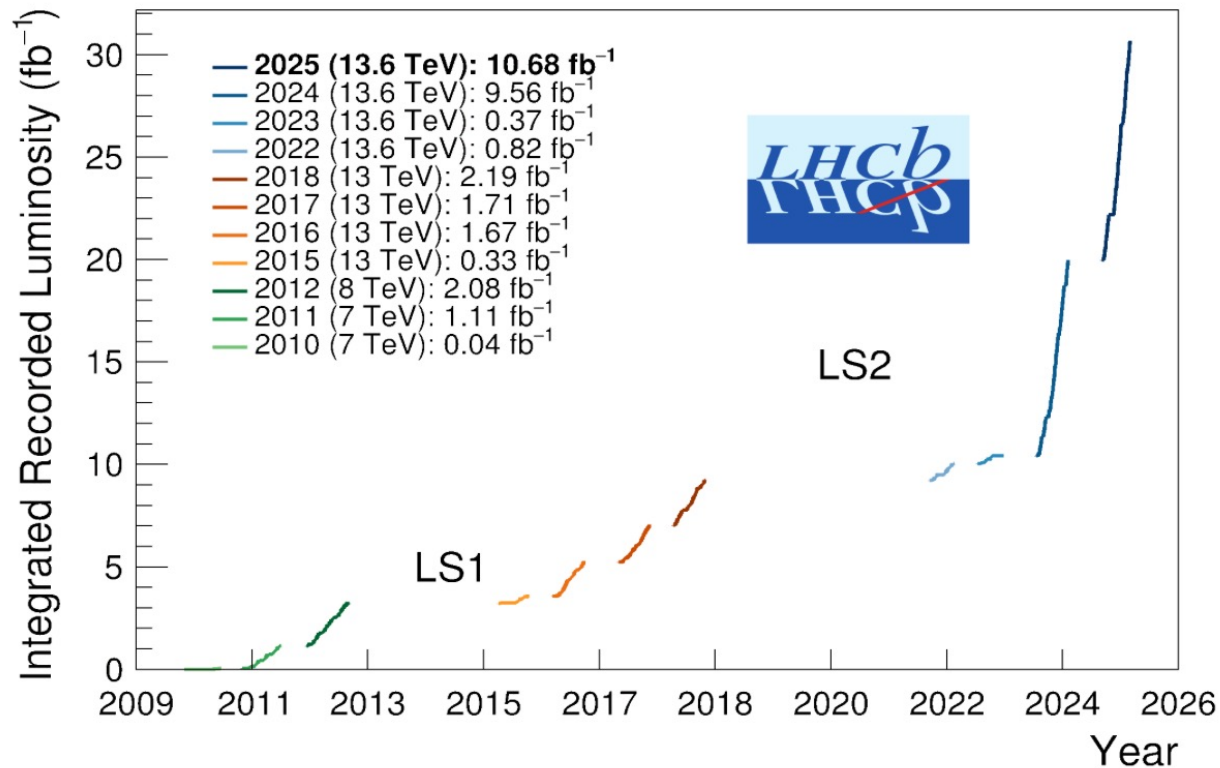
S wave only



- 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



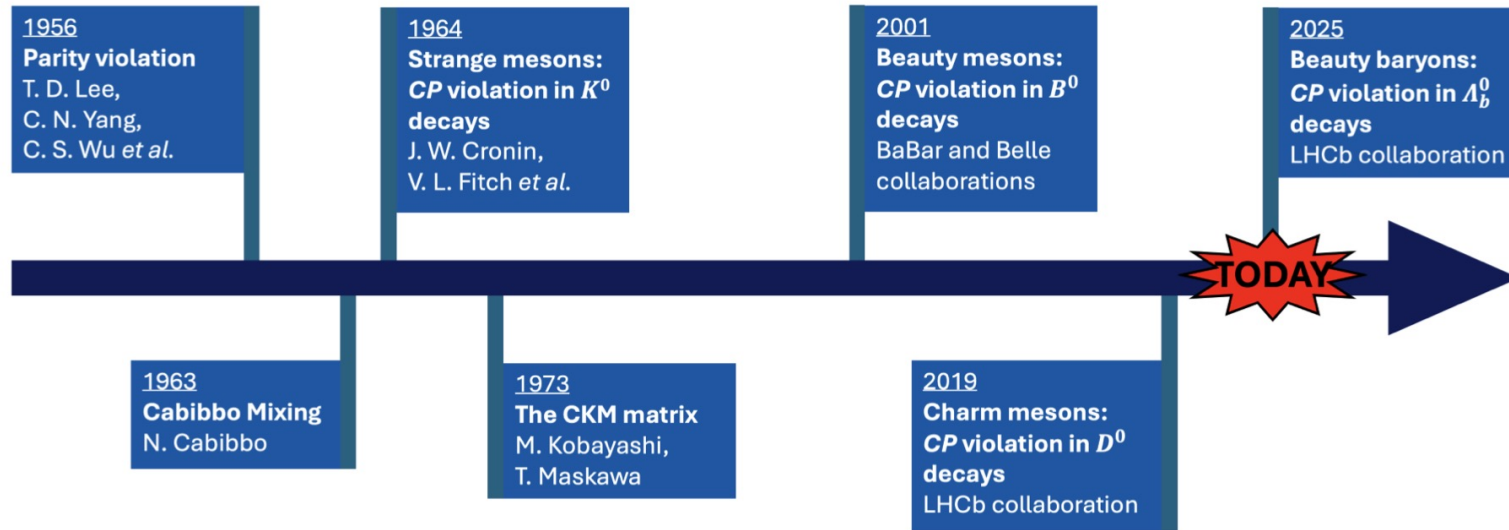
LHCb Run 1

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

- 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.