CP violation in charmless Λ_b^0 decays at LHCb

Xinchen Dai
on behalf of the LHCb Collaboration

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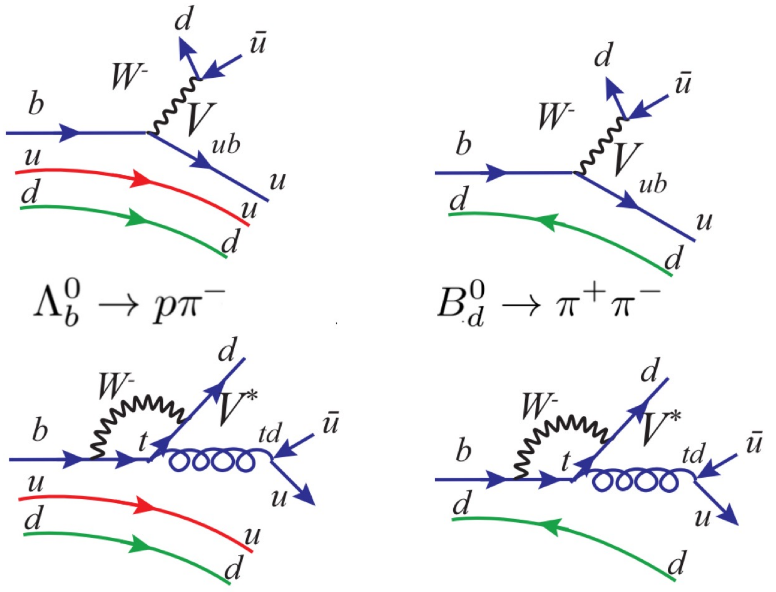
Why CPV in baryon decays

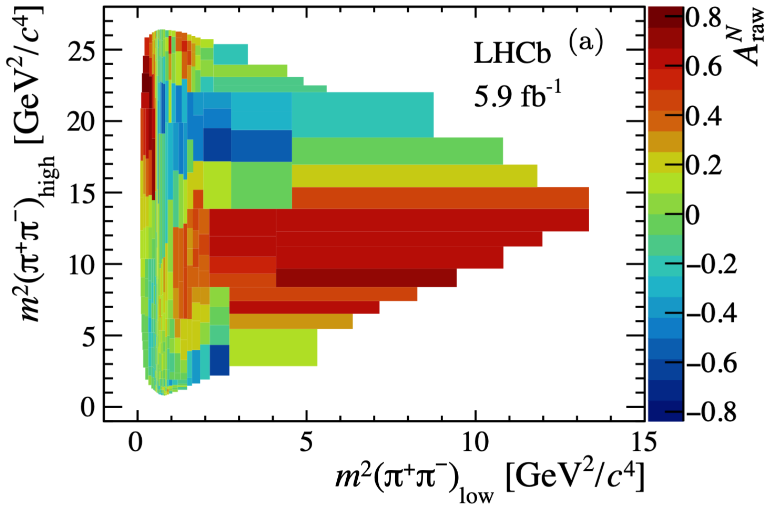
- ☐ CPV is one of the necessary conditions for baryogenesis
- ☐ CPV is well established in meson decays
  - ➢ no significant deviation from SM prediction
  - ➢ not strong enough to account for the baryogenesis
- ☐ No CPV has been observed in baryon sector yet
  - ➢ Evidence of CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$(3.3 σ) [Nat.Phys.13(2017)391]
  - ➢ Updated measurement shows no CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$(2.9 σ)
  - ➢ New results from analysis of $\Lambda_b^0 \to \Lambda h h'$ (Chenxu's presentation)
- ☐ The Standard Model predicts similar CP violation in baryon and meson decays
- ☐ Unlike mesons, only direct CPV occurs in baryon decays due to baryon number conservation



- ☐ Searching for CPV in baryon decays:
  - ➢ Test of the SM and the CKM mechanism
  - ➢ Explore new physics

Experimental methods & observables

- Asymmetry in the yields of CP-conjugate processes $A_{raw} = \frac{N(H \to f) - N(\bar{H} \to \bar{f})}{N(H \to f) + N(\bar{H} \to \bar{f})}$ $\quad A_{CP} \propto sin\Delta\phi sin\Delta\delta$
  - $A_{CP} = A_{raw} - A_{prod} - A_{det} - A_{other}$
  - $\Delta A_{CP} = A_{CP}^{signal} - A_{CP}^{control}$



- Miranda technique: Measuring CPV on binned phase space
  - asymmetry significance: $S_{CP}^{i} = \frac{n_i - \alpha\bar{n}_i}{\sqrt{\alpha(n_i + \bar{n}_i)}}$
- Energy test: A statistical T test to compare the baryon anti-baryon samples
  - $T \equiv \frac{1}{2n(n-1)}\Sigma_{i\neq j}^{n}\psi_{ij} + \frac{1}{2\bar{n}(\bar{n}-1)}\Sigma_{i\neq j}^{\bar{n}}\psi_{ij} - \frac{1}{n\bar{n}}$
- k-nearest neighbour (kNN):
  - $T \equiv \frac{1}{n_k(n_+ - n_-)}\Sigma_{i=1}^{n_+ + n_-}\Sigma_{k}^{n_k} I(i,k)$
- Triple product asymmetry:
  - $A_{\hat{T}}(C_{\hat{T}}) = \frac{N(C_{\hat{T}}>0) - N(C_{\hat{T}}<0)}{N(C_{\hat{T}}>0) + N(C_{\hat{T}}<0)}$, $a_{CP}^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} - \bar{A}_{\hat{T}}), A_{CP} \propto cos\Delta\phi cos\Delta\delta$
- Amplitude analysis:
  - $A = \Sigma a_i A_i, \bar{A} = \Sigma \bar{a}_i \bar{A}_i, A_{CP} = \frac{|a_i|^2 - |\bar{a}_i|^2}{|a_i|^2 + |\bar{a}_i|^2}$

Overview of CPV in baryon decays

	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
$\Lambda_b^0 \to ph^-h^+h^-$	ΔA_{CP}, TPA, Energy test	3fb^{-1}&6.6fb^{-1}	EPJC (2019) 79:745 PRD 102 (2020) 051101
$\Lambda_b^0 \to \Lambda_c^+h^-$	decay parameters	9fb^{-1}	arXiv:2409.02759
$\Xi_b^- \to pK^-K^+$	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

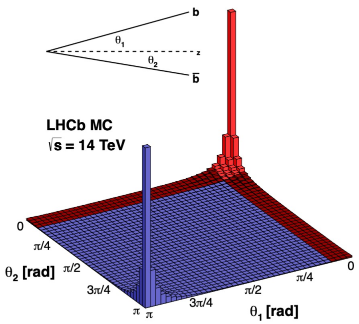
CP Violation in Baryon Decays at LHCb
Symmetry 2023, 15(2), 522

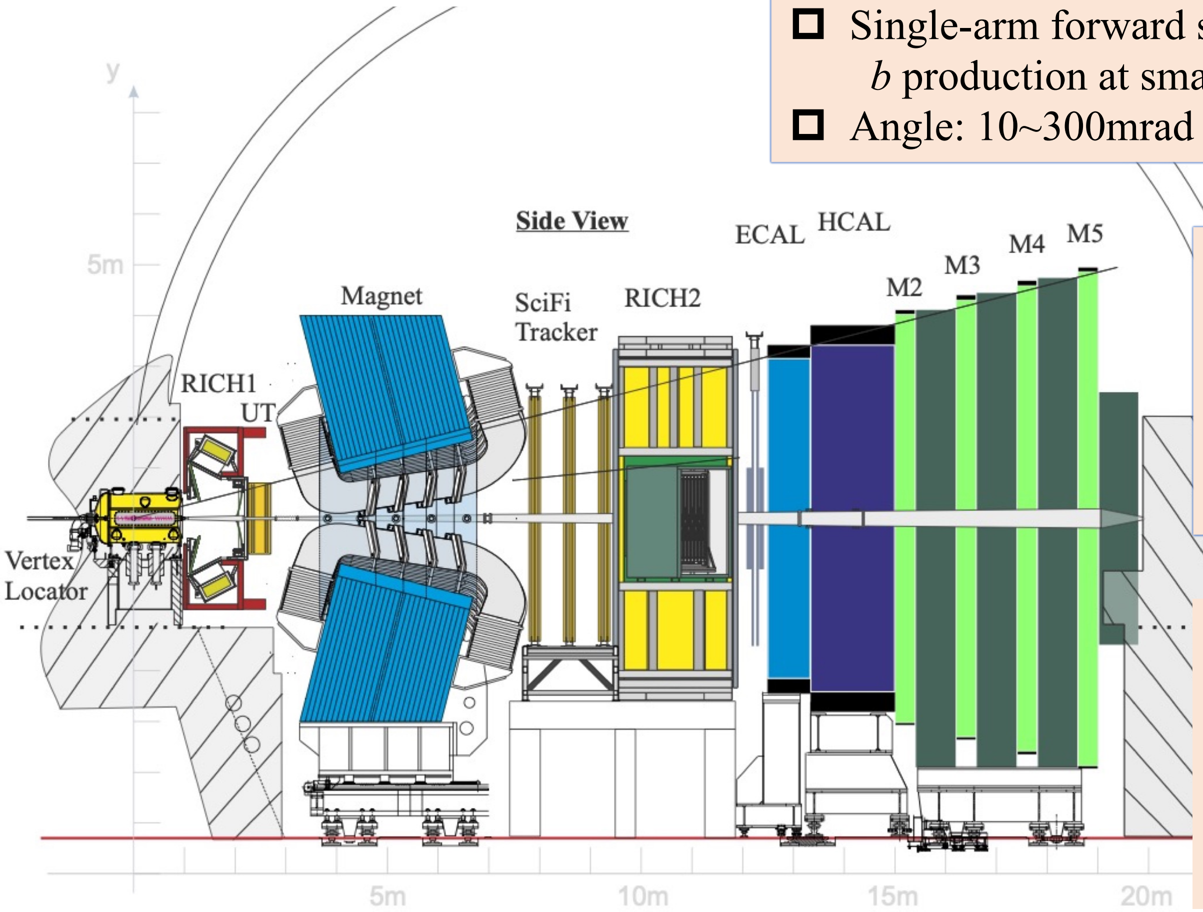
Overview of CPV in baryon decays

	Data	Institutions
$\Lambda_b^0 \to ph\pi^0$	$9\mathrm{fb}^{-1}$	PKU/WHU/UCAS
$\Lambda_b^0 \to pK_s^0\pi^-$	$9\mathrm{fb}^{-1}$	PKU/CCNU/UCAS
$\Lambda_b^0 \to \Lambda hh'$	$9\mathrm{fb}^{-1}$	UCAS/CCNU/PKU
$\Lambda_b^0 \to ph^-h^+h^-$	$9\mathrm{fb}^{-1}$	PKU/CCNU/UCAS/IHEP

LHCb experiment

- Dedicated to *b* physics
  - Precision measurements of CPV & CKM angles
- Single-arm forward spectrometer
  - *b* production at small polar angles
- Angle: 10~300mrad





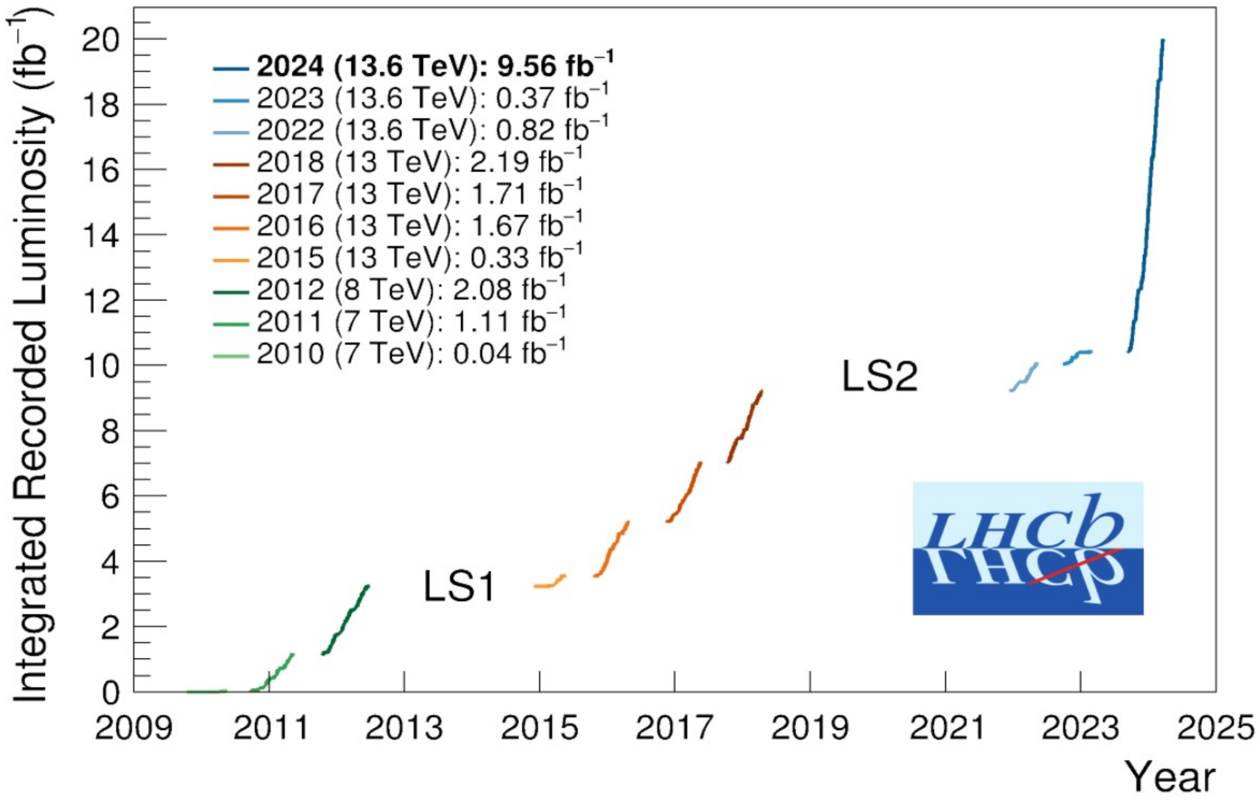
precise tracking, vertexing system
- Vertex Locator detector
- Upstream tracker
- Scintillating fibre tracker
- Muon

high-efficiency PID
- RICH
- ECAL
- HCAL
- Muon

- New FE and DAQs for all subdetector
- Fully software trigger at 40MHz on GPU+CPU

LHCb experiment

Trigger efficiency for hadron final states increased by factor of 2



- Run I: ~3/fb @ $\sqrt{s}$=7-8TeV
- Run II: ~6/fb @ $\sqrt{s}$ =13 TeV
- Run III: ~25/fb @ $\sqrt{s}$ = 13.6 TeV

- $\frac{f_{\Lambda_b^0}}{f_u+f_d} = 0.259 \pm 0.018$
- Average over $P_T \in [4, 25]$ GeV and $\eta \in [2, 5]$ @ $\sqrt{s}$ = 13 TeV

More charm baryons: Λ_c, Ξ_c ...

Theoretical prediction for b-baryon CPV are at ~1%
Current statistics enable us to reduce the uncertainty to ~0.1%

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

Phys.Lett.B 787 (2018) 124-133

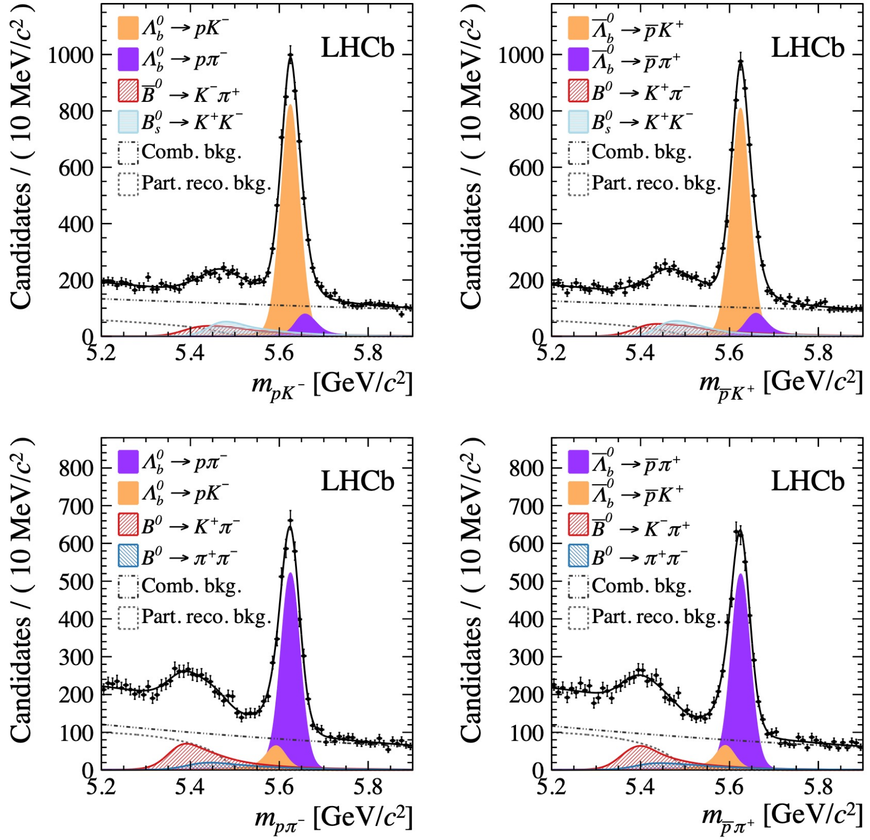
Search for CP violation in $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$ decays

Run1 3/fb

LHCb-PAPER-2024-048, Run I+II 9/fb

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

- Mediated by the same quark-level transitions contributing to $B^0 \to hh$, receiving similar contribution from $b \to u$(tree) and $b \to d(s)$(penguin) diagrams
- Predicted CPV in $\Lambda_b^0 \to pK^-/p\pi^-$ up to ~30%



	$\Lambda_b^0 \to pK^-$	$\Lambda_b^0 \to p\pi^-$
Yu et al. arXiv:2409.02821	-5.8%	4.1%
Geng et al. PRD 102(2020), 034033	6.7%	-4.4%
Hsiao et al. PRD 95 (2017) 9, 093001	$(5.8 \pm 0.2)\%$	$(-3.9 \pm 0.2)\%$
Zhu et al. PRD 99 (2019) 5, 054020	$(10.1^{+1.3}_{-2})\%$	$(-3.37^{+0.29}_{-0.37})\%$
Lu et al. PRD 80, 034011 (2009)	$(-5^{+26}_{-5})\%$	$(-31^{+43}_{-1})\%$
CDF	$(-10 \pm 8 \pm 4)\%$	$(6 \pm 7 \pm 3)\%$

$$A_{CP}(\Lambda_b^0 \to pK^-) = (-2.0 \pm 1.3 \pm 1.9)\%$$

$$A_{CP}(\Lambda_b^0 \to p\pi^-) = (-3.5 \pm 1.7 \pm 2.0)\%$$

- $\Delta A_{CP} = A_{CP}(\Lambda_b^0 \to pK^-) - A_{CP}(\Lambda_b^0 \to p\pi^-) = 0.014 \pm 0.022 \pm 0.010$

CPV in $\Lambda_b^0 \to pK^-/p\pi^-$(New)

- Update CP measurement using combined Run I and Run II data (9fb^{-1})

- For Run I data: $A_{CP}^{pK} = A_{raw} - A_{det}^{p} - A_{det}^{K} - A_{PID}^{pK} - A_{trigger}^{pK} - A_{P}^{\Lambda_b^0}$
  - All the nuisance asymmetries studied using data driven method and existing inputs
  - The precision of Run 1 has improved thanks to the updated measurements of $A_P^{\Lambda_b^0}$ and A_{det}^{p}

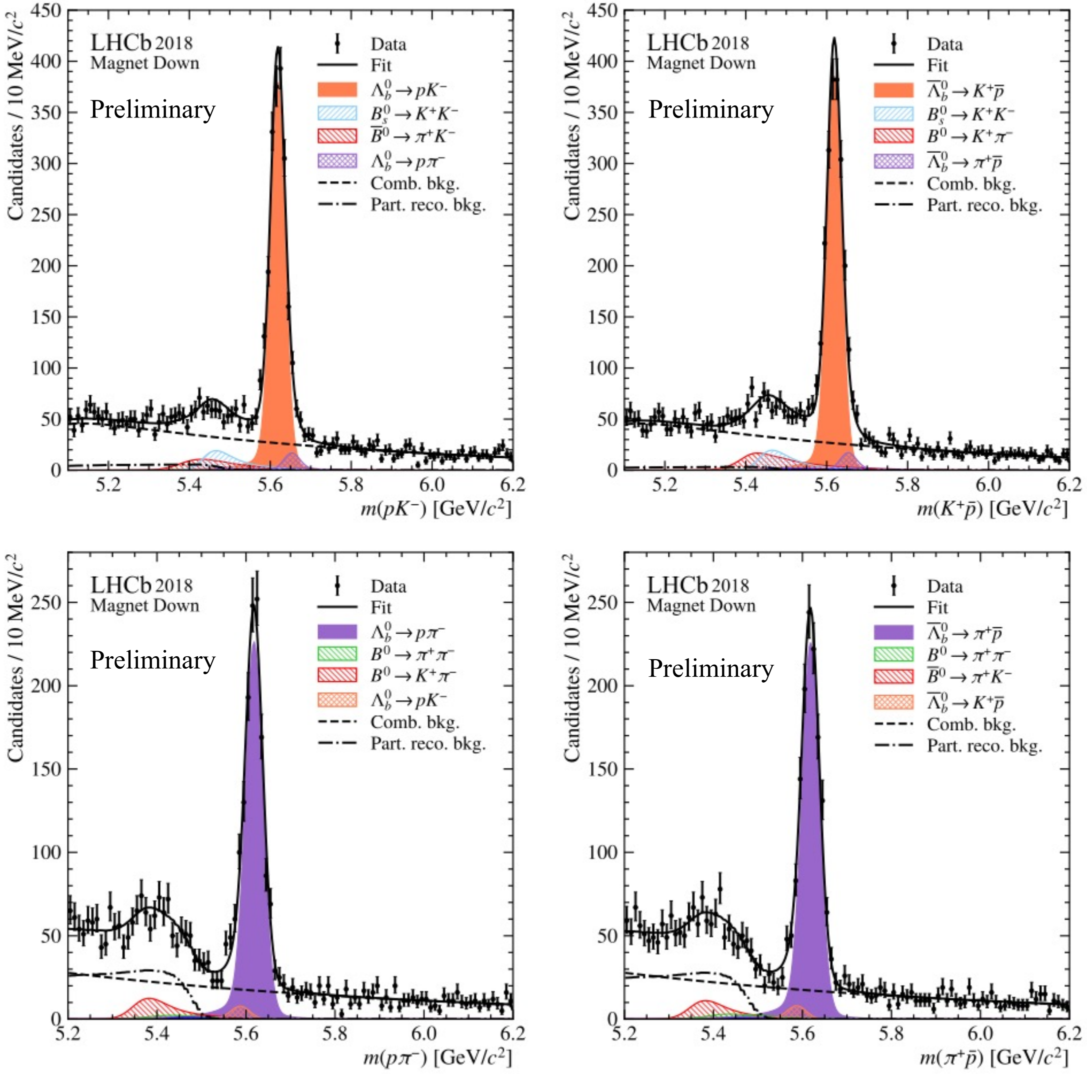
- For Run II data: $A_{CP}^{pK} = \Delta A_{raw} - \Delta A_{det}^{p} - \Delta A_{det}^{K} - \Delta A_{PID}^{pK} - \Delta A_{trigger}^{pK} + A_{det}^{\pi^-} + A_{det}^{\pi^+} + A^{\Lambda_c^+\pi^-}$
  - $A_P^{\Lambda_b^0}$ cancelled by control channel $\Lambda_b^0 \to \Lambda_c^+(pK^-\pi^+)\pi^-$
  - reweight over the kinematic of the Λ_b^0 in control samples.

- New data driven method developed to correct $A_{trigger}^{pK}$

- Better control of uncertainties from PID

CPV in $\Lambda_b^0 \to pK^-/p\pi^-$(New)

- Simultaneously fit to eight m(hh) spectrums
  - $K^\pm\pi^\mp, K^+K^-, \pi^+\pi^-, pK^-, \bar{p}K^+, p\pi^-, \bar{p}\pi^+$
- Signal: Johnson + two gaussian: shape fixed from MC
- Cross-feed bkg: KDE on simulated samples, yields are fixed from signal yields with PID mis-ID efficiency
- Part.reco.bkg: Argus or simulated samples
- Comb.bkg: exponential



CPV in $\Lambda_b^0 \to pK^-/p\pi^-$(New)

- New Run I results:

Statistically dominated!

$$A_{CP}^{pK} = (-0.27 \pm 1.55 \pm 0.57)\%$$
$$A_{CP}^{p\pi} = (-0.59 \pm 1.86 \pm 0.53)\%$$

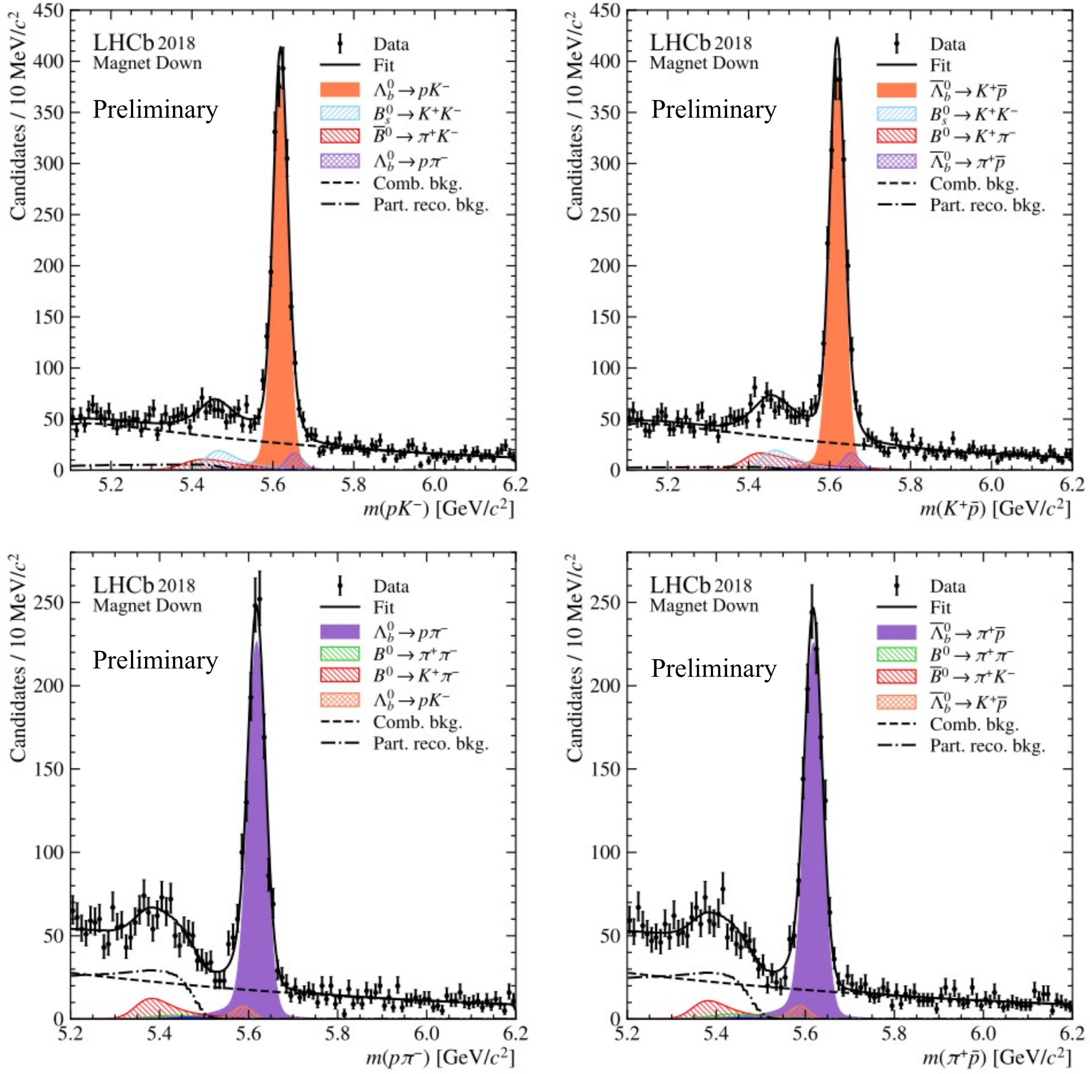
- New Run II results:

$$A_{CP}^{pK} = (-1.39 \pm 0.75 \pm 0.41)\%$$
$$A_{CP}^{p\pi} = (0.42 \pm 0.93 \pm 0.42)\%$$

- Combined results:

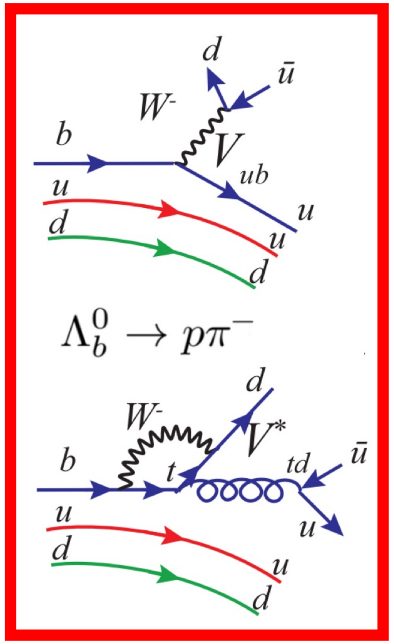
$$A_{CP}^{pK} = (-1.14 \pm 0.67 \pm 0.36)\%$$
$$A_{CP}^{p\pi} = (0.02 \pm 0.83 \pm 0.37)\%$$

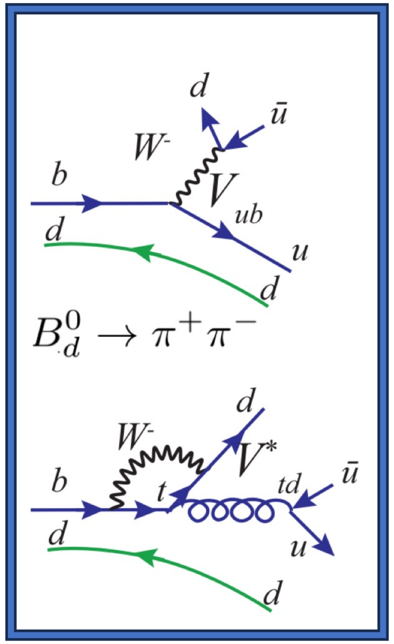
No evidence of CP violation!



Theoretical explanation

arXiv:2409.02821





$\frac{1}{2}^+ \to \frac{1}{2}^+ + 0^-$

S wave & P wave

$0^- \to 0^- + 0^-$

S wave only!

- The cancellation between different partial wave turns in small net direct CPV
- A partial-wave CPV of similar magnitude to that in *B* mesons is predicted.

	$\Lambda_b \to p\pi^-$	$\Lambda_b \to pK^-$
Br	3.3×10^{-6}	2.9×10^{-6}
A_{CP}^{dir}	4.1%	−5.8%
A_{CP}^{S}	0.15	−0.05
A_{CP}^{P}	−0.07	−0.23
α	−0.81	0.38
β	0.26	−0.65
γ	−0.52	0.66
A_{CP}^{α}	0.046	0.20
A_{CP}^{β}	2.12	−9.34
A_{CP}^{γ}	−0.12	0.10

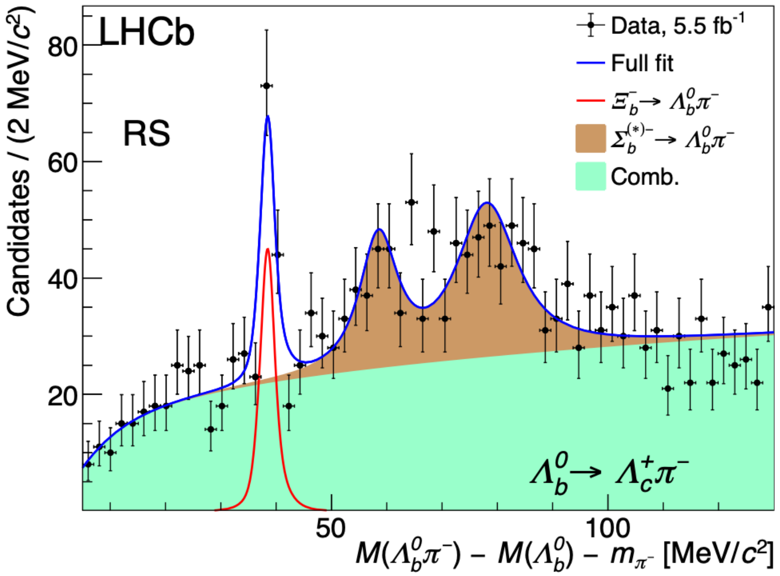
$$\alpha \equiv \frac{2Re(S\times P)}{|S|^2 + |P|^2} \qquad \beta \equiv \frac{2Im(S\times P)}{|S|^2 + |P|^2} \qquad \gamma \equiv \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}$$

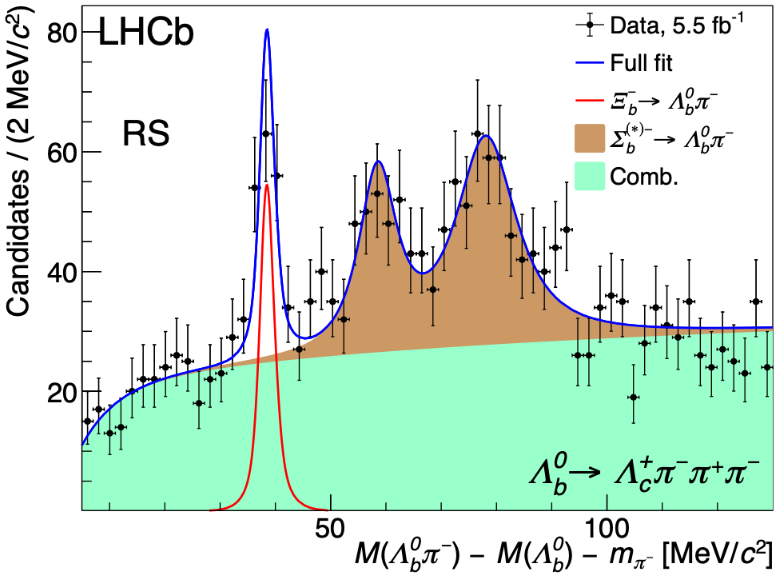
Outlook

- The polarization of Λ_b^0 at the LHC is consistent with zero [PLB 724 (2013) 27-35]
- A sample of Λ_b^0 decay from heavier b baryons can be used to probe the CPV in decay parameters and partial-waves

Signal yields ($5.5\mathrm{fb}^{-1}$):
$N(\Lambda_b^0 \to \Lambda_c^+\pi^-) = 85 \pm 13$
$N(\Lambda_b^0 \to \Lambda_c^+\pi^+\pi^+\pi^-) = 103 \pm 15$

Observation of $\Xi_b^- \to \Lambda_b^0\pi^-$ [PRD108 (2023) 7, 072002]





More data expected from HL-LHC

Conclusion

- Search for CPV in b-baryon is a frontier of flavor physics
- More contributions from the LHCb China team
- Best measurement of CPV in $\Lambda_b^0 \rightarrow ph^-$
- Further investigation is needed to understand CPV in baryon decays
- More data in Run3+4 is coming
- Many new analyses coming soon

Backup

CPV in $\Lambda_b^0(\Xi_b^0) \to p h^- h^+ h^-$

Eur. Phys. J. C (2019) 79:745

Measurements of CP asymmetries in charmless four-body Λ_b^0 and Ξ_b^0 decays

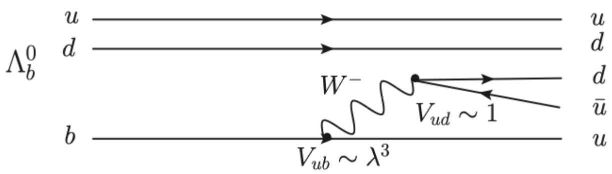
Run I 3/fb

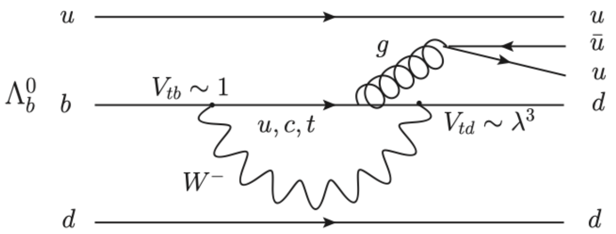
CPV in $\Lambda_b^0(\Xi_b^0) \to ph^-h^+h^-$

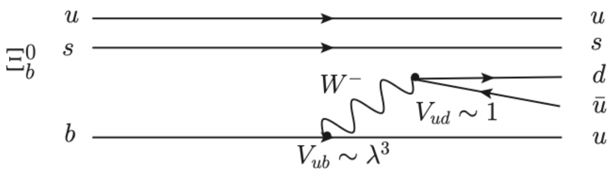
- Follow the path of the observation of CPV in charmless multibody decays of B mesons
- Dominant diagrams with amplitudes of similar magnitude
- Contain rich resonance structures, both in the two- or three-body baryonic invariant-mass spectra
- Large CPV expected due to the strong-phase differences induced by the interference patterns
- Six decay modes from 0.5-10K signals
- CP observables: $\Delta A_{CP} = A_{CP} - A_{CP}^{con.}$

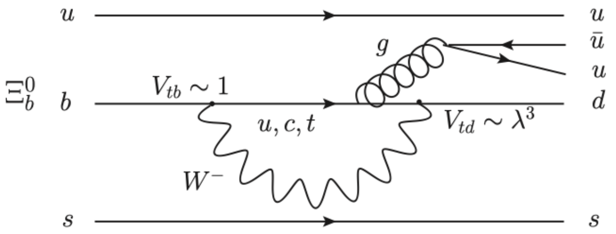
Charmless decay	Quark transition	Charmed decay	Quark transition
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$	$b \to u\bar{u}d$ (T + P)	$\Lambda_b^0 \to (\Lambda_c^+ \to p\pi^-\pi^+)\pi^-$	$b \to c\bar{u}d$ (T)
$\Lambda_b^0 \to pK^-\pi^+\pi^-$	$b \to u\bar{u}s$ (T + P)	$\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\pi^-$	$b \to c\bar{u}d$ (T)
$\Lambda_b^0 \to pK^-K^+\pi^-$	$b \to d\bar{s}s$ (T + P)	$\Lambda_b^0 \to (\Lambda_c^+ \to p\pi^-\pi^+)\pi^-$	$b \to c\bar{u}d$ (T)
$\Lambda_b^0 \to pK^-K^+K^-$	$b \to s\bar{s}s$ (T + P)	$\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\pi^-$	$b \to c\bar{u}d$ (T)
$\Xi_b^0 \to pK^-\pi^+\pi^-$	$b \to u\bar{u}d$ (T + P)	$\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\pi^-$	$b \to c\bar{u}d$ (T)
		$\Xi_b^0 \to (\Xi_c^+ \to pK^-\pi^+)\pi^-$	$b \to c\bar{u}d$ (T)
$\Xi_b^0 \to pK^-\pi^+K^-$	$b \to s\bar{d}d$ / $b \to u\bar{u}s$ (P / T)	$\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\pi^-$	$b \to c\bar{u}d$ (T)
		$\Xi_b^0 \to (\Xi_c^+ \to pK^-\pi^+)\pi^-$	$b \to c\bar{u}d$ (T)

Signal channels | Control channels





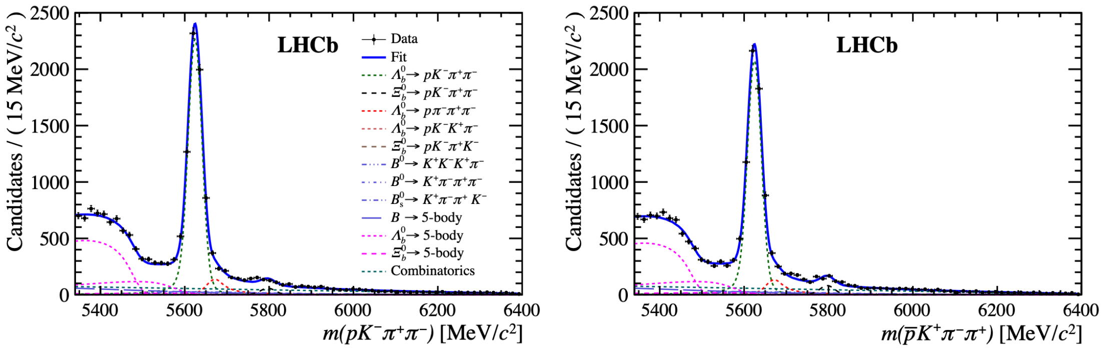


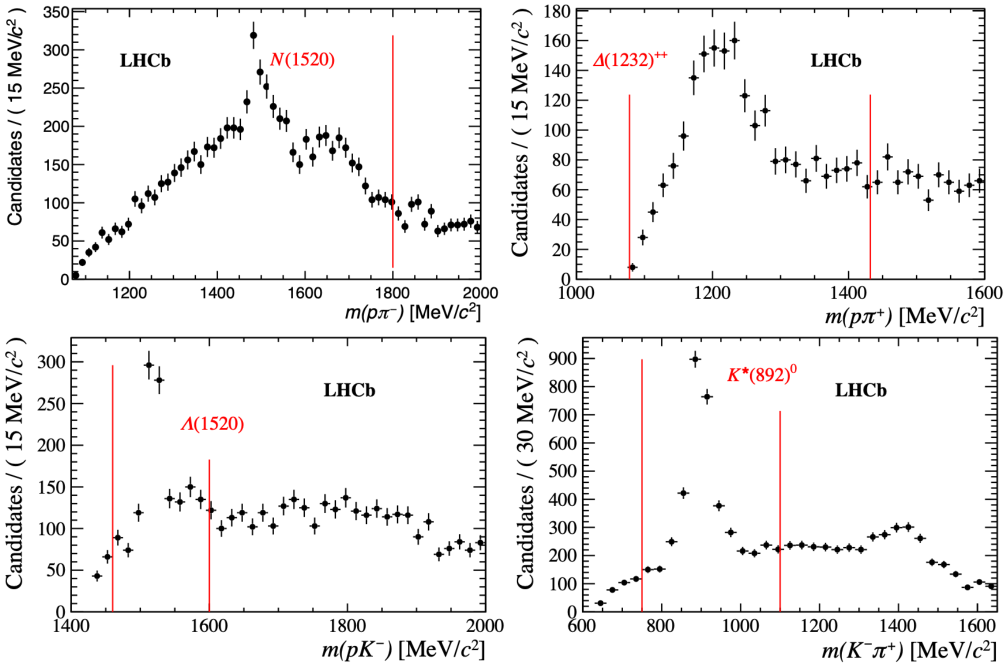


CPV in $\Lambda_b^0(\Xi_b^0) \to ph^-h^+h^-$

- Simultaneous fit to 6 decay modes

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





- Global CPV measurement:
  - $\Delta A_{CP}(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) = (1.1 \pm 2.5 \pm 0.6)\%$
  - $\Delta A_{CP}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (3.2 \pm 1.1 \pm 0.6)\%$
  - $\Delta A_{CP}(\Lambda_b^0 \to pK^-K^+\pi^-) = (6.9 \pm 4.9 \pm 0.8)\%$
  - $\Delta A_{CP}(\Lambda_b^0 \to pK^-K^+K^-) = (0.2 \pm 1.8 \pm 0.6)\%$
  - $\Delta A_{CP}(\Xi_b^0 \to pK^-\pi^+\pi^-) = (17 \pm 11 \pm 1)\%$
  - $\Delta A_{CP}(\Xi_b^0 \to pK^-\pi^+K^-) = (-6.8 \pm 8.0 \pm 0.8)\%$
- Statistical uncertainty dominated, consistent with CP conservation at 1% precision

- Local CPV measurement:
  - $\Delta A_{CP}(\Lambda_b^0 \to pa_1(1260)) = (-1.5 \pm 4.2 \pm 0.6)\%$
  - $\Delta A_{CP}(\Lambda_b^0 \to N(1520)\rho) = (2.0 \pm 4.9 \pm 0.4)\%$
  - $\Delta A_{CP}(\Lambda_b^0 \to \Delta^{++}\pi^+\pi^-) = (0.1 \pm 3.2 \pm 0.6)\%$
  - $\Delta A_{CP}(\Lambda_b^0 \to pK_1(1410)) = (4.7 \pm 3.5 \pm 0.8)\%$
  - $\Delta A_{CP}(\Lambda_b^0 \to \Lambda(1520)\rho) = (0.6 \pm 6.0 \pm 0.5)\%$
  - $\Delta A_{CP}(\Lambda_b^0 \to N(1520)K^*(892)) = (5.5 \pm 2.5 \pm 0.5)\%$
  - $\Delta A_{CP}(\Lambda_b^0 \to \Delta^{++}K^+\pi^-) = (4.4 \pm 2.6 \pm 0.6)\%$
  - $\Delta A_{CP}(\Lambda_b^0 \to \Lambda(1520)\phi) = (4.3 \pm 5.6 \pm 0.4)\%$
  - $\Delta A_{CP}(\Lambda_b^0 \to pK^-\phi) = (-0.7 \pm 3.3 \pm 0.7)\%$

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

Nature Physics 13, 391–396 (2017)

Measurement of matter-antimatter differences in beauty baryon decays

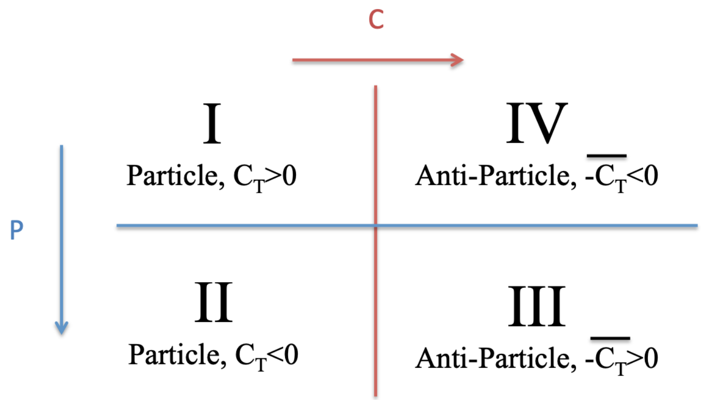
Run I 3/fb

Phys. Rev. D 102 (2020) 051101

Search for CP violation and observation of P violation in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays

Run I+II (2011-2017) 6.6/fb

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



- Search for CPV with scalar triple-product asymmetries, $\hat{T}$ flips the direction of fir state momenta and spin

$$C_{\hat{T}} \equiv \vec{p}_p \cdot (\vec{p}_{h_1} \times \vec{p}_{h_2}),\ \ \overline{C}_{\hat{T}} \equiv \vec{p}_{\overline{p}} \cdot (\vec{p}_{\overline{h}_1} \times \vec{p}_{\overline{h}_2})$$

- Data divided into 4 subsamples: $C_{\hat{T}} > 0, C_{\hat{T}} < 0, -\overline{C_{\hat{T}}} > 0, -\overline{C_{\hat{T}}} < 0$

$$A_{\hat{T}}(C_{\hat{T}}) = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)} \qquad \overline{A}_{\hat{T}}(\overline{C}_{\hat{T}}) = \frac{\overline{N}(-\overline{C}_{\hat{T}} > 0) - \overline{N}(-\overline{C}_{\hat{T}} < 0)}{\overline{N}(-\overline{C}_{\hat{T}} > 0) + \overline{N}(-\overline{C}_{\hat{T}} < 0)}$$

- $A_{\hat{T}}$ and $\bar{A}_{\hat{T}}$ are not clean CPV observables, FSI effects can introduce fake asymmetries.
- Define the clean CP-violating observable:

$$a_{CP}^{\hat{T}\text{-odd}} = \frac{1}{2}(A_{\hat{T}} - \overline{A}_{\hat{T}}) \qquad a_{P}^{\hat{T}\text{-odd}} = \frac{1}{2}(A_{\hat{T}} + \overline{A}_{\hat{T}}) \qquad A_{CP}^{f} \equiv \frac{\Gamma(H_b \to f) - \Gamma(\overline{H}_b \to \overline{f})}{\Gamma(H_b \to f) + \Gamma(\overline{H}_b \to \overline{f})}$$

$\propto sin\phi cos\delta$

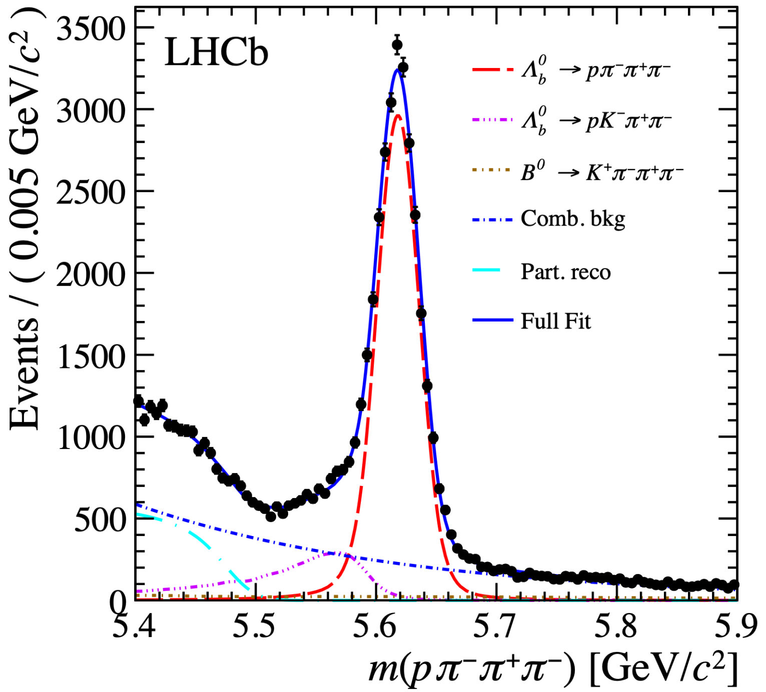
$\propto sin\phi sin\delta$

Does not require a non-zero strong phase difference!

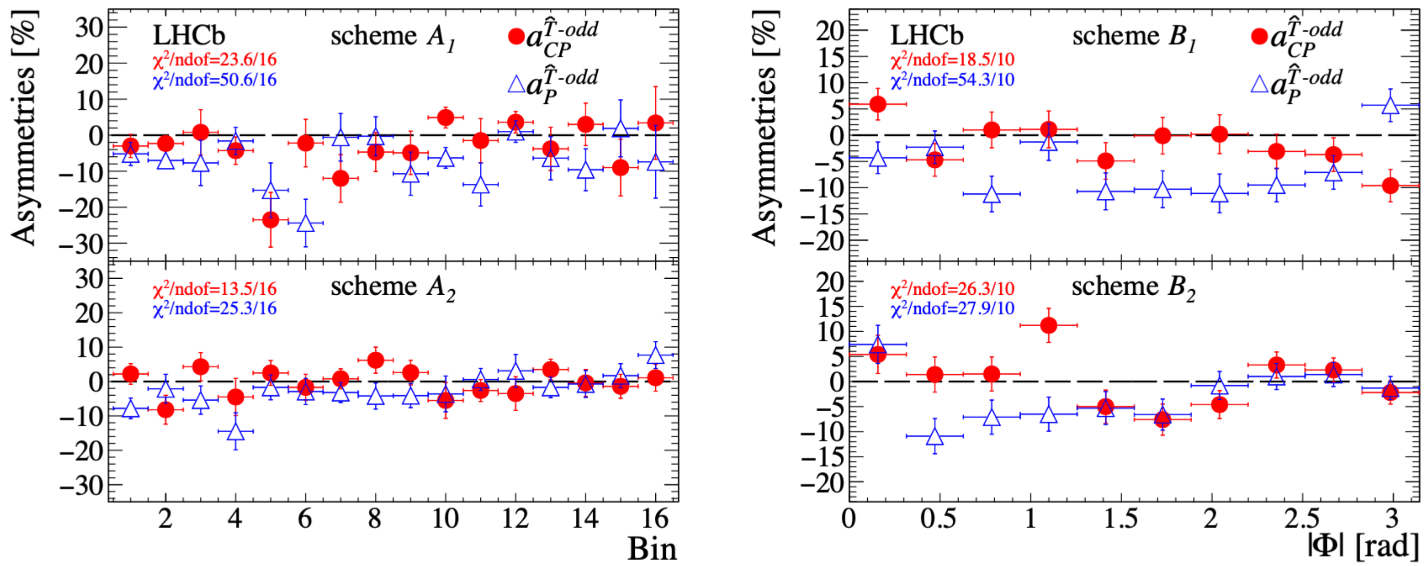
Both strong phase and weak phase differences are needed

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

- CPV integrated over the whole phase space:
  - $a_{CP}^{T-odd} = (-0.7 \pm 0.7 \pm 0.2)\%$



- Asymmetries for different binning scheme:
  - A: 16 bins of polar and azimuthal angle of proton and $\Delta^{++}(\to p\pi^+)$
  - B: asymmetries as a function of $|\Phi|$ angle
  - 1: $m(p\pi^-\pi^+) > 2.8GeV$, dominated by $a_1(1260)$
  - 2: $m(p\pi^-\pi^+) < 2.8GeV$, dominated by N^{*+}



- χ^2 taking into account statistical and systematic effects
- In B_2 region, deviation from CP conservation 2.9σ. CPV not established

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

- Energy test is a model-independent unbinned test sensitive to local differences between two samples
- Provide superior discriminating power between different samples than traditional χ^2 test

$$T \equiv \frac{1}{2n(n-1)}\Sigma_{i\neq j}^{n}\psi_{ij} + \frac{1}{2\bar{n}(\bar{n}-1)}\Sigma_{i\neq j}^{\bar{n}}\psi_{ij} - \frac{1}{n\bar{n}}$$

- $\psi_{ij} = e^{-d_{ij}^2/2\delta^2}$: d_{ij} is their Euclidean distance in phase space, δ the distance scale probed using the energy test
- The p-value is calculated using a permutation method

Distance scale δ	1.6 GeV^2/c^4	2.7 GeV^2/c^4	13 GeV^2/c^4
p-value (CP conservation, P even)	3.1×10^{-2}	2.7×10^{-3}	1.3×10^{-2}
p-value (CP conservation, P odd)	1.5×10^{-1}	6.9×10^{-2}	6.5×10^{-2}
p-value (P conservation)	1.3×10^{-7}	4.0×10^{-7}	1.6×10^{-1}

marginally consistent with the CP-conserving

- A new test is statistic is defined as $Q = p_1 p_2 p_3$, significance for CPV $< 3\sigma$

CPV in $\Lambda_b^0 \to pD^0[K^+\pi^-]K^-$

Phys. Rev. D104 (2021) 112008

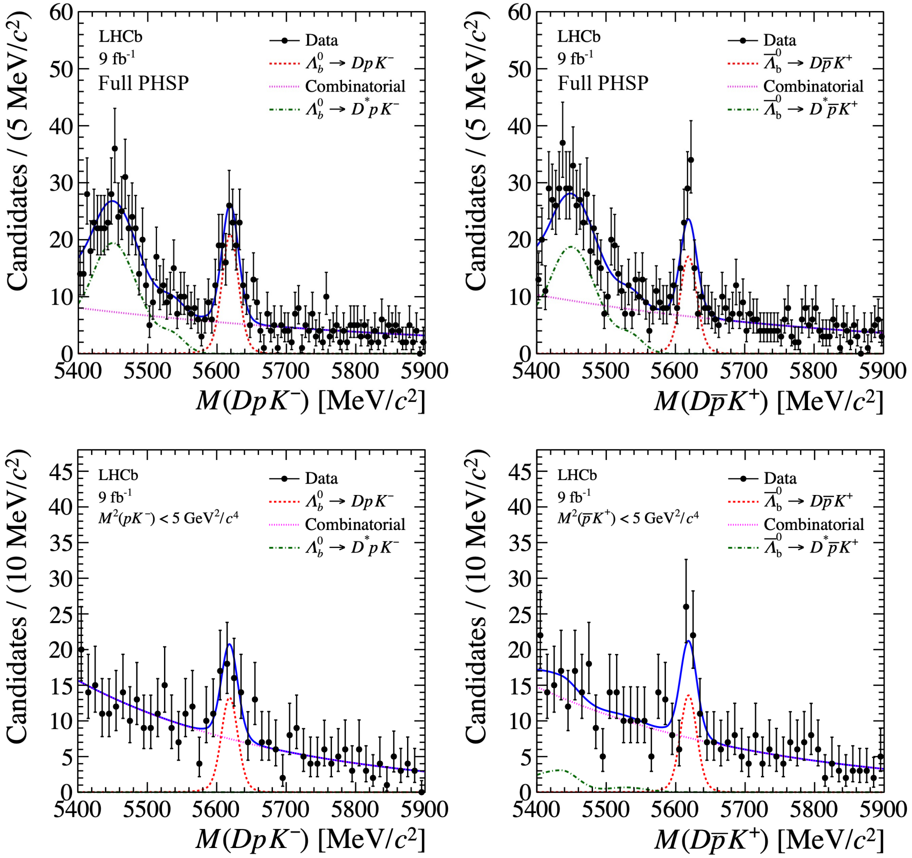
Studies of beauty baryon decays to D^0ph^- and $\Lambda_c^+h^-$ final states

Run I+II 9/fb

CPV in $\Lambda_b^0 \to pD^0[K^+\pi^-]K^-$

- $\Lambda_b^0 \to pD^0[K^+\pi^-]K^-$ receives contributions from $b \to c$ (DCS) and $b \to u$ of similar magnitude
- The interference between these two amplitudes is expected to be large
- Interference is anticipated to be amplified in $\Lambda^*(pK^-)$ region

$$\left|\frac{\mathcal{M}(B^- \to K^- D^0[\to f])}{\mathcal{M}(B^- \to K^- \overline{D}^0[\to f])}\right|^2 \approx \left|\frac{V_{cb}V_{us}^*}{V_{ub}V_{cs}^*}\right|^2 \left|\frac{a_1}{a_2}\right|^2 \frac{Br(D^0 \to f)}{Br(\overline{D}^0 \to f)} \approx$$
$$\approx \left|\frac{0.22}{0.08}\right|^2 \left|\frac{1}{0.26}\right|^2 0.0077 \sim 1\ ,$$



- Asymmetry in the full PHSP:
  $A_{CP} = 0.12 \pm 0.09^{+0.02}_{-0.03}$
- Asymmetry in the low $M(pK^-)$ region:
  $A_{CP} = 0.01 \pm 0.16^{+0.03}_{-0.02}$

Consistent with CP conservation!

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

JHEP 06 (2017) 108

Observation of the decay $\Lambda_b^0 \to pK^-\mu^+\mu^-$ and a search for CP violation

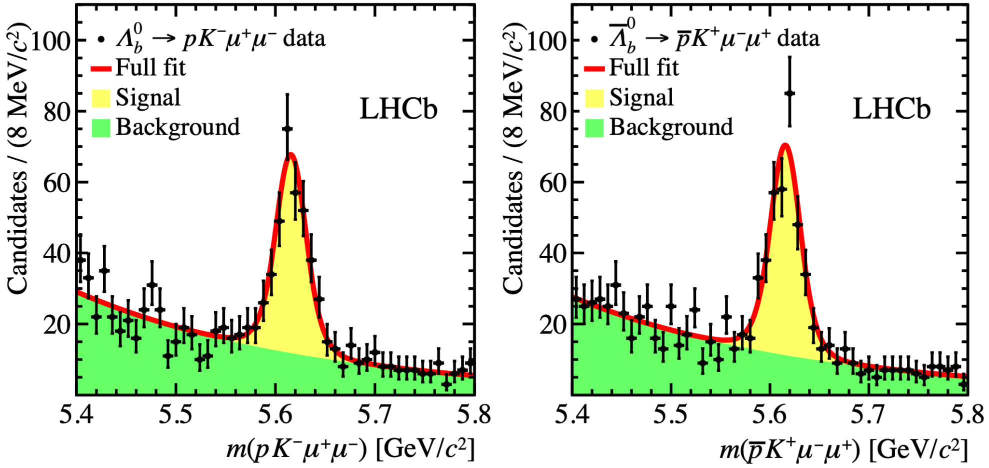
Run I: 3/fb

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

- Search for CPV in FCNC process
- Dominated by loop diagrams
- new heavy particles could provide additional weak phases
- sensitive to CPV effects from physics beyond the SM

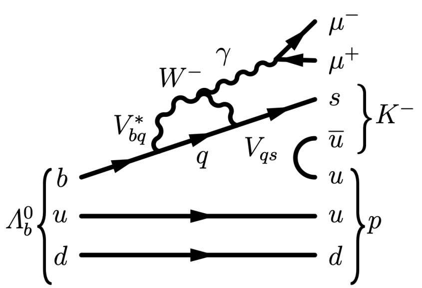
- direct CP asymmetry:

$$\Delta A_{CP} = A_{CP}(\Lambda_b^0 \to pK^-\mu^+\mu^-) - A_{CP}(\Lambda_b^0 \to pK^-J/\psi)$$

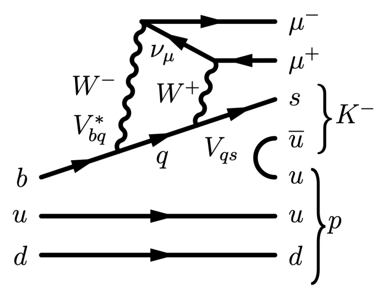


$$\Delta A_{CP}(\Lambda_b^0 \to pK^-\mu^+\mu^-) = (-3.5 \pm 5.0 \pm 0.2)\%$$

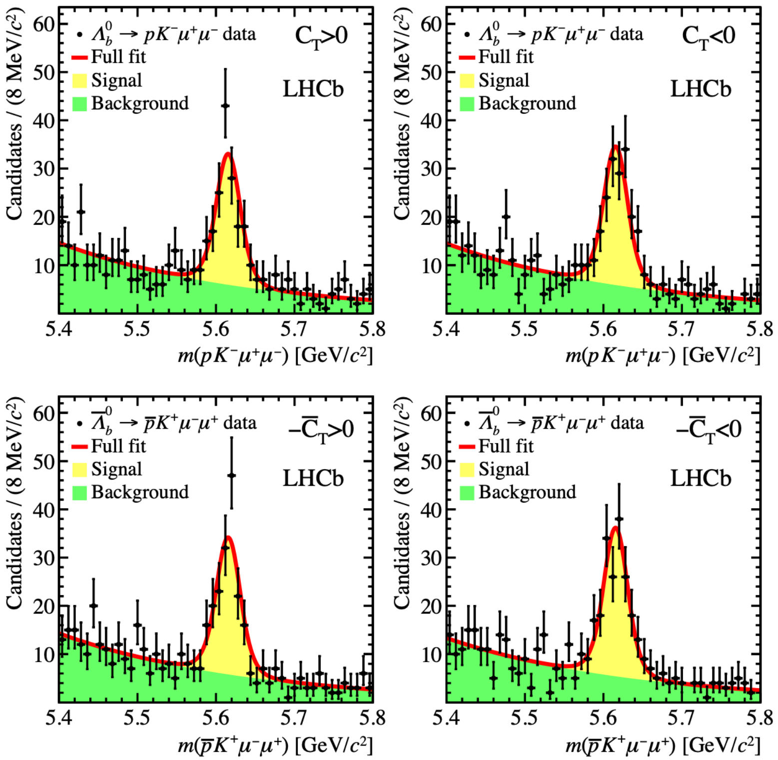
JHEP 11 (2011) 122



PTEP 2015 (2015) 033B04



Triple product asymmetry



$$a_{CP}^{T-odd} = (1.2 \pm 5.0 \pm 0.7)\%$$

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

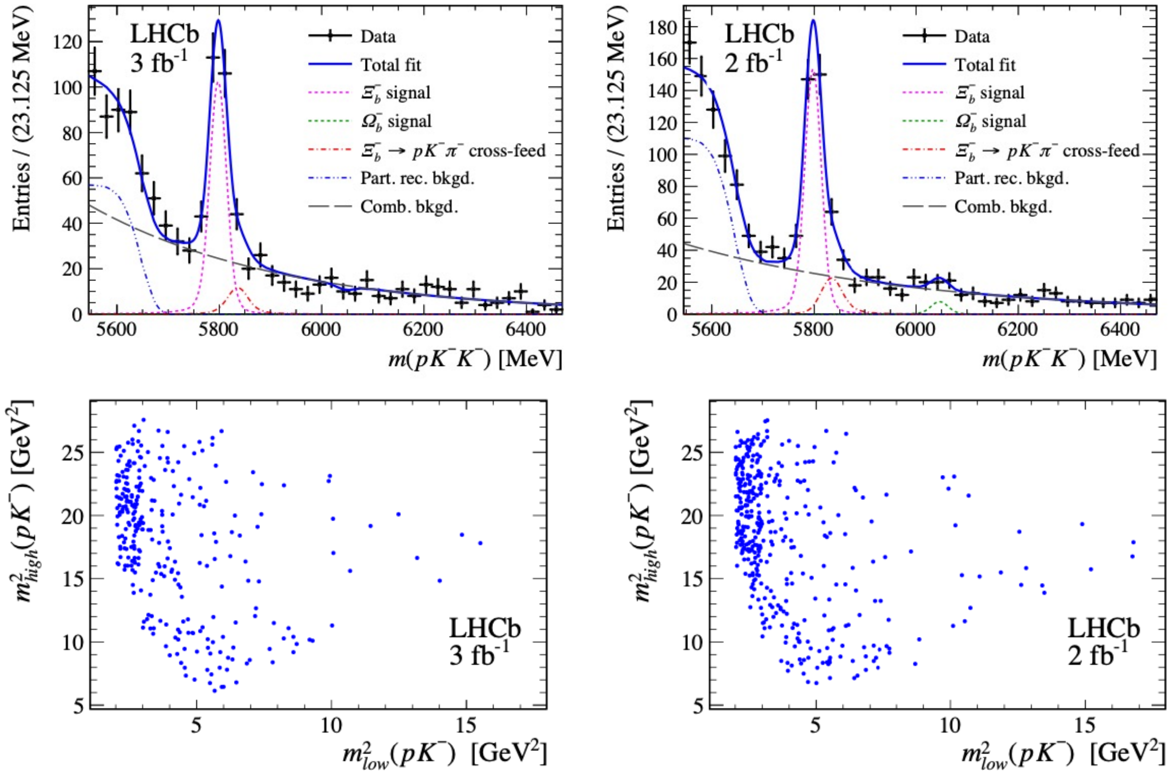
Phys. Rev. D 104, 052010

Search for CP violation in $\Xi_b^- \to pK^-K^-$ decays

Run I: 3/fb
Run II: 2/fb (2015-2016)

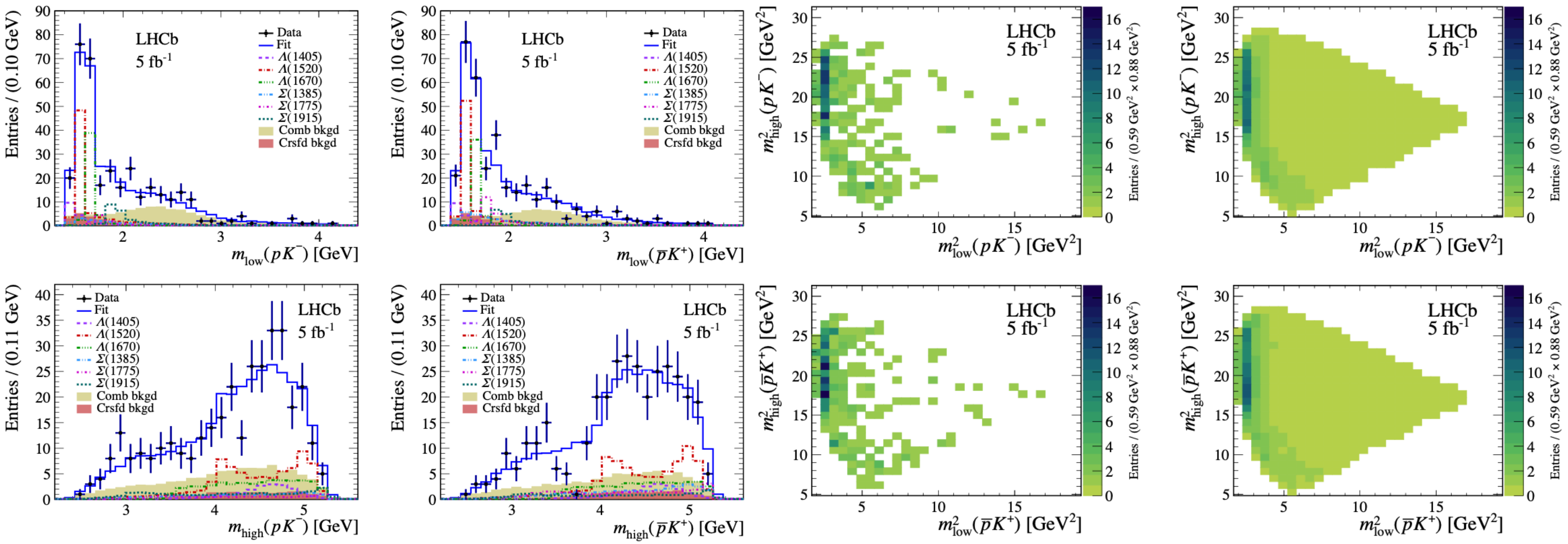
CPV in $\Xi_b^- \to pK^-K^-$

- Charmless $b \to u, b \to s$ transition
- Study CPV over PHSP using model dependent amplitude analysis



Approximately 685 candidates with a purity of 67% are retained for amplitude analysis

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



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, larger samples are needed.

CPV in $\Lambda_c^0 \to pK^-K^+/p\pi^-\pi^+$

JHEP 03 (2018) 182

A measurement of the *CP* asymmetry difference between $\Lambda_c^+ \to pK^-K^+$ and $p\pi^-\pi^+$ decays

Run I: 3/fb

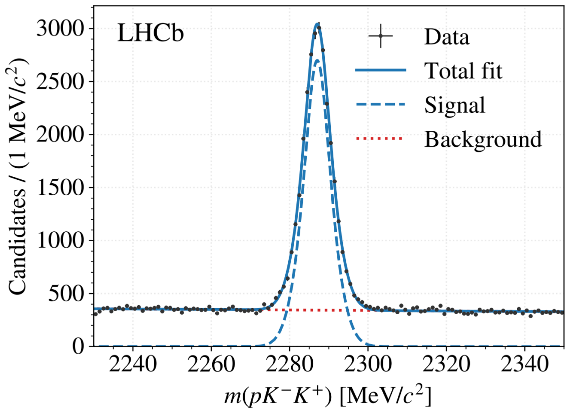
CPV in $\Lambda_c^0 \to pK^-K^+/p\pi^-\pi^+$

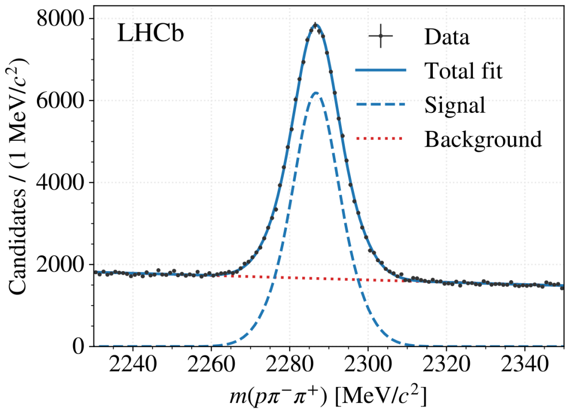
$$V_{\rm CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \delta_{V_{\rm CKM}}$$

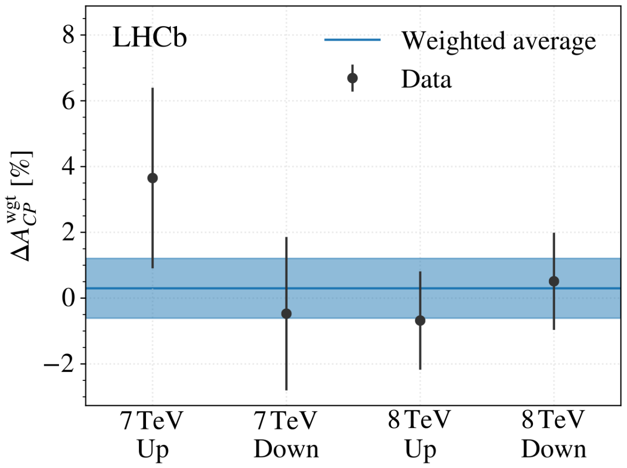
- complementary to measurements in b-hadrons
- CPV only occur in SCS decays at the $O(10^{-3})$ level
- FSI, NP and SU(3)F breaking could enhance the CPV

$$\delta_{V_{\rm CKM}} = \begin{pmatrix} -\frac{1}{8}\lambda^4 & 0 & 0 \\ \frac{1}{2}A^2\lambda^5(1-2(\rho+i\eta)) & -\frac{1}{8}\lambda^4(1+4A^2) & 0 \\ \frac{1}{2}A\lambda^5(\rho+i\eta) & \frac{1}{2}A\lambda^4(1-2(\rho+i\eta)) & -\frac{1}{2}A^2\lambda^4 \end{pmatrix} + \mathcal{O}(\lambda^6)$$

Search for CPV in cabibbo suppress decay $\Lambda_c^0 \to pK^-K^+/p\pi^-\pi^+$







$\sqrt{s}$	Polarity	Int. lumi. [pb^{-1}]	pK^-K^+ yield	$p\pi^-\pi^+$ yield
7 TeV	Up	422 ± 7	2880 ± 70	$18\,450 \pm 190$
7 TeV	Down	563 ± 9	3940 ± 80	$25\,130 \pm 230$
8 TeV	Up	1000 ± 11	9040 ± 120	$57\,730 \pm 350$
8 TeV	Down	992 ± 11	9330 ± 120	$60\,080 \pm 360$

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

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

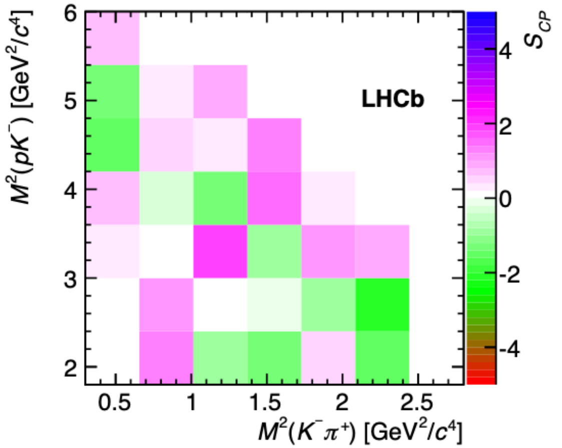
Eur. Phys. J. C **2020**, 80, 986

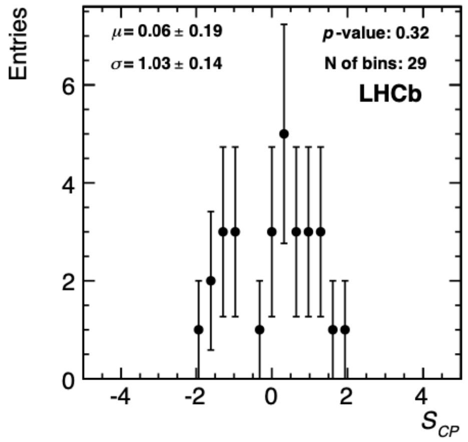
Search for CP violation in $\Xi_c^+ \to pK^-\pi^+$ decays using model-independent techniques

Run I: 3/fb

CPV in $\Xi_c^0 \to pK^-\pi^+$ (S_{CP} method)

- Search for CPV using model independent binned/unbinned method

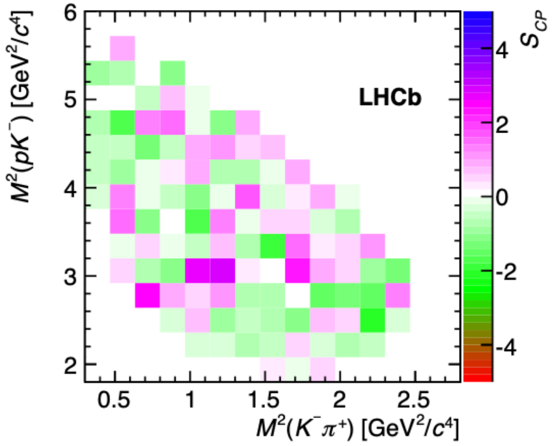


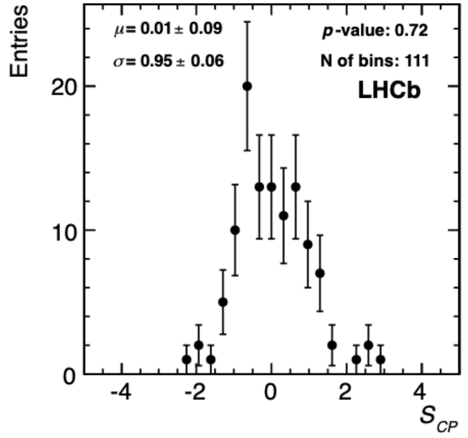


$$S_{CP}^i = \frac{n_+^i - \alpha n_-^i}{\sqrt{\alpha(n_+^i + n_-^i)}}$$

$\alpha = \frac{n_+}{n_-}$ account for production asymmetry

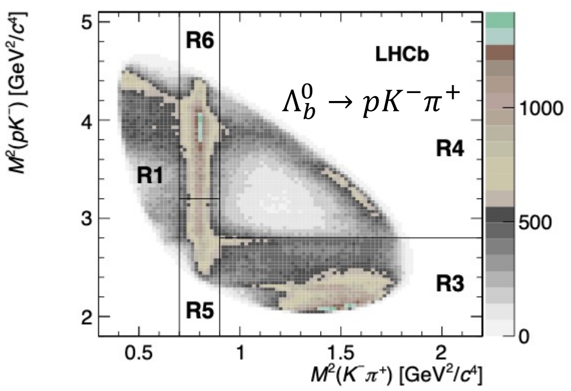
$$\chi^2 \equiv \Sigma(S_{CP}^i)^2$$

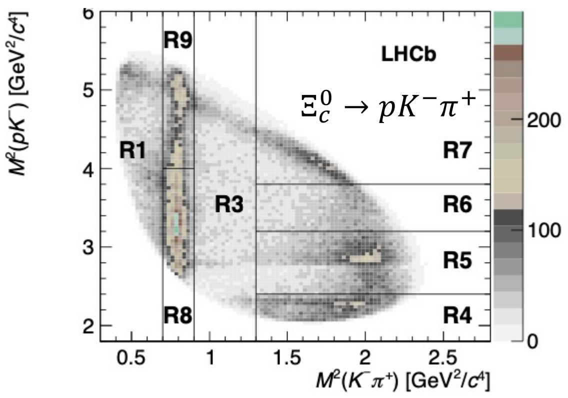




The p-values using χ^2 test are larger than 32% consistent with no evidence for CPV

CPV in $\Xi_c^0 \to pK^-\pi^+$(kNN method)

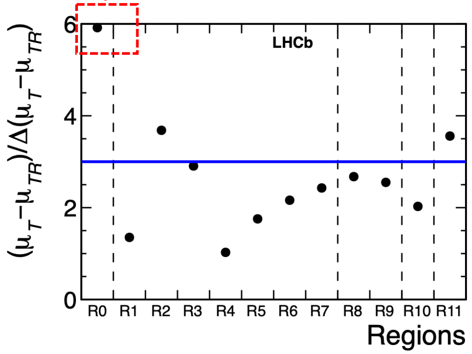


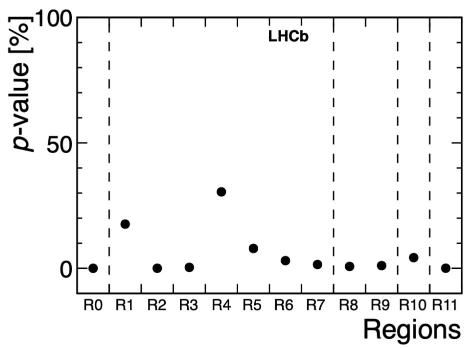


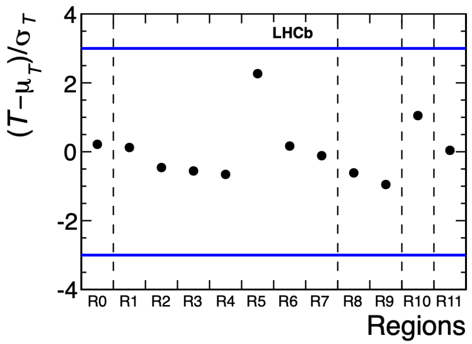
Region	Definition
R0	Full Dalitz plot
R1	$M^2(K^-\pi^+) < 0.7$ GeV$^2/c^4$
R2	$0.7 \leq M^2(K^-\pi^+) < 0.9$ GeV$^2/c^4$
R3	$0.9 \leq M^2(K^-\pi^+) < 1.3$ GeV$^2/c^4$
R4	$M^2(K^-\pi^+) \geq 1.3$ GeV$^2/c^4$, $M^2(pK^-) < 2.4$ GeV$^2/c^4$
R5	$M^2(K^-\pi^+) \geq 1.3$ GeV$^2/c^4$, $2.4 \leq M^2(pK^-) < 3.2$ GeV$^2/c^4$
R6	$M^2(K^-\pi^+) \geq 1.3$ GeV$^2/c^4$, $3.2 \leq M^2(pK^-) < 3.8$ GeV$^2/c^4$
R7	$M^2(K^-\pi^+) \geq 1.3$ GeV$^2/c^4$, $M^2(pK^-) \geq 3.8$ GeV$^2/c^4$
R8	$0.7 \leq M^2(K^-\pi^+) < 0.9$ GeV$^2/c^4$, $M^2(pK^-) < 4$ GeV$^2/c^4$
R9	$0.7 \leq M^2(K^-\pi^+) < 0.9$ GeV$^2/c^4$, $M^2(pK^-) \geq 4$ GeV$^2/c^4$
R10	$M^2(K^-\pi^+) \geq 1.3$ GeV$^2/c^4$, $M^2(pK^-) < 3.2$ GeV$^2/c^4$
R11	$M^2(K^-\pi^+) \geq 1.3$ GeV$^2/c^4$

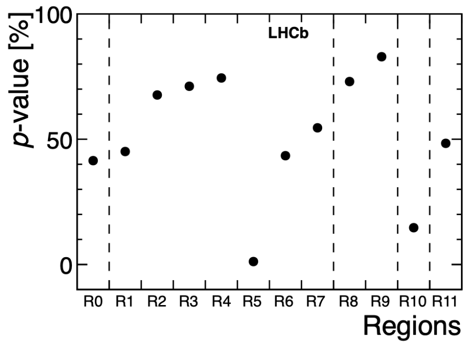
$$T = \frac{1}{n_k(n_+ + n_-)} \sum_{i=1}^{n_+ + n_-} \sum_{k=1}^{n_k} I(i,k) \qquad \mu_T = \frac{n_+(n_+ - 1) + n_-(n_- - 1)}{n(n-1)}$$

Arising from production and detection asymmetry









no significant deviation from the hypothesis of CP symmetry

CPV in $\Lambda_b^0 \to \Lambda\gamma$

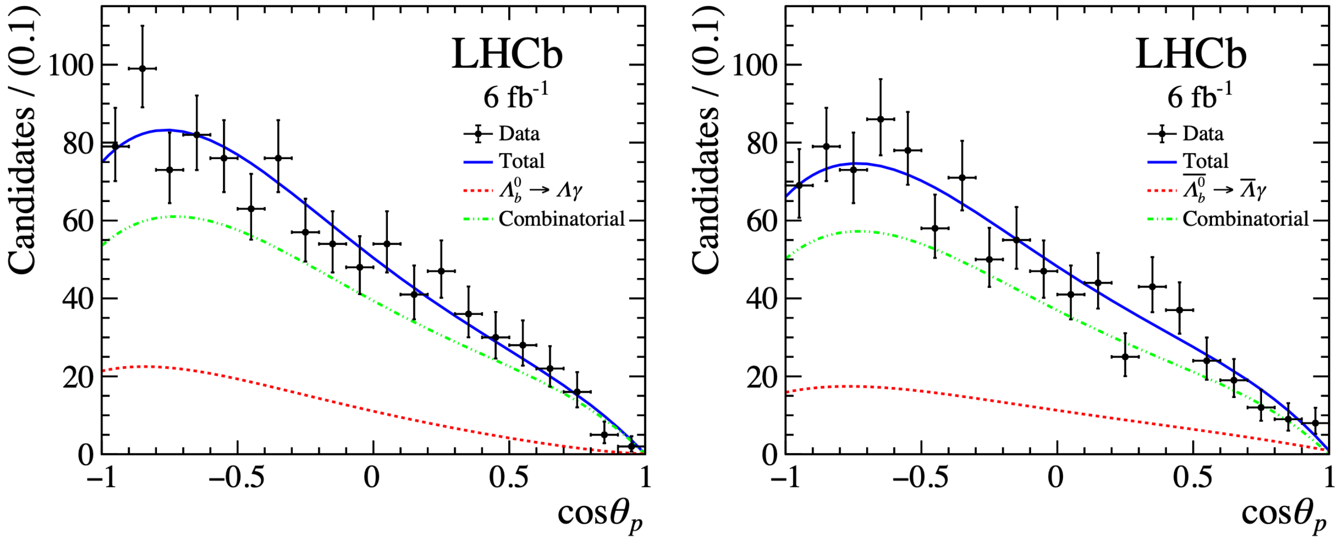
Phys. Rev. D105 (2022) L051104

Measurement of the photon polarization in $\Lambda_b^0 \to \Lambda\gamma$ decays

Run II: 6/fb

CPV in $\Lambda_b^0 \to \Lambda\gamma$

- FCNC decay is sensitive to new heavy particles in the loop
- Due to the chirality of the electroweak interaction, the photons produced in $b(\bar{b})$ quark are predominantly left(right) handed polarized
  - $\alpha_\gamma = \frac{\gamma_L - \gamma_R}{\gamma_L + \gamma_R}$
- A discrepancy in the absolute value of the photon polarization in b and $\bar{b}$ decays would be a hint of CP asymmetry



Distribution of $cos\theta_p$ for $\Lambda_b^0 \to \Lambda\gamma$ and $\overline{\Lambda}_b^0 \to \overline{\Lambda}\gamma$ decays

$$\alpha_\gamma = 0.82 \pm 0.23 \pm 0.13$$

$$\alpha_\gamma(\Lambda_b^0) = 0.55 \pm 0.32 \pm 0.10$$

$$\alpha_\gamma(\overline{\Lambda}_b^0) = 1.26 \pm 0.42 \pm 0.20$$

consistent with CP symmetry