CP Violation in baryon decays

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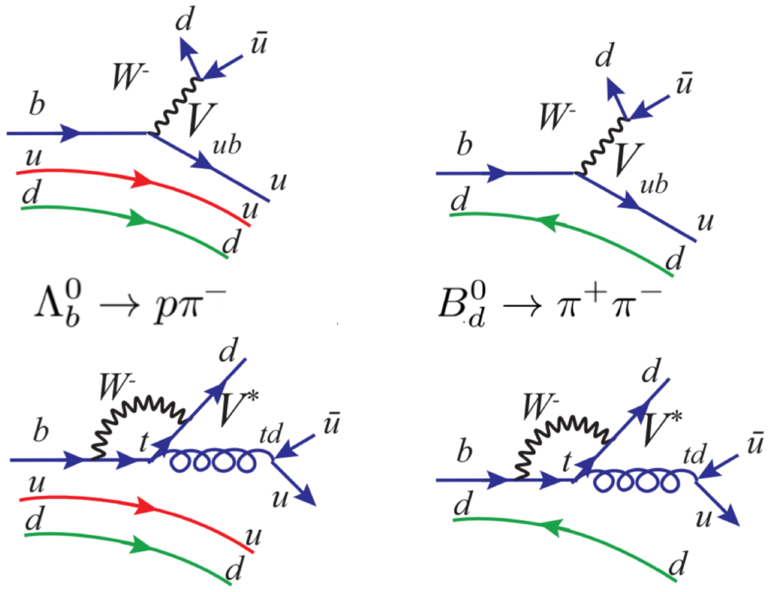
第四届LHCb前沿物理研讨会
2024年7月30日

Why CPV in baryon decays



- ☐ CPV may be 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
- ☐ However, 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]
  - ➢ Recent measurement shows no CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$(2.9 σ)

- ☐ 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

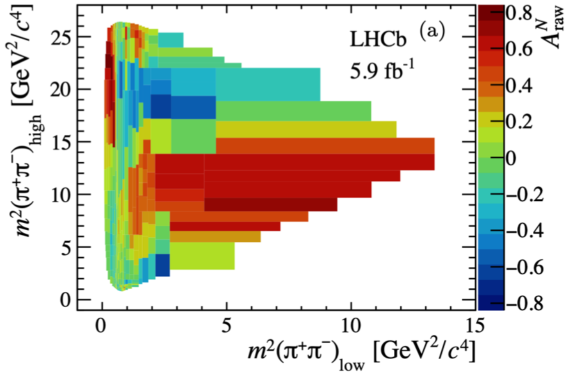
Experimental methods & observables

- Asymmetry in the yields of CP-conjugate processes
  - $A_{CP} = A_{raw} - A_{prod} - A_{det} - A_{other}$
  - $\Delta A_{CP} = A_{CP}^{signal} - A_{CP}^{control}$

$$A_{raw} = \frac{N(H \to f) - N(\bar{H} \to \bar{f})}{N(H \to f) + N(\bar{H} \to \bar{f})}$$

$$A_{CP} \propto cos\Delta\phi sin\Delta\delta$$

- 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

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

- Triple product asymmetry: $A_{\hat{T}}(C_{\hat{T}}) = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}$ $\quad \bar{A}_{\hat{T}}(\bar{C}_{\hat{T}}) = \frac{\bar{N}(-\bar{C}_{\hat{T}} > 0) - \bar{N}(-\bar{C}_{\hat{T}} < 0)}{\bar{N}(-\bar{C}_{\hat{T}} > 0) + \bar{N}(-\bar{C}_{\hat{T}} < 0)}$ $\quad a_{CP}^{\hat{T}\text{-odd}} = \frac{1}{2}(A_{\hat{T}} - \bar{A}_{\hat{T}})$

$$A_{CP} \propto cos\Delta\phi cos\Delta\delta$$

- k-nearest neighbour (kNN): $T = \frac{1}{n_k(n_+ + n_-)}\sum_{i=1}^{n_+ + n_-}\sum_{k=1}^{n_k} I(i,k)$

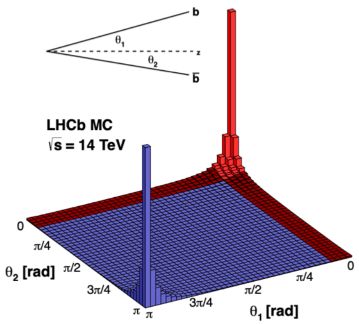
- Amplitude analysis: $\overset{(-)}{\mathcal{A}} = \sum_i \overset{(-)}{a_i}\overset{(-)}{\mathcal{A}_i}$ $\quad \mathcal{A}_{CP}^{i} = \frac{|a_i|^2 - |\bar{a}_i|^2}{|a_i|^2 + |\bar{a}_i|^2}$

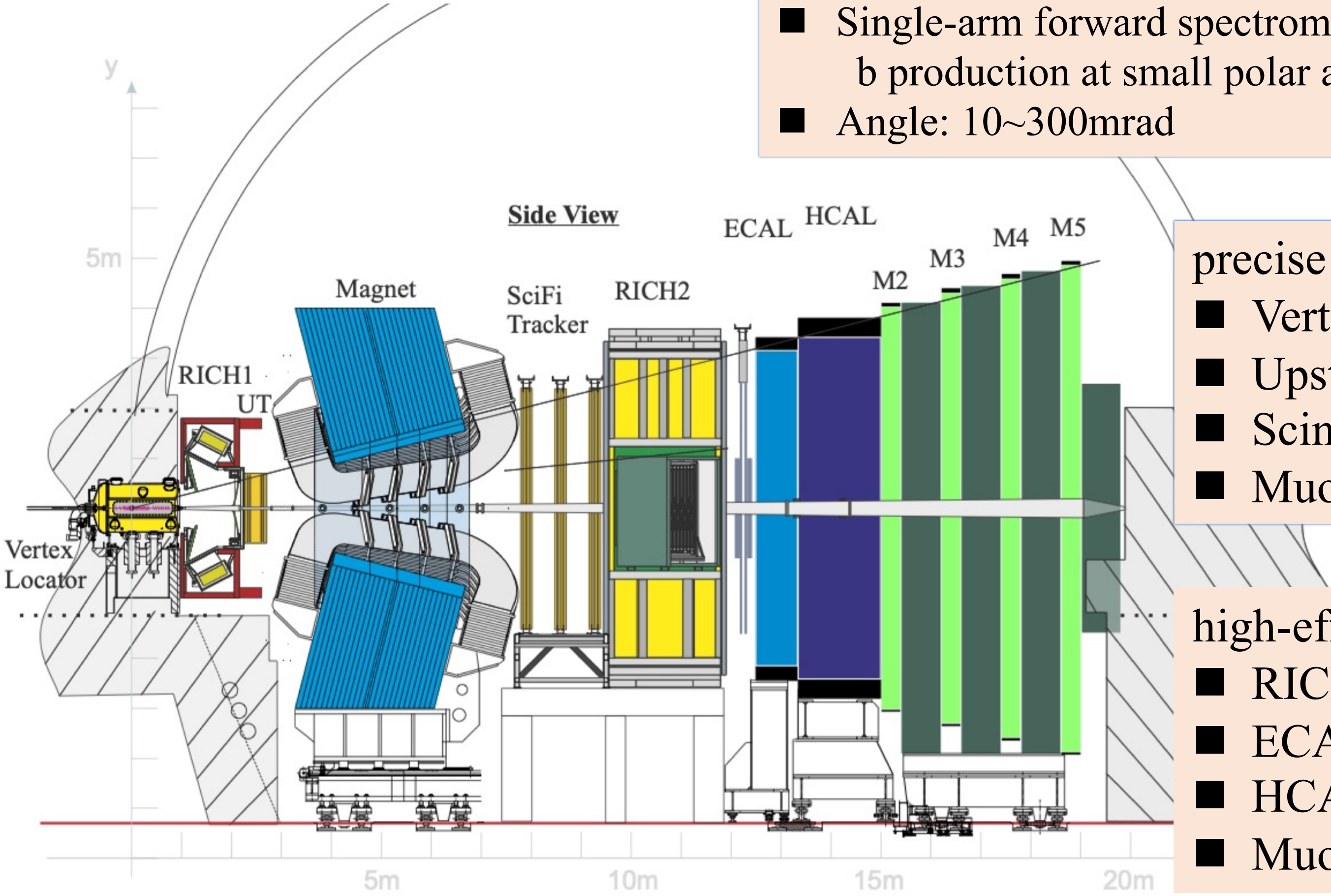
Overview of CPV in baryon decays

- $\Lambda_b^0 \to pK^-/p\pi^-$
- $\Lambda_b^0 \to pK_s^0\pi^-$
- $\Lambda_b^0 \to pD^0K^-$
- $\Lambda_b^0 \to \Lambda K^+\pi^-/K^-K^+$
- $\Lambda_b^0 \to pK^-\mu^+\mu^-$
- $\Lambda_c^+ \to pK^-K^+/p\pi^-\pi^+$
- $\Xi_b^- \to pK^-K^+$
- $\Lambda_b^0 \to ph^-h^+h^-$

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

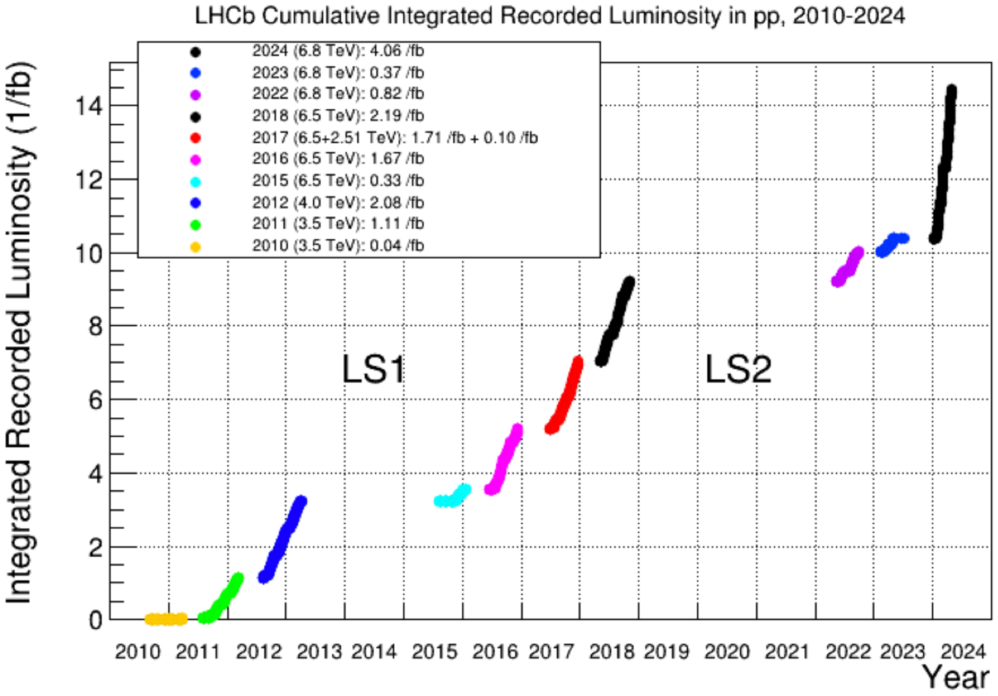
- Vertex Locator detector
- Upstream tracker
- Scintillating fibre tracker
- Muon

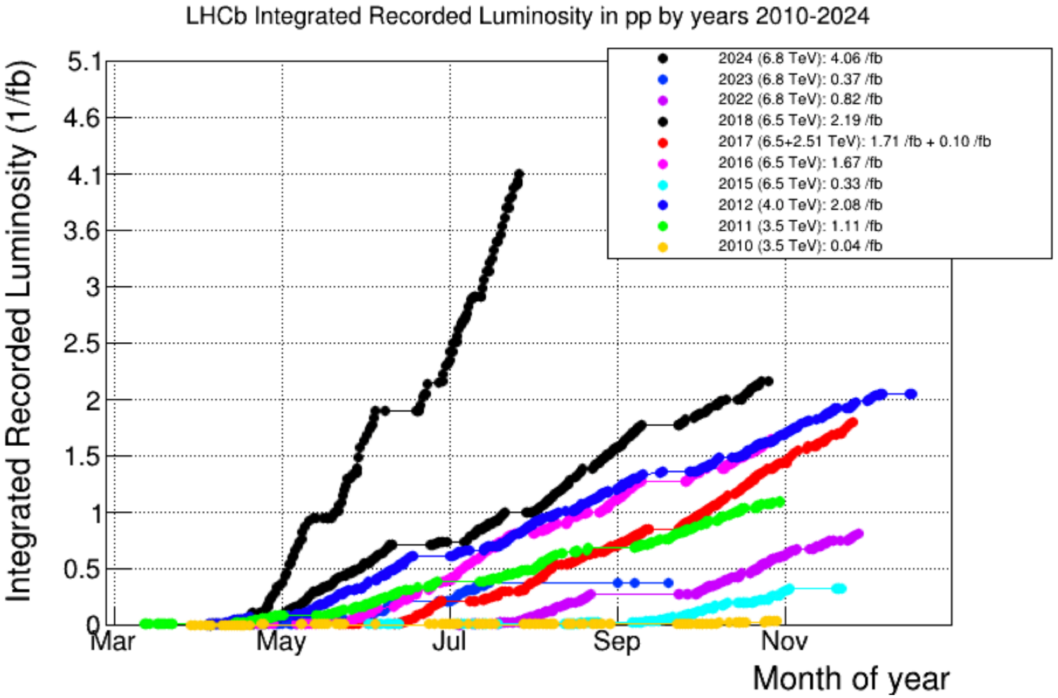
high-efficiency PID

- RICH
- ECAL
- HCAL
- Muon

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

LHCb experiment





- Run I: ~3/fb @ Ecm=7-8TeV
- Run II: ~6/fb @ Ecm =13 TeV
- Run III: ~25/fb @ Ecm = 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 $\eta \in [2, 5]$ @ Ecm = 13 TeV

More charm baryons: Λ_c, Ξ_c ...

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 @ Ecm=7-8TeV

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

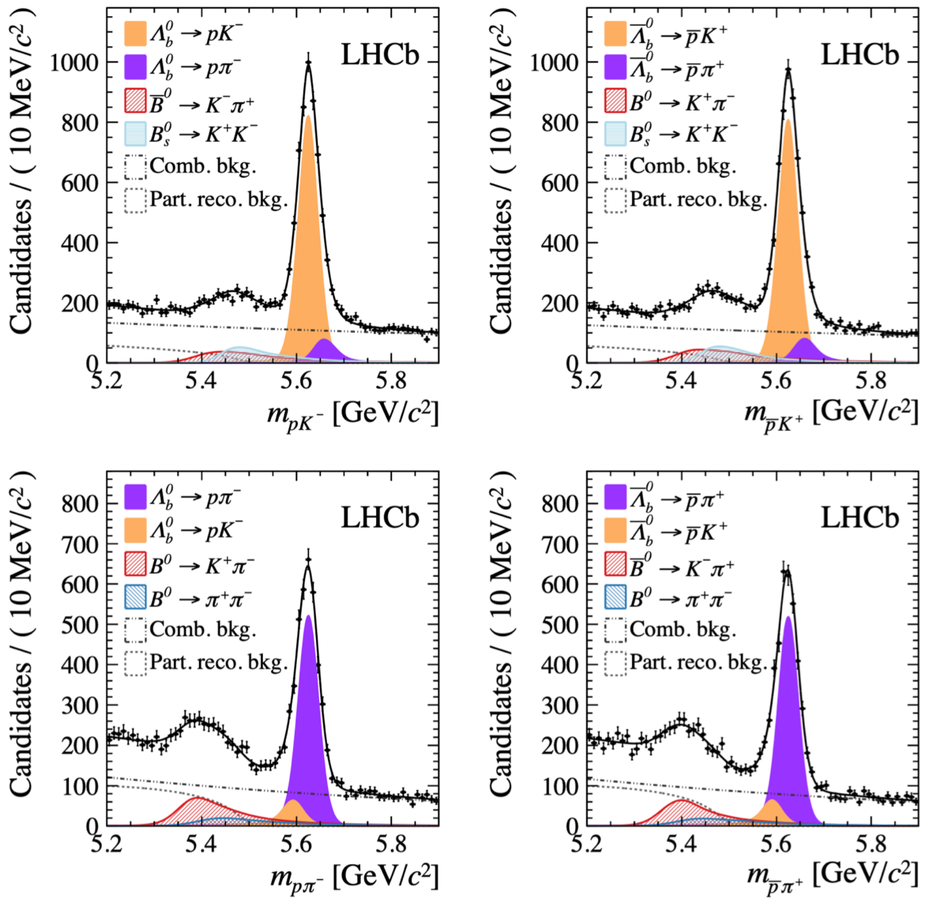
- Mediated by the same quark-level transitions contributing to B^0/B_s^0
- Predicted CPV in $\Lambda_b^0 \to pK^-/p\pi^-$ up to ~30%

	generalized factorization approach	pQCD
$10^2\mathcal{A}_{CP}(\Lambda_b \to pK^-)$	$5.8 \pm 0.2 \pm 0.1$	$-5^{+26}_{-\ 5}$
$10^2\mathcal{A}_{CP}(\Lambda_b \to p\pi^-)$	$-3.9 \pm 0.2 \pm 0.0$	$-31^{+43}_{-\ 1}$

Phys.Rev.D 91 (2015) 11, 116007

$A_{CP}(\Lambda_b^0 \to pK^-) = -0.020 \pm 0.013 \pm 0.019$

$A_{CP}(\Lambda_b^0 \to p\pi^-) = -0.035 \pm 0.017 \pm 0.020$



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

INDEPENDENT from the proton detection and Λ_b^0 production asymmetry

CPV in decays with K_S^0 and Λ^0

JHEP05(2016)081 Run I 3/fb

Observations of $\Lambda_b^0 \to \Lambda K^+\pi^-$ and $\Lambda_b^0 \to \Lambda K^+K^-$ decays and searches for other Λ_b^0 and Ξ_b^0 decays to $\Lambda h^+h'^-$ final states

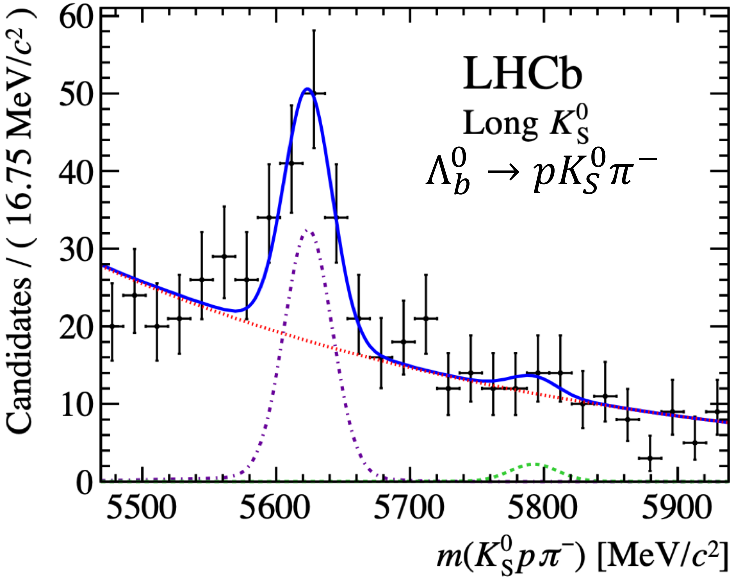
JHEP 04 (2014) 087 Run I 1/fb

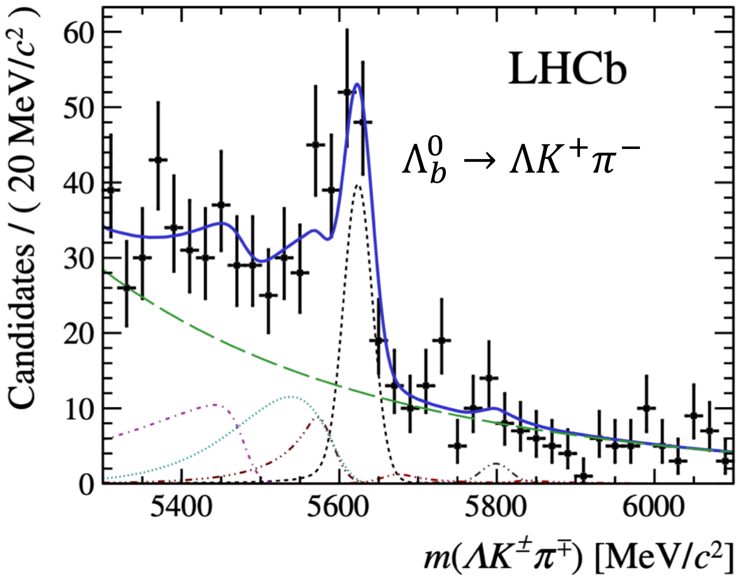
Searches for Λ_b^0 and Ξ_b^0 decays to $K_S^0 p\pi^-$ and $K_S^0 pK^-$ final states with first observation of the $\Lambda_b^0 \to K_S^0 p\pi^-$ decay

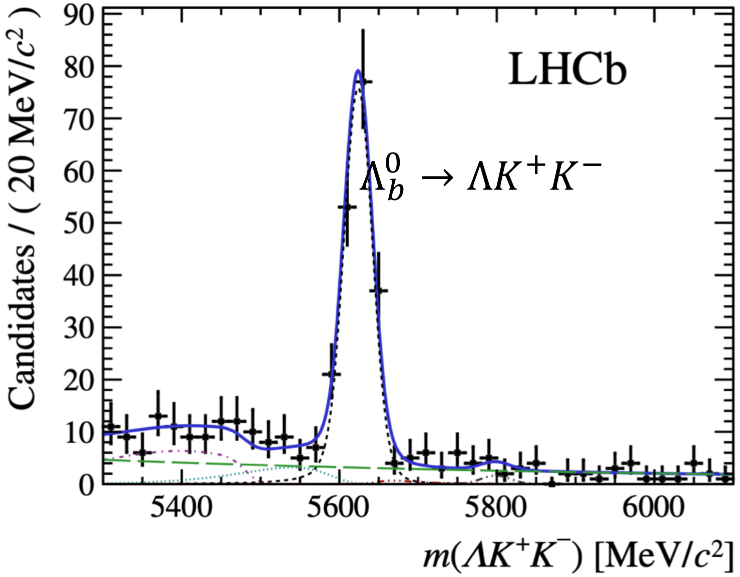
CPV in decays with K_S^0 and Λ^0

- Not favored by the LHCb due to low detection efficiencies for K_S^0 and Λ^0
- Large CPV expected for $\Lambda_b^0 \to p K_S^0 \pi^-$
- First attempt to find CP violation in multi-body decays of Λ_b^0

$10^2 \mathcal{A}_{CP}(\Lambda_b \to p K^{*-})$	$19.6 \pm 1.3 \pm 1.0$
$10^2 \mathcal{A}_{CP}(\Lambda_b \to p \rho^-)$	$-3.7 \pm 0.3 \pm 0.0$







- First observation, ~200 signal
- BF measurement:
  $B = 1.26 \pm 0.19 \pm 0.09 \pm 0.34 \pm 0.05$
- $A_{CP} = 0.22 \pm 0.13 \pm 0.03$

- $\Delta A_{CP}(\Lambda K^+ \pi^-) = -0.53 \pm 0.23 \pm 0.11$
- $\Delta A_{CP}(\Lambda K^+ K^-) = -0.28 \pm 0.10 \pm 0.07$

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

Phys. Rev. D104 (2021) 112008

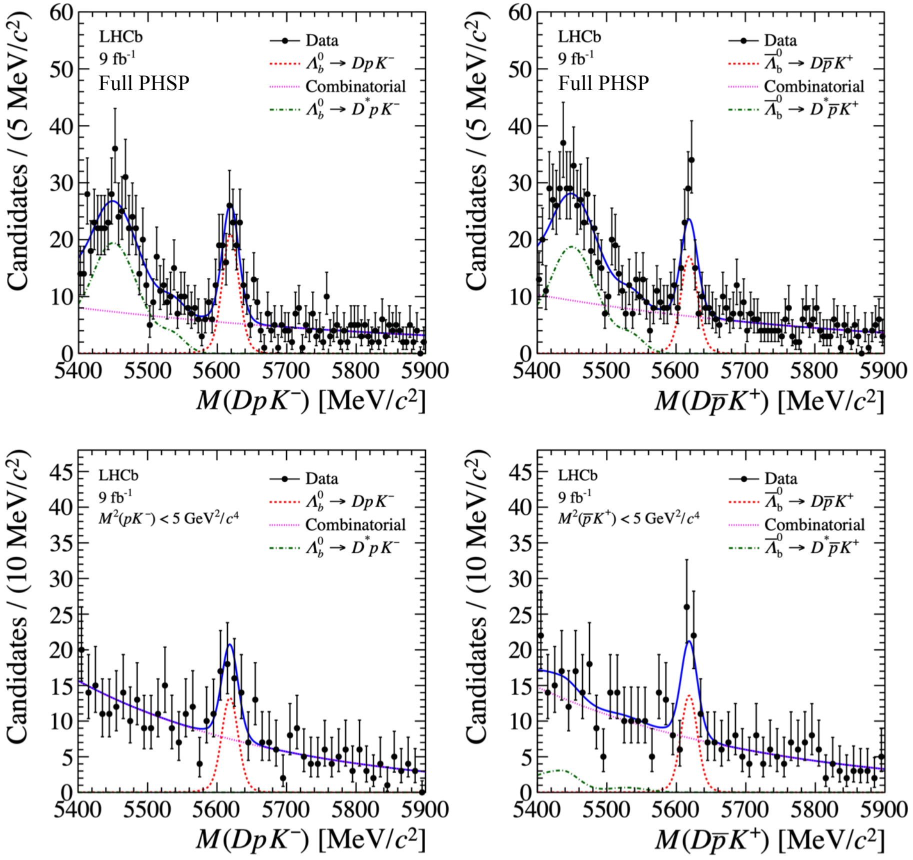
Studies of beauty baryon decays to D^0ph^- and $\Lambda_c^+h^-$ final states

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

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

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

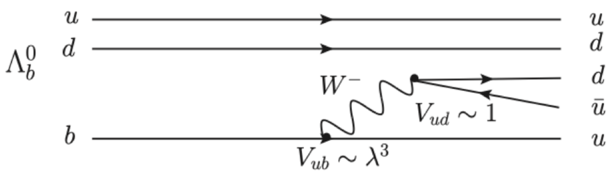
Run I 3/fb

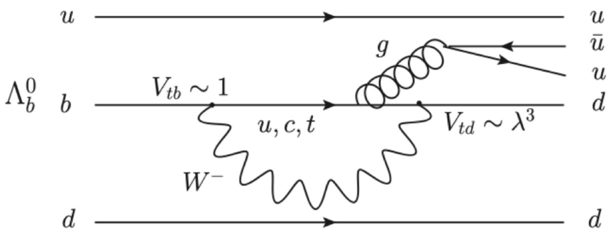
CPV in $\Lambda_b^0(\Xi_b^0) \to ph^-h^+h^-$

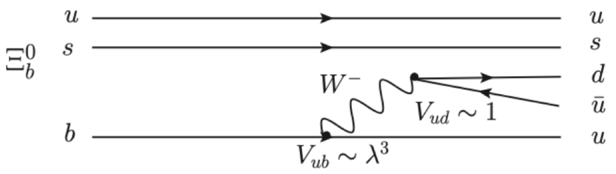
- Follow the path of the observation of CPV in charmless multibody decays of B mesons
- Dominant diagrams with amplitudes of similar magnitude
- Contain rich resonance structures, both in the two- or three-body baryonic invariant-mass spectra
- Large CPV expected due to the strong-phase differences induced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

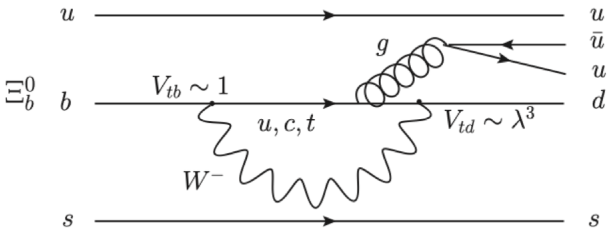
Charmless decay	Quark transition	Charmed decay	Quark transition
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$	$b\to u\bar{u}d$ (T + P)	$\Lambda_b^0 \to (\Lambda_c^+ \to p\pi^-\pi^+)\pi^-$	$b\to c\bar{u}d$ (T)
$\Lambda_b^0 \to pK^-\pi^+\pi^-$	$b\to u\bar{u}s$ (T + P)	$\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\pi^-$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





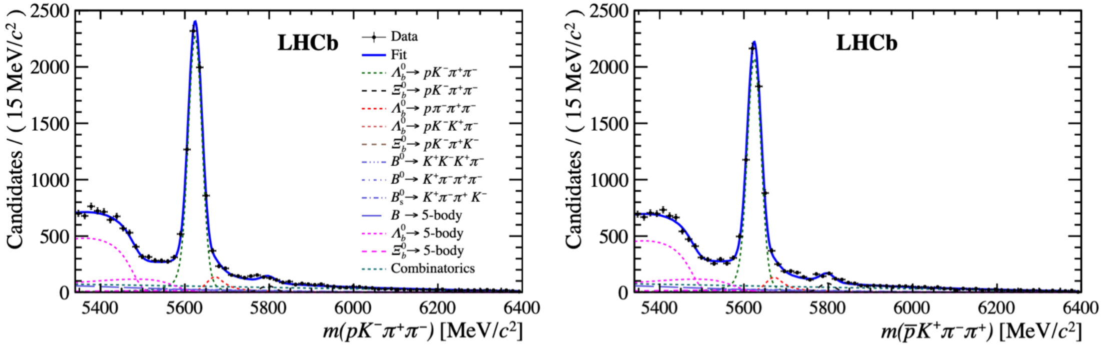


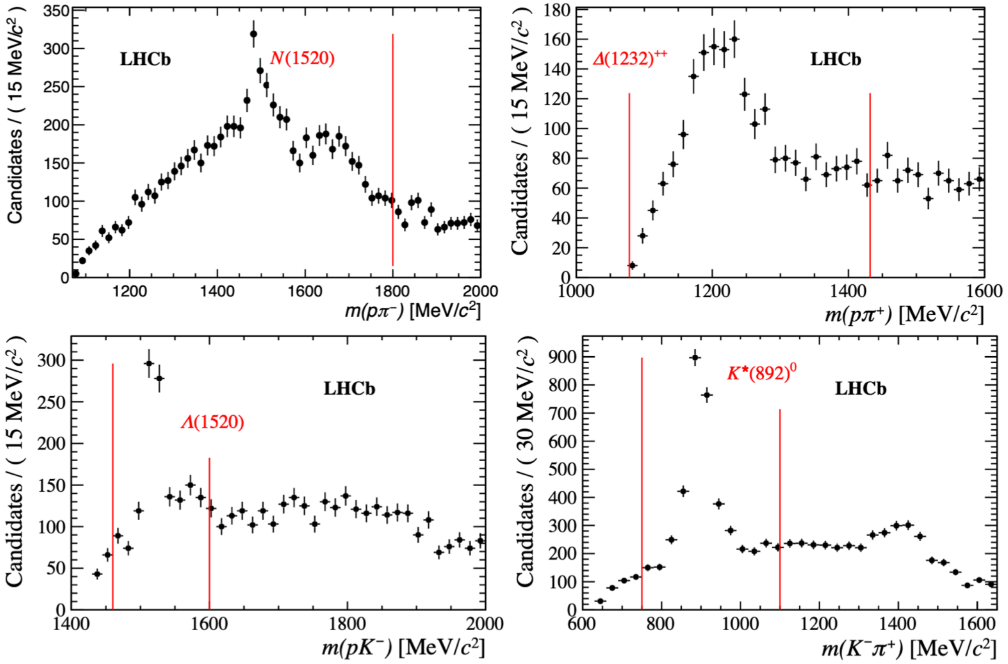


CPV in $\Lambda_b^0(\Xi_b^0) \to p h^- h^+ h^-$

- 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

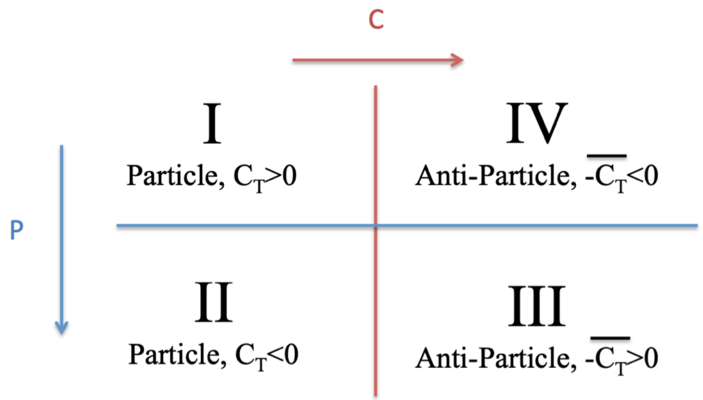
Run I 3/fb

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 final state momenta and spin

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

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

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

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

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

$\propto \sin\phi\cos\delta$

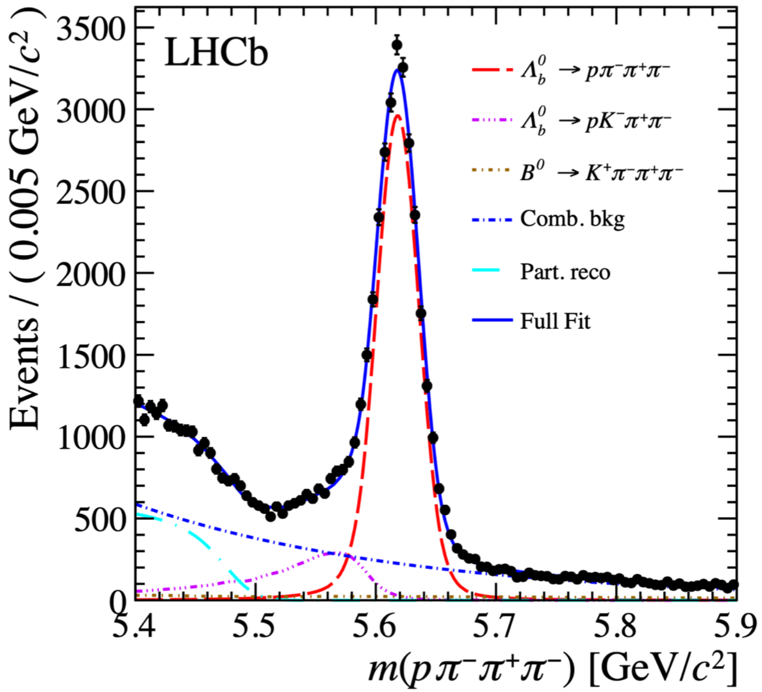
$\propto \sin\phi\sin\delta$

Does not require a non-zero strong phase difference!

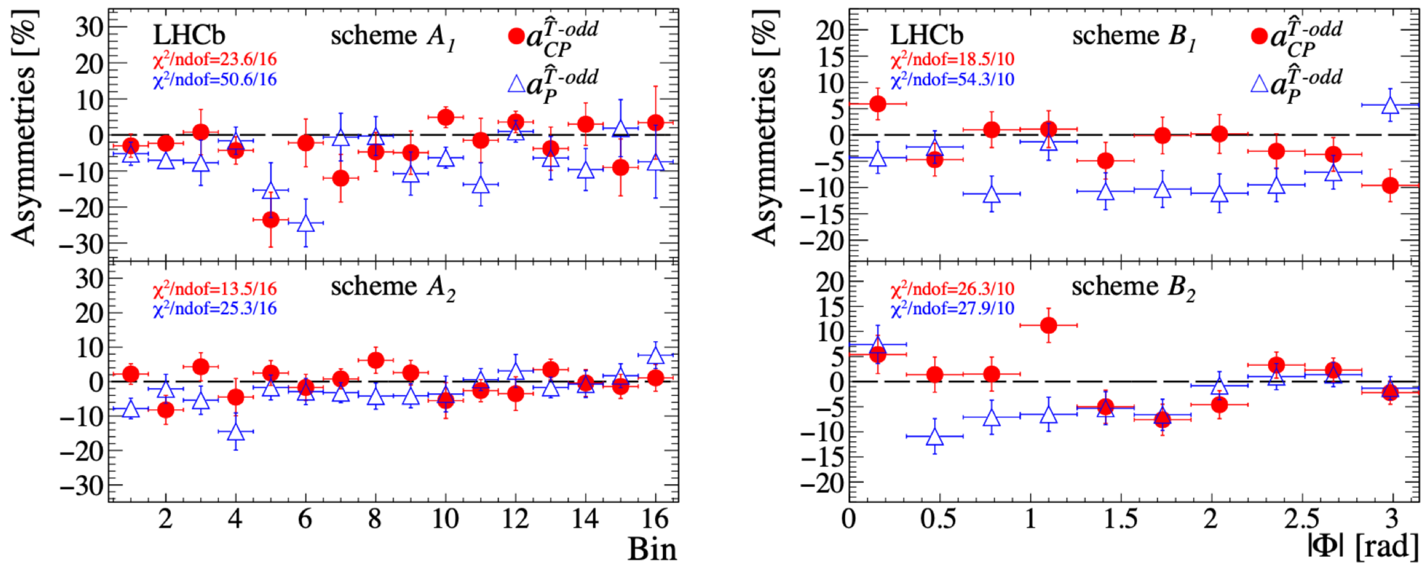
Both strong phase and weak phase differences are needed

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

- PV and 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 Δ^{++}
  - 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

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

- $\psi_{ij} = e^{-d_{ij}^2/2\delta^2}$: 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	$1.6\ \mathrm{GeV}^2/c^4$	$2.7\ \mathrm{GeV}^2/c^4$	$13\ \mathrm{GeV}^2/c^4$
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 $\Lambda_b^0 \to pK^-\mu^+\mu^-$

JHEP 06 (2017) 108

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

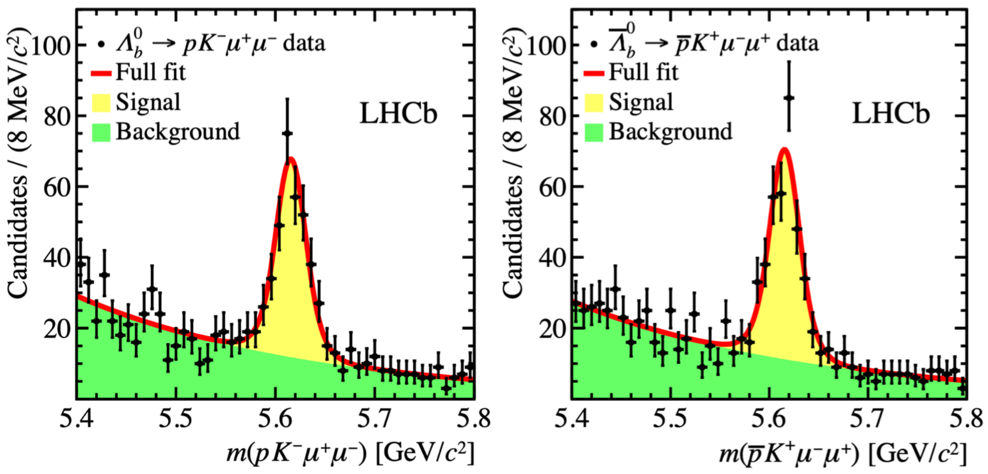
Run I: 3/fb

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:

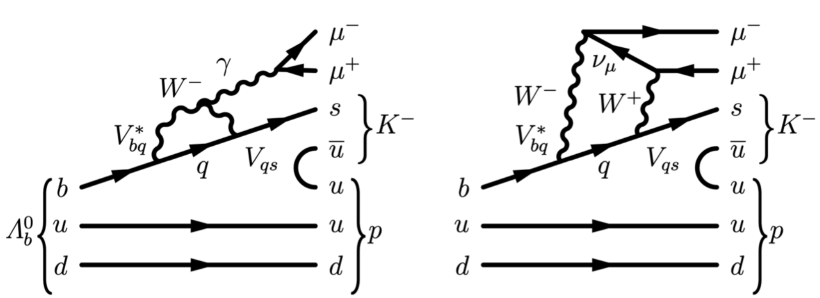
$$\Delta A_{CP} = \mathrm{A_{CP}}(\Lambda_b^0 \to pK^-\mu^+\mu^-) - \mathrm{A_{CP}}(\Lambda_b^0 \to pK^-J/\psi)$$



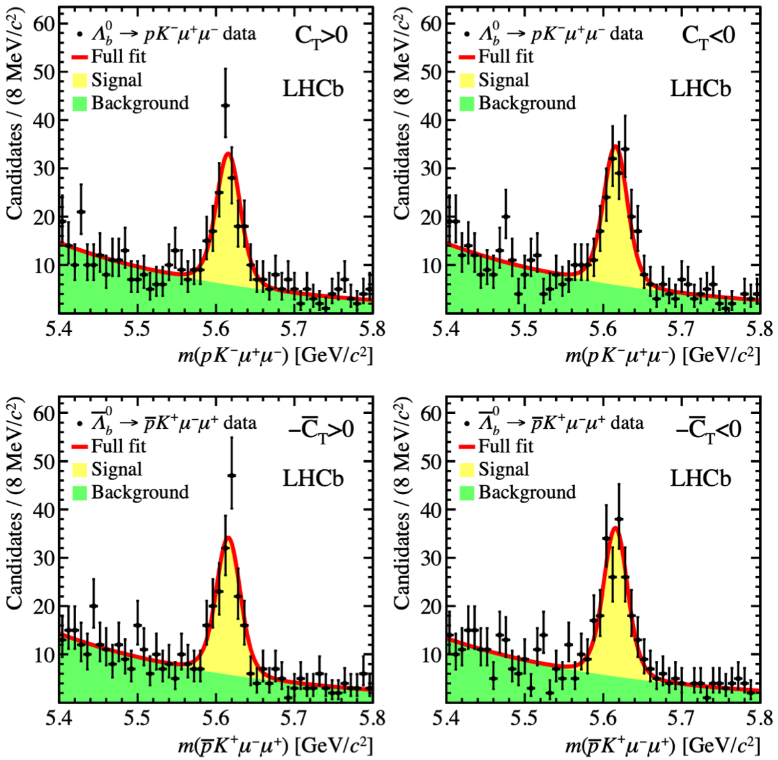
$$\Delta A_{CP}(\Lambda_b^0 \to pK^-\mu^+\mu^-) = (-3.5 \pm 5.0 \pm 0.2)\%$$

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

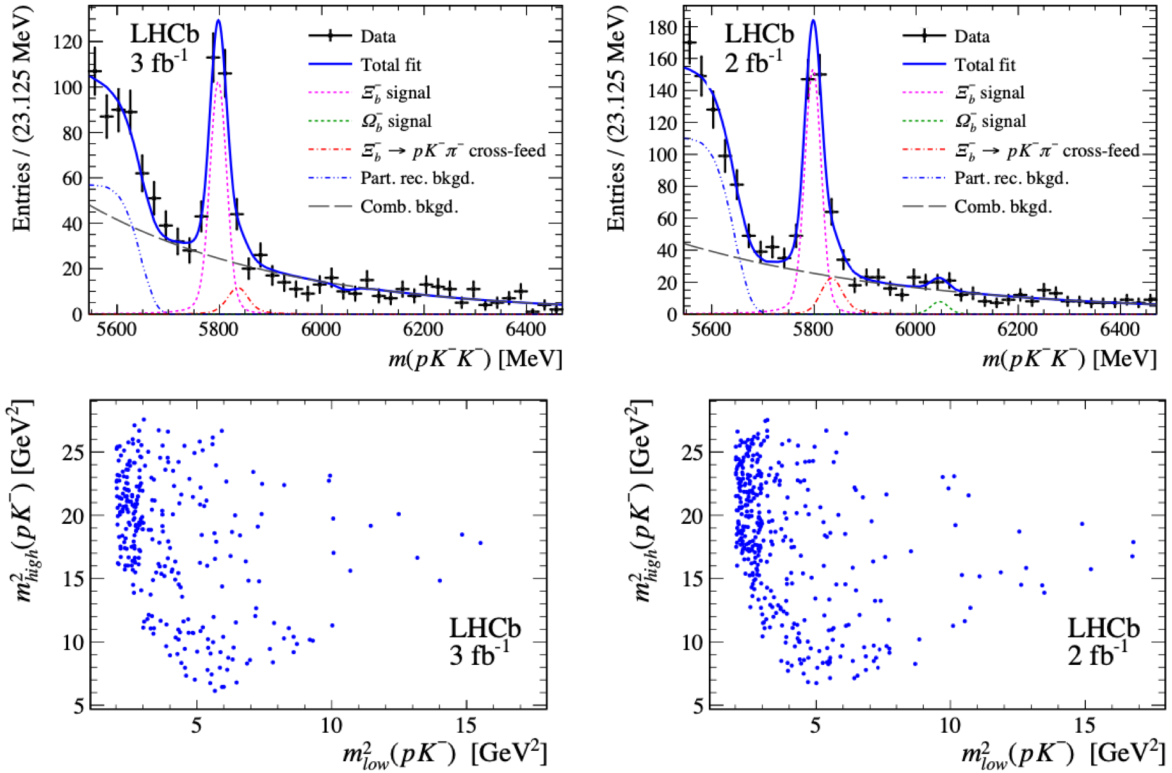
Phys. Rev. D 104, 052010

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

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

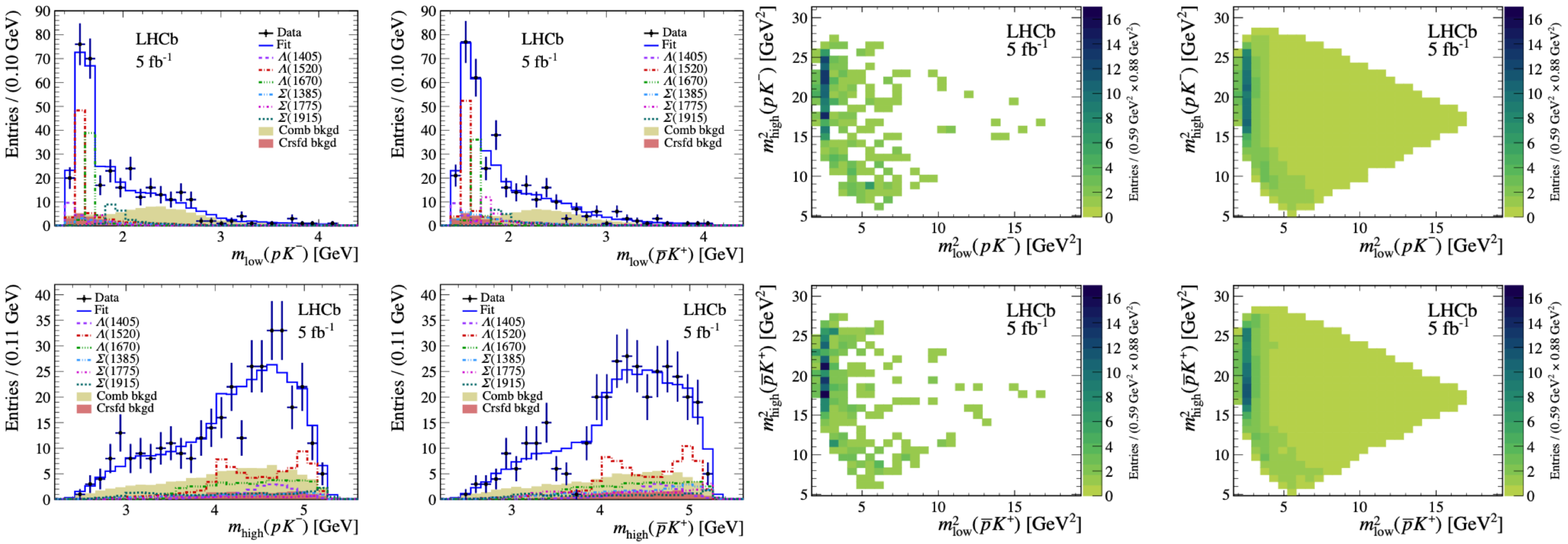
CPV in $\Xi_b^- \to pK^-K^-$

- 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

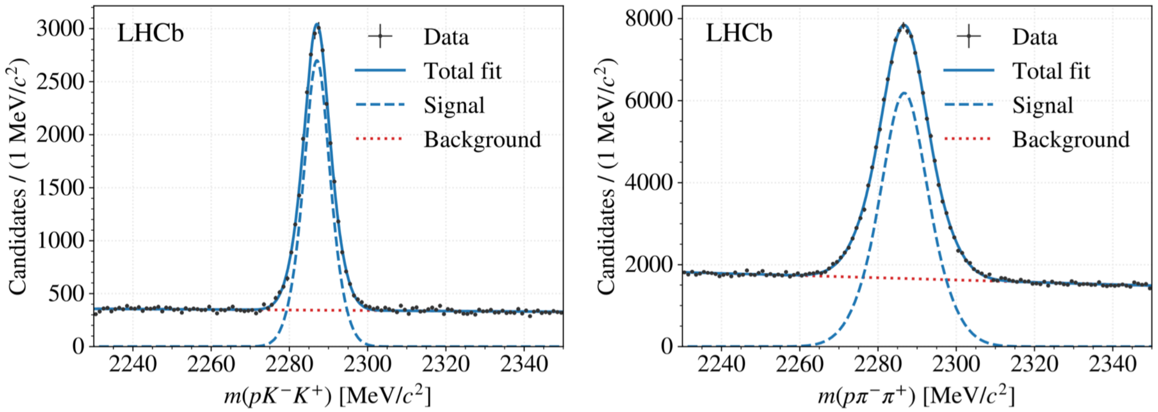
CPV in $\Lambda_c^0 \to pK^-K^+/p\pi^-\pi^+$

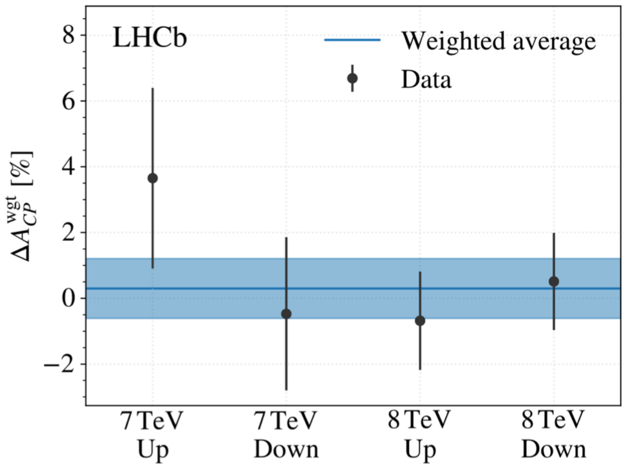
$$V_{\rm CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \delta_{V_{\rm CKM}}$$

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

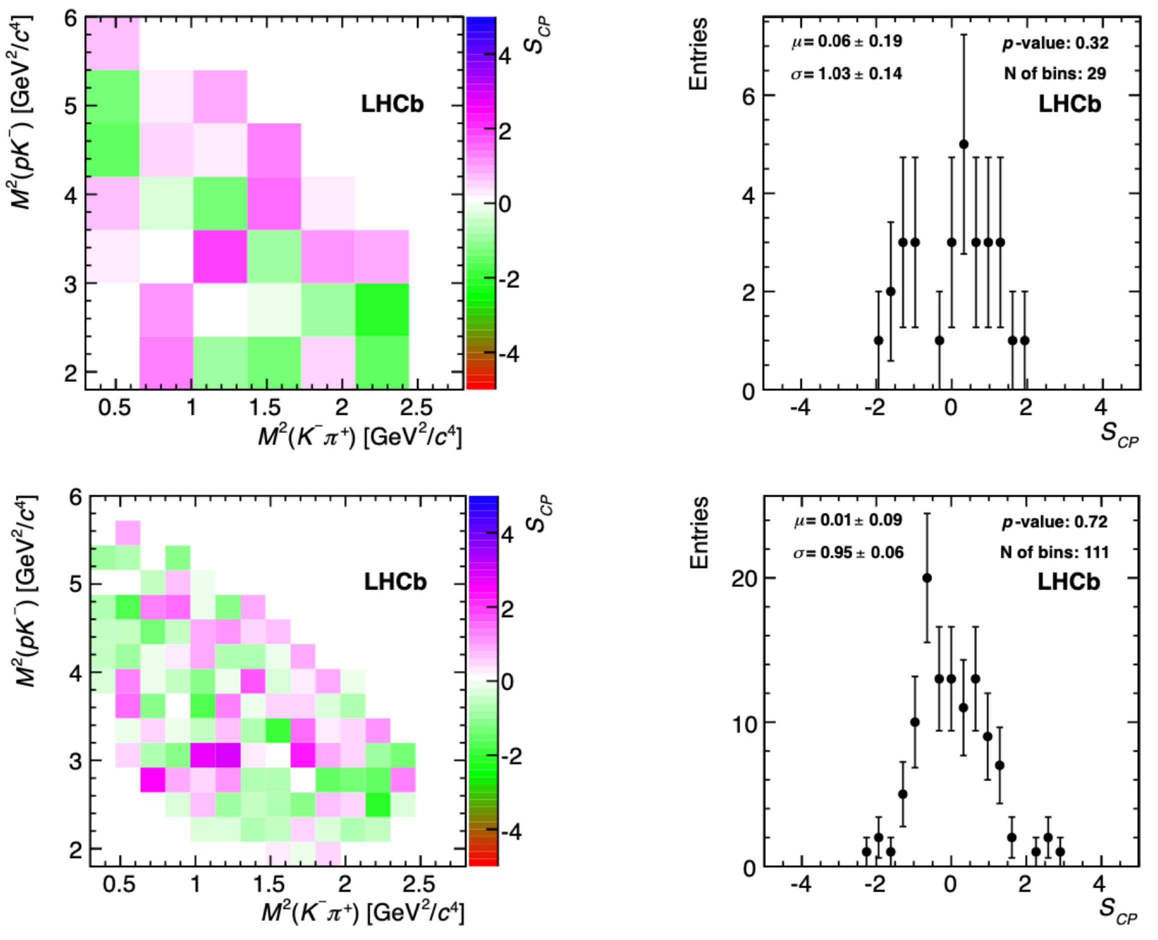
Eur. Phys. J. C **2020**, 80, 986

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



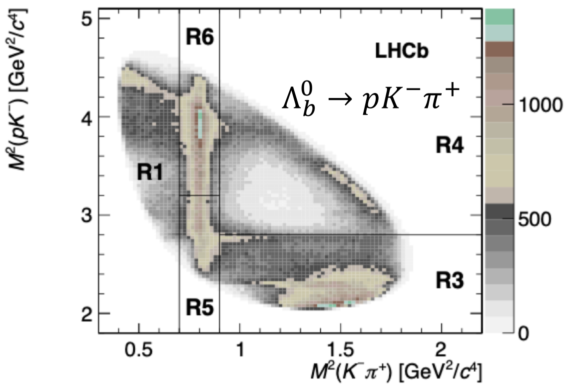
$$S_{CP}^i = \frac{n_+^i - \alpha n_-^i}{\sqrt{\alpha(n_+^i + n_-^i)}}$$

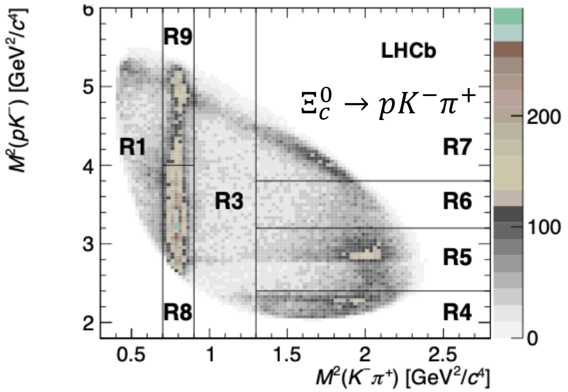
$\alpha = \frac{n_+}{n_-}$ account for production asymmetry

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

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

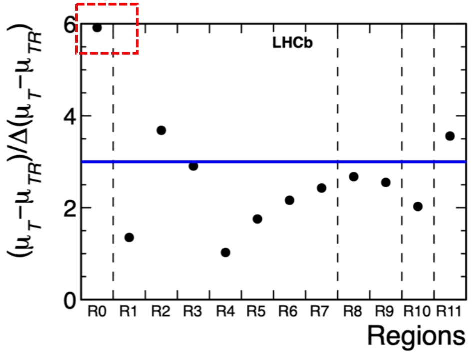
CPV in $\Xi_c^0 \to pK^-\pi^+$(kNN method)

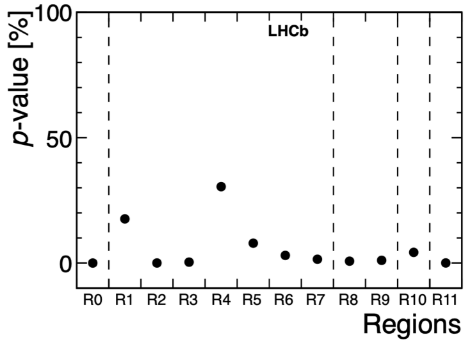




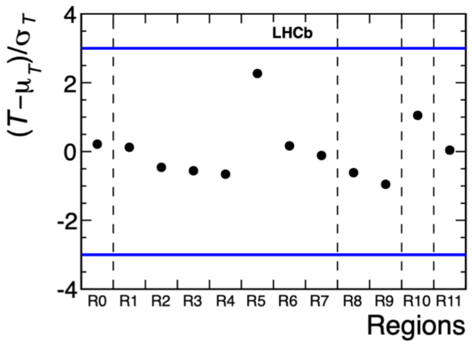
$$T = \frac{1}{n_k(n_+ + n_-)} \sum_{i=1}^{n_+ + n_-} \sum_{k=1}^{n_k} I(i,k) \qquad \mu_T = \frac{n_+(n_+ - 1) + n_-(n_- - 1)}{n(n-1)}$$

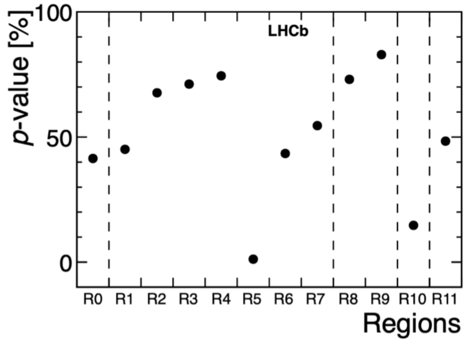
Arising from production and detection asymmetry





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$^2/c^4$





no significant deviation from the hypothesis of CP symmetry

Conclusion

- Search for CPV in b-baryon is a frontier of flavor physics
- Still no CPV observed
- More data in LHCb upgrade I is coming.
- Many new analyses coming soon

Backup

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

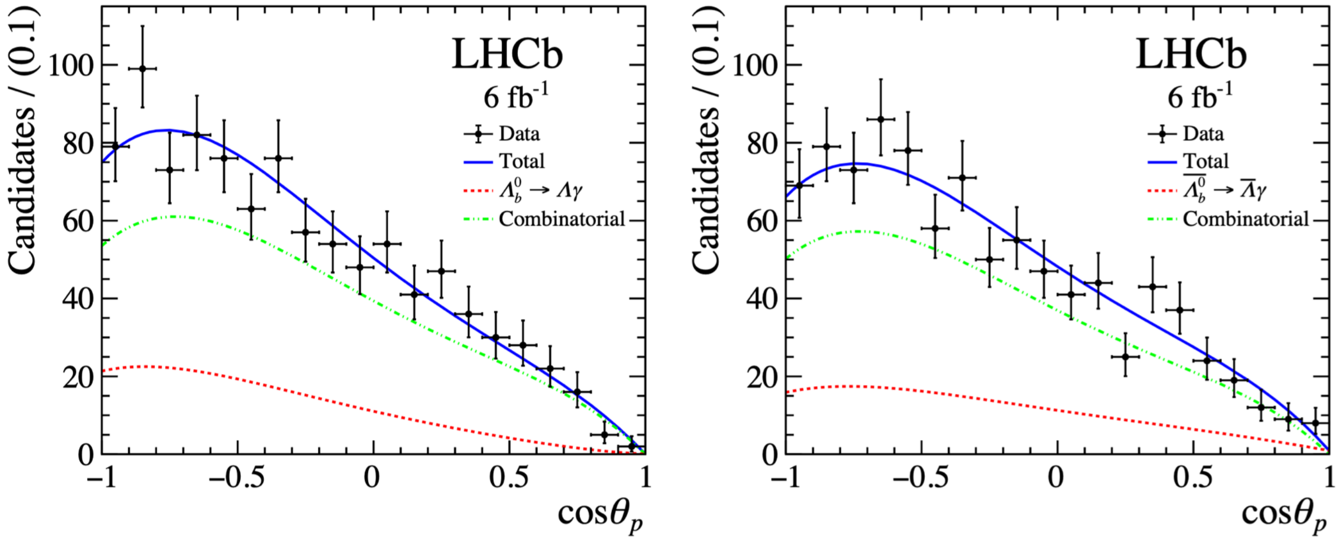
Phys. Rev. D105 (2022) L051104

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 $\bar{\Lambda}_b^0 \to \bar{\Lambda}\gamma$ decays

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

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

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

consistent with CP symmetry