CP violation in baryons at LHCb

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on behalf of the LHCb collaboration

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Istituto Nazionale di Fisica Nucleare

European Research Council
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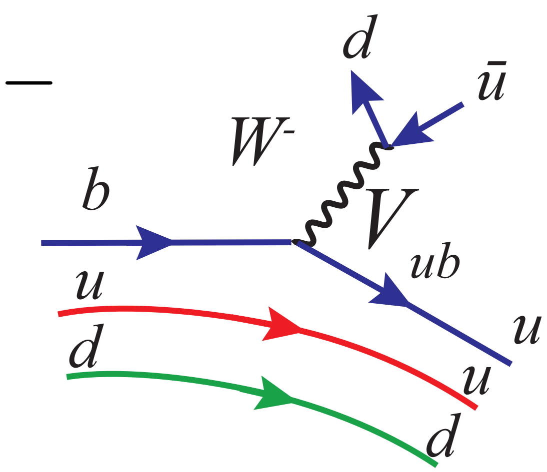
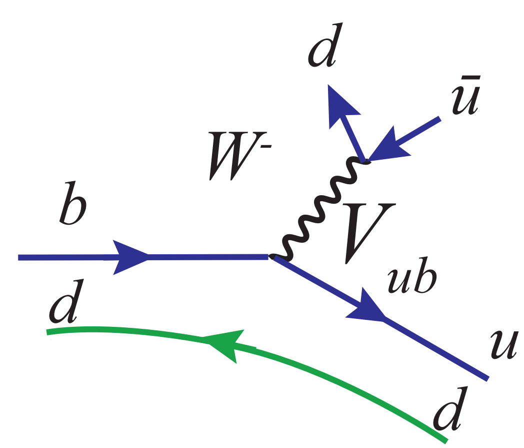
Physics motivation

- CKM mechanism predicts sizeable amount of CPV in b-baryons that can be precisely measured
- Test in baryons the transitions $c \to ud\bar{d}(s\bar{s})$ that led to the first evidence in charm

$$\Lambda_b^0 \to p\pi^-$$





$$B_d^0 \to \pi^+\pi^-$$

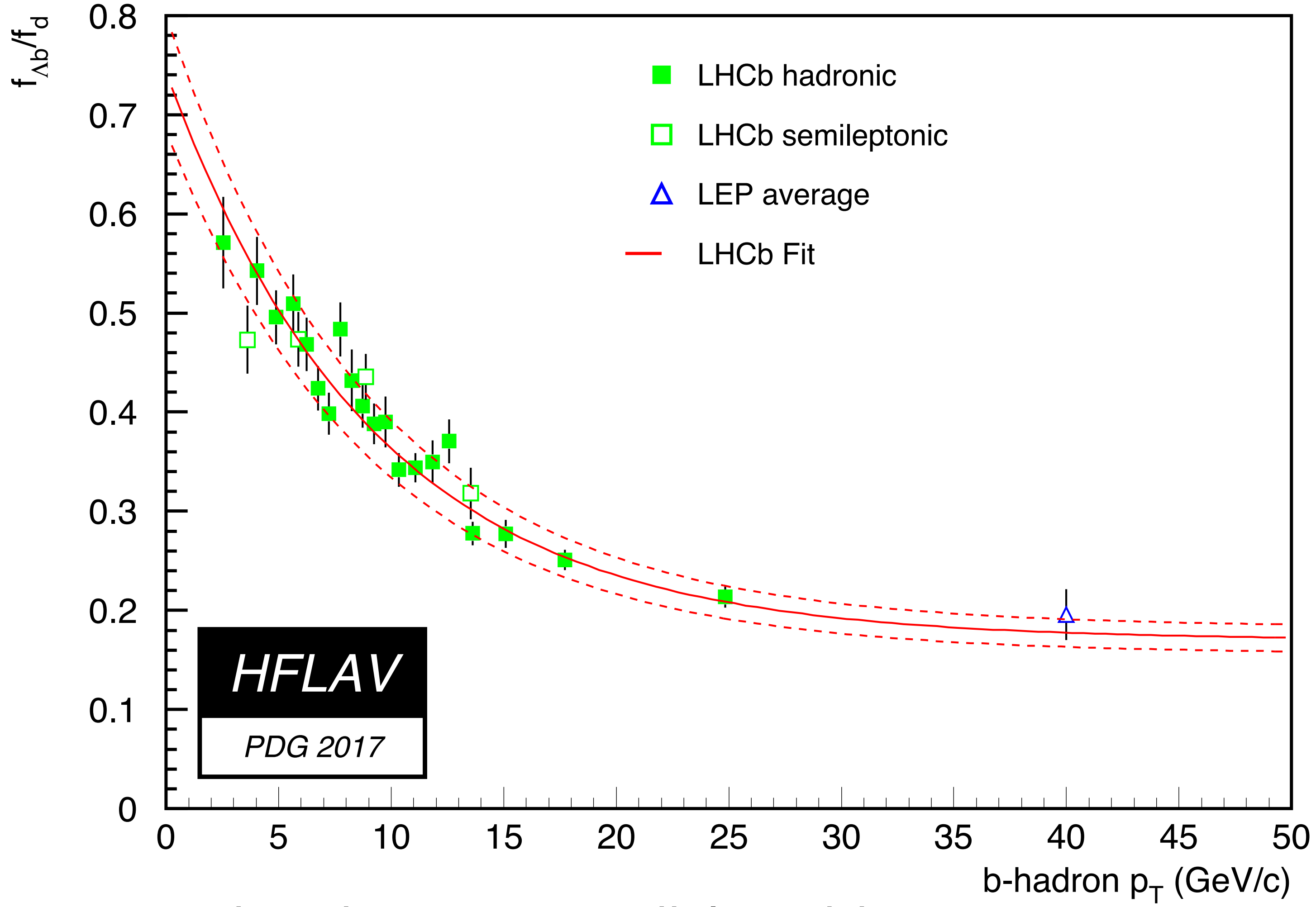
- Same underlying short distance physics as B mesons, with different spin and QCD structure
- New CPV sources

b-baryons production

- Production cross-section strongly depends on p_T of the hadron:
- Large production of Λ_b^0

$$f_{\Lambda_b^0} = P(b \to \Lambda_b^0)$$

$$f_d = P(b \to B^0)$$



- Λ_b^0 polarization measured to be compatible with 0:
  - $P_{\Lambda_b^0} = (-2.0 \pm 2.3)\,\%$ PRL 7 (2015), 115
  - $P_{\Lambda_b^0} = (6 \pm 7 \pm 2)\,\%$ Phys. Lett. B 724 (2013), 27

Status of CPV searches in Λ_b^0

$\mathcal{O}(10\%)$

- CDF (prior LHC era):
  - $A_{CP}(\Lambda_b^0 \to p\pi^-) = (6 \pm 7 \pm 3)\,\%$ Phys. Rev. Lett. 113 (2014) 242001
  - $A_{CP}(\Lambda_b^0 \to pK^-) = (10 \pm 8 \pm 4)\,\%$ Phys. Rev. Lett. 113 (2014) 242001

$\mathcal{O}(\%)$

- LHCb:
  - $A_{CP}(\Lambda_b^0 \to K_S^0 p\pi^-) = (22 \pm 13 \pm 3)\,\%$ JHEP 04 (2014) 087
  - $\Delta A_{CP}(\Lambda_b^0 \to J/\psi p\pi^-/K^-) = A_{CP}(\Lambda_b^0 \to J/\psi p\pi^-) - A_{CP}(\Lambda_b^0 \to J/\psi pK^-) = (5.7 \pm 2.4 \pm 1.2)\,\%$ JHEP 07 (2014) 103
  - $A_{CP}(\Lambda_b^0 \to \Lambda K^+\pi^-) = (53 \pm 23 \pm 11)\,\%$ JHEP 05 (2016) 081
  - $A_{CP}(\Lambda_b^0 \to \Lambda K^+K^-) = (28 \pm 10 \pm 7)\,\%$ JHEP 05 (2016) 081
  - $A_{CP}(\Lambda_b^0 \to pK^-) = (-2.0 \pm 1.3 \pm 1.9)\,\%$ Phys. Lett. B787 (2018) 124
  - $A_{CP}(\Lambda_b^0 \to p\pi^-) = (-3.5 \pm 1.7 \pm 2.0)\,\%$ Phys. Lett. B787 (2018) 124
  - $a_{CP}^{\hat{T}-odd}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (-0.81 \pm 0.84 \pm 0.31)\,\%$ JHEP 39 (2018) 1808
  - $a_{CP}^{\hat{T}-odd}(\Lambda_b^0 \to pK^-K^+K^-) = (1.12 \pm 1.51 \pm 0.32)\,\%$ JHEP 39 (2018) 1808
  - $a_{CP}^{\hat{T}-odd}(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) = (1.15 \pm 1.45 \pm 0.32)\,\%$ Nature Phys. 13 (2017) 391
  - $a_{CP}^{\hat{T}-odd}(\Lambda_b^0 \to pK^-K^+\pi^-) = (-0.93 \pm 4.54 \pm 0.42)\,\%$ Nature Phys. 13 (2017) 391

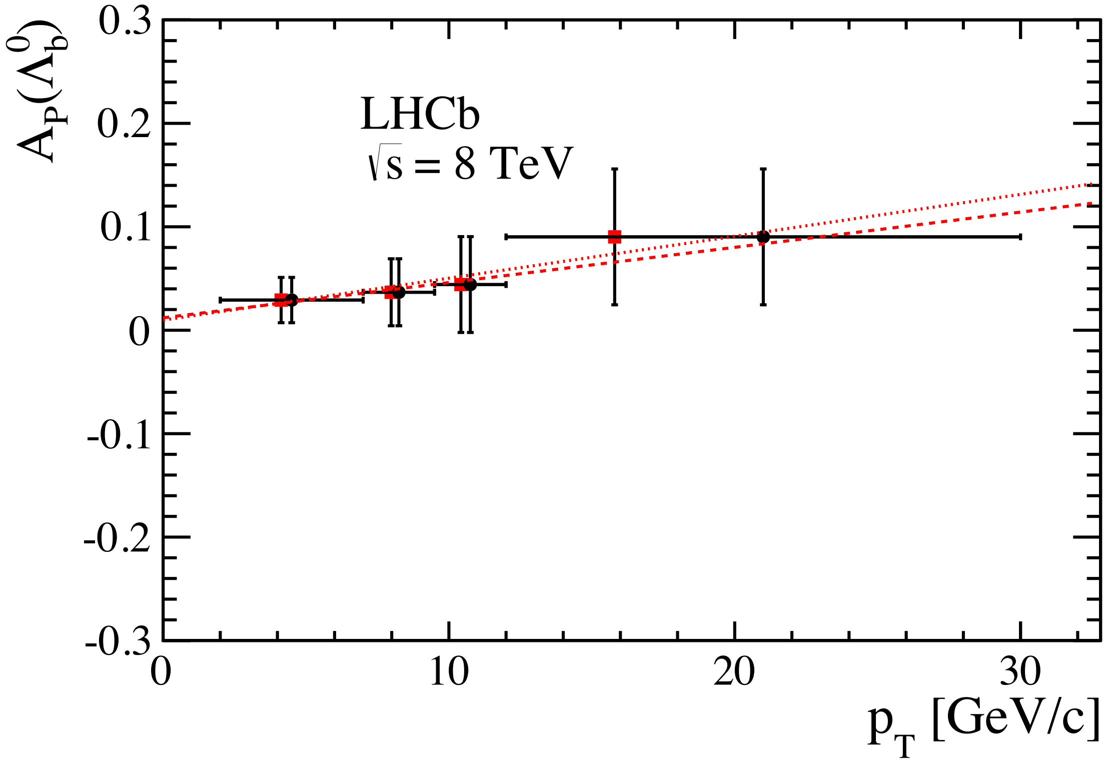
Experimental issue

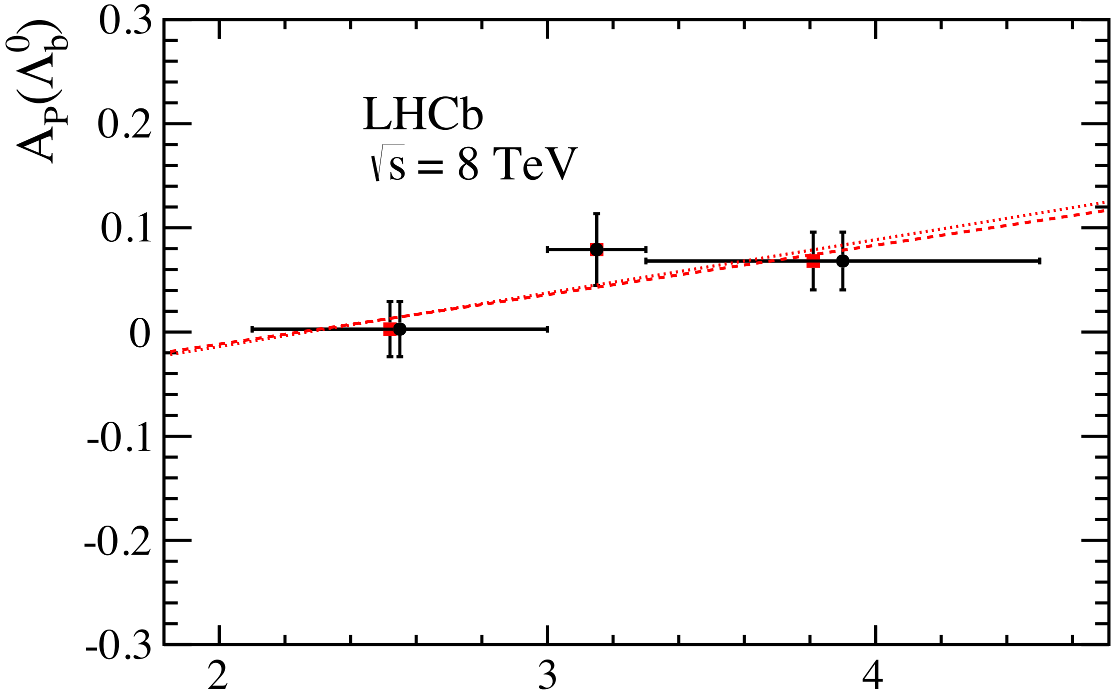
Particle-antiparticle production asymmetries

LHCb: Phys. Lett. B 774 (2017)

- Initial state pp
  - is not CP symmetric
- Initial asymmetry $\approx 1\%$ could mimic CPV

$$A_P = \frac{\sigma(P) - \sigma(\overline{P})}{\sigma(P) + \sigma(\overline{P})}$$





- By means of the unitary relation:

$$A_P(\Lambda_b^0) = -\left[\frac{f_d}{f_{\Lambda_b^0}} A_P(B^0) + \frac{f_u}{f_{\Lambda_b^0}} A_P(B^+) + \frac{f_s}{f_{\Lambda_b^0}} A_P(B_s^0)\right]$$

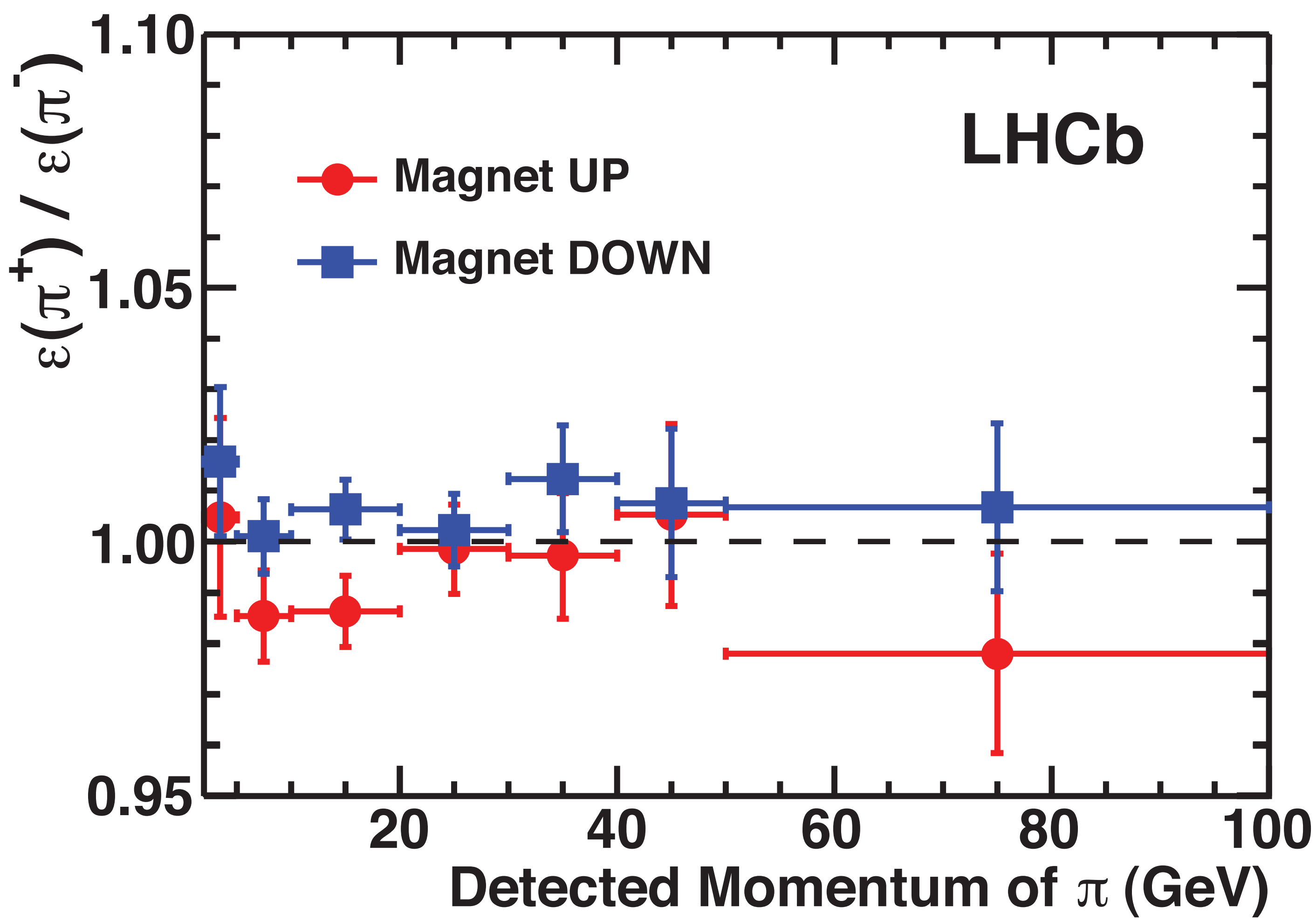
Experimental issue

Detector reconstruction asymmetries

- Detector is made of matter
  - is not CP symmetric

$$A_D(\pi^{\pm}) \approx 0.1\%, A_D(K^{\pm}) \approx 1\%, A_D(p/\overline{p}) \approx 1-2\%$$

- A_D can be measured using "ad hoc" abundant control sample



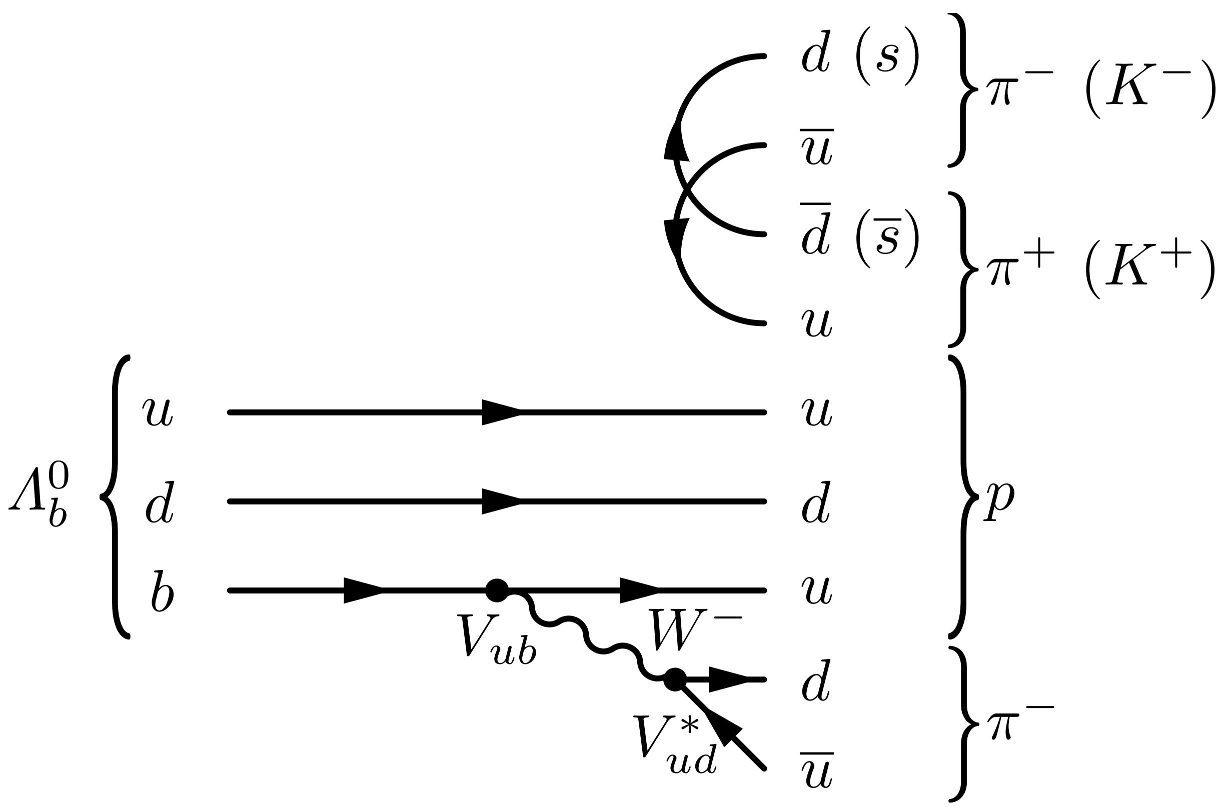
LHCb: Phys. Lett. B 713 (2012)

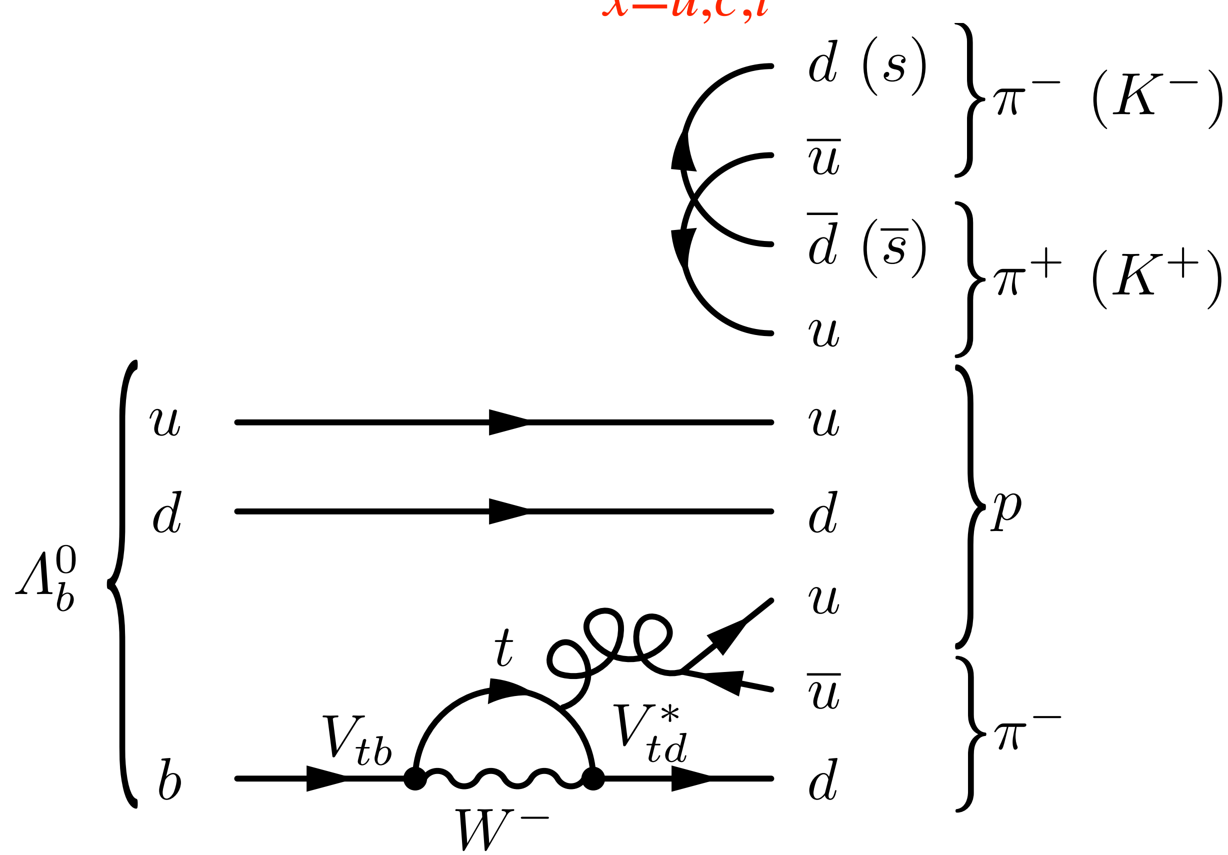
Search for CPV in $\Lambda_b^0 \to ph^-h^+h^-$

- Transitions governed by $b \to ud\bar{u}$ tree and $b \to du\bar{u}$ penguin amplitudes of similar magnitude
- Large relative weak phase $\alpha/\phi_2 = Arg\left(\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}}\right)$ in SM from the CKM elements
- Potential non negligible CPV effects in the SM

Tree $\propto V_{ub}^* V_{ud} \sim \lambda^3$

Penguin $\propto \sum_{x=u,c,t} V_{xb}^* V_{xd} \sim \lambda^3$

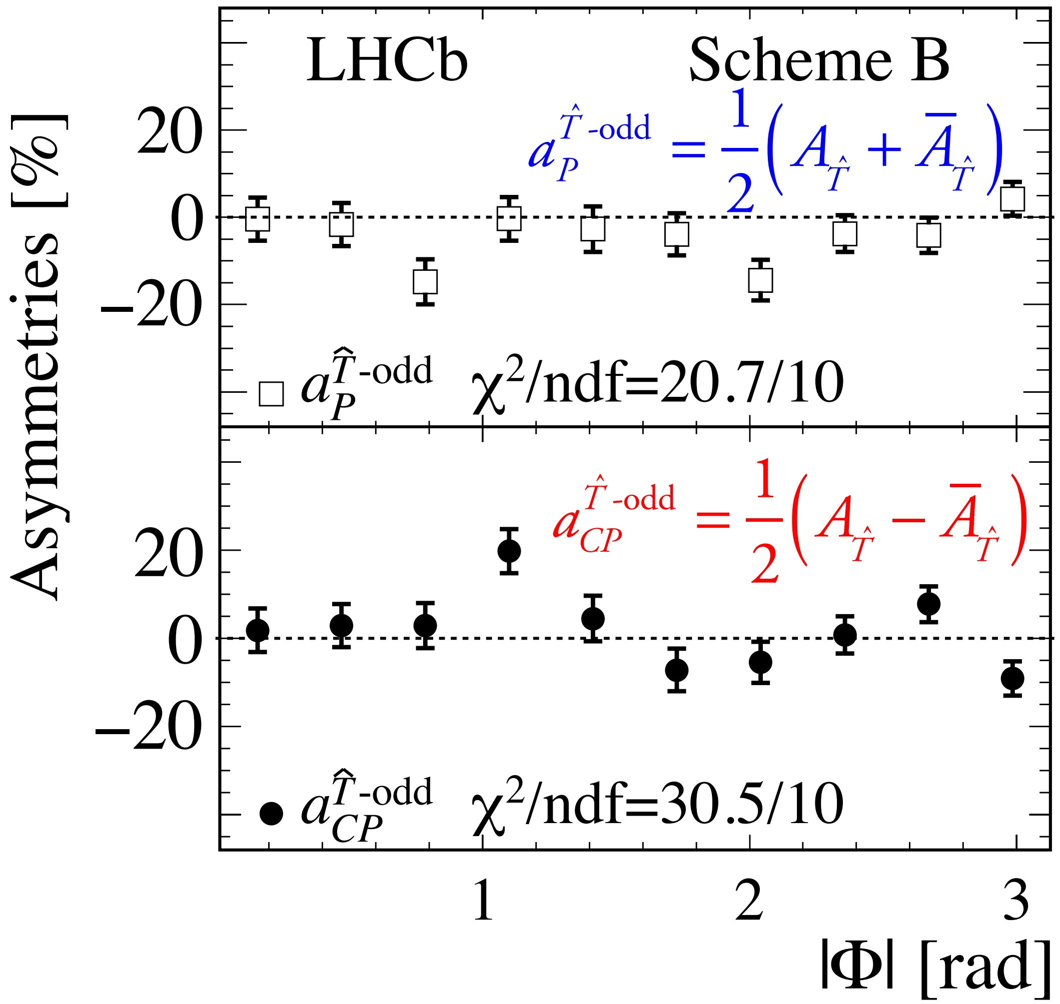




First evidence of CPV in baryons in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

Nature Physics 13, 391-396 (2017)

Scheme B: on Φ angle intervals



Refer to backup slides for bins definition

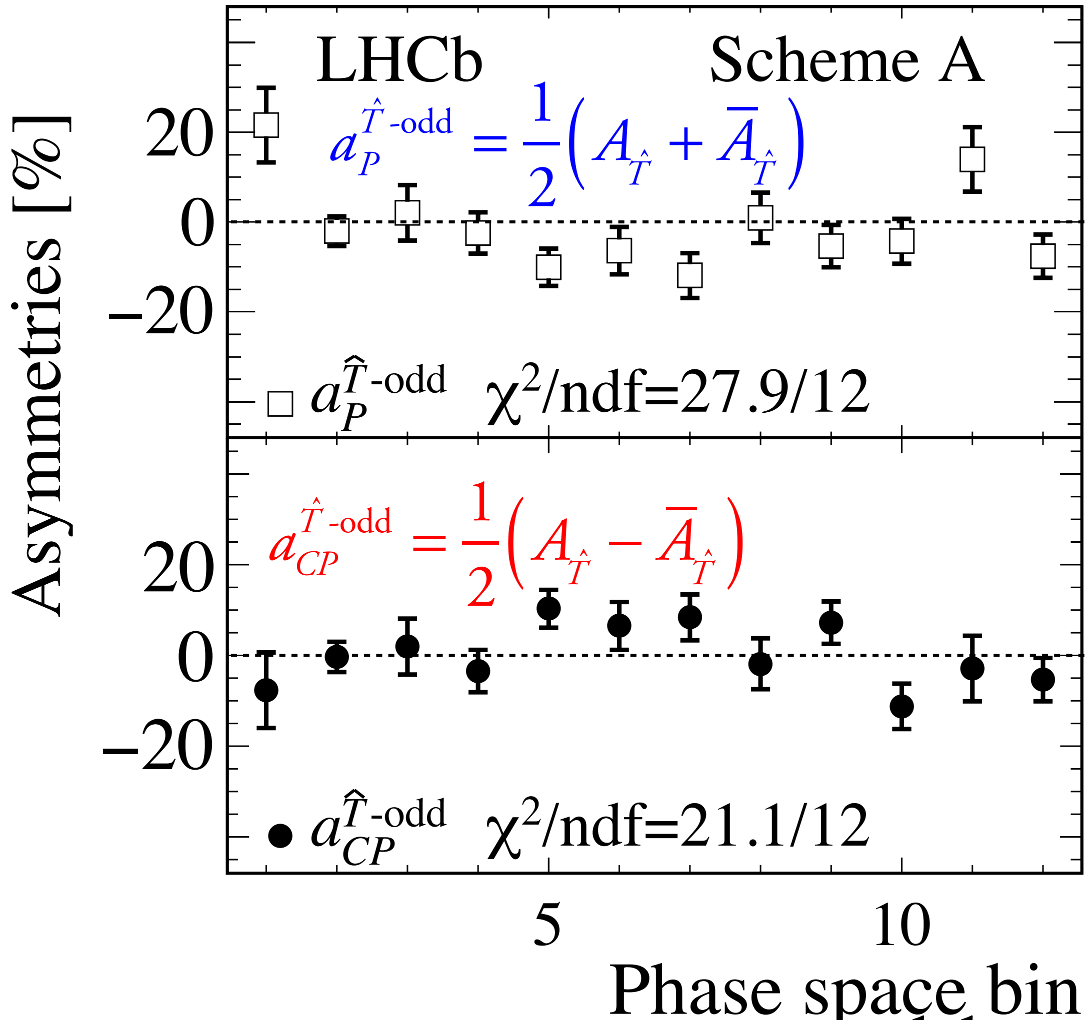
$\mathscr{L}_{int} = 3\ \text{fb}^{-1}$

CP symmetry p-value = $9.8\text{x}10^{-4}$

3.3 σ deviation

P symmetry compatible at 2.2 σ

Scheme A: on dominant resonances



- Integrated results compatible with *CP* & *P* conservation
- Largely insensitive to A_P & A_D
- Low systematic uncertainties <1%
- Already triggered some theorists

Experimental approaches

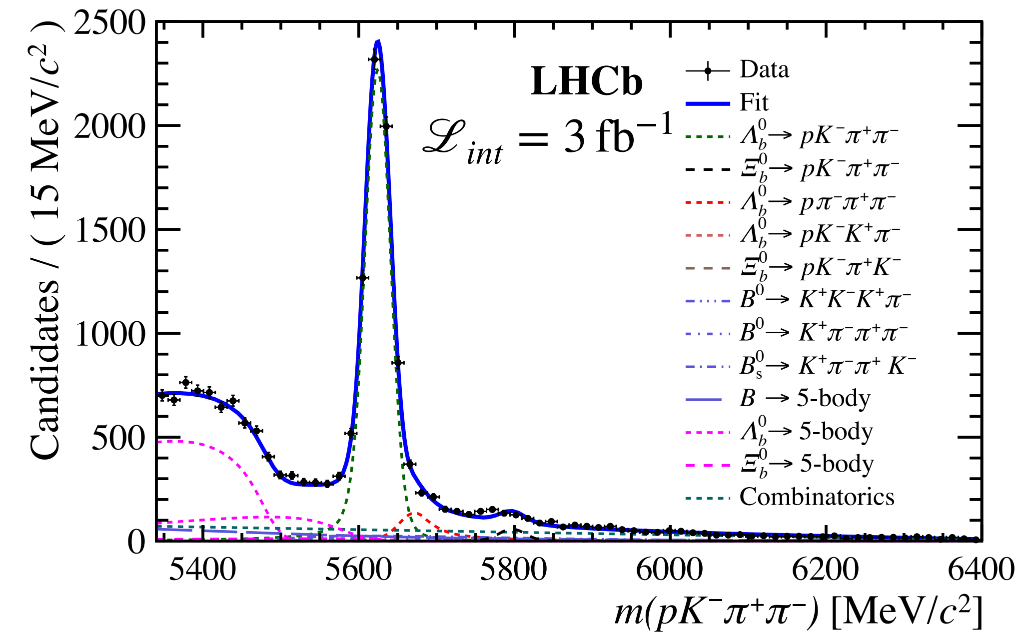
Eur. Phys. J. C79 (2019) 745

Measure ΔA_{CP} difference of *CP* asymmetries

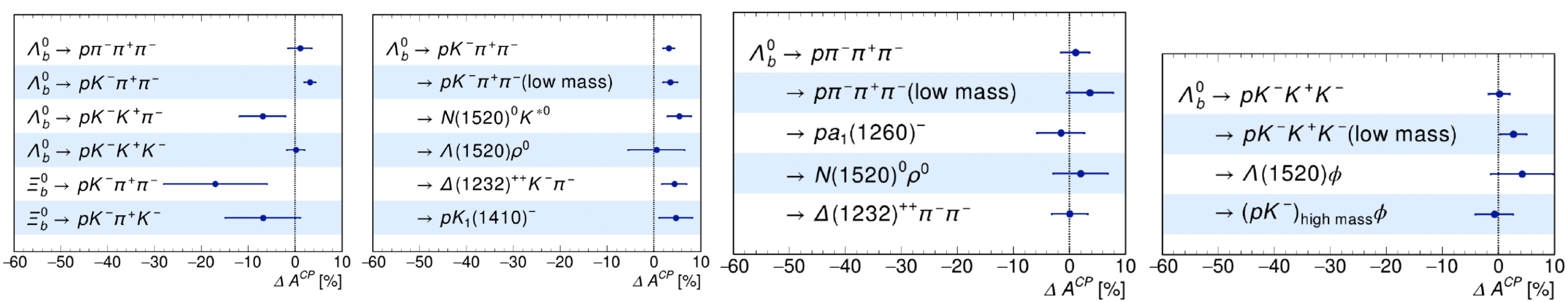
$$A_{raw}(\Lambda_b^0 \to p3h) = A_{CP}(\Lambda_b^0 \to p3h) + A_{prod}(\Lambda_b^0) + A_{reco}(p) + \ldots$$

$$\Delta A_{CP} = A_{raw}(\Lambda_b^0 \to p3h) - A_{raw}(\Lambda_b^0 \to \Lambda_c^+\pi)$$
$$= A_{CP}(\Lambda_b^0 \to p3h) - A_{CP}(\Lambda_b^0 \to \Lambda_c^+\pi^-)$$

Cancel A_{prod} and A_{reco}



- Results consistent with no CPV
- Asymmetries measured wrt control channels $\Lambda_b^0 \to \Lambda_c^+\pi^-, \Xi_b^0 \to \Xi_c^+\pi^-$

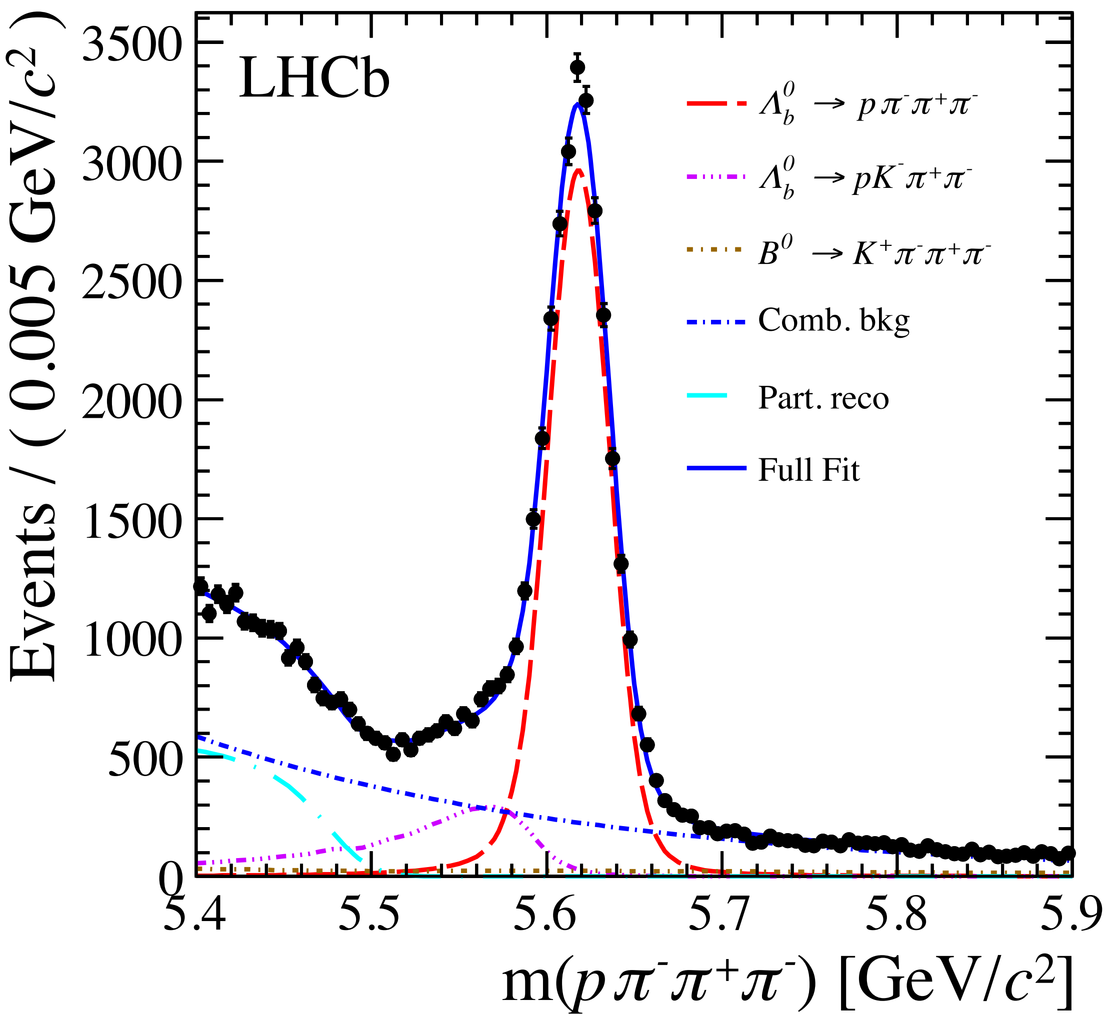


Search for CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

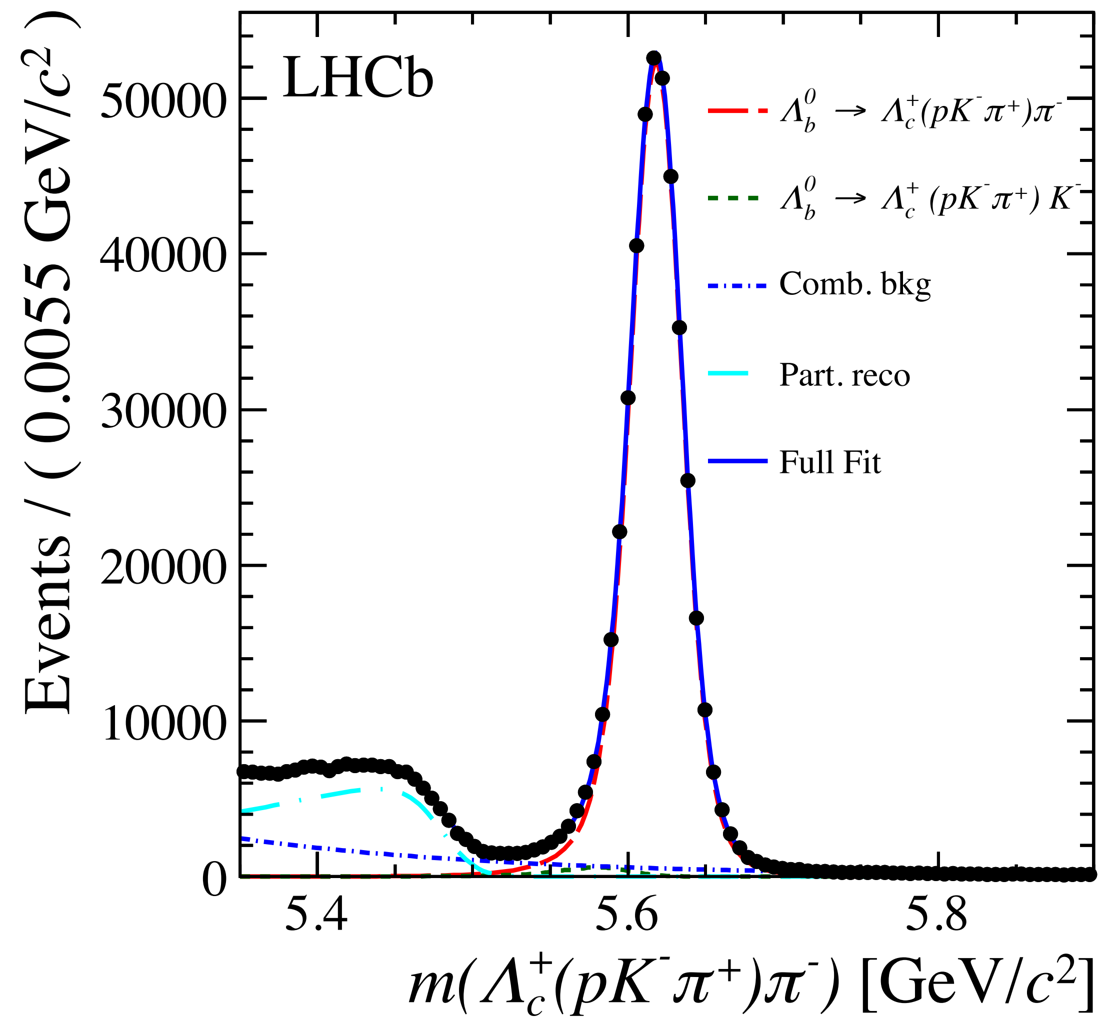
LHCb-PAPER-2019-028

- 6.6 fb^{-1} data analysed
- Signal yield = x4 signal yield Run1
- Applied 2 method to exploit CPV: Triple Product and Energy Test
- Improved understanding of decay dynamics and reproduction in simulations of Run1 result

$$N_{sig} = 27600 \pm 200$$



$$N_{sig} = 434500 \pm 800$$



Experimental approaches

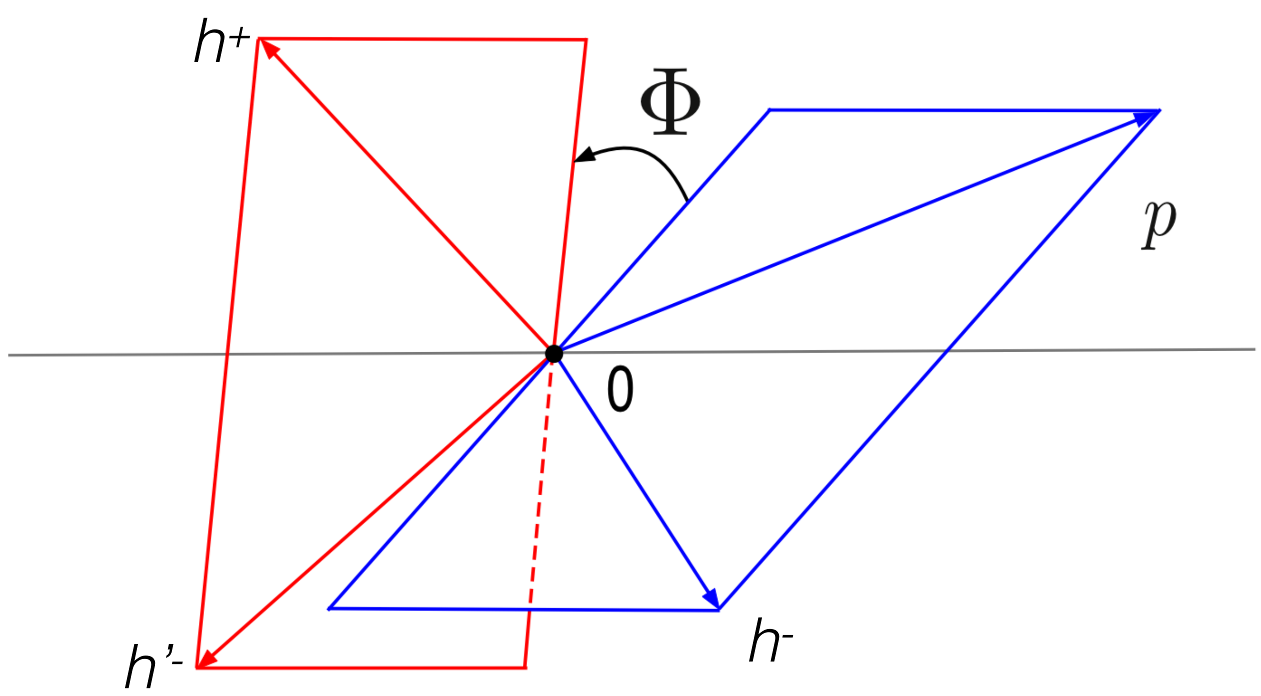
LHCb-PAPER-2019-028

Measure *CPV* via $\hat{T}$-violating aymmetries:

$\hat{T}$ = spin and momentum reversal operator

- Triple products in Λ_b rest frame

$$C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{h^-} \times \vec{p}_{h^+}) \propto \sin\Phi$$
$$\overline{C}_{\hat{T}} = \vec{p}_{\overline{p}} \cdot (\vec{p}_{h^+} \times \vec{p}_{h^-}) \propto \sin\overline{\Phi}$$



- $\hat{T}(P)$-odd asymmetries:

$$A_{\hat{T}} = \frac{N_{\Lambda_b^0}(C_{\hat{T}} > 0) - N_{\Lambda_b^0}(C_{\hat{T}} < 0)}{N_{\Lambda_b^0}(C_{\hat{T}} > 0) + N_{\Lambda_b^0}(C_{\hat{T}} < 0)}$$

$$\overline{A}_{\hat{T}} = \frac{N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}} > 0) - N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}} < 0)}{N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}} > 0) + N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}} < 0)}$$

- *CP*-violating observable:

$$a_{CP}^{\hat{T}-\mathrm{odd}} = \frac{1}{2}\left(A_{\hat{T}} - \overline{A}_{\hat{T}}\right)$$

- *P*-violating observable:

$$a_{P}^{\hat{T}-\mathrm{odd}} = \frac{1}{2}\left(A_{\hat{T}} + \overline{A}_{\hat{T}}\right)$$

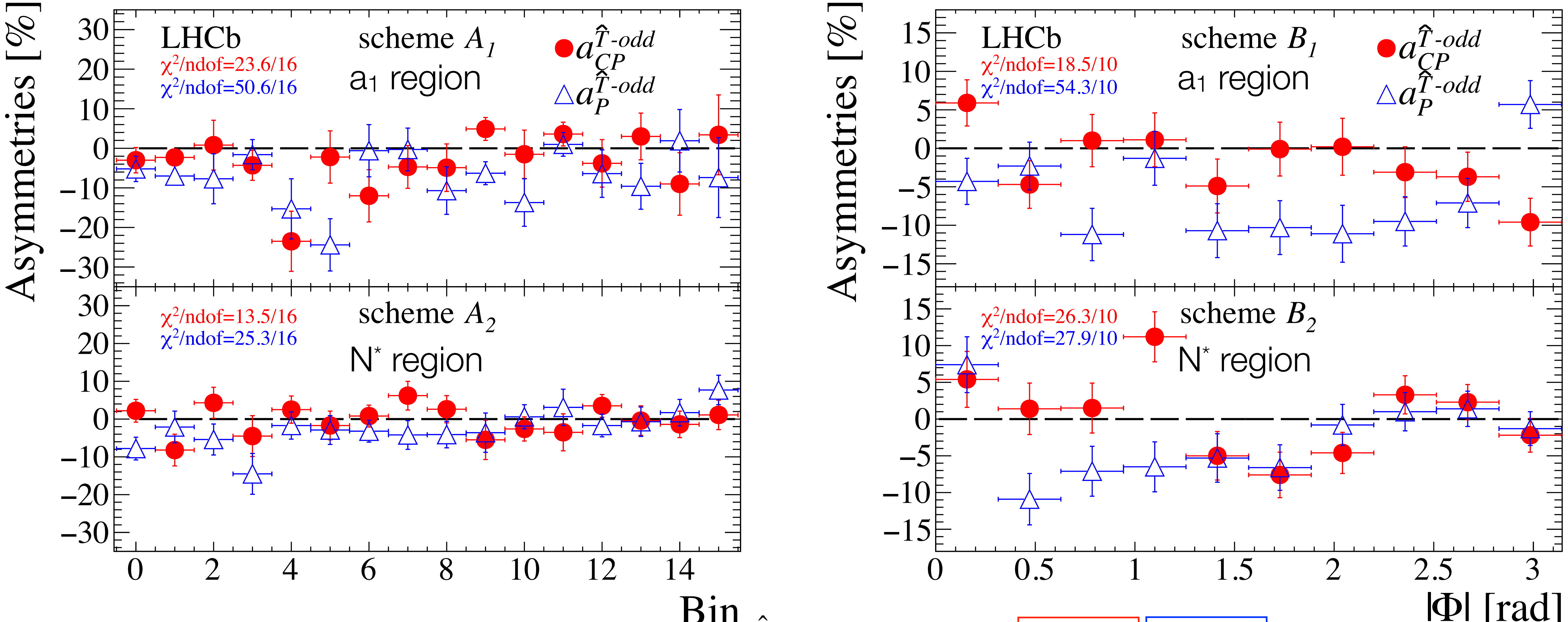
Search for CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

LHCb-PAPER-2019-028

- Update wrt the previous result

Scheme A: based on helicity angles

Scheme B: on $\mathbf{\Phi}$ angle intervals



- Integrated measurements:

$$a_{CP}^{\hat{T}-odd} = (-0.70 \pm 0.70 \pm 0.17)\ \%$$ Stat. unc.

$$a_{P}^{\hat{T}-odd} = (3.98 \pm 0.70 \pm 0.17)\ \%$$ Syst. unc.

- CPV at the level of 2.9σ, no CPV integrated in phase space
- First observation of P violation in b-baryon decay at the level of 5.5σ

Experimental approach

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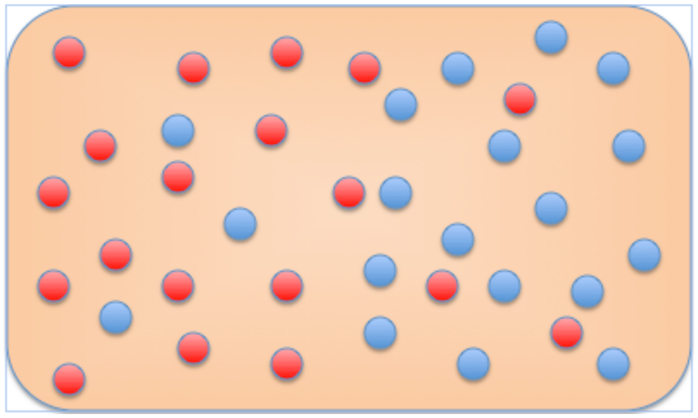
Energy Test

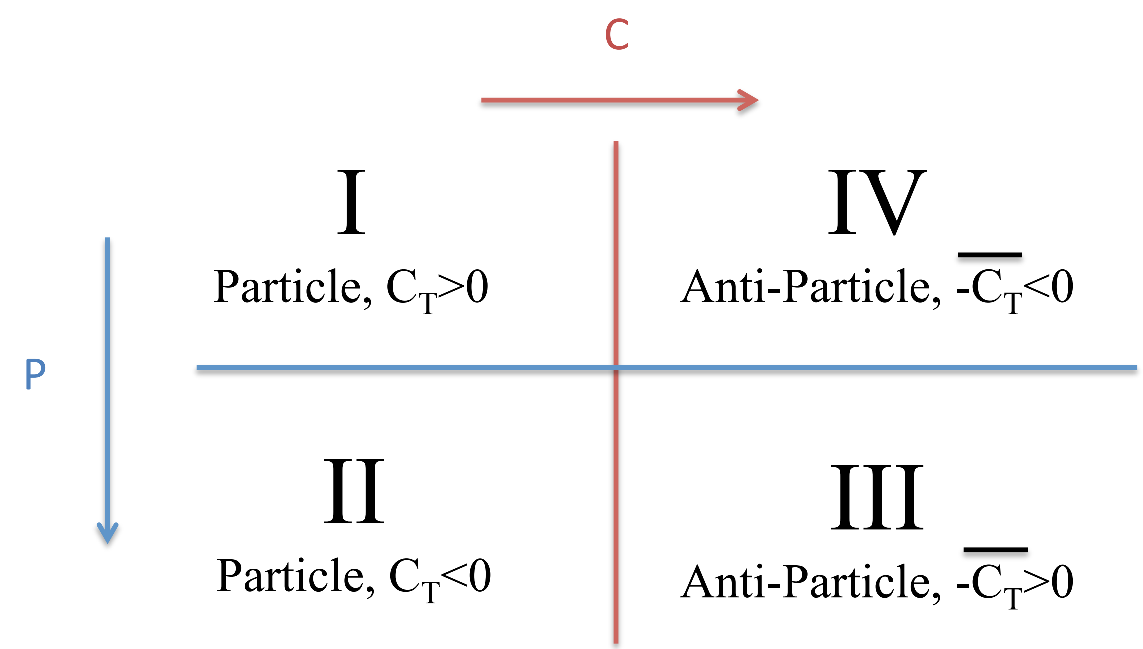


Test Statistic:

$$T = \underbrace{\frac{1}{n(n-1)}\sum_{i,j>1}^{n}\psi(d_{ij})}_{\Lambda_b^0 - \Lambda_b^0} + \underbrace{\frac{1}{\bar{n}(\bar{n}-1)}\sum_{i,j>1}^{\bar{n}}\psi(d_{i,j})}_{\overline{\Lambda}_b^0 - \overline{\Lambda}_b^0} - \underbrace{\frac{1}{n\bar{n}}\sum_{i,j}^{n,\bar{n}}\psi(d_{ij})}_{\Lambda_b^0 - \overline{\Lambda}_b^0}$$

- $\psi(d_{ij}) = e^{-d_{ij}^2/\delta^2}$: distance function
- $n, \bar{n}$: number of particle (antiparticle) candidates
- d_{ij} : distance in phase space
- δ : parameter to optimize

- **P violation**:
  - CP-even P-odd: [I]+[III] vs [II]+[IV]
- **CP violation**:
  - CP-odd P-even test: [I+II] vs [III+IV]
  - CP-odd P-odd test: [I+IV] vs [II+III]



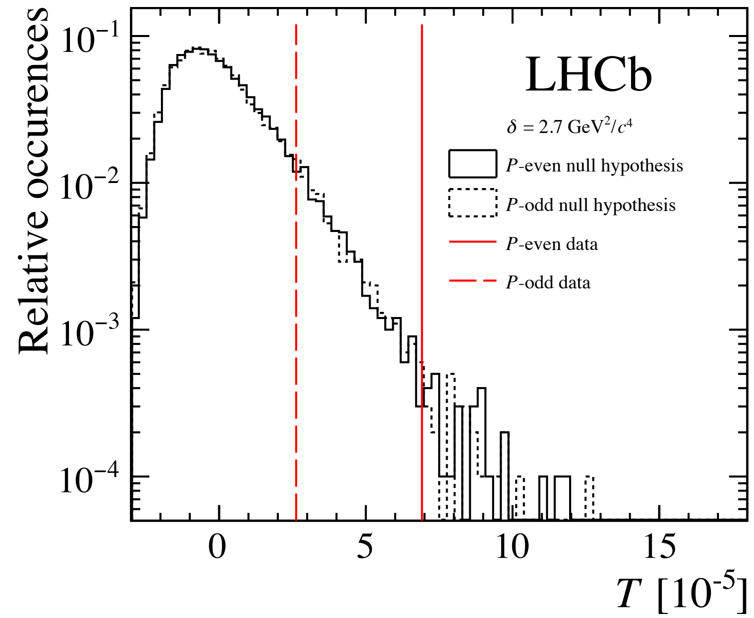
Energy Test results

LHCb-PAPER-2019-028

- CP(P)-symmetry hypothesis (with permutation test)

δ	$1.6\ \text{GeV}^2/c^4$	$2.7\ \text{GeV}^2/c^4$	$13\ \text{GeV}^2/c^4$
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}

- Permutation test to take into account LEE



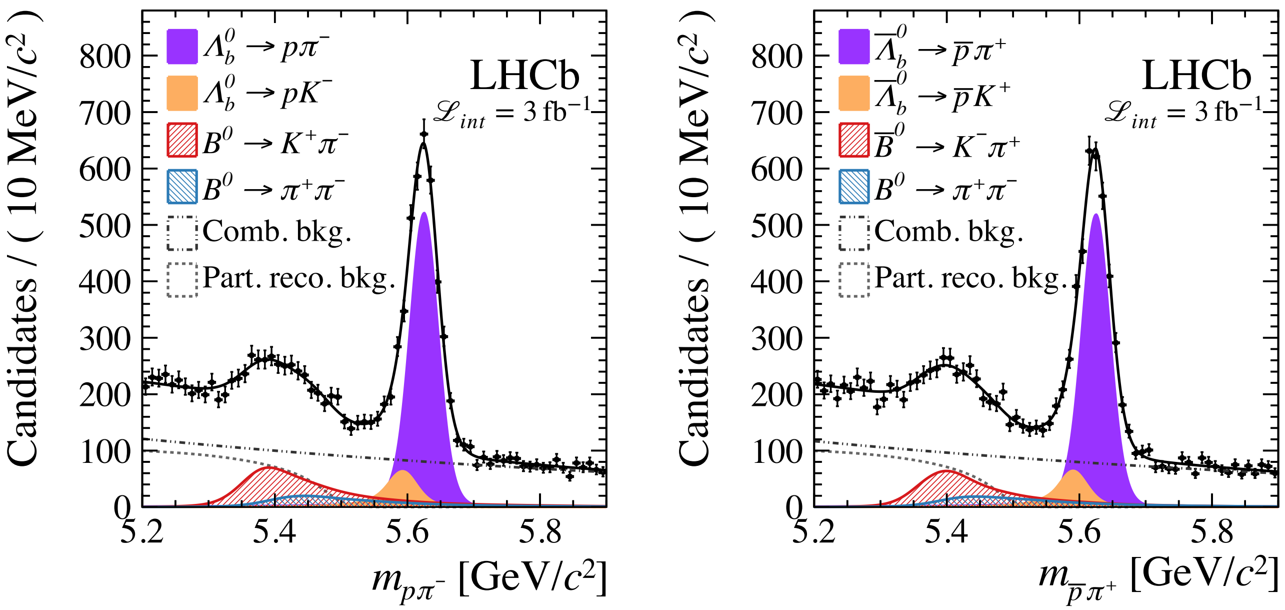
- Overall P-even CPV significance is at 2.8σ (taking into account LEE)
- P violation exceeds 5σ

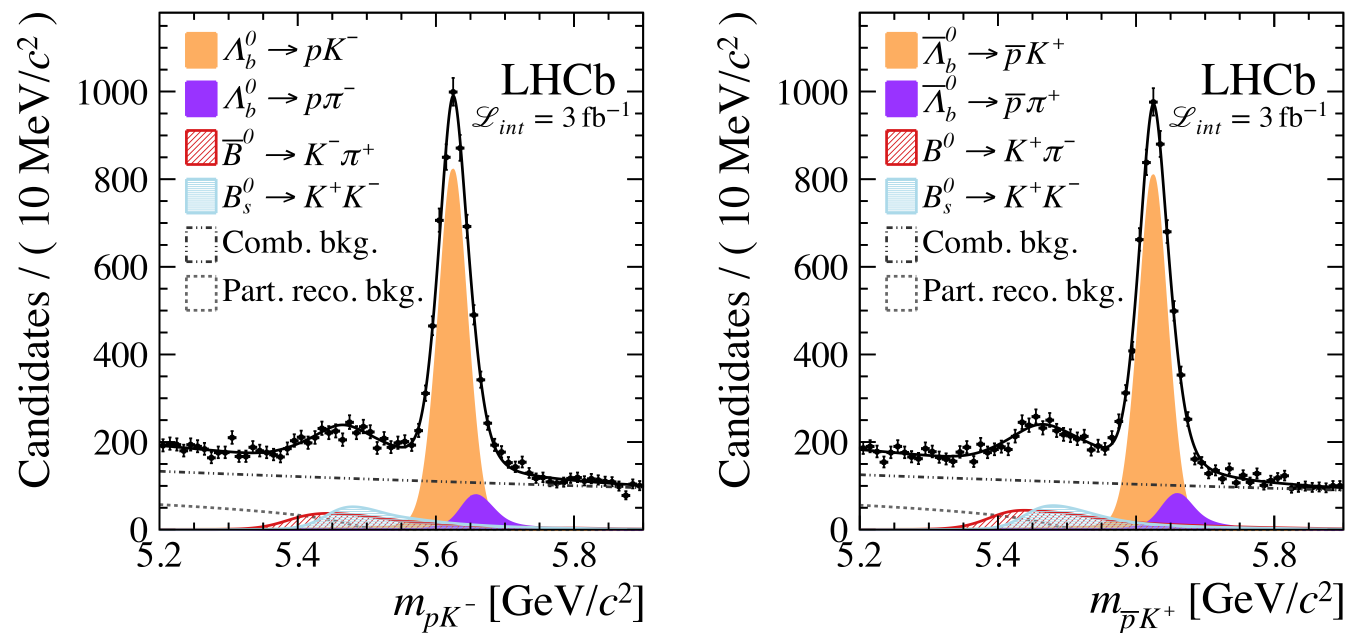
Search for CPV in $\Lambda_b^0 \to p\pi^-$ and $\Lambda_b^0 \to pK^-$

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

$\Lambda_b^0 \to pK^-$ 8800 signal events

$\Lambda_b^0 \to p\pi^-$ 6000 signal events





$$A_{CP}^{ph^-} = A_{raw}^{ph^-} - A_D^p - \left(A_D^{h^-} - A_{PID}^{ph^-}\right) - A_P^{\Lambda_b^0} - A_{trigger}^{ph^-}$$

Measured on data — From simulation — Estimated from control samples — External input

$$A_{CP}^{p\pi^-} = -0.035 \pm 0.017 \pm 0.020$$

$$A_{CP}^{pK^-} = -0.020 \pm 0.013 \pm 0.019$$

$$\Delta A_{CP} = A_{CP}^{pK^-} - A_{CP}^{p\pi^-} = 0.014 \pm 0.022 \pm 0.010$$

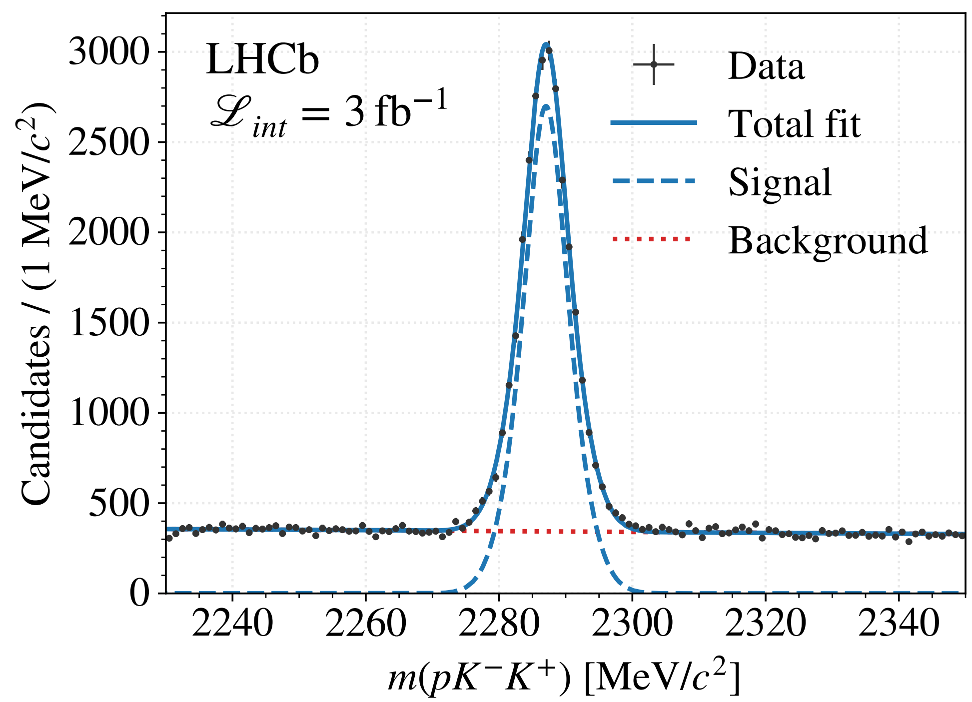
% level of precision

No sign of CPV

Search for CPV in $\Lambda_c^+ \to p h^- h^+$

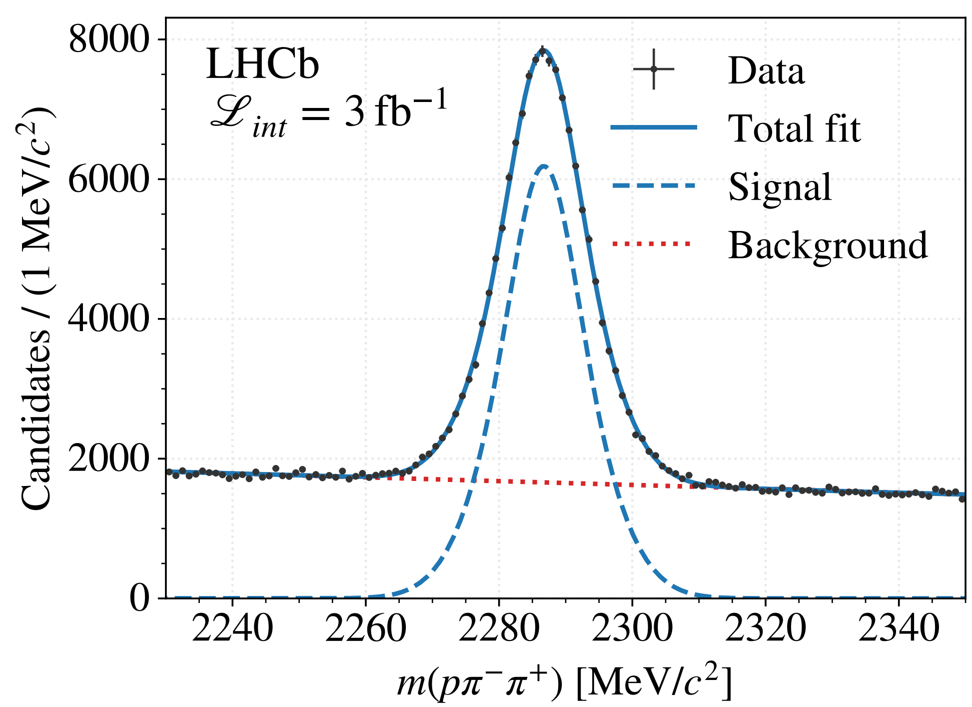
JHEP 03(2018) 182

- Test the same transitions $c \to u d \bar{d} (s \bar{s})$ that led to the first observation of CPV in charm
- Integrated over the phase space search for global CP-violating effects
- Selected $\Lambda_b^0 \to \Lambda_c^+ \mu^- X$ to reduce bkg
- Measure ΔA_{CP}



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

- Reweighted to match the Λ_b, μ and p kinematics to cancel $A_{prod}(\Lambda_b^0)$ and in the difference $A_{reco}(f)$
- Result compatible with no CPV



Conclusions

- LHCb opens a new window to search CPV in baryon decays. Many b-baryon decays are observed for the first time
- Updated measurement for $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$: first observation of P violation at 5.5σ integrated over phase space and CP violation at 2.9σ in regions of phase space
- CPV searches ongoing in several b-baryon decays. With additional data new b-baryons and new decays will be studied
- Not only b-baryons: effort to find CPV also in charm baryon decays
  - Work ongoing in Ξ_c^+ decay

Backup

Sensitivity to CPV

- By construction, $A_{\hat{T}}$, $\overline{A}_{\hat{T}}$, $a_{CP}^{\hat{T}\text{-odd}}$ and $a_{P}^{\hat{T}\text{-odd}}$ are insensitive to
  - ✓ particle/antiparticle production asymmetries
  - ✓ detector-induced charge asymmetries
  - $\Longrightarrow$ reduced systematic uncertainties

δ: strong phase

ϕ: weak phase

- Complementary approach to ΔA_{CP} analysis

$$a_{CP}^{\hat{T}-\text{odd}} \propto \cos\left(\delta_{even} - \delta_{odd}\right) \sin\left(\phi_{even} - \phi_{odd}\right)$$

not sensitive if $\delta_{even} - \delta_{odd} = \pi/2$ or $3\pi/2$

$\hat{T}$-*even*, $\hat{T}$-*odd* amplitudes

$$A_{CP} \propto \sin\left(\delta_1 - \delta_2\right) \sin\left(\phi_1 - \phi_2\right)$$

not sensitive if $\delta_1 - \delta_2 = 0$ or π

A_1, A_2 amplitudes

- Sensitive to potential new physics effects

W. Bensalem, A. Datta, and D. London, New physics effects on triple product correlations in Λ_b decays, Phys. Rev. D66 (2002) 094004, arXiv:hep-ph/0208054

Beauty baryons at LHCb (a bit of history)

- Most precise measurement of $|V_{ub}|$ using $\Lambda_b^0 \to p\mu^- \overline{\nu}_\mu$ decays
  LHCb: Nature Physics 10(2015) 1038
- First observation of pentaquark using $\Lambda_b^0 \to J/\psi p K^-$ decays
  LHCb: Phys. Rev. Lett. 115, 072001 (2015)
- Observation of $\Xi_b^{\prime -}$ and $\Xi_b^{\prime *}$ in $\Xi_b^0 \pi^-$ mode LHCb: Phys. Rev. Lett. 114, 062004 (2015)
- Observation of two orbitally excited Λ_b^{*0} states
  LHCb: Phys. Rev. Lett. 109, 172003 (2012)
- Mass, lifetimes and branching ratios measurements
- Search for CPV CDF: Phys. Rev. Lett. 113, 242001
  And other from LHCb presented here
- At LHCb b-baryons are produced in unprecedented quantities
  - Opens a new field in flavour physics for precision measurements

$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ phase space regions

Nature Physics 13, 391-396 (2017)

Scheme A: division based on dominant resonant structures

Δ^{++}

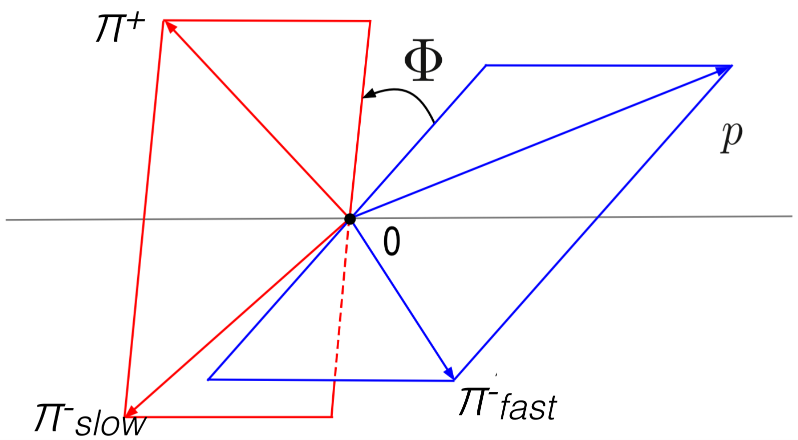
N^*

ρ^0 peak

Phase space bin	$m(p\pi^+)$	$m(p\pi^-_{\rm slow})$	$m(\pi^+\pi^-_{\rm slow})$, $m(\pi^+\pi^-_{\rm fast})$	$\lvert\Phi\rvert$
1	$(1.07, 1.23)$			$(0, \frac{\pi}{2})$
2	$(1.07, 1.23)$			$(\frac{\pi}{2}, \pi)$
3	$(1.23, 1.35)$			$(0, \frac{\pi}{2})$
4	$(1.23, 1.35)$			$(\frac{\pi}{2}, \pi)$
5	$(1.35, 5.34)$	$(1.07, 2.00)$	$m(\pi^+\pi^-_{\rm slow}) < 0.78$ or $m(\pi^+\pi^-_{\rm fast}) < 0.78$	$(0, \frac{\pi}{2})$
6	$(1.35, 5.34)$	$(1.07, 2.00)$	$m(\pi^+\pi^-_{\rm slow}) < 0.78$ or $m(\pi^+\pi^-_{\rm fast}) < 0.78$	$(\frac{\pi}{2}, \pi)$
7	$(1.35, 5.34)$	$(1.07, 2.00)$	$m(\pi^+\pi^-_{\rm slow}) > 0.78$ and $m(\pi^+\pi^-_{\rm fast}) > 0.78$	$(0, \frac{\pi}{2})$
8	$(1.35, 5.34)$	$(1.07, 2.00)$	$m(\pi^+\pi^-_{\rm slow}) > 0.78$ and $m(\pi^+\pi^-_{\rm fast}) > 0.78$	$(\frac{\pi}{2}, \pi)$
9	$(1.35, 5.34)$	$(2.00, 4.00)$	$m(\pi^+\pi^-_{\rm slow}) < 0.78$ or $m(\pi^+\pi^-_{\rm fast}) < 0.78$	$(0, \frac{\pi}{2})$
10	$(1.35, 5.34)$	$(2.00, 4.00)$	$m(\pi^+\pi^-_{\rm slow}) < 0.78$ or $m(\pi^+\pi^-_{\rm fast}) < 0.78$	$(\frac{\pi}{2}, \pi)$
11	$(1.35, 5.34)$	$(2.00, 4.00)$	$m(\pi^+\pi^-_{\rm slow}) > 0.78$ and $m(\pi^+\pi^-_{\rm fast}) > 0.78$	$(0, \frac{\pi}{2})$
12	$(1.35, 5.34)$	$(2.00, 4.00)$	$m(\pi^+\pi^-_{\rm slow}) > 0.78$ and $m(\pi^+\pi^-_{\rm fast}) > 0.78$	$(\frac{\pi}{2}, \pi)$

Scheme B: based on Φ angle intervals

i (i=1,2,…,12) $\quad (\frac{i-1}{12}\pi, \frac{i}{12}\pi)$

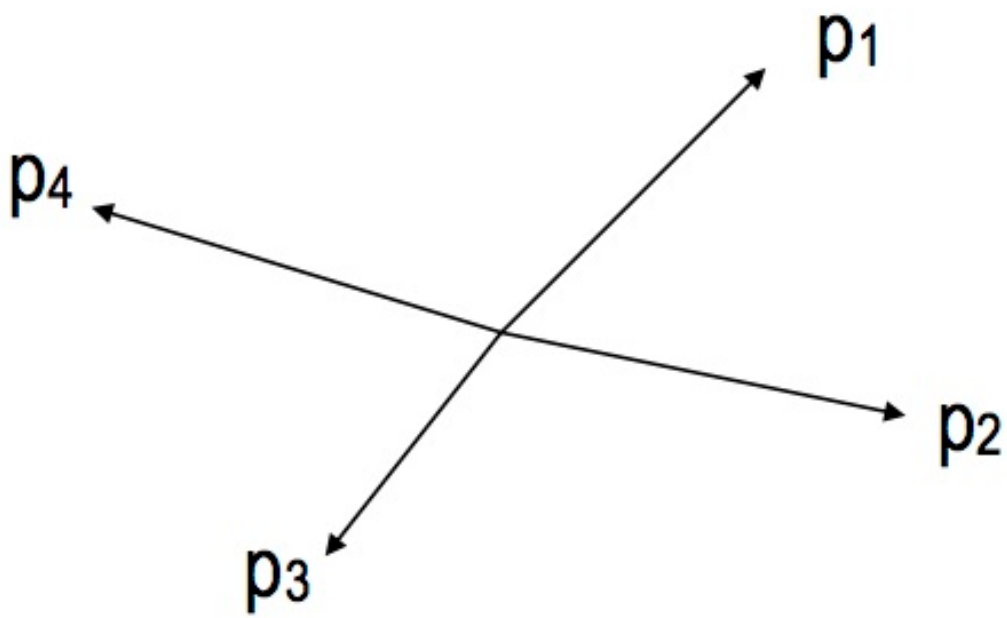


Definition of a $\hat{T}$-odd (P-odd)

Definition of a $\hat{T}$-odd observable

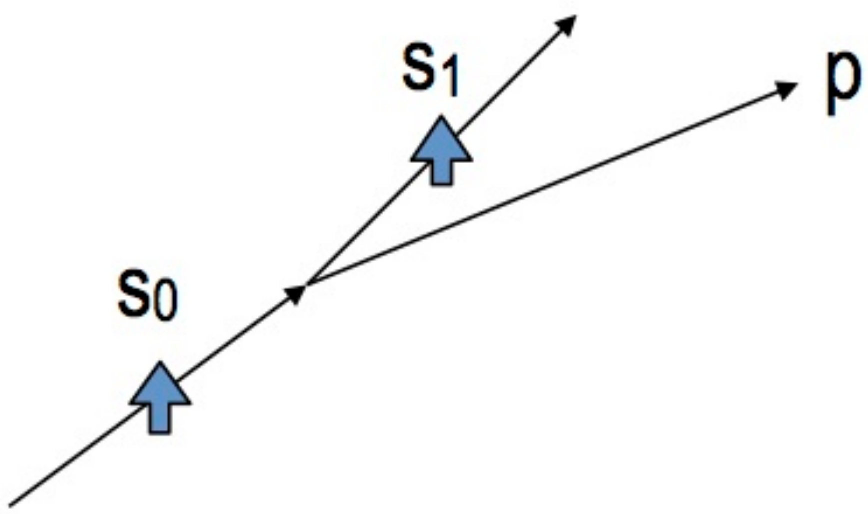
$\hat{T}$ = spin and momentum reversal operator

- Using the momenta



$$C_{\hat{T}} = p_1 \cdot (p_2 \times p_3)$$
$$\overline{C}_{\hat{T}} = \overline{p}_1 \cdot (\overline{p}_2 \times \overline{p}_3)$$

- Using spin and momenta



$$C_{\hat{T}} = s_0 \cdot (s_1 \times p)$$
$$\overline{C}_{\hat{T}} = \overline{s}_0 \cdot (\overline{s}_1 \times \overline{p})$$

- We build the $\hat{T}$-odd asymmetries using the momenta of the final state particles

Symmetries violation

- E = event under $\hat{T}$
- O = odd under $\hat{T}$
- (+) = even under parity
- (-) = odd under parity

Table 30-1

	$E^{(+)}$	$E^{(-)}$	$O^{(+)}$	$O^{(-)}$
$\cos(\delta_J - \delta_{J'})$ (present even in absence of final state interaction)	—	P, C	T, C	P, T
$\sin(\delta_J - \delta_{J'})$ (depends on the strength of the final state interaction)	T, C	P, T	—	P, C

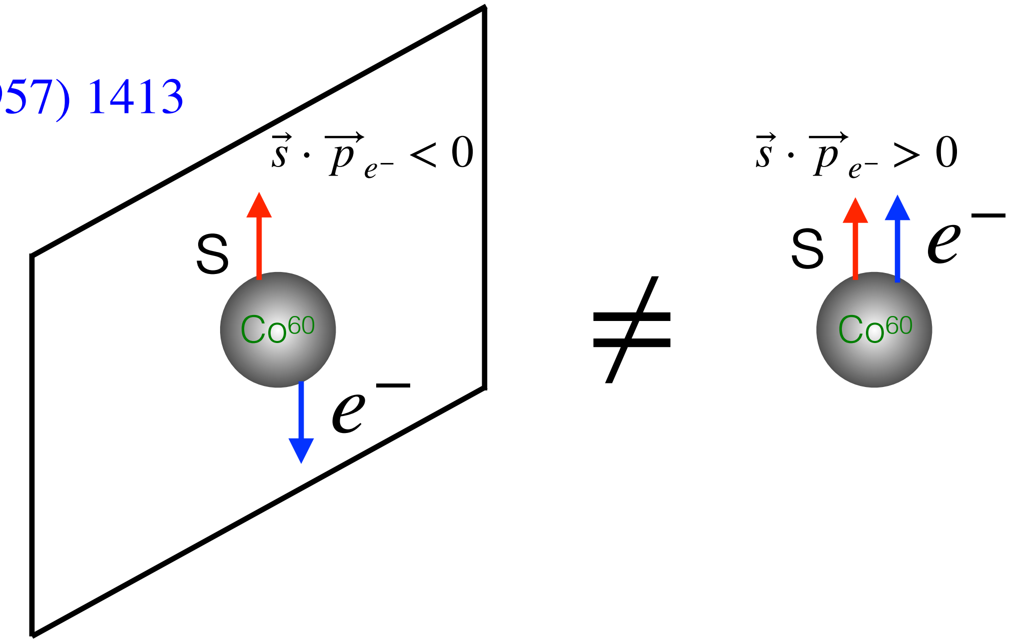
Stephen Gasiorowicz - Elementary Particle Physics-John Wiley & Sons (1966)

Test the symmetries

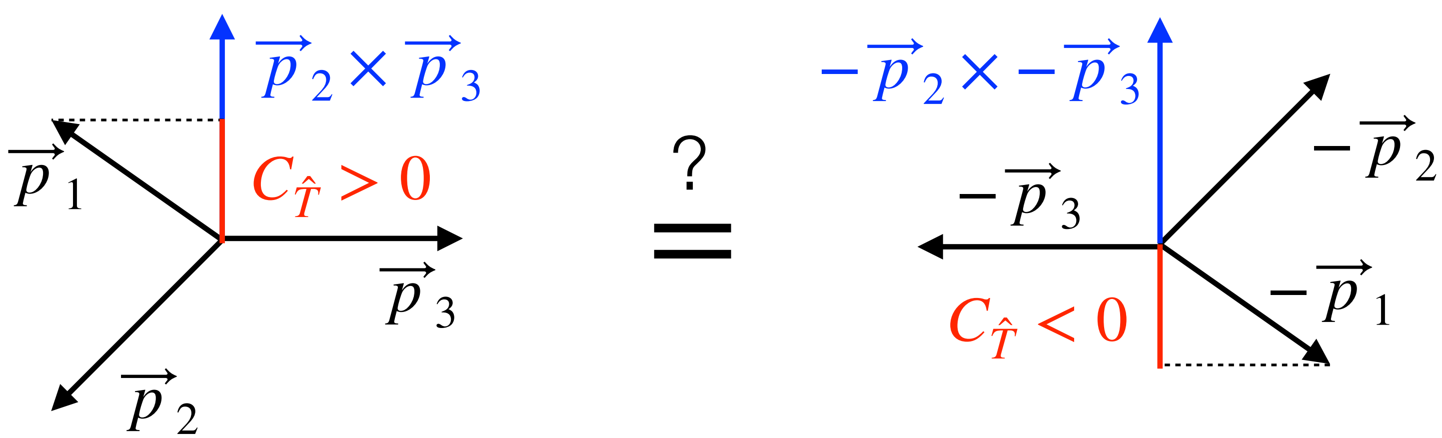
- P violation Madame Wu et al., Phys. Rev. 105 (1957) 1413

  Compare P-odd quantities of the same decay

  In particular: $< \vec{s} \cdot \vec{p}_{e^-} > \neq 0$



- P violation in our case



Test the symmetries

P-even CP

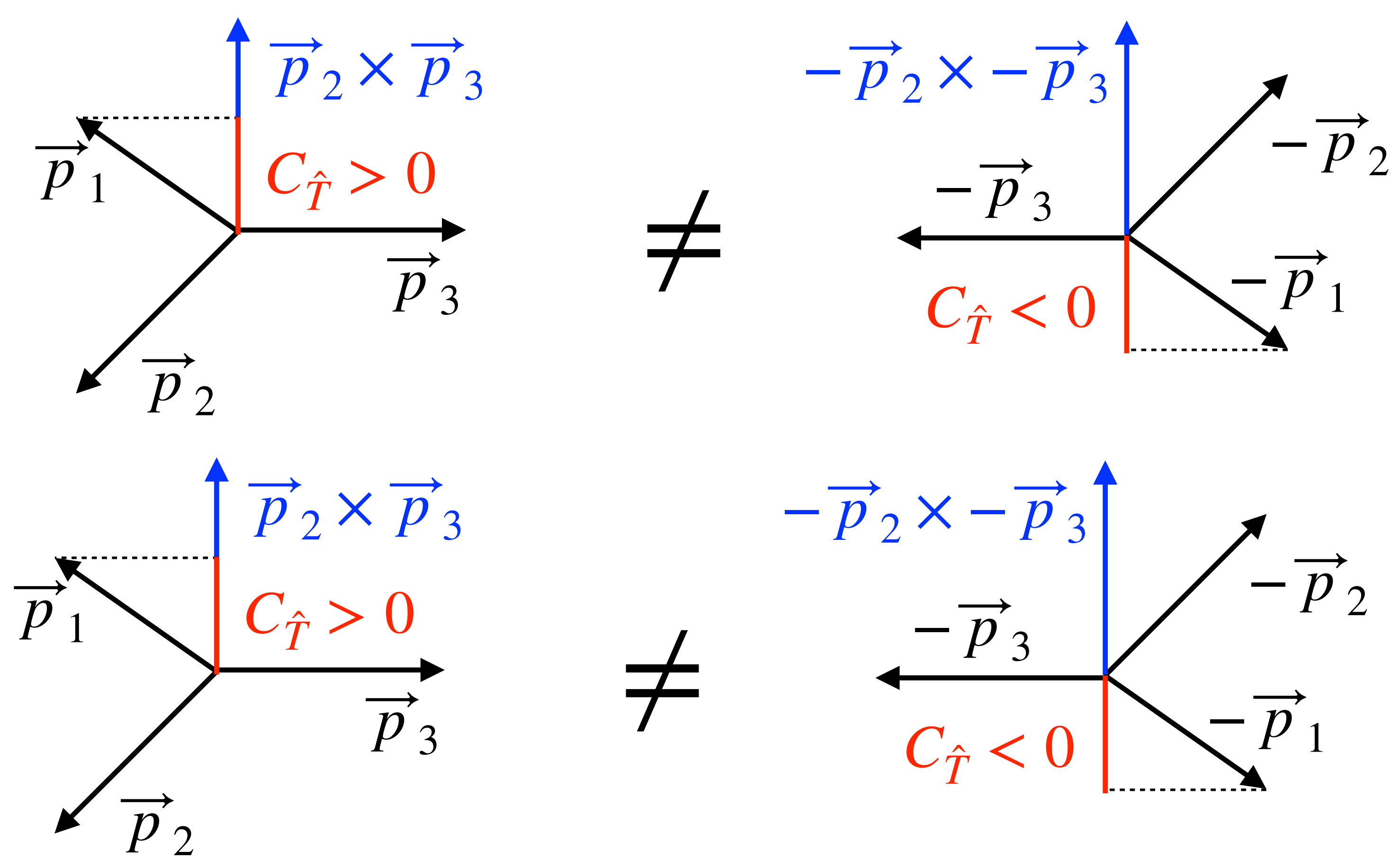
- Compare P-even quantities for particle and antiparticle: $\Gamma_{\Lambda_b^0} \stackrel{?}{=} \Gamma_{\overline{\Lambda}_b^0}$

P-odd CP

- P-odd CP violation in our case

For Λ_b^0 particle:

For $\overline{\Lambda}_b^0$ antiparticle:



- Is the P violation different between particle and antiparticle?