b-baryon decays

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On behalf of the LHCb Collaboration

Motivations – theoretical and experimental

- CP violation (CPV) is very well established in meson decays – not just B-meson decays
- But no CPV has yet been *observed* in decays involving baryons, only
  - Evidence for CPV in baryonic B decays, in $B^+ \to p\, \bar{p}\, K^+$ [PRL 113, 141801 (2014)]
  - Evidence for CPV in the b-baryon decay, in $\Lambda_b^0 \to p\, \pi^-\, \pi^+\, \pi^-$ [Nat. Phys. 13 (2017) 391]

- Due to conservation of baryon number, there can be no b-baryon mixing, hence no indirect CP violation
  $\Rightarrow$ CPV in b-baryons only CPV in decay !
- Theoretical calculations predict asymmetries up to ~20% [Phys. Rev. D 91, 116007 (2015)]
- Multi-body final states can have a rich resonant structure and exhibit interesting CPV patterns (see e.g. $B^+ \to 3h$ decays - Phys. Rev. D101 (2020) 012006 and refs. therein)

	our result	pQCD [5]
$10^6 \mathcal{B}(\Lambda_b \to pK^-)$	$4.8 \pm 0.7 \pm 0.1 \pm 0.3$	$2.0^{+1.0}_{-1.3}$
$10^6 \mathcal{B}(\Lambda_b \to p\pi^-)$	$4.2 \pm 0.6 \pm 0.4 \pm 0.2$	$5.2^{+2.5}_{-1.9}$
$10^6 \mathcal{B}(\Lambda_b \to pK^{*-})$	$2.5 \pm 0.3 \pm 0.2 \pm 0.3$	—
$10^6 \mathcal{B}(\Lambda_b \to p\rho^-)$	$11.4 \pm 1.6 \pm 1.2 \pm 0.6$	—
$10^2 \mathcal{A}_{CP}(\Lambda_b \to pK^-)$	$5.8 \pm 0.2 \pm 0.1$	-5^{+26}_{-5}
$10^2 \mathcal{A}_{CP}(\Lambda_b \to p\pi^-)$	$-3.9 \pm 0.2 \pm 0.0$	-31^{+43}_{-1}
$10^2 \mathcal{A}_{CP}(\Lambda_b \to pK^{*-})$	$19.6 \pm 1.3 \pm 1.0$	—
$10^2 \mathcal{A}_{CP}(\Lambda_b \to p\rho^-)$	$-3.7 \pm 0.3 \pm 0.0$	—

- LHCb is ideally suited for these studies: it's a b-baryon factory, with ~1 Λ_b^0 for 2 B^0 produced
- Charmless decays are good candidates to search for CPV in b-baryons: tree-level & Penguin amplitudes expected to be of ~ the same magnitude

Quick recap – overview of searches for CP violation in b-baryons

CDF	$\Lambda_b^0 \to p h^-$ Phys. Rev. Lett. 113 (2014) 242001	$A_{CP}(\Lambda_b^0 \to p\pi^-) = +0.06 \pm 0.07\,(stat) \pm 0.03\,(syst)$ $A_{CP}(\Lambda_b^0 \to pK^-) = -0.10 \pm 0.08\,(stat) \pm 0.04\,(syst)$
LHCb	$\Lambda_b^0(\Xi_b^0) \to K_S^0 p h^-$ JHEP 04 (2014) 087	$A_{CP}(\Lambda_b^0 \to K_S^0 p\pi^-) = 0.22 \pm 0.13\,(stat) \pm 0.03\,(syst)$
LHCb	$\Lambda_b^0(\Xi_b^0) \to \Lambda h^+ h^-$ JHEP 05 (2016) 081	$A_{CP}(\Lambda_b^0 \to \Lambda K^+\pi^-) = -0.53 \pm 0.23\,(stat) \pm 0.11\,(syst)$ $A_{CP}(\Lambda_b^0 \to \Lambda K^+K^-) = -0.28 \pm 0.10\,(stat) \pm 0.07\,(syst)$
LHCb	$\Lambda_b^0 \to \Lambda\eta, \Lambda\phi$ JHEP 09 (2015) 006 Phys. Lett. B 759 (2016) 282	Evidence for Λ_b^0 decay to $\Lambda\eta$ final state. Observed $\Lambda_b^0 \to \Lambda\phi$ decay but CPV consistent with zero.
LHCb	$\Lambda_b^0 \to pK^-\mu^+\mu^-$ JHEP 06 (2017) 108	$\Delta A_{CP}(\Lambda_b^0 \to pK^-\mu^+\mu^-) = (-3.5 \pm 5.0 \pm 0.2)\times 10^{-2}$ $a_{CP}^{\hat{T}-odd} = (1.2 \pm 5.0 \pm 0.7)\times 10^{-2}$
LHCb	$\Xi_b^-(\Omega_b^-) \to p h^- h^-$ Phys. Rev. Lett. 118 (2017) 071801	1st observation of Ξ_b^- decay to charmless final state. No CPV measurements performed yet.
LHCb	$\Lambda_b^0(\Xi_b^0) \to p h^- h^- h^+$ Nature Physics 13 (2017) 391–396	First evidence for CP violation in a baryon !

Hint of a possible non-zero CP asymmetry ?

Consistent with CP symmetry

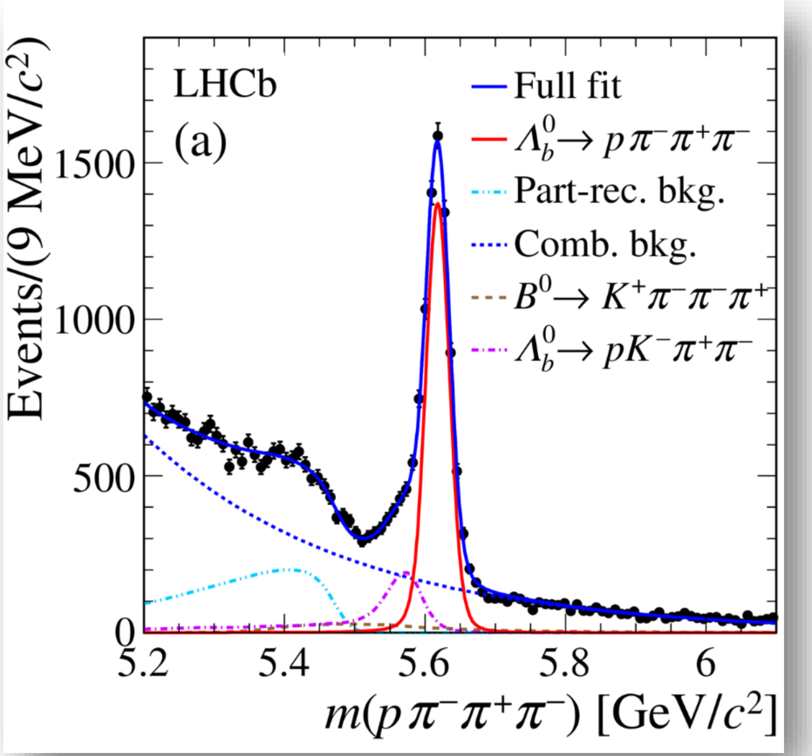
Called for further investigation of this family of decays … … and more data !

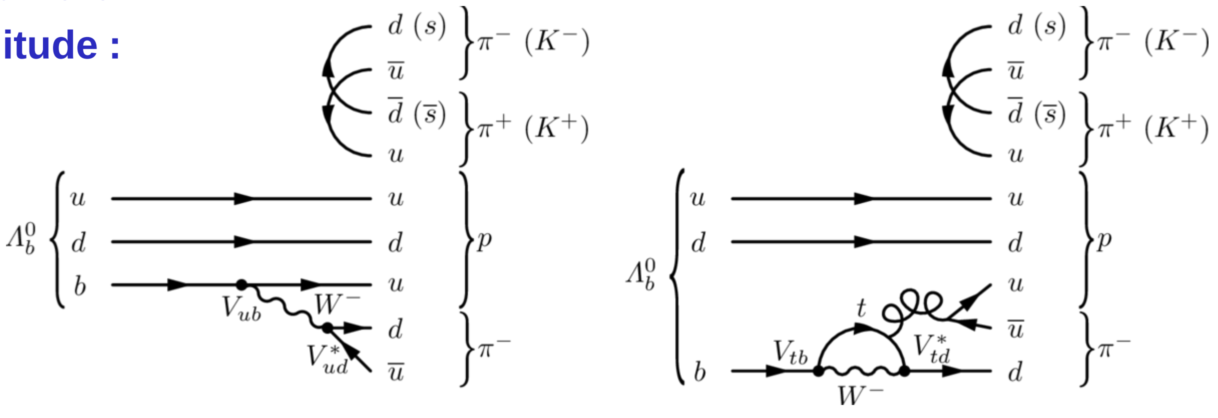
(Summary taken from Tom Latham)

First evidence for CP violation in the baryon sector

Nat. Phys. 13 (2017) 391

- Family of decays $\Lambda_b^0 \to p\, h^-\, h'^+\, h''^-$ ($h^{(\prime,\prime\prime)} = K, \pi$) interesting for CP violation studies
- Large CP violating effects expected for $\Lambda_b^0 \to p\, \pi^-\, \pi^+\, \pi^-$ and decays $\Lambda_b^0 \to p\, \pi^-\, K^+\, K^-$, studied here
  - Dominant diagrams with amplitudes of similar magnitude :
- Rich resonance structures ⇒ contributions to CPV





- Analysis with run 1 data sample
  - Showed significant signals (1st observation of both decays)

First evidence for CP violation (@ 3.3σ) in the baryon sector

- In measurement of triple product asymmetries in $\Lambda_b^0 \to p\, \pi^-\, \pi^+\, \pi^-$

LHCb studies of Λ_b^0 , $\Xi_b^0 \to p\, h^- \, h'^+ \, h''^-$ decays

JHEP 08 (2018) 039

Search for CP violation using triple product asymmetries in $\Lambda_b^0 \to pK^-\pi^+\pi^-$, $\Lambda_b^0 \to pK^-K^+K^-$ and $\Xi_b^0 \to pK^-K^-\pi^+$ decays

Nat. Phys. 13 (2017) 391

Measurement of matter-antimatter differences in beauty baryon decays

(*) Eur. Phys. J. C79 (2019) 745

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

(*) LHCb-PAPER-2019-028

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

(*) Presented in this talk

Measurements of CP asymmetries in charmless 4-body Λ_b^0 and Ξ_b^0 decays

- Eur. Phys. J. C79 (2019) 745
- Run 1 analysis of direct CP asymmetries in charmless 4-body Λ_b^0 and Ξ_b^0 decays

Run 1 direct CPV analysis of Λ_b^0 and Ξ_b^0 decays

Eur. Phys. J. C79 (2019) 745

- Family of decays $\Lambda_b^0, \Xi_b^0 \to p\, h^- h'^+ h''^-$ (h = K, π)
- Direct Delta-CP asymmetries measured for 18 final states
  - Either in the full phase space of the decay
  - Or exploring specific regions of the decay kinematics

$$\Delta\mathcal{A}^{CP} \equiv \mathcal{A}^{CP}_{\text{no-c}} - \mathcal{A}^{CP}_{\text{c}}$$

- $\mathcal{A}^{CP}_{\text{no-c}}$ $(\mathcal{A}^{CP}_{\text{c}})$ = asymmetry measured in the charmless (charmed, control) decay mode

Charmless mode	Control channel
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$	$\Lambda_b^0 \to (\Lambda_c^+ \to p\pi^-\pi^+)\pi^-$
$\Lambda_b^0 \to pK^-\pi^+\pi^-$	$\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\pi^-$
$\Lambda_b^0 \to pK^-K^+\pi^-$	$\Lambda_b^0 \to (\Lambda_c^+ \to p\pi^-\pi^+)\pi^-$
$\Lambda_b^0 \to pK^-K^+K^-$	$\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\pi^-$
$\Xi_b^0 \to pK^-\pi^+\pi^-$	$\Xi_b^0 \to (\Xi_c^+ \to pK^-\pi^+)\pi^-$
$\Xi_b^0 \to pK^-\pi^+K^-$	$\Xi_b^0 \to (\Xi_c^+ \to pK^-\pi^+)\pi^-$

- $\Delta\mathcal{A}^{CP}$ $\Rightarrow$ cancel to 1st order production, detection and reconstruction asymmetries

No significant CPV observed in any of the measurements

6 Λ_b^0 modes, 3 Ξ_b^0 modes (first group); 9 Λ_b^0 modes (last group)

Decay mode	Signal yields X_b^0	Signal yields $\overline{X}_b^0$
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$	2335 ± 56	2264 ± 55
$\Lambda_b^0 \to pK^-\pi^+\pi^-$	6807 ± 92	6232 ± 89
$\Lambda_b^0 \to pK^-K^+\pi^-$	555 ± 38	630 ± 38
$\Lambda_b^0 \to pK^-K^+K^-$	2312 ± 54	2248 ± 54
$\Xi_b^0 \to pK^-\pi^+\pi^-$	180 ± 28	252 ± 29
$\Xi_b^0 \to pK^-\pi^+K^-$	265 ± 25	305 ± 26
$\Lambda_b^0 \to (\Lambda_c^+ \to p\pi^-\pi^+)\pi^-$	1607 ± 40	1586 ± 40
$\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\pi^-$	24687 ± 159	24052 ± 157
$\Xi_b^0 \to (\Xi_c^+ \to pK^-\pi^+)\pi^-$	259 ± 18	260 ± 18
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ (LBM)	498 ± 25	455 ± 24
$\Lambda_b^0 \to pK^-\pi^+\pi^-$ (LBM)	3217 ± 61	2929 ± 58
$\Lambda_b^0 \to pK^-K^+K^-$ (LBM)	1240 ± 38	1146 ± 36
$\Lambda_b^0 \to pa_1(1260)^-$	422 ± 23	425 ± 23
$\Lambda_b^0 \to \Delta(1232)^{++}\pi^-\pi^-$	783 ± 30	771 ± 29
$\Lambda_b^0 \to N(1520)^0\rho(770)^0$	241 ± 16	230 ± 16
$\Lambda_b^0 \to pK_1(1410)^-$	548 ± 26	488 ± 25
$\Lambda_b^0 \to \Delta(1232)^{++}K^-\pi^-$	998 ± 37	895 ± 34
$\Lambda_b^0 \to \Lambda(1520)\rho(770)^0$	167 ± 14	160 ± 14
$\Lambda_b^0 \to N(1520)^0K^*(892)^0$	977 ± 33	856 ± 31
$\Lambda_b^0 \to \Lambda(1520)\phi(1020)$	192 ± 15	172 ± 14
$\Lambda_b^0 \to (pK^-)_{\text{high-mass}}\phi(1020)$	548 ± 25	542 ± 25

LBM = low 2×2-body mass (ph and hh')

Run 1 direct CPV analysis of Λ_b^0 and Ξ_b^0 decays

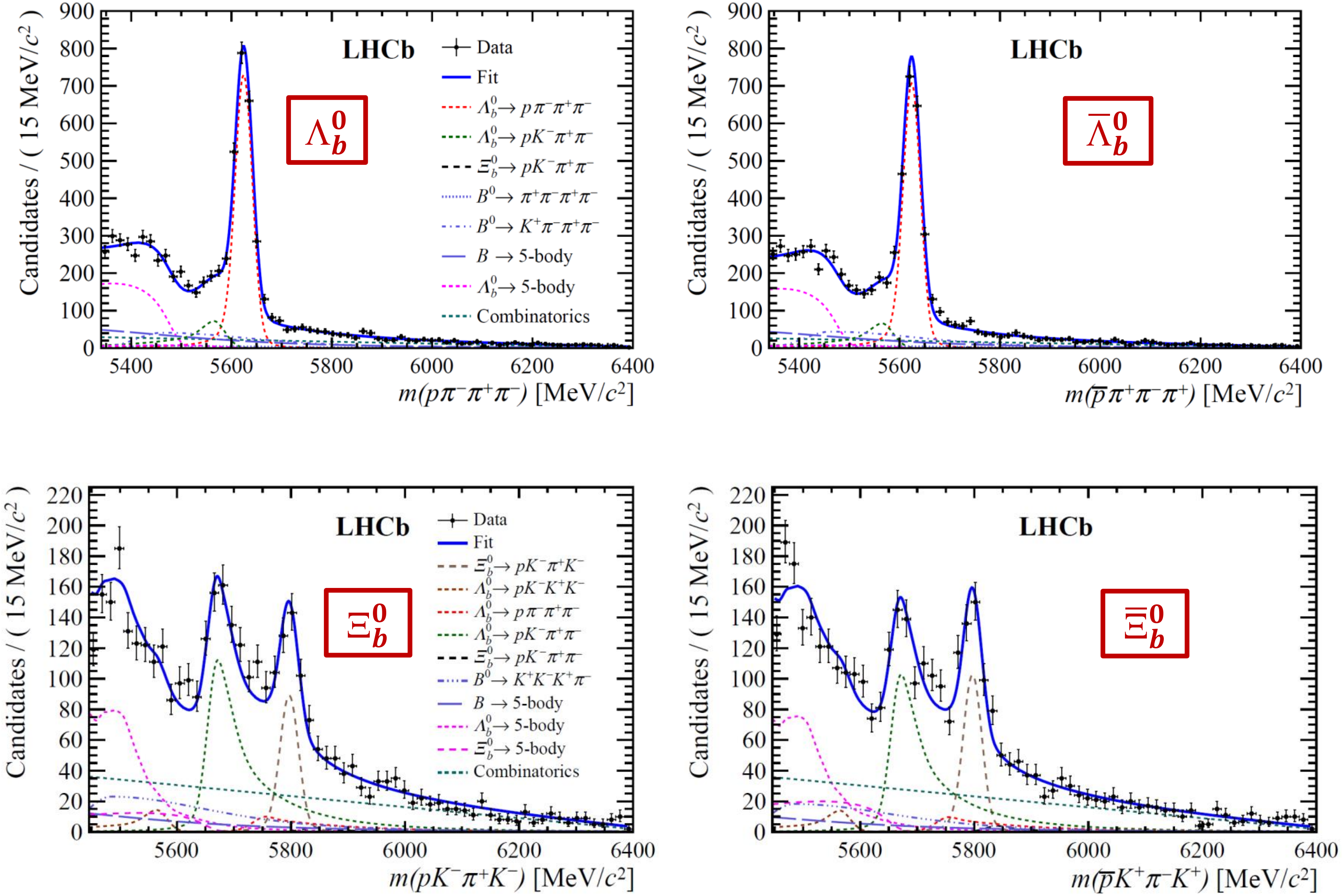
Eur. Phys. J. C79 (2019) 745

Example distributions

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

- $\Xi_b^0 \to p\,K^-\,\pi^+\,K^-$

- **A similar, complementary, analysis used TPAs**
  [JHEP 08 (2018) 039]



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

- LHCb-PAPER-2019-028

- Updated analysis with combined run 1 and 2 data sample
- Asymmetries measured with 2 independent methods
  - Triple product asymmetries
  - Unbinned energy test

Run 1 & 2 analysis of $\Lambda_b^0 \to p\,\pi^-\,\pi^+\,\pi^-$

LHCb-PAPER-2019-028

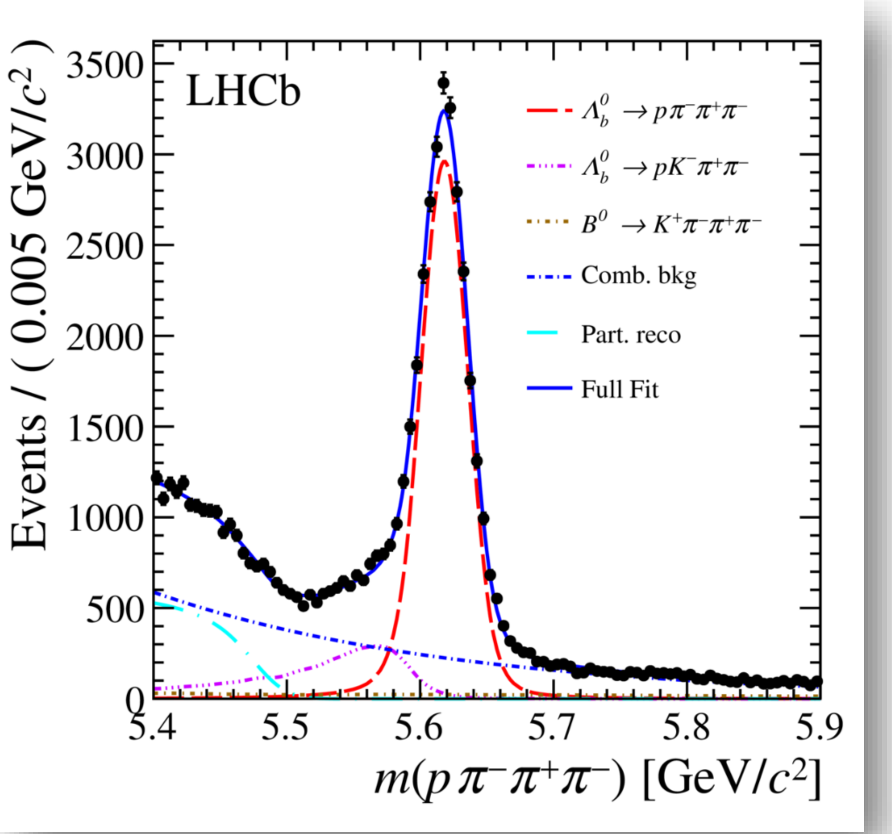
Compared with the previous run 1 analysis

- ❑ Inclusion of run 2 data (2015-17) significantly increases data sample
- ❑ Optimised selection

⇒ data sample (signal yield) 4× larger compared to run 1 sample

- ❑ Searches for CP and P violation measured with 2 independent methods
  1) TPAs with improved binning schemes
     - Both local and integrated asymmetries considered
  2) Unbinned energy test
     - Designed to look for localised differences in phase-space between 2 samples

~27600 signal decays

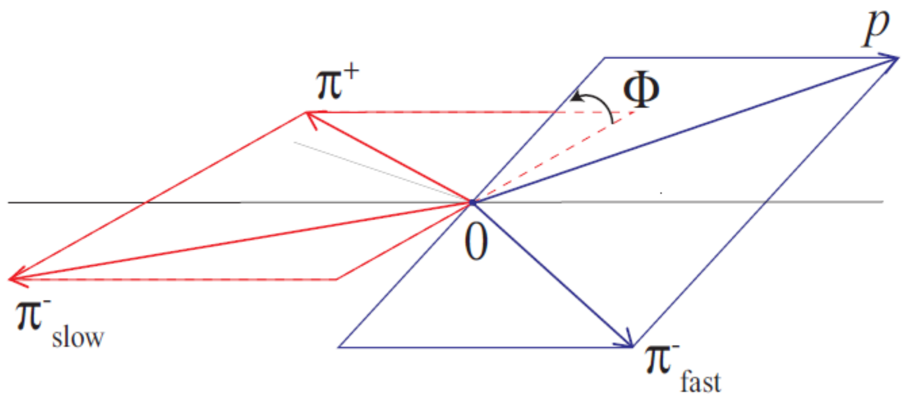


Intermezzo – Triple Product Asymmetries (TPAs)

- **Scalar triple products from momenta of 3 final-state particles**
  (in the rest frame of the mother particle)

$$C_{\widehat{T}} \equiv \vec{p}_p \cdot \left(\vec{p}_{\pi^-_{\rm fast}} \times \vec{p}_{\pi^+}\right)$$

$$\overline{C}_{\widehat{T}} \equiv \vec{p}_{\overline{p}} \cdot \left(\vec{p}_{\pi^+_{\rm fast}} \times \vec{p}_{\pi^-}\right)$$



- **Triple product (T-odd) asymmetries**
  (by construction largely insensitive to global production and detector-induced charge 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 and P violating asymmetries**

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

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

Intermezzo – testing CP and P violation

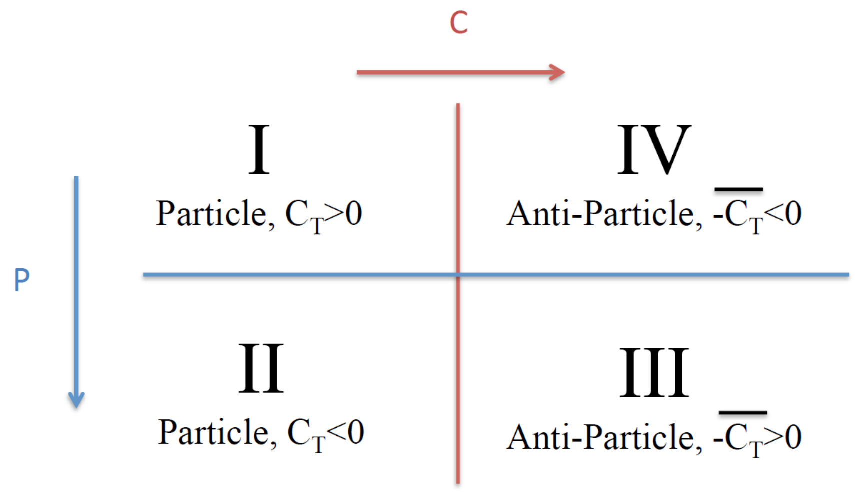
- Data hence divided in 4 statistically independent sub-samples, depending on flavour of Λ_b^0 and sign of the triple-product asymmetry

- CP transformations
  I $\leftrightarrow$ III or II $\leftrightarrow$ IV

- CPV searched for in 2 combinations
  P-even: (I + II) versus (III + IV)
  P-odd: (I + IV) versus (II + III)

- P violation test
  (I + III) versus (II + IV)

3 tests possible



Run 1 & 2 analysis of $\Lambda_b^0 \to p\,\pi^-\,\pi^+\,\pi^-$ – integrated TPA results

- TPAs integrated over the phase-space

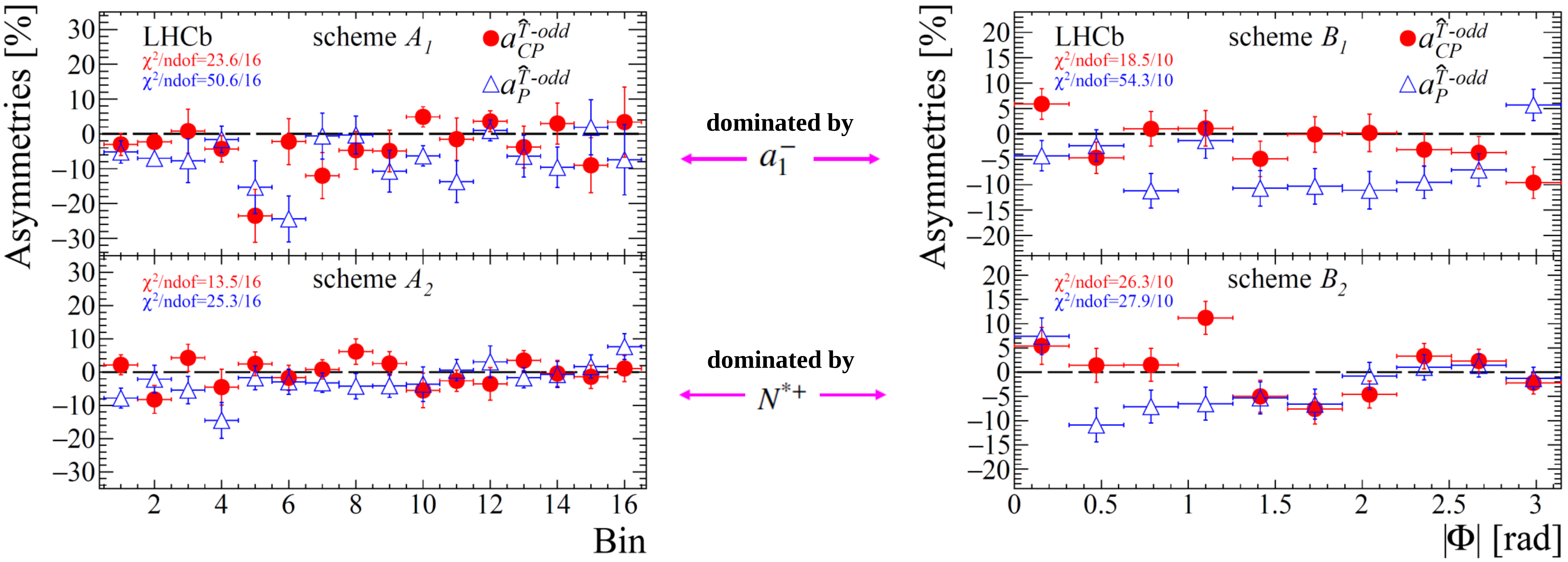
- Observation of P violation at 5.5σ
- CP conserved at > 2.9σ

$$a_P^{\widehat{T}\text{-odd}} = (-4.0 \pm 0.7 \pm 0.2)\%$$

$$a_{CP}^{\widehat{T}\text{-odd}} = (-0.7 \pm 0.7 \pm 0.2)\%$$

Run 1 & 2 analysis of $\Lambda_b^0 \to p\,\pi^-\,\pi^+\,\pi^-$ – binned TPA results

- Improved binning schemes to maximise sensitivity to CPV, exploring the 2-body resonances
  - Scheme A: 16 bins in polar and azimuthal angles of the proton (Δ^{++}) in the Δ^{++} (N^{*+}) rest frame
  - Scheme B: 10 bins in Φ, as in previous measurement



(The χ^2 per number of degrees-of-freedom is calculated with respect to the null hypothesis with stat. + syst. uncertainties)

Run 1 & 2 analysis of $\Lambda_b^0 \to p\,\pi^-\,\pi^+\,\pi^-$ – binned TPA results

- **Observation of P violation at 5.5σ**
- **No evidence for CPV (highest significance at 2.9σ in B2)**

Table 2: Results obtained with different binning schemes; the p-values take into account systematic effects and are reported for the CP- and P-conserving hypotheses.

Binning scheme	Dominant contribution	Hypothesis	p-value
A_1 (helicity angles)	$\Lambda_b^0 \to p a_1^-$	CP-conserving	9.8×10^{-2}
		P-conserving	1.8×10^{-5}
A_2 (helicity angles)	$\Lambda_b^0 \to N^{*+}\pi^-$	CP-conserving	6.4×10^{-1}
		P-conserving	6.4×10^{-2}
B (in $\lvert\Phi\rvert$)	Entire sample	CP-conserving	5.0×10^{-3}
		P-conserving	3.5×10^{-7}
B_1 (in $\lvert\Phi\rvert$)	$\Lambda_b^0 \to p a_1^-$	CP-conserving	4.7×10^{-2}
		P-conserving	4.3×10^{-8}
B_2 (in $\lvert\Phi\rvert$)	$\Lambda_b^0 \to N^{*+}\pi^-$	CP-conserving	3.4×10^{-3}
		P-conserving	1.9×10^{-3}

Run 1 & 2 analysis of $\Lambda_b^0 \to p\,\pi^-\,\pi^+\,\pi^-$ – energy test description

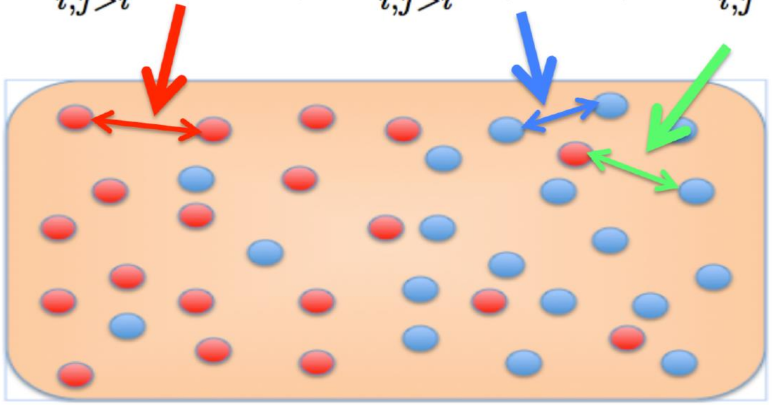
- **Energy test**
  - Model-independent unbinned test sensitive to local differences between 2 samples [Phys. Rev. D 84, 054015 (2011)]
  - Can provide superior discriminating power compared to traditional χ^2 tests
  - Test via calculation of a test statistic T

- **Samples**
  Particle & antiparticle decays in the phase-space

- **Test statistic T**
  n ($\overline{n}$): number of Λ_b^0 ($\overline{\Lambda}_b^0$) candidates
  d_{ij} : Euclidian distance in phase-space
  δ : distance scale to be optimised
  $\psi(d_{ij}) = e^{-d_{ij}^2/2\delta^2}$: pair weight

- **Scale at which CPV may appear is unknown**
  $\Rightarrow$ different distance scales δ are probed…

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



(Taken from Gediminas Sarpis)

Run 1 & 2 analysis of $\Lambda_b^0 \to p\,\pi^-\,\pi^+\,\pi^-$ – energy test results

- The p-values from the energy tests for different distance scales δ and test configurations

3σ deviation from no CPV hypothesis for 1 distance parameter

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}

P violation exceeds 5σ for 2 distance parameters

- **Observation of P violation at 5.3σ**
- **CP conserved at > 3.0σ**

Conclusions & outlook

- Study of b-baryons is a hot area of Flavour Physics
- Many topics – production, spectroscopy, CPV, exotic states, etc.
- LHCb but also ATLAS and CMS in the game

- P violation in b-baryon decays observed for the first time
- But so far, stil no CPV observed

- The upgraded LHCb experiment will boost the data samples,
  making many new and/or more precise measurement possible
- Much more physics to expect !

- Purely baryonic decay processes (i.e. decay processes involving only spin-carrying particles)
  are yet to be explored – complementary avenue e.g. for CPV studies
  - See Phys. Rev. D 94, 014027 (2016); Scientific Reports 9, 1358 (2019)

Thank you for listening