Search for baryon *CP* violation at the LHCb

Matteo Bartolini (University of Cambridge)

On behalf of the LHCb collaboration

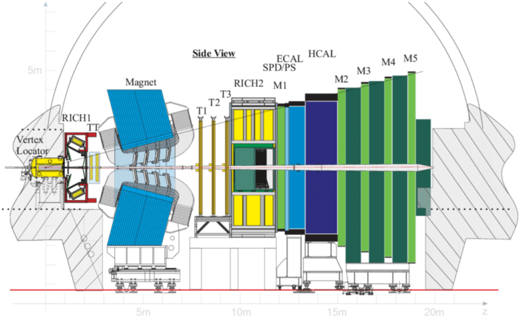
CKM 2021

Melbourne, 22-26 November 2021

- CP violation established in K, B and D meson decays and well consistent with SM prediction
- CP violation not yet observed in baryon decays

In this talk:

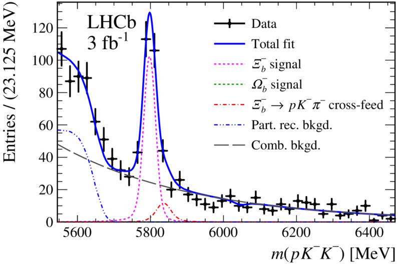
- Search for CP violation in $\Xi_b^- \to pK^-K^-$
- Measurement of CP asymmetry for the decay $\Lambda_b^0 \to DpK^-$
- Search for CP violation in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

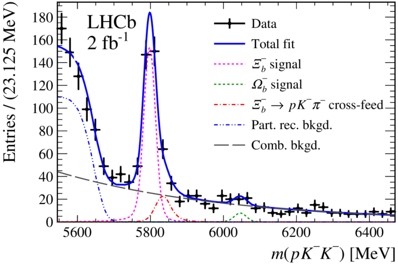


- Experiment at the LHC mainly dedicated to heavy flavour physics
- It ran (until 2018) at $\mathcal{L} = 2 \times 10^{32}$ cm^{-2}s^{-1}
- Covers only 4% of solid angle, but detects $\approx$ 25% of $b\bar{b}$ pairs produced in the collisions
- Very efficient at identifying p, K and π in the final state thanks to PID information provided by the two RICH detectors

Search for CP violation in $\Xi_b^- \to pK^-K^-$ Phys. Rev. D 104, 052010

- Integrated luminosity of 5 fb^{-1} collected with the LHCb detector at $\sqrt{s}$= 7, 8 and 13 TeV
- **First amplitude analysis of any baryon decay mode allowing for *CP*-violation effects**

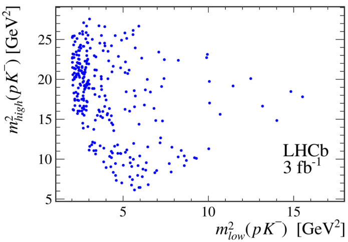


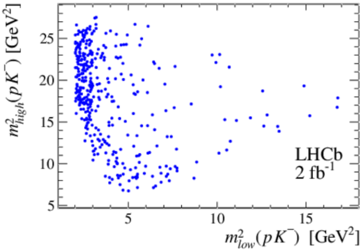


- **Signal purity of (63 $\pm$ 3)% and (70 $\pm$ 2)% for Run 1 and Run 2** in the region $\pm$40 MeV around the Ξ_b^- mass

Phase space asymmetries extracted using an amplitude analysis:

- Ξ_b^- baryons assumed to be produced with negligible polarization in *pp* collisions, as observed for the Λ_b^0 baryons
  - **2 kinematic variables are sufficient to characterise the phase space instead of 5**
- Use variables $m^2_{low}(pK^-)$ and $m^2_{high}(pK^-)$ to remove Bose symmetry given by the presence of two identical kaons in the final state





- Decay assumed to proceed through one intermediate resonance R:

$$\Xi_b^- \to (R \to pK^-)K^-$$

- Analysis done using the **helicity formalism**
  - $\frac{d\Gamma^Q}{d\Omega}$ is written as:

$$\frac{d\Gamma^Q}{d\Omega} = \frac{1}{(8\pi m_{\Xi_b})^3} \sum_{M_{\Xi_b},\lambda_p} |A^Q_{R,M_{\Xi_b},\lambda_p}(\Omega)|^2$$

- $A^Q_{R,M_{\Xi_b},\lambda_p}(\Omega)$ is the symmetrized decay amplitude for a given intermediate state R
  - Resonances are parameterized with relativistic Breit–Wigner functions

$\Xi_b^- \to pK^-K^-$ may decay through various Λ^* and Σ^* resonances:

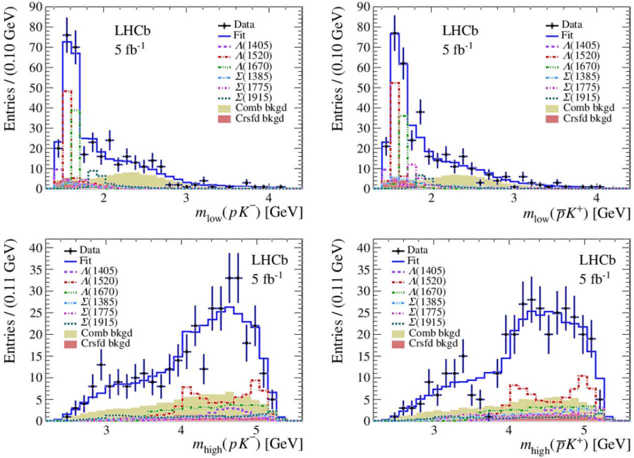
- Only sufficiently well established resonances are considered in this study
- Baseline model obtained by adding resonances iteratively to maximise the change in $-2ln\mathcal{L}$

State	Mass (MeV/c^2)	Width (MeV/c^2)	J^P
$\Lambda(1405)$	1405.1 $\pm$ 1.3	50.5 $\pm$ 2.0	$\frac{1}{2}^-$
$\Lambda(1520)$	1518 to 1520	15 to 17	$\frac{3}{2}^-$
$\Lambda(1670)$	1660 to 1680	25 to 50	$\frac{1}{2}^-$
$\Sigma(1385)$	1383.7 $\pm$ 1	36 $\pm$ 5	$\frac{3}{2}^+$
$\Sigma(1775)$	1770 to 1780	105 to 135	$\frac{5}{2}^-$
$\Sigma(1915)$	1900 to 1935	80 to 160	$\frac{5}{2}^+$

- Combinatorial background modeling from 5890 MeV$/c^2 < m(pK^-K^-) <$ 6470 MeV$/c^2$ sideband

Asymmetries extracted with an unbinned maximum-likelihood fit

- Fit performed simultaneously to the Run 1 and Run 2 data



The asymmetry for each contributing component shows no significant *CP* violation effect

Component	$A_{CP}(10^{-2})$
$\Lambda(1405)$	-27 ± 34 (stat) ± 73 (syst)
$\Lambda(1520)$	-1 ± 24 (stat) ± 32 (syst)
$\Lambda(1670)$	-5 ± 9 (stat) ± 8 (syst)
$\Sigma(1385)$	3 ± 14 (stat) ± 10 (syst)
$\Sigma(1775)$	-47 ± 26 (stat) ± 14 (syst)
$\Sigma(1915)$	11 ± 26 (stat) ± 22 (syst)

- **Main source of systematics:**
  - Ξ_b Polarization
  - Production asymmetries
  - Relativistic Breit-Wigner parameters
  - Alternative fit model
  - Efficiency
  - Background shape

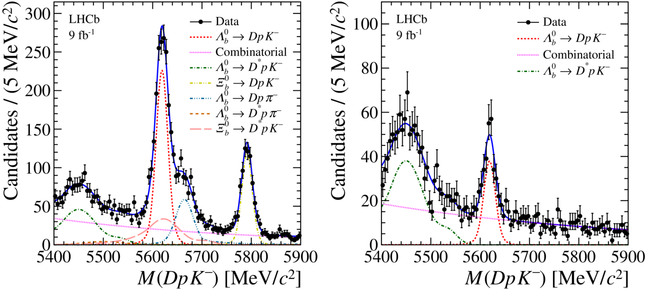
Two $\Lambda_b^0 \to DpK^-$ decays:

- $\Lambda_b^0 \to [K^-\pi^+]_D pK^-$ with same sign kaon is favoured
- $\Lambda_b^0 \to [K^+\pi^-]_D pK^-$ with opposite sign kaon is suppressed
  - suppressed by a factor $R \sim \left|\frac{V_{cb}V_{us}^*}{V_{ub}V_{cs}^*}\right|^2 = 7.4$
  - receives contributions from $b \to c$ and $b \to u$ amplitudes
  - interference between these two amplitudes depends upon the CKM angle γ

Beauty-baryon decays to final states involving a single charm meson are promising for measurements of CP violation:

$$A = \frac{\mathcal{B}(\Lambda_b^0 \to [K^+\pi^-]_D pK^-) - \mathcal{B}(\bar{\Lambda}_b^0 \to [K^-\pi^+]_D \bar{p}K^+)}{\mathcal{B}(\Lambda_b^0 \to [K^+\pi^-]_D pK^-) + \mathcal{B}(\bar{\Lambda}_b^0 \to [K^-\pi^+]_D \bar{p}K^+)}$$

Data sample corresponding to an integrated luminosity of 9 fb^{-1} collected with the LHCb detector at $\sqrt{s} = 7$, 8, and 13 TeV



- **Suppressed decay $\Lambda_b^0 \to [K^+\pi^-]_D pK^-$ seen for the first time**

The measured yield in the full phase space is:

- 1437 ± 92 for the favoured mode
- 241 ± 22 for the suppressed mode

CP asymmetry extracted after applying efficiency correction factors

- The efficiency corrections are determined as a function of the Λ_b^0 phase-space variables $M^2(Dp)$ and $M^2(pK^-)$ using simulation

$$A_{CP} = \frac{\sum_i w^i_{SUP,\Lambda_b^0}/\epsilon^i - \sum_i w^i_{SUP,\bar{\Lambda}_b^0}/\epsilon^i}{\sum_i w^i_{SUP,\Lambda_b^0}/\epsilon^i + \sum_i w^i_{SUP,\bar{\Lambda}_b^0}/\epsilon^i}$$

CP asymmetry measured in two regions of the phase space:

- Phase space integrated asymmetry
- Asymmetry in the region involving excited Λ^* states $\Lambda_b^0 \to D\Lambda^*$

Asymmetries show no significant *CP*-violation effect

- Phase space integrated asymmetry

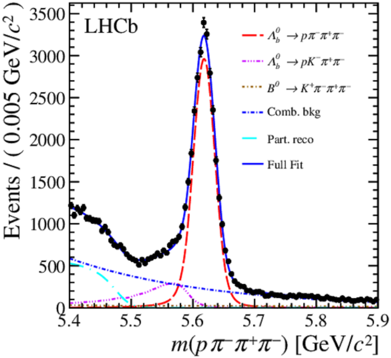
$$\boxed{A_{CP} = 0.12 \pm 0.09(stat)^{+0.02}_{-0.03}(syst.)}$$

- $M(pK^-)^2 < 5\ \text{GeV}^2/c^4$ region

$$\boxed{A_{CP} = 0.01 \pm 0.16(stat)^{+0.03}_{-0.02}(syst.)}$$

- **Main source of systematics:**
  - Fit model
  - Efficiency corrections
  - Hardware trigger efficiency
  - PID efficiency
  - Λ_b^0 production asymmetry
  - p detection asymmetry
  - π detection asymmetry

- Integrated luminosity of 6.6 fb^{-1} collected from 2011 to 2017 at $\sqrt{s}$ = 7, 8 and 13 TeV
- CP asymmetry measured using two different approaches:
  - Triple product correlations
  - Energy test method



- $N_{\Lambda_b^0+\bar{\Lambda}_b^0} = 27600 \pm 200$

- $\hat{T}-odd$ observables are built using the momenta $\vec{p}_i$ of three final state particles in the mother C.M. frame: $C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_h \times \vec{p}_{h'})$, $\overline{C}_{\hat{T}} = \vec{p}_{\bar{p}} \cdot (\vec{p}_{\bar{h}} \times \vec{p}_{\bar{h}'})$:

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

- **True CP and P violating observables are defined as:**

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

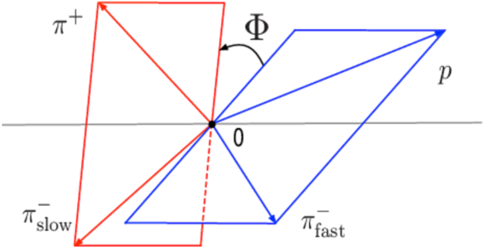
Different sensitivity to systematic effects:

$a_{CP}^{\hat{T}-odd}$ marginally affected by reconstruction efficiency and $b-$hadron production asymmetries

Triple products are calculated in the Λ_b^0 rest frame:

G.Durieux, JHEP 10 (2016) 005
G.Durieux, PRD 92 (2015) 07601

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



- Asymmetries are measured both integrating over the full phase space and in bins of the phase space to enhance local sensitivity to *CP* violation

Very rich resonant structure in the decay, dominant contributions proceed through:

- $\Lambda_b^0 \to N^{*+}\pi^-$, $N^{*+} \to \Delta^{++}(1234)\pi^-$, $\Delta^{++} \to p\pi^+$
- $\Lambda_b^0 \to pa_1^-(1260)$, $a_1^-(1260) \to \rho^0(770)\pi^-$, $\rho^0(770) \to \pi^+\pi^-$

Phase space binning according to two schemes

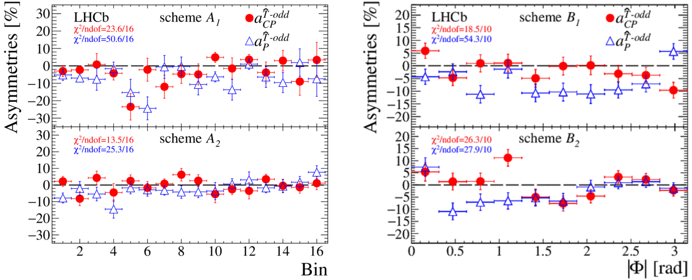
- Scheme A:
  16 bins on polar and azimuthal angles of proton in the Δ^{++} frame
- Scheme B:
  10 bins on Φ angle between decay planes $\pi^+\pi^-_{slow}$ and $p\pi^-_{fast}$

- Phase space integrated asymmetries

$$a_{CP}^{\hat{T}-odd} = (-0.7 \pm 0.7 \pm 0.2)\% \qquad \textbf{consistent with } CP \textbf{ symmetry}$$
$$a_{P}^{\hat{T}-odd} = (-4.0 \pm 0.7 \pm 0.2)\% \qquad \textbf{5.5 } \sigma \textbf{ deviation from } P \textbf{ symmetry}$$

- Systematics assigned using high statistics control sample containing charm $\Lambda_b^0 \to \Lambda_c^+ \pi^-$
- **Main source of systematics:**
  - Reconstruction
  - Detector acceptance

- Asymmetries measured in bins of the phase space
- Cut on $m(p\pi^+\pi^-_{slow})$ invariant mass:
  - $m > 2.8$ GeV/c^2 to enhance the $\Lambda_b^0 \to pa_1^-(\to \rho\pi^-)$ (A_1 and B_1 schemes)
  - $m < 2.8$ GeV/c^2 to enhance the $\Lambda_b^0 \to N^*(\Delta^{++}\pi^-)\pi^-$ (A_2 and B_2 schemes)



- CP violation hypothesis checked with a χ^2 test

No evidence for CP violation, highest significance 2.9 σ in B2

- Model-independent unbinned test **M. Williams, Phys. Rev. D 84, 054015**
- Method sensitive to local differences between two samples

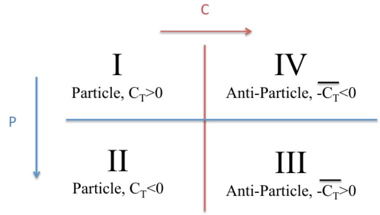
$$T \equiv \frac{1}{2n(n-1)} \sum_{i \neq j}^{n} \psi_{ij} + \frac{1}{2\overline{n}(\overline{n}-1)} \sum_{i \neq j}^{\overline{n}} \psi_{ij} - \frac{1}{n\overline{n}} \sum_{i=1}^{n} \sum_{j=1}^{\overline{n}} \psi_{ij}$$

$\psi_{ij} = e^{-d_{ij}^2/2\delta^2}$, d_{ij} Euclidean distance between two candidates in the phase space

PHS: $m^2(p\pi^+)$, $m^2(\pi^+\pi^-_{slow})$, $m^2(p\pi^+\pi^-_{slow})$, $m^2(\pi^+\pi^-_{slow}\pi^-_{fast})$, $m^2(p\pi^-_{slow})$

δ is the distance scale (free parameter)

T large when significant localized differences between samples exist and has an expectation of 0 when there is no difference



3 Tests:

- CP test
  - P-odd: I+IV vs II+III
  - P-even: I+II vs III+IV
- P test: I+III vs II+IV

***p*-values calculated for 3 different values of δ:**

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}

- **Combined significance $< 3.0\ \sigma$ in *CP* test**
- **5.3 σ significance in *P* test**

Summary of this talk:

- Multibody decays are interesting place to search for *CP* violation due to their rich phase space structure
- No evidence for *CP* violation in Λ_b^0 and Ξ_b^- decays for the moment
- Expected significant improvement in sensitivity in Run3:
  - Higher instantaneous luminosity
  - Channels with final state hadrons will be selected with higher efficiencies after the removal of the L0 hardware trigger