Measurement of matter-antimatter differences in beauty baryon decays

Group E Collaboration.

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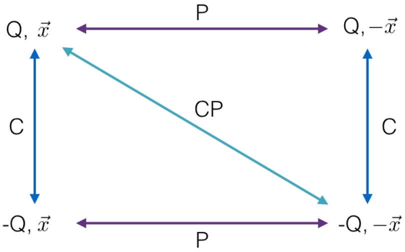
Introduction

Using 3 fb^{-1} of proton-proton collision data collected at a centre of mass energy of 7 and 8 TeV by the LHCb experiment at the Large Hadron Collider, a search is made for CP-violating asymmetries in the decays of Λ_b^0 baryons [**1**].

We find evidence for CP violation with a statistical significance corresponding to 3.3 standard deviations. This represents the first evidence for CP violation in the baryon sector.

Motivation and Theory

- Differences in the behaviour of matter and antimatter have been observed in K and B meson, but not yet in any baryon decay.



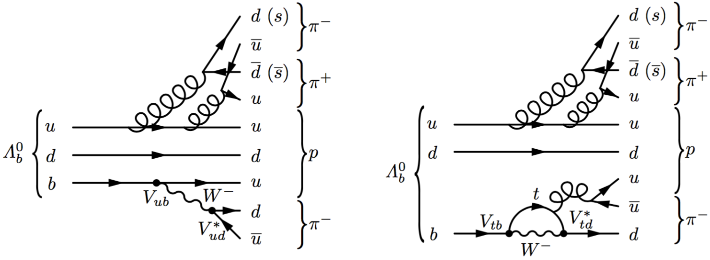
- The only source of CP violation in the SM is in the CKM matrix (insufficient).
- Has **never** been observed in Baryons before. Estimated small asymmetries make it an ideal place to look for NP.

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

Motivation and Theory

- For observing CP, we need at least two processes of similar amplitudes containing two different weak phases:

$$T_1 e^{i\eta_1} e^{i\delta_1} + T_2 e^{i\eta_2} e^{i\delta_2}.$$



- Usual rate asymmetries are very sensitive to relative strong phases, so we build new observables:

$$\mathcal{A} \propto \sin(\Delta\eta)\sin(\Delta\delta) \rightarrow \mathcal{A}' \propto \cos(\Delta\eta)\sin(\Delta\delta).$$

Motivation and Theory

$$C_{\hat{T}} = \vec{p}_p.(\vec{p}_{h_1^-} \times \vec{p}_{h_2^+})$$
$$\overline{C}_{\hat{T}} = \vec{p}_{\overline{p}}.(\vec{p}_{h_1^+} \times \vec{p}_{h_2^-})$$

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

$$a_P^{\hat{T}-\text{odd}} = \frac{1}{2}\left(A_{\hat{T}} + \overline{A}_{\hat{T}}\right), \qquad a_{CP}^{\hat{T}-\text{odd}} = \frac{1}{2}\left(A_{\hat{T}} - \overline{A}_{\hat{T}}\right)$$

Experimental Setup

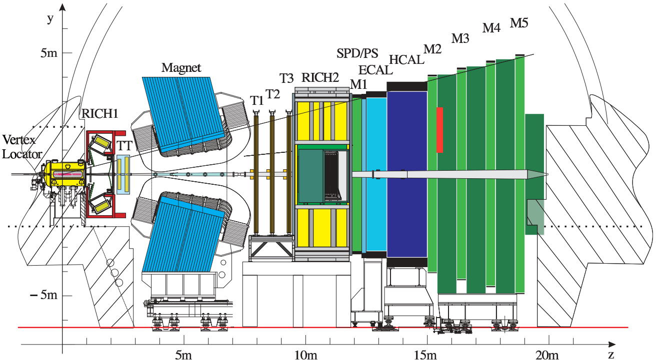
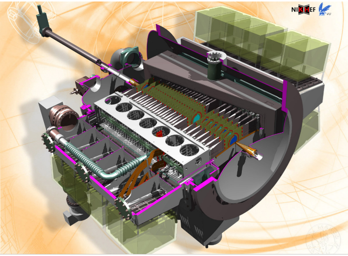
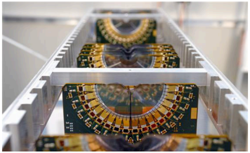
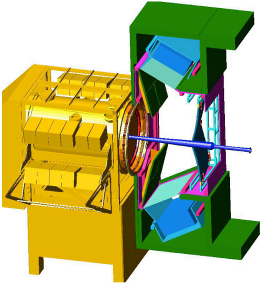


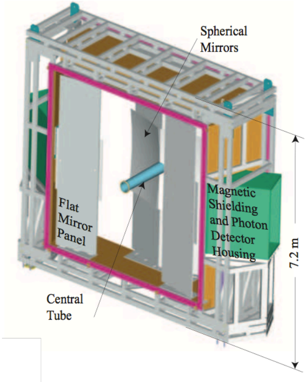
Figure 1: LHCb layaout. Vertex Locator: **VELO** . Cherenkov radiation detectors: **RICH 1** and **2**. Tracker detectors: **TT**, **T1**, **T2** and **T3**. Dipole Magnet. Scintillator Pad Detector and Preshower: **SPD/PS**. Electromagnetic and Hadronic calorimeters: **ECAL** & **HCAL**. Muon detectors: **M1**, **M2**, **M3**, **M4** and **M5**.

VELO & RICH detectors









Event Selection

- Boosted Decision Tree (BDT).
- Few Variables (>4).
- Real Data to Train.
- MC is used to cross check.
- ${}_s\mathcal{P}lot$ technique is used to subtract the background.

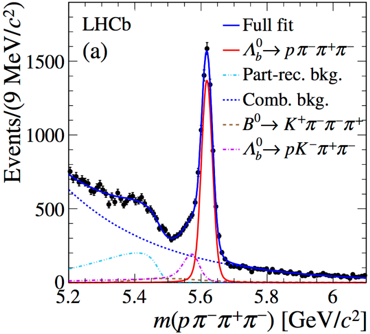
Decays	S	B	$S/\sqrt{S+B}$	ϵ_S	ϵ_B
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$	2713	4431	45.56	0.9015	0.0983

Table 1: Signal (S) and background (B) yields before BDT selection are estimated from fit with PID cuts. Significance and efficiencies for S and B are also in the table

Statistical Analysis

Perform simultaneous likelihood fit to invariant mass distribution to extract number of signal events and calculate $a_P^{\hat{T}-\text{odd}}$ and $a_{CP}^{\hat{T}-\text{odd}}$.

Four distributions: Λ_b^0 (with $C_{\hat{T}} > 0$ and $C_{\hat{T}} < 0$) and $\overline{\Lambda}_b^0$ (with $\overline{C}_{\hat{T}} > 0$ and $\overline{C}_{\hat{T}} < 0$).



Modelling

- Signal: Gaussian + power law tails
- Combinatorial background: Exponential
- $\Lambda_b^0 \to pK^-\pi^-\pi^+$: BG Simulation
- $\Lambda_b^0 \to K^+\pi^-\pi^-\pi^+$: BG Simulation
- Partially reconstructed Λ_b^0: Empirical function convoluted with a Gaussian

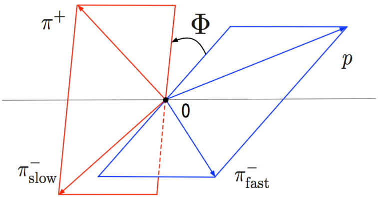
Statistical Analysis

Measurements of asymmetries integrated over the entire phase space do not show any evidence of P or CP violation.

We develop two different binning schemes to maximize our sensitivity to the asymmetries:

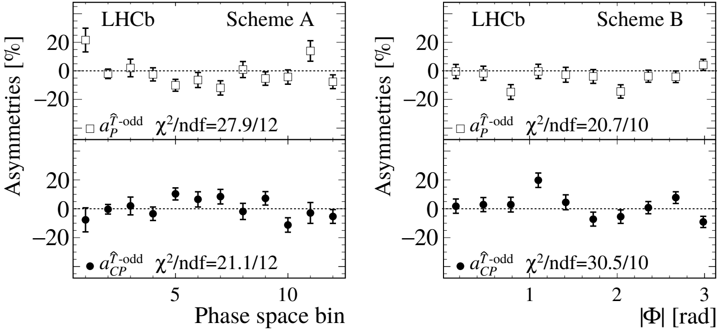
Scheme A: Defined to isolate the contributions from different resonances to the asymmetries.

Scheme B: Bins in the angle Φ to exploit interferences which could be visible as a function of the angle.



Statistical Analysis

Results of the asymmetry measurements per bin for each scheme.



Systematic Uncertainties

Three different sources of systematic uncertainties.

Decays	Contribution	$a_{CP}^{\hat{T}-odd}(\%)$
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$	Experimental bias	± 0.60
	C_T resolution	± 0.05
	Fit model	± 0.03
	Total	± 0.60

Statistical Analysis and Results

Compatibility with the CP-symmetry hypothesis is evaluated by means of a χ^2 test:

$$\chi^2 = R^T V^{-1} R \,,$$

where R is an array with the $a_{CP}^{\hat{T}-\mathrm{odd}}$ measurements, and V is the covariance matrix (taken to be the sum of the statistical and systematic covariance matrices, where the systematic uncertainties are considered to be fully correlated between bins).

Significance per scheme:

	Scheme A	Scheme B
P symmetry	2.8 σ	2.3 σ
CP symmetry	2.0 σ	3.4 σ

Statistical Analysis and Results

- Combine the results for schemes A and B to obtain the overall significance by means of a permutation test (since the schemes are not statistically independent).
- 40,000 pseudoexperiments are generated from the data by assigning each event a random flavour (Λ_b^0, $\overline{\Lambda}_b^0$). The sign of C_T is unchanged if a Λ_b^0 candidate stays Λ_b^0, and reversed if it becomes $\overline{\Lambda}_b^0$. This enforces CP-symmetry.
- The product of the two p-values measured in data is compared with the distribution of the product of the p-values of the two binning schemes from the pseudoexperiments.
- An overall p-value of $\mathbf{9.8 \times 10^{-4}}$ **(3.3 $\boldsymbol{\sigma}$)** is obtained for the CP-symmetry hypothesis.

Summary

- Searches for localized P or CP violation are performed by measuring asymmetries in different regions of the phase space.
- The results show evidence for CPV at the 3.3σ level in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays, and no significant P violation is found.
- This represents the first evidence of CP violation in the baryon sector and indicates an asymmetry between baryonic matter and antimatter.

Summary

3.3σ significance.

References

- LHCb collaboration: R. Aaij et al., Measurement of matter-antimatter differences in beauty baryon decays. (2016)
- Bensalem, W., Datta, A. and London, D. New physics effects on triple product correlations in Λ_{0b} decays. Phys. Rev. D 66, 094004. (2002)

BackUp

Cross-checks were made to check the stability of the results:

- Reconstruction efficiency vs C_T values.
- Different periods of data taking.
- Different magnet polarities.
- Selection of multiple candidates.
- Trigger and selection criteria.

BackUp - Event Selection

The concept of ${}_s\mathcal{P}lot$ is to reweight the data using information from the fit model and fit result. The sWeights is computed, from which one can reweight the data to make ${}_s\mathcal{P}lot$.

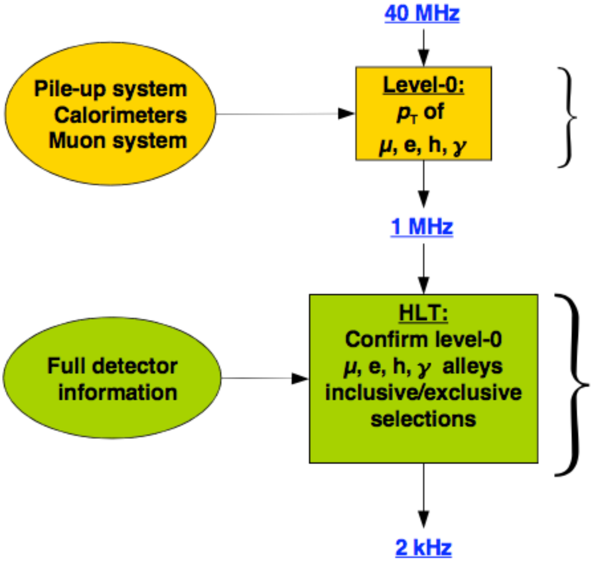
sWeights: ${}_s\mathcal{P}$

$$\mathrm{s}\mathcal{P}_n(y_e) = \frac{\sum_{j=1}^{N_s} \mathbf{V}_{nj} f_j(y_e)}{\sum_{K=1}^{N_s} N_k f_k(y_e)} \quad (1)$$

where:

1. y_e is the set of discriminating variables used in the fit.
2. $f_{j/k}(y_e)$ is the PDF for the $j^{\text{th}}/k^{\text{th}}$ component in the fit model.
3. $\mathbf{V}_{nj}$ is the covariance matrix obtained from fitting the data.
4. N_k is the event yield fitted for the k^{th} component.

BackUp - Trigger



BackUp - Trigger

From LHCb report:

Trigger Level	Trigger line
L0	Hadron TOS on Λ_b^0 Global TIS on Λ_b^0
HLT1	TrackALLL0 TOS on Λ_b^0
HLT2	Topo(2,3,4)Simple TOS on Λ_b^0 Topo(2,3,4)BBDT TOS on Λ_b^0

BackUp - Systematic Uncertainties

Three main sources of systematic uncertainty identified:

- Experimental bias
  - Use control sample $\Lambda^0 \to \Lambda_c^+(\to pK^-\pi^+)\pi^-$ with negligible CPV. Deviation of $a_{CP}^{\hat{T}-\mathrm{odd}}$ from zero is the systematic.
  - Both integrated and binned measurements.
- Detector resolution
  - Resolution on measurement of $C_{\hat{T}}$ and $\overline{C}_{\hat{T}}$ can cause migration between bins.
  - Estimated from MC by measuring difference between the reconstructed and generated asymmetry.
- Fit model
  - Use alternate model for signal and background and perform fit.
  - Deviation of mean of pull distributions from zero is the systematic.