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Search for baryon CP violation at LHCb

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The latest results from the LHCb Collaboration related to the search for CP violation in baryon decays are reported here. These include the search for CP violation in $\Xi_b^- \to pK^-K^-$, search for CP asymmetry for the decay $\Lambda_b^0 \to DpK^-$ and search for CP violation in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$.

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1. Introduction

CP violation is experimentally well established in K [1], B [2, 3] and D [4] meson decays and consistent with SM prediction. However, these asymmetries are too small to explain the absence of antimatter in our universe and new searches are needed. For instance, CP violation has never been observed in b-baryon decays yet. The LHCb Collaboration has measured the CP asymmetry in different decay modes of Λ_b^0 and Ξ_b^0 baryons, which are copiously produced in pp collisions. In the following a summary of the latest results is given.

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

The LHCb collaboration has recently reported the first amplitude analysis of any baryon decay mode allowing for CP violation effects [5]. The analysis is performed with pp collisions and uses a data set corresponding to an integrated luminosity of 5 fb^{-1} collected with the LHCb detector at $\sqrt{s}$= 7, 8 and 13 TeV.
After the selection procedure, which aims at optimizing the signal to background ratio, a purity of about 70% is obtained in the region ± 40 MeV around the Ξ_b^- mass, which is then retained for the amplitude analysis.
In the amplitude analysis it is assumed that the Ξ_b^- baryons are produced with negligible polarization. Such assumption is based on the fact that for the Λ_b^0 no polarization has been observed when it is produced in proton-proton collisions [9]. This assumption has the benefit of reducing the number of independent kinematic variables necessary to fully describe the phase space of the decay from five to two. The chosen variables are $m^2_{low}(pK^-)$ and $m^2_{high}(pK^-)$, where low and high denote the lower and the higher of $m^2(pK_1^-)$ and $m^2(pK_2^-)$. This choice is made in order to remove the Bose symmetry given by the presence of two identical kaons in the final state.
The helicity formalism is used to parametrize the decay dynamics, which is assumed to proceed via the weak decay $\Xi_b^- \to (R \to pK^-)K^-$, where R is an intermediate resonance. With these assumptions the differential decay density is expressed as

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

where $Q = +1$ is for Ξ_b^- and $Q = -1$ for Ξ_b^+, $A^Q_{R,M_{\Xi_b},\lambda_p}(\Omega)$ is the symmetrized decay amplitude for a given intermediate state R, Ξ_b^- spin component along a chosen quantization axis $M_{\Xi_b^-}$ and proton helicity λ_p. The modeling of the combinatorial background is obtained from the 5890 MeV/c^2 $< m(pK^-K^-) <$ 6470 MeV/c^2 sideband region. A good description of the data is obtained with an amplitude model containing the contributions reported in Tab. 1. The distributions of $m^2_{low}(pK^-)$ and $m^2_{high}(pK^-)$ for the Ξ_b^- and Ξ_b^+ candidates with the result of the fit superimposed is shown in Fig. 1. No significant CP -violation effect is observed in any component.

3. Measurement of CP asymmetry for the decay $\Lambda_b^0 \to DpK^-$

The LHCb Collaboration has recently studied Λ_b^0 decays to the DpK^- final state, where D represents a superposition of D^0 and $\overline{D}^0$ states [6]. The Λ_b^0 decay to opposite sign kaons, denoted

State	Mass (MeV/c^2)	Width (MeV/c^2)	J^P	$A_{CP}(10^{-2})$
$\Lambda(1405)$	1405.1 ± 1.3	50.5 ± 2.0	$\frac{1}{2}^-$	-27 ± 34 (stat) ± 73 (syst)
$\Lambda(1520)$	1518 to 1520	15 to 17	$\frac{3}{2}^-$	-1 ± 24 (stat) ± 32 (syst)
$\Lambda(1670)$	1660 to 1680	25 to 50	$\frac{1}{2}^-$	-5 ± 9 (stat) ± 8 (syst)
$\Sigma(1385)$	1383.7 ± 1	36 ± 5	$\frac{3}{2}^+$	3 ± 14 (stat) ± 10 (syst)
$\Sigma(1775)$	1770 to 1780	105 to 135	$\frac{5}{2}^-$	-47 ± 26 (stat) ± 14 (syst)
$\Sigma(1915)$	1900 to 1935	80 to 160	$\frac{5}{2}^+$	11 ± 26 (stat) ± 22 (syst)

Table 1: Results for the CP -asymmetry parameters for the different components extracted by the fit.

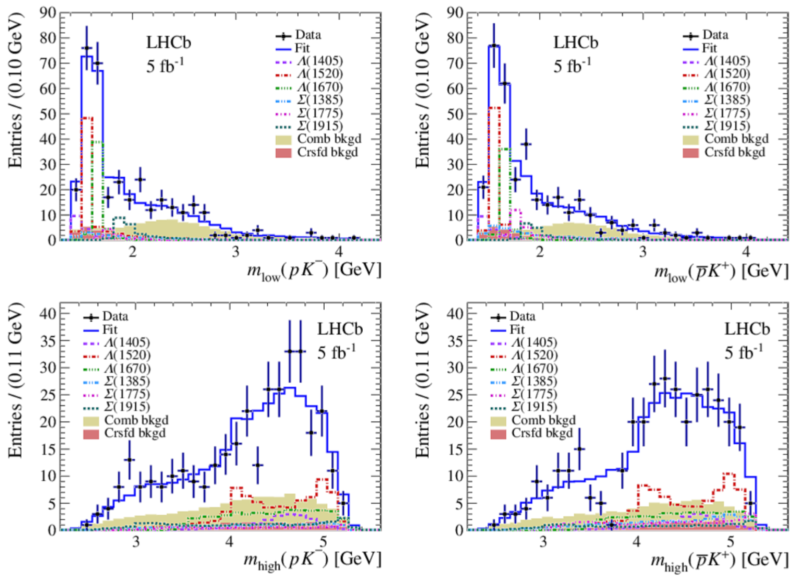

Figure 1: Distribution of m_{low}(top) and m_{high}(bottom) for the Ξ_b^-(left) and Ξ_b^+(right) candidates, with the result of the fit superimposed.

as $\Lambda_b^0 \to [K^+\pi^-]_D pK^-$ is expected to be suppressed by a factor $R \sim \left|\frac{V_{cb}V_{us}^*}{V_{ub}V_{cs}^*}\right|^2 = 6.0$ relative to the favoured $\Lambda_b^0 \to [K^-\pi^+]_D pK^-$ decay with same sign kaons. The suppressed decay is of particular interest when searching for CP violation effects because its decay amplitude receives contributions from $b \to c$ and $b \to u$ amplitudes, which are of similar magnitude. The interference between these two amplitudes depends upon the CKM angle γ and is expected to be large. The analyzed data set corresponds to an integrated luminosity of 9 fb^{-1} collected with the LHCb detector in pp collisions at $\sqrt{s}$= 7, 8 and 13 TeV. In this analysis the suppressed decay $\Lambda_b^0 \to [K^+\pi^-]_D pK^-$ is observed for the first time. Fig. 2 shows the invariant mass distribution of both the favoured and suppressed Λ_b^0 decays.

The CP asymmetry of the suppressed decay is extracted from the data in the following way

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

The sum is over the selected candidates, w^i_{SUP} are the weights obtained using the sPlot

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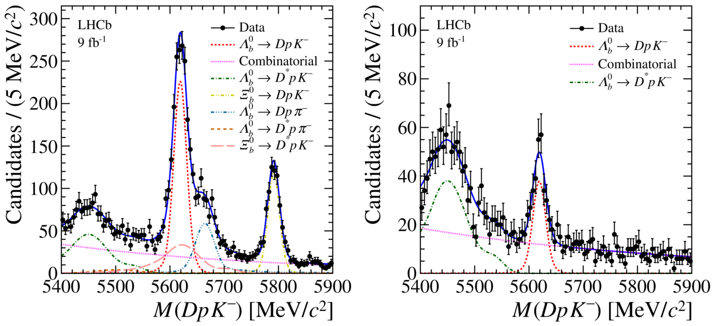

Figure 2: Distributions of the invariant mass for selected (left) and (right) candidates in the full phase space (black points) corresponding to the favoured and suppressed decays, respectively

technique for background subtraction and ϵ^i are the efficiencies determined as a function of the phase space variables $M^2(Dp)$ and $M^2(pK^-)$ using the simulated decay $\Lambda_b^0 \to [K^+\pi^-]_D pK^-$.
Two different CP asymmetry measurements are provided: the asymmetry integrated over the full phase space and the asymmetry in the restricted phase-space region $M^2(pK^-) < 5\ \mathrm{GeV}^2/c^4$, which involves mainly contributions from excited Λ states. The measured values of the asymmetry in the full phase space is

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

whereas the asymmetry in the restricted phase space region is

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

The measured asymmetries are consistent with zero, both in the full phase space and in the region where enhanced sensitivity to the CKM angle γ is expected.

4. Search for CP violation in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

This analysis uses a data sample corresponding to an integrated luminosity of 6.6 fb^{-1} [8], which was collected by the LHCb experiment in pp collisions at $\sqrt{s}$= 7, 8 and 13 TeV. Two model-independent methods are used to search for CP violation effects: triple product asymmetries and the unbinned energy test.
Triple product asymmetries (TPA) can be constructed by using the momenta of final states particles in the Λ_b^0 center-of-mass frame. By defining the variable $C_T \equiv \vec{p}_p \cdot (\vec{p}_h \times \vec{p}_{h'})$ and $\overline{C}_T \equiv \vec{p}_{\overline{p}} \cdot (\vec{p}_{\overline{h}} \times \vec{p}_{\overline{h}'})$, we can build the following two asymmetries:

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

where N and $\overline{N}$ are the numbers of Λ_b^0 and $\overline{\Lambda}_b^0$ decays.
From these asymmetries true CP-violating observable and a true P-violating observable can be

constructed as

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

The $CP-$ and $P-$ violating asymmetries have been measured both integrating over all phase space and in specific phase-space regions. The measured asymmetries from the fit to the full dataset are

$$a_{CP}^{T-odd} = (-0.7 \pm 0.7 \pm 0.2)\%, \qquad a_{P}^{T-odd} = (-4.0 \pm 0.7 \pm 0.2)\%.$$

Consistency with the CP-conserving hypothesis is observed while a significant non-zero value for a_P^{T-odd} is found; this corresponds to a significance of 5.5 σ.
In order to maximize the sensitivity to local CP violation effects, the phase space was divided into bins according to two different schemes. The scheme A is based on the decay topology $\Lambda_b^0 \to (N^{*+} \to (\Delta^{++} \to p\pi^+)\pi^-)\pi^-$ and the data sample is divided into 16 subsamples to explore the distribution of the polar and azimuthal angles of the proton (Δ^{++}) in the Δ^{++} (N^{**}) rest frame. Scheme B is based on ϕ, the angle between the decay planes formed by the tracks $\pi^+\pi^-_{slow}$ and $p\pi^-_{fast}$ in the mother rest frame and the data sample is divided into 10 subsamples uniformly distributed in the range [0,π]. The invariant-mass regions $m(p\pi^+\pi^-_{slow}) > 2.8$ GeV/c^2 (schemes A1 and B1), dominated by the $a_1^-(1260)$ resonance, and $m(p\pi^+\pi^-_{slow}) < 2.8$ GeV/c^2 (schemes A2 and B2), dominated by many N^{**} resonances are studied separately. The measured asymmetries are shown in Fig. 3. No compelling evidence for CP violation is found in any of them, but scheme B2 shows an interesting deviation at the 2.9 σ level from the null hypothesis of CP conservation.

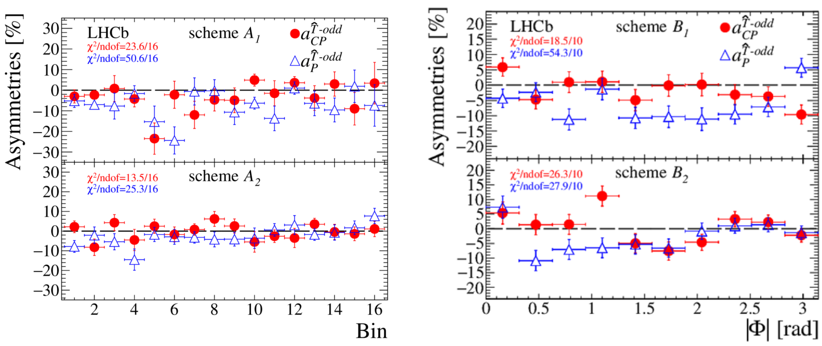

Figure 3: Measured asymmetries for the binning scheme (top) A1 and B1 and (bottom) A2 and B2. The error bars represent the sum in quadrature of the statistical and systematic uncertainties. The $\chi^2/ndof$ is calculated with respect to the null hypothesis and includes statistical and systematic uncertainties

The energy test is a model-independent unbinned test sensitive to local differences between two samples, as it would be in case of CP violation. In this case the difference between two samples is probed through the calculation of the following test statistic:

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

where $n(\overline{n})$ indicates the candidates in the first(second) sample. Each pair of candidates ij is assigned a weight $\psi_{ij} = e^{-d_{ij}^2/2\delta^2}$, where d_{ij} is their Euclidean distance in phase space and δ is

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^{-3}	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}

Table 2: The p-values from the energy test for different distance scales and test configurations

a free parameter that determines the distance scale probed using the energy test. The phase space is defined using the squared masses $m^2(p\pi^+)$, $m^2(\pi^+\pi^-_{slow})$, $m^2(p\pi^+\pi^-_{slow})$, $m^2(\pi^+\pi^-_{slow}\pi^-_{fast})$, $m^2(p\pi^-_{slow})$. Here π^-_{fast} (π^-_{slow}) refers to the faster (slower) of two negative pions in the Λ^0_b rest frame.

Results for different configurations of the energy test are summarized in Tab. 2 All CP-violation searches using the energy test result in $p-$ values with a significance of 3 σ or smaller. The P-violation test shows a significance of 5.3 σ at the two smaller scales probed.

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