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Searches for CP violation in charmless b-baryon decays at LHCb

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Multibody decays of b-baryons are a good place to search for CP violation due to their rich resonant structure. The results obtained by the LHCb collaboration in the search for CP violation in charmless decays like $X_b^0 \to phh'h''$, where X_b^0 stands for Λ_b^0 or Ξ_b^0 and h,h',h'' either for a π or a K meson, are presented here.

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1. Introduction

CP violation is well established in K [1], B [2, 3] and D [4] meson decays and is consistent with SM prediction, but it has not yet been observed in b-baryon decays, despite some interesting indications of non vanishing CP asymmetries [5].
Λ_b^0 and Ξ_b^0 production is abundant in proton-proton collisions and this gives LHCb the opportunity to study multi-body decays of b-flavoured baryons. Multi-body decays are a good place to search for CP violation because, due to their rich resonant structures, different amplitudes may interfere and cause local CP violation effects to appear in regions of the phase space [6]. In the analyses performed by the LHCb collaboration, different model-independent methods are used to search for CP violation in charmless decays like $X_b^0 \to phh'h''$ and they will be discussed in the following.

2. Triple product asymmetries

Triple product asymmetries (TPA) can be constructed by using the momenta of final states particles in the b-baryon center-of-mass frame. By defining the T-odd variable $C_T \equiv \vec{p}_p \cdot (\vec{p}_h \times \vec{p}_{h'})$ for X_b^0 and $\overline{C}_T \equiv \vec{p}_{\overline{p}} \cdot (\vec{p}_{\overline{h}} \times \vec{p}_{\overline{h}'})$ for $\overline{X}_b^0$, 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 X_b^0 and $\overline{X}_b^0$ decays.
However, final state interactions (FSI) can also introduce asymmetries [7]. A true CP-violating observable and a true P-violating observable can be defined as

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

In this way FSI effects cancel out in the difference.
The observable a_{CP}^{T-odd} is more sensitive to CP violation effects when the difference in strong phase between interfering amplitudes is small [8].
The physics observables $A_{\hat{T}}$, $\overline{A}_{\hat{T}}$ and a_{CP}^{T-odd} are, by construction, largely insensitive to production $X_b^0/\overline{X}_b^0$ asymmetry and detector-induced charge asymmetries of the final-state particles.
Using a data sample corresponding to an integrated luminosity of 1 fb^{-1} collected in 2011 at $\sqrt{s} = 7$ TeV and 2 fb^{-1} collected in 2012 at $\sqrt{s} = 8$ TeV, the LHCb collaboration first measured TPA in three different 4-body decays of the Λ_b^0 and one 4-body decay Ξ_b^0 baryons: $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ [5], $\Lambda_b^0 \to pK^-\pi^+\pi^-$, $\Lambda_b^0 \to pK^-K^+K^-$, $\Xi_b^0 \to pK^-\pi^+\pi^-$ [9].
Although phase-space integrated asymmetries showed no evidence for CP violation in any of the above mentioned channels, an interesting hint of local CP violation at the 3.3 σ level including systematic uncertainties was observed in the channel $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ [5]. This result was recently superseded by an updated analysis using a data sample corresponding to an integrated luminosity of 6.6 fb^{-1} [10] and collected from 2011 to 2017.
The channel $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ proceeds mainly through the following quasi-two-body decays:

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

The invariant-mass distribution $m(p\pi^-\pi^+\pi^-)$ for the dataset is shown in Fig. 1.
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 schemes A1, A2, B1 and B2 (see [10]). In the binning schemes A1 and B1 the single resonance $a_1^-(1260)$ dominates whereas schemes A2 and B2 are dominated by contributions from multiple N^{*+} resonances very close in mass.
Schemes A are based on the helicity angles $\theta_{\Delta^{++}}$ and θ_p of the decay topology $\Lambda_b^0 \to (N^{*+} \to (\Delta^{++} \to p\pi^+)\pi^-)\pi^-$, where $\theta_{\Delta^{++}}(\theta_p)$ is the polar angle of the $\Delta^{++}(p)$ in the $N^{*+}(\Delta^{++})$ rest frame. Schemes B are 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. The values of the TPA for the different binning schemes are shown in Fig. 2. 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.

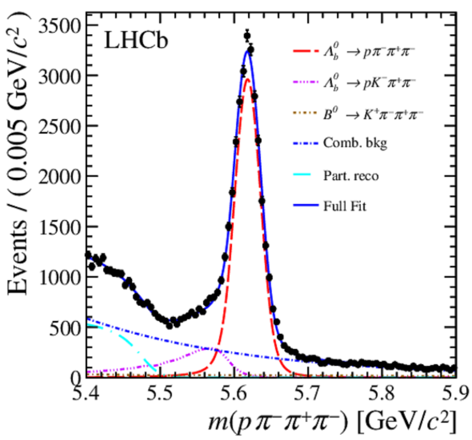

Figure 1: Invariant-mass distribution for $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ candidates with the result of the fit overlaid

3. Unbinned energy test

In the same article [10] a second method is also used to search for CP violation effects in the channel $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$: the energy test. 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

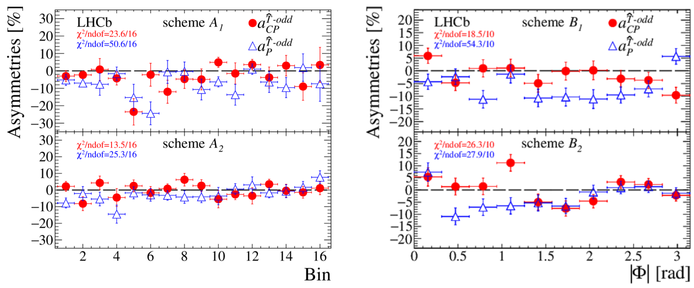

Figure 2: Measured asymmetries for the binning scheme (left) A1 and A2 and (right) B1 and B2. The error bars represent the sum in quadrature of the statistical and systematic uncertainties. The $\chi^2/ndof$ is calculated with respect to the null hypothesis and includes statistical and systematic uncertainties

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 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 $\pi^-_{fast}(\pi^-_{slow})$ refers to the faster (slower) of two negative pions in the Λ_b^0 rest frame.

Similar to the TPA method, one can define 4 subsamples: subsample I consists of particles with $C_T > 0$, subsample II of particles with $C_T < 0$, subsample III of particle with $-\overline{C}_T > 0$ and subsample IV of particles with $-\overline{C}_T < 0$. The comparison of sample I+IV to sample II+III allows for a $P-$odd and $CP-$odd test while the comparison of sample I+II to sample III+IV for a $P-$even and $CP-$odd test. The P violation is also tested by comparing the combination of sample I+ III to sample II+IV. Every test was performed for three different values of δ with their corresponding $p-$values. The obtained results are summarised in Fig. 3.

All CP-violation searches using the energy test result in $p-$ values with a significance of 3 σ or smaller. On the other hand, the P-violation test shows a significance of 5.3 σ at the two smaller scales probed.

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}

Figure 3: The p-values from the energy test for different distance scales and test configurations

4. Direct CP asymmetry

In addition to the TPA and energy test methods, the LHCb collaboration also reported measurements of direct CP asymmetries in four-body b-baryon decays. These measurements exhibit

different sensitivity to CP violation with respect to TPA, which makes the two approaches complementary.
Direct CP violation happens when the decay rate of an X_b^0 to a final state f differs from the rate of $\overline{X}_b^0$ to the $CP-$ conjugated final state $\overline{f}$:

$$A^{CP} = \frac{\Gamma(X_b^0 \to f) - \Gamma(\bar{X}_b^0 \to \bar{f})}{\Gamma(X_b^0 \to f) + \Gamma(\bar{X}_b^0 \to \bar{f})}.$$

Overall, four different Λ_b^0 and two different Ξ_b^0 decays were studied: $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$, $\Lambda_b^0 \to pK^-\pi^+\pi^-$, $\Lambda_b^0 \to pK^-K^+\pi^-$, $\Lambda_b^0 \to pK^-K^+K^-$, $\Xi_b^0 \to pK^-\pi^+\pi^-$ and $\Xi_b^0 \to pK^-\pi^+K^-$ [11].
The data sample corresponds to an integrated luminosity of 1 fb^{-1} collected in 2011 at $\sqrt{s} = 7$ TeV and 2 fb^{-1} collected in 2012 at $\sqrt{s} = 8$ TeV.
The observable A^{CP} is sensitive to production asymmetry in X_b^0 and $\overline{X}_b^0$ and to reconstruction-induced charge asymmetries. In order to remove these systematic effects, charmed control channels comprising the same final-state particles such as $\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\pi^-$, $\Lambda_b^0 \to (\Lambda_c^+ \to p\pi^-\pi^+)\pi^-$ and $\Xi_b^0 \to (\Xi_c^+ \to pK^-\pi^+)\pi^-$ are used. These channels have kinematics similar to that of the corresponding charmless mode and no measurable CP violation according to the SM prediction; in practice the following CP-violating asymmetry is measured:

$$\Delta A^{CP} = A^{CP}_{no-c} - A^{CP}_{c}$$

where A^{CP}_{no-c} (A^{CP}_{c}) is the asymmetry measured in the charmless (charmed) decays. As was the case for the TPA, the CP violating asymmetries in these channels have been measured both integrating over all phase space and in specific phase-space regions. The integrated ΔA^{CP} asymmetries are measured to be:

$$\Delta A^{CP}(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) = (+1.1 \pm 2.5 \pm 0.6)\%$$
$$\Delta A^{CP}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (3.2 \pm 1.1 \pm 0.6)\%$$
$$\Delta A^{CP}(\Lambda_b^0 \to pK^-K^+\pi^-) = (-6.9 \pm 4.9 \pm 0.8)\%$$
$$\Delta A^{CP}(\Lambda_b^0 \to pK^-K^+K^-) = (0.2 \pm 1.8 \pm 0.6)\%$$
$$\Delta A^{CP}(\Xi_b^0 \to pK^-\pi^+\pi^-) = (-17 \pm 11 \pm 1)\%$$
$$\Delta A^{CP}(\Xi_b^0 \to pK^-\pi^+K^-) = (-6.8 \pm 8.0 \pm 0.8)\%$$

In all cases the first uncertainties are statistical and the second systematic. These asymmetries are all consistent with the hypothesis of CP conservation. CP asymmetries have also been measured in the low mass region of the baryonic pair (i.e. $p\pi^\pm$ or pK^-) and in regions of the phase space that contain specific quasi-two-body decays or three-body decays. No significant CP violation effect was observed in any region of the phase space.

5. Conclusions

In this article the latest measurements of CP asymmetries in four-body b-baryon decays performed by the LHCb collaboration have been presented. Different Λ_b^0 and Ξ_b^0 decays have been tested with complementary methods and no evidence of CP violation has been found though a

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interesting deviation at the 2.9 σ level was observed in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$, in a region of the phase space dominated by N^{*+} resonances. The same channel showed compelling evidence of P violation with a significance of 5.5 σ in the region dominated by the $a_1^-(1260)$ resonance.

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