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Search for CPV in charmless decays of beauty baryons at LHCb

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This document presents the most recent measurements by the LHCb collaboration on *CP* violation (CPV) in charmless decays of beauty baryons, addressing a fundamental question in particle physics related to the matter-antimatter asymmetry in the Universe. Two new analyses exploit the data collected by the LHCb experiment in Run 1 and Run 2, corresponding to a total integrated luminosity of 9 fb^{-1} of pp collisions at $\sqrt{s} = 7,\ 8$ and 13 TeV. The first one concerns measurements of *CP* asymmetries in $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$ decays, whose results represent the most precise estimates of these observables to date, improving upon previous world averages by a factor of three. Additionally, a detailed analysis of Λ_b^0 and Ξ_b^0 decays to $\Lambda h^+ h'^-$ ($h^{(\prime)} = \pi, K$) final states is presented, revealing the first evidence of *CP* violation in baryonic decays with a significance of 3.1 σ in the $\Lambda_b^0 \to \Lambda K^+ K^-$ channel. These findings contribute to a deeper understanding of CPV in the baryon sector and provide valuable insights for constraining theoretical models beyond the Standard Model.

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1. Introduction

In the Standard Model (SM) of particle physics, symmetry breaking under the combined charge-conjugation and parity transformations (*CP* violation) originates from a complex phase within the Cabibbo–Kobayashi–Maskawa (CKM) matrix [1, 2]. To date, all observed *CP* violation (CPV) phenomena are consistent with the CKM mechanism. However, the amount of CPV in the SM is insufficient to explain the observed matter-antimatter imbalance in the Universe, motivating further studies of *CP* violation and searches for possible new sources beyond the SM contributions. CPV has been established in processes involving K, B, and D meson decays, while no evidence has been reported so far in the baryon sector, despite the many searches performed in the past years. In this scenario, charmless decays of baryons containing b quarks constitute a promising line of research, as the interference between suppressed tree-level transitions and loop-level processes (penguin diagrams) may enhance the *CP* violation in the decay. In this document, two new measurements by the LHCb collaboration will be presented, namely the measurement of *CP* asymmetries in $\Lambda_b^0 \to p h^-$ decays [3] and a study of Λ_b^0 and Ξ_b^0 decaying to $\Lambda h^+ h'^-$ [4], where $h^{(\prime)}$ stands henceforth for a pion or a kaon. Both measurements are performed on the full Run 1 and Run 2 dataset of pp collisions collected by the LHCb experiment [5, 6], at center-of-mass energies of 7, 8 and 13 TeV, for a total integrated luminosity of $9\,\text{fb}^{-1}$. These two classes of decays share some features with similar mesonic decays that make them interesting candidates in the search for CPV in baryons: the two-body decays $\Lambda_b^0 \to p K^-$ and $\Lambda_b^0 \to p\pi^-$ are dominated by the same transition as the $B^0 \to K^+\pi^-$ decay, where CPV has already been observed [7], while the three-body decays $\Lambda_b^0(\Xi_b^0) \to \Lambda h^+ h'^-$ has a similar underlying dynamics as the three-body decay $B^+ \to h^+ h'^- h''^-$, where *CP*-violating effects as high as 75% have been observed in localized regions of the phase space [8].

2. Measurement of *CP* asymmetries in $\Lambda_b^0 \to p h^-$ decays

To obtain the *CP* asymmetries in the $\Lambda_b^0 \to p h^-$ decays, two different strategies have been employed for the Run 1 and Run 2 samples, due to the absence of a measurement of the Λ_b^0 baryon production asymmetry for the latter. For the Run 1 samples, the *CP* asymmetries are computed as the sums of various experimental quantities

$$A_{CP}^{ph^-} = A_{\text{raw}}^{ph^-} - A_{\text{D}}^{p} - A_{\text{D}}^{h^-} - A_{\text{PID}}^{ph^-} - A_{\text{T}}^{ph^-} - A_{\text{P}}^{\Lambda_b^0}, \tag{1}$$

where $A_{\text{raw}}^{ph^-}$ is the measured raw asymmetry between the yields of the decays $\Lambda_b^0 \to p h^-$ and $\overline{\Lambda}_b^0 \to \overline{p} h^+$; A_{D}^{p} and $A_{\text{D}}^{h^-}$ are the asymmetries between the detection efficiencies of a given final-state hadron species and its charge conjugate; $A_{\text{PID}}^{ph^-}$ is the asymmetry between the PID efficiencies for the final states $p h^-$ and $\overline{p} h^+$; $A_{\text{T}}^{ph^-}$ is the asymmetry between the trigger efficiencies for the particles in the final states $p h^-$ and $\overline{p} h^+$; and $A_{\text{P}}^{\Lambda_b^0}$ is the asymmetry between the production cross-sections of Λ_b^0 and $\overline{\Lambda}_b^0$ baryons. For the Run 2 sample, a different strategy to obtain the *CP* asymmetries has been devised, as no measurement of $A_{\text{P}}^{\Lambda_b^0}$ is available for pp collisions at the corresponding energy ($\sqrt{s} = 13\,\text{TeV}$). Employing a control sample of $\Lambda_b^0 \to (\Lambda_c^+ \to p K^- \pi^+)\pi^-$ decays, the following

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Table 1: Values of A_{CP} for the $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$ decays in the Run 1, Run 2, and Run 1+2 samples. The uncertainties are respectively statistical and systematic [3].

Sample	$A_{CP}^{pK^-}$ [%]	$A_{CP}^{p\pi^-}$ [%]
Run 1	$-0.3 \pm 1.5 \pm 0.6$	$-0.6 \pm 1.9 \pm 0.5$
Run 2	$-1.4 \pm 0.7 \pm 0.4$	$0.4 \pm 0.9 \pm 0.4$
Run 1+2	$-1.1 \pm 0.7 \pm 0.4$	$0.2 \pm 0.8 \pm 0.4$

formulae are used:

$$A_{CP}^{pK^-} = \Delta A_{\text{raw}} - \Delta A_{\text{D}}^{p} - \Delta A_{\text{D}}^{K^-} - \Delta A_{\text{PID}} - \Delta A_{\text{P}}^{\Lambda_b^0} - \Delta A_{\text{T}} - A_{\text{D}}^{\pi^-} - A_{\text{D}}^{\pi^+} + A_{CP}^{\Lambda_c^+\pi^-}, \tag{2}$$

$$A_{CP}^{p\pi^-} = \Delta A_{\text{raw}} - \Delta A_{\text{D}}^{p} - \Delta A_{\text{D}}^{\pi^-} - \Delta A_{\text{PID}} - \Delta A_{\text{P}}^{\Lambda_b^0} - \Delta A_{\text{T}} - A_{\text{D}}^{K^-} - A_{\text{D}}^{\pi^+} + A_{CP}^{\Lambda_c^+\pi^-}, \tag{3}$$

where ΔA indicates the difference between the asymmetries determined for the signal and control modes, and $A_{\text{D}}^{\pi^-}$, $A_{\text{D}}^{\pi^+}$, and $A_{\text{D}}^{K^-}$ are the detection asymmetries of the additional particles from the control sample that are not accounted for in $\Delta A_{\text{D}}^{h^-}$. The *CP* asymmetry in the control sample, $A_{CP}^{\Lambda_c^+\pi^-}$, is expected to be zero in the SM, within the experimental uncertainties of this analysis. The production asymmetry was observed to depend on the kinematic of the Λ_b^0 baryon [9], hence the control sample is weighted to equalize the two-dimensional distribution in the (p_{T}, η) plane of the Λ_b^0 baryon with that from $\Lambda_b^0 \to ph^-$ decays, such that the $\Delta A_{\text{P}}^{\Lambda_b^0}$ term is zero by construction in Eqs. (2) and (3). After the online trigger selection, additional offline requirements are applied to the data samples. Separate optimizations of the selection criteria are performed to the output of a multivariate classifier designed to reduce the combinatorial background and the PID variables. A BDT algorithm combining information on the candidate kinematic and reconstruction quality is used to reject the combinatorial background, while the final state particles are identified thanks to information from the RICH subsystem. The optimization of the BDT and PID criteria is performed separately Run 1 and Run 2, but using the same strategy. It was designed for the previous analysis by LHCb [10] to obtain the best sensitivity on the raw asymmetries and is based on pseudoexperiments. To achieve a better control of the misidentified components (cross-feed background), eight finals state are considered (pK^-, $p\pi^-$, $\overline{p}K^+$, $\overline{p}\pi^+$, $K^\pm\pi^\mp$, $\pi^+\pi^-$, and K^+K^-) and candidates are divided in mutually exclusive subsamples. In addition, the dataset is split into 12 disjoint subsets based on the year of acquisition (2011, 2012, 2015-2018) and polarity of the dipole magnet (Up, Down). The raw asymmetries are measured with extended binned maximum likelihood fit performed simultaneously to the invariant-mass distributions of the eight final states. The $m(pK^-)$ and $m(\overline{p}K^+)$ invariant-mass distributions are displayed in Fig. 1 with the results of the fit superimposed and combining all the subsamples. The other asymmetries introduced above are determined from control samples and are not described in this proceeding because of brevity requirements. Using Eqs. (1)-(3) in each subsample and computing their average value the Run 1, Run 2, and the combined *CP* asymmetries are measured; the results are reported in Table 1 for both $A_{CP}^{pK^-}$ and $A_{CP}^{p\pi^-}$. No evidence of *CP* violation is found. These are the most precise measurements of these observables to date, improving over the current world averages by a factor of three. These results supersede those previously obtained by LHCb [10], and will help in constraining theoretical models for QCD effects contributing

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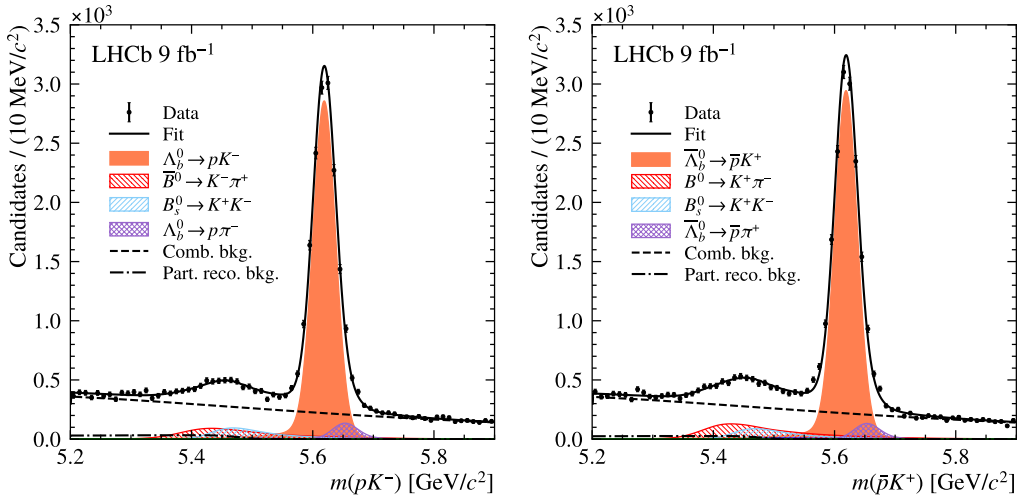

Figure 1: Invariant-mass spectrum of $\Lambda_b^0 \to pK^-$ (left) and $\overline{\Lambda}_b^0 \to \overline{p}K^+$ (right) decays, with the results of the fit also shown [3].

to these two-body baryonic decays.

3. Study of Λ_b^0 and Ξ_b^0 decays to Λh^+h^-

In this paper [4], the branching fraction of the decays $\Lambda_b^0/\Xi_b^0 \to \Lambda h^+h'^-$, with $h^{(\prime)} \in \{\pi, K\}$, are measured relatively to that of the control sample $\Lambda_b^0 \to \Lambda_c^+ (\to \Lambda\pi^+)\,\pi^-$; in addition, four out of the six decay channels with the highest signal yield are selected for a measurement of the corresponding *CP* asymmetry. The branching-fraction ($\mathcal{B}$) ratio of a signal decay to that of the control mode is measured according to

$$\frac{\mathcal{B}(\Lambda_b^0/\Xi_b^0 \to \Lambda h^+h'^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ (\to \Lambda\pi^+)\pi^-)} = \frac{N_{\Lambda_b^0/\Xi_b^0 \to \Lambda h^+h'^-}}{N_{\Lambda_b^0 \to \Lambda_c^+(\to\Lambda\pi^+)\pi^-}} \times \frac{\varepsilon_{\Lambda_b^0 \to \Lambda_c^+(\to\Lambda\pi^+)\pi^-}}{\varepsilon_{\Lambda_b^0/\Xi_b^0 \to \Lambda h^+h'^-}} \times \frac{f_{\Lambda_b^0}}{f_{\Lambda_b^0/\Xi_b^0}}, \tag{4}$$

where N and ε are the yield and efficiency for the considered decay, respectively, and the final factor is the ratio of b-quark fragmentation fractions. The yields are determined through the fit to data while the efficiencies are determined from simulation validated and corrected with calibration samples; the fragmentation fractions are taken from previous LHCb measurements [11, 12].

The *CP* asymmetry of the decay to a final state f is defined as

$$A_{CP}(\Lambda_b^0/\Xi_b^0 \to f) \equiv \frac{\Gamma(\Lambda_b^0/\Xi_b^0 \to f) - \Gamma(\overline{\Lambda}_b^0/\overline{\Xi}_b^0 \to \overline{f})}{\Gamma(\Lambda_b^0/\Xi_b^0 \to f) + \Gamma(\overline{\Lambda}_b^0/\overline{\Xi}_b^0 \to \overline{f})}, \tag{5}$$

where Γ is the partial decay rate defined without inclusion of its charge-conjugate process. The raw asymmetry of signal yields between baryon and antibaryon decays, denoted as $A_{\rm raw}$, is first extracted directly from the mass fits. Then, this quantity is corrected with data-driven techniques detailed in the paper, to remove the effects due to the other experimental asymmetries. The two main contributions are: the asymmetry of the baryon and antibaryon production rates, $A_{\rm P}$, and the asymmetry of

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Table 2: *CP*-averaged branching fraction and *CP*-asymmetry difference for each decay mode [4]. The uncertainties are statistical, systematic, and due to the branching fraction of the control mode [11].

Decay	$\mathcal{B}$ $[10^{-6}]$	ΔA_{CP} [%]
$\Lambda_b^0 \to \Lambda\pi^+\pi^-$	$5.3 \pm 0.4 \pm 0.5 \pm 0.5$	$-1.3 \pm 5.3 \pm 1.8$
$\Lambda_b^0 \to \Lambda K^+\pi^-$	$4.6 \pm 0.2 \pm 0.4 \pm 0.5$	$-11.8 \pm 4.5 \pm 2.1$
$\Lambda_b^0 \to \Lambda K^+K^-$	$10.7 \pm 0.3 \pm 0.4 \pm 1.1$	$8.3 \pm 2.3 \pm 1.6$
$\Xi_b^0 \to \Lambda\pi^+\pi^-$	$11.0 \pm 2.6 \pm 1.4 \pm 3.8$	-
$\Xi_b^0 \to \Lambda K^-\pi^+$	$10.4 \pm 1.4 \pm 1.2 \pm 3.5$	$27 \pm 12 \pm 5$
$\Xi_b^0 \to \Lambda K^+K^-$	< 2.4 (2.8) at 90% (95%) CL	-

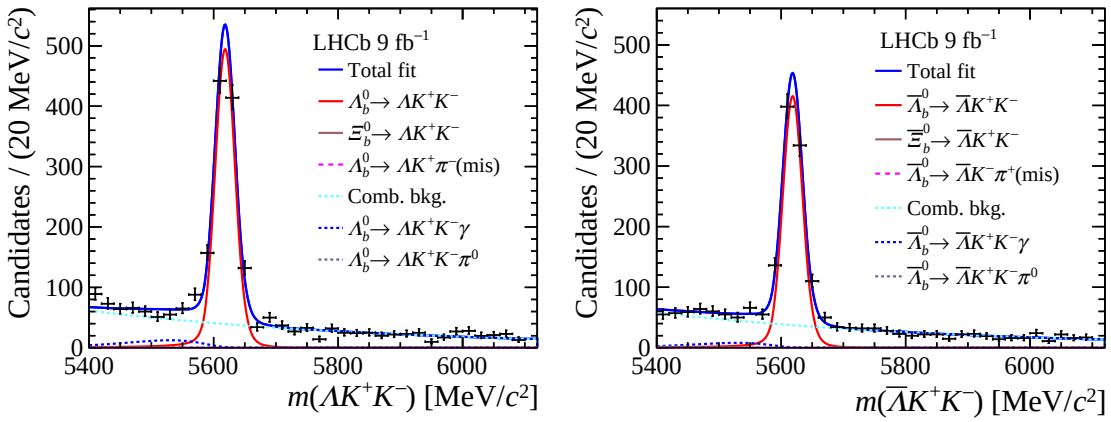

Figure 2: Invariant-mass spectrum of $\Lambda_b^0 \to \Lambda K^+K^-$ (left) and $\overline{\Lambda}_b^0 \to \overline{\Lambda} K^+K^-$ (right) decays, with the results of the fit also shown [4].

the final-state detection and selection efficiencies, A_{exp}. To reduce systematic uncertainties, the difference between the *CP* asymmetry of each signal decay and the $\Lambda_b^0 \to \Lambda_c^+(\Lambda\pi^+)\pi^-$ decay, ΔA_{CP}, is measured. Assuming there is no *CP* violation for the control mode, valid within the experimental uncertainties of this analysis, ΔA_{CP} gives the measurement of the *CP* asymmetry for the signal decay. The branching-fraction results are summarized in the middle column of Table 2. The statistical significances of the $\Lambda_b^0 \to \Lambda\pi^+\pi^-$ and $\Xi_b^0 \to \Lambda K^-\pi^+$ decays are measured to be more than 10σ, giving the first observation of these decays; a 4σ evidence is also found for the $\Xi_b^0 \to \Lambda\pi^-\pi^+$ decay; as no significant contribution from the $\Xi_b^0 \to \Lambda K^+K^-$ decay is found, upper limits are determined on its branching fraction at 90% and 95% confidence levels. The mass distributions of ΛK^+K^- for both baryon and antibaryon decays, with fit results also plotted, are shown in Fig. 2. The ΔA_{CP} results are summarized in the last column of Table 2, where the uncertainties are statistical and systematic. The ΔA_{CP} measurement for the ΛK^+K^- decay has a significance of 3.1 σ based on the negative log-likelihood method, accounting for both statistical and systematic uncertainties. As the decay is dominated by intermediate $N^{*+}(\to \Lambda K^+)$ or $\phi(\to K^+K^-)$ resonances, separate ΔA_{CP} measurements are performed within these two resonant regions. In the region dominated by the N^{*+} resonance, the asymmetry is determined to be $\Delta A_{CP} = 0.165 \pm 0.048 \pm 0.017$, which differs

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from zero by $3.2\,\sigma$. The *CP* asymmetry in the ϕ region is consistent with zero, as well as the *CP* asymmetries of the other modes.

4. Conclusions

To summarize, in this document two recent results from the LHCb collaboration have been presented involving searches for *CP* violation in beauty baryon decays. First, a measurement of the integrated *CP* asymmetries in $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$ decays has been shown, which yields the world's best precision on these two observables, improving over the previous world average by a factor 3. Finally, a study of Λ_b^0 and Ξ_b^0 decays to $\Lambda h^+ h'^-$, where the branching fraction relatively to a normalization channel of $\Lambda_b^0 \to \Lambda_c^+ (\to \Lambda\pi^+)\,\pi^-$ decays are measured, as well as the *CP* asymmetries of four of the six channels, was summarized. The measured *CP* asymmetry of $\Lambda_b^0 \to \Lambda K^+ K^-$ deviates from zero by 3.1σ, giving the first evidence of *CP* violation in baryon decays, which is expected to originate from an $N^{*+}(\to \Lambda K^+)$ resonance contribution. This results represent a first crucial step in solving the long-standing search for *CP* violation in beauty baryons.

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