CP-violation measurements in charmless decays of beauty baryons at LHCb

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Summary. — In these proceedings, recent results from the LHCb Collaboration in the field of charmless beauty-baryon decays are presented. These results concern the measurement of CP violation in $\Lambda_b^0 \to ph^-$, $\Lambda_b^0/\Xi_b^0 \to \Lambda h^+h'^-$ ($h \in \{\pi, K\}$) and $\Lambda_b^0 \to pK^-\pi^+\pi^-$ decays. Events were collected at the LHC in proton-proton collision at centre-of-mass energies of 7, 8 and 13.6 TeV during Run 1 and Run 2 data taking campaigns. The results include both the first evidence and the first observation of direct CP violation in baryon decays to date.

1. – Introduction

The observed asymmetry between matter and antimatter in our universe cannot be explained by our current knowledge of the Standard Model of particle physics (SM). In particular, the SM predicts the non-invariance of weak interactions under the combined charge conjugation (C) and spatial parity-reversal (P) transformations (CP) [1, 2], but experimental measurements point towards a non sufficient entity of such violation [3, 4]. Furthermore, CP Violation (CPV) in mesons was established in 1964 [5], whereas no hints of this violation was found in baryon decays for almost six decades despite numerous experimental efforts.

Charmless decays of beauty hadrons are particularly well suited for CPV searches. By virtue of tree-level contribution suppression, penguin diagrams become more relevant and eventual contribution due to physics beyond the SM may be detected via precise measurements of branching ratios and CPV observables. In these proceedings, the latest measurements of CPV observables in the charmless beauty-hadron $\Lambda_b^0 \to ph^-$, $\Xi_b^0/\Lambda_b^0 \to \Lambda h^+h'^-$ and $\Lambda_b^0 \to pK^-\pi^+\pi^-$ decays performed by the LHCb Collaboration are presented, where the h represent $\pi^\pm$ and $K^\pm$. For what concerns $\Xi_b^0/\Lambda_b^0 \to \Lambda h^+h'^-$ decays, branching-ratio measurements were also produced. The analyses were performed using the full sample collected during Run 1 and Run 2 by the LHCb experiment [6]

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during proton-proton collision campaigns at the LHC, with centre-of-mass energies of 7, 8 and 13 TeV, corresponding to an integrated luminosity of $9\,\text{fb}^{-1}$. These analyses are particularly interesting since *CP*V is well established in the corresponding meson decays, where the difference is exclusively given by the absence of the spectator quark.

The direct *CP*-asymmetry observable is defined as

$$A^f_{CP} = \frac{\Gamma(H^0_b \to f) - \Gamma(\overline{H}^0_b \to \overline{f})}{\Gamma(H^0_b \to f) + \Gamma(\overline{H}^0_b \to \overline{f})}, \tag{1}$$

where H^0_b ($\overline{H}^0_b$) is the considered beauty (anti)baryon, f ($\overline{f}$) the (anti-)final state and Γ is the partial width of the decay. In the case of time-integrated analyses, the asymmetry is given by the observed asymmetry A_{raw} of the countings in the detector N, corrected by accounting for all nuisance asymmetries, A_{nuis}, given by experimental effects

$$A^f_{raw} = \frac{N(H^0_b \to f) - N(\overline{H}^0_b \to \overline{f})}{N(H^0_b \to f) + N(\overline{H}^0_b \to \overline{f})}, \tag{2a}$$

$$A^f_{CP} = A^f_{raw} - \sum A_{nuis}. \tag{2b}$$

Nuisance asymmetries typically include, but are not limited to: asymmetries in the production of the decaying particles, due to the matter initial state *pp*; in the detection, identification or reconstruction of the final states, due to asymmetries in the detector acceptance or different cross-sections within the matter material of the detector. In many cases, a valid approach to constrain the nuisance asymmetries is to introduce a control channel with respect to which measuring the *CP* asymmetry. This approach may result in either partial or total simplification of the experimental asymmetries. The use of a control channel leads to measuring the ΔA_{CP} quantity defined as

$$\Delta A_{CP} = A_{CP} - A^{control}_{CP}. \tag{3}$$

For certain choices of the control sample, solid theoretical motivations predict the *CP* asymmetry, $A^{control}_{CP}$, to be negligible compared to the measurement uncertainty, effectively leading to $\Delta A_{CP} \simeq A_{CP}$.

2. – Search for *CP*V in $\Lambda^0_b \to ph^-$ decays

The $\Lambda^0_b \to ph^-$ ($h \in \{\pi, K\}$) decays *CP*V measurements were performed in the past using only LHCb Run 1 data, with results limited by the systematic uncertainties [7]. Thanks to a new analysis approach [8], Run 1 results were improved. Namely, since the systematics related to the particle-identification calibration samples were contributing significantly towards the total uncertainties, veto regions in the kinematic space were introduced to remove data lying in the regions where the calibration sample statistics was not sufficient. Furthermore, thanks to the inclusion of Run 2 data, the precision on the measurement of the observables were improved by a factor of almost 3.

In order to perform the analysis, two selections were devised, improving the sensitivity on the *CP*V observable of each decay channel. For each selection, year and magnet configuration, simultaneous fits to the invariant mass of the different ph^- final states were performed, yielding to the raw asymmetries for the channels. The fit to the invariant-mass spectrum for the pK^- selection is shown in Fig. 1.

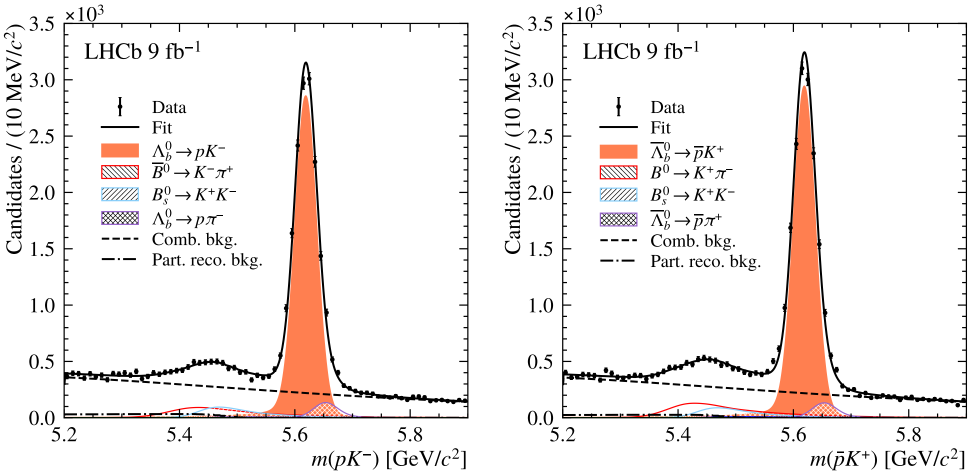

Fig. 1. – Fit to the pK^- invariant-mass spectrum (full dataset) for the $A_{CP}(\Lambda_b^0 \to pK^-)$ selection [8].

To extract the physical asymmetry, all nuisance asymmetries were estimated through specific calibration samples and subtracted (see Eq. (2*b*)). In particular, two different strategies were employed for the production asymmetry. Since a dedicated and precise measurement of the Λ_b^0 production asymmetry was available only for Run 1 [9], this input was used for this subsample. Instead, the control $\Lambda_b^0 \to \Lambda_c^+\pi^-$ decay channel was exploited in the Run 2 case to simplify the production asymmetry (see Eq. 3). Finally, the results of the two runs were combined, leading to $A_{CP}(\Lambda_b^0 \to pK^-) = (-1.1 \pm 0.7 \pm 0.4)\%$ and $A_{CP}(\Lambda_b^0 \to p\pi^-) = (0.2 \pm 0.8 \pm 0.4)\%$, where the first uncertainty is statistical and the second one is systematic. Overall, they are compatible with the hypothesis of no-*CP*V in the decays. These results are the most precise to date. Thanks to the newly developed strategy they are not limited by systematic uncertainties anymore.

3. – Branching ratio measurements and first *CP*V evidence in $\Xi_b^0/\Lambda_b^0 \to \Lambda h^+h'^-$ decays

The branching ratios of $\Xi_b^0/\Lambda_b^0 \to \Lambda h^+h'^-$ decays, where $h, h' \in \{\pi, K\}$, were measured with respect to the $\Lambda_b^0 \to (\Lambda_c^+ \to \Lambda\pi^+)\pi^-$ control sample. When a 3 or more sigma evidence for the decay was found, *CP*V observables were also measured [10]. Branching ratios $\mathcal{B}$ are determined according to

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

where N represent the yield of the considered decay, ε its reconstruction efficiency, while the final factor represents the hadronisation fraction of the b quark leading to the formation of different beauty hadrons.

After event selection, a simultaneous unbinned maximum-likelihood fit to all possible $\Lambda h^+h'^-$ final states, where the two *CP*-conjugate states are combined, is performed.

Thanks to Eq. (4), branching ratios are extracted. The procedure leads to the first observation of the $\Lambda_b^0 \to \Lambda\pi^+\pi^-$ and $\Xi_b^0 \to \Lambda\pi^+K^-$ decays and the first evidence of the $\Xi_b^0 \to \Lambda\pi^+\pi^-$ decay.

In order to determine *CP*V observables, the fit is repeated separating the different *CP*-conjugate states. The use of the control channel allows for a simplification of some of the experimentally induced asymmetries and since the *CP* asymmetry in the control channel is expected to be small with respect to the studied channel, by virtue of the decay being Cabibbo-favoured, the observed asymmetry can be considered the one of the investigated channel. The fit to the ΛK^+K^- invariant-mass spectrum is shown in Fig. 2. Overall, the analysis produced the results reported in Table I.

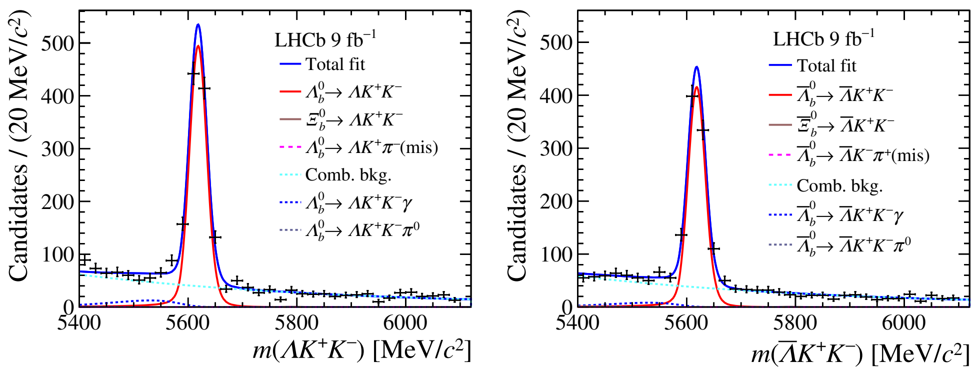

Fig. 2. – Fit to the invariant-mass spectrum for the ΛK^+K^- final state and its *CP* conjugate [10].

Table I. – *Branching ratios and CP asymmetries of the different decay channels with respect to the control mode. The ΔA_{CP} observable was measured only for the decay modes whose measured branching ratio differs from zero by more than 3 standard deviations. The uncertainties are respectively statistical, systematic and the one related to the uncertainty of the control channel [10].*

Decay	$\mathcal{B}\,(\times 10^{-6})$	$\Delta A_{CP}\ (\times 10^{-2})$
$\Lambda_b^0 \to \Lambda\pi^+\pi^-$	$5.3 \pm 0.4 \pm 0.5 \pm 0.5$	$-\ 1.3 \pm\ 5.3 \pm 1.8$
$\Lambda_b^0 \to \Lambda K^+\pi^-$	$4.6 \pm 0.2 \pm 0.4 \pm 0.5$	$-11.8 \pm\ 4.5 \pm 2.1$
$\Lambda_b^0 \to \Lambda K^+K^-$	$10.7 \pm 0.3 \pm 0.4 \pm 1.1$	$8.3 \pm\ 2.3 \pm 1.6$
$\Xi_b^0 \to \Lambda\pi^+\pi^-$	$11.0 \pm 2.6 \pm 1.4 \pm 3.8$	
$\Xi_b^0 \to \Lambda\pi^+K^-$	$10.4 \pm 1.4 \pm 1.2 \pm 3.5$	$27 \pm 12 \pm 5$
$\Xi_b^0 \to \Lambda K^+K^-$	$< 2.4\,(2.8)$ at $90\,(95)\%$ CL	

A $3.1\,\sigma$ departure from 0 of ΔA_{CP} in the $\Lambda_b^0 \to \Lambda K^+K^-$ decay, obtained with the negative log-likelihood method, is the first ever evidence of *CP*V in a baryon decay. Since resonances may play a role in the enhancement of *CP*V observables, the measurement is repeated in both the $\phi \to K^+K^-$ and $N^{*+} \to \Lambda K^+$ resonance regions. In the first one, ΔA_{CP} is compatible with 0, while in the second one an enhancement of *CP*V is observed, namely $\Delta A_{CP} = (16.5 \pm 4.8 \pm 1.7)\%$, which differs from 0 at the level of $3.2\,\sigma$.

4. – First observation of CPV in $\Lambda_b^0 \to pK^-\pi^+\pi^-$ decays

The first observation of CPV in baryon decays was found in the charmless $\Lambda_b^0 \to pK^-\pi^+\pi^-$ decay [11]. The result was obtained by fitting the $pK^-\pi^+\pi^-$ invariant mass spectrum, leading to a raw asymmetry of the countings between the two opposite CP final states. The fit is shown in Fig. 3. Experimental asymmetries were removed by

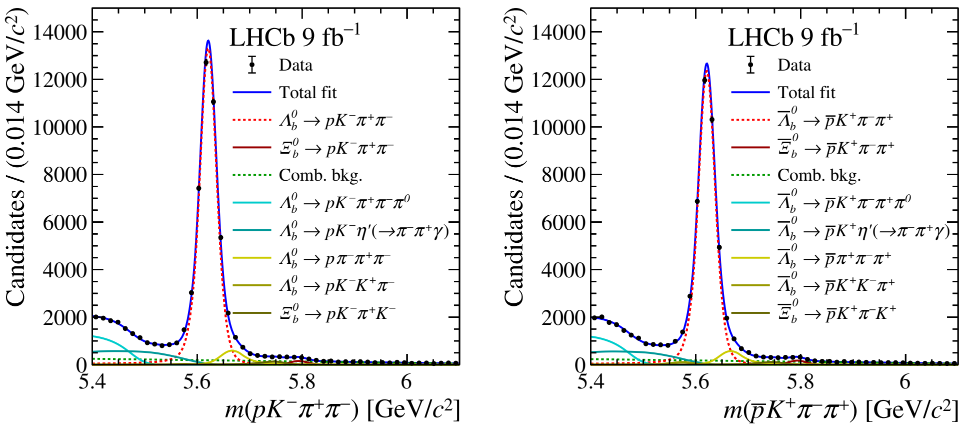

Fig. 3. – Fit to the invariant-mass spectrum for the $pK^-\pi^+\pi^-$ final state and its CP conjugate [11].

means of the $\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\pi^-$ control channel. A major advantage of this choice of the control sample is that it precisely match the final state of the investigated decay, leading to a large simplification of the nuisance asymmetries, yielding, under the assumption of no-CPV in the control channel due to its Cabibbo-favoured nature, to $A_{CP} = (2.45 \pm 0.46 \pm 0.10)\%$, where the first uncertainty is given by the sizes of the signal and control samples and the second one is related to the systematics. This result shows a $5.2\,\sigma$ departure from the hypothesis of CP symmetry. Since intermediate hadronic resonant states may play a role in the enhancement of the asymmetry, the analysis is repeated in several resonance regions, calculated with respect to the invariant mass of either 2 or 3 of the particles in the final state. As it can be seen in Table II, some of the regions effectively show an enhancement of the asymmetry.

5. – Conclusion

In these proceedings, recent results by the LHCb Collaboration on charmless beauty-baryon decays were presented. These results, produced analysing LHCb Run 1 and 2 data, included both the first evidence and the first observation of CP violation in baryon decays, setting a new milestone in the CPV journey that started more than six decades ago. Between 2018 and 2022, the LHCb detector underwent an important upgrade. Thanks to the upgraded detector and the amount of collected integrated luminosity, the Run 3 data taking campaign, which is currently ongoing, is expected to almost quadruple the amount of events in the b-quark sector, which will lead to ever refined analyses.

TABLE II. – *Observed asymmetry in the different hadronic resonance regions R. Quoted uncertainties are statistical and systematic respectively [11].*

Decay topology	Selected mass region [GeV/c^2]	ΔA_{CP} ($\times 10^{-2}$)
$\Lambda_b^0 \to pK^-\pi^+\pi^-$	-	$2.45 \pm 0.46 \pm 0.10$
$\Lambda_b^0 \to R(pK^-)R(\pi^+\pi^-)$	$m_{pK^-} < 2.2$ $m_{\pi^+\pi^-} < 1.1$	$5.3 \pm 1.3 \pm 0.2$
$\Lambda_b^0 \to R(p\pi^-)R(K^-\pi^+)$	$m_{p\pi^-} < 1.7$ $0.8 < m_{\pi^+K^-} < 1.0$ or $1.1 < m_{\pi^+K^-} < 1.6$	$2.7 \pm 0.8 \pm 0.1$
$\Lambda_b^0 \to R(p\pi^+\pi^-)K^-$	$m_{\pi^+\pi^-} < 2.7$	$5.4 \pm 0.9 \pm 0.1$
$\Lambda_b^0 \to R(K^-\pi^+\pi^-)p$	$m_{K^-\pi^+\pi^-} < 2.0$	$2.0 \pm 1.2 \pm 0.3$

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