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Searches for CP violation in beauty baryons at LHCb

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Summary. — The understanding of *CP*-violating mechanisms in the baryon sector is of particular importance in light of the observed matter-antimatter asymmetry in the Universe, but few studies have been performed in baryon decays to date. The searches for *CP* violation in beauty baryons performed by the LHCb Collaboration on LHC Run I data are reported, including the first evidence for *CP* violation in a baryon decay, $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$. Prospects for LHC Run II are also outlined.

1. – Introduction

The phenomenon of *CP* violation (CPV), related to matter-antimatter differences, is included within the Standard Model (SM) of particle physics via the Cabibbo-Kobayashi-Maskawa (CKM) mechanism, successfully describing the observed CPV in strange and beauty mesons. However, the degree of matter-antimatter asymmetry in the Universe suggests the existence of CPV sources from beyond the SM physics. Since (visible) matter is basically constituted by baryons, a deeper understanding of CPV in this sector may be very important to shed light on baryogenesis. While extensive CPV searches have been performed in mesons, few studies concentrated on baryons, and a CPV observation is still lacking for baryon decays.

2. – *CP* violation observables

CP symmetry violation is probed by comparing a given process with its *CP*-conjugate, the one involving charge-conjugated particles with reversed momenta. The simplest observable is the asymmetry in the number of *CP*-conjugate processes, $\mathcal{A}_{\rm raw}$, sensitive to the direct *CP* asymmetry, $\mathcal{A}_{CP}$, but also to particle-antiparticle production, $\mathcal{A}_{\rm prod}$, and

reconstruction, $\mathcal{A}_{\rm reco}$, asymmetries. Taking the $\Lambda_b^0 \to pK^-\mu^+\mu^-$ decay for illustration,

$$\mathcal{A}_{\rm raw} \equiv \frac{N(\Lambda_b^0) - N(\bar{\Lambda}_b^0)}{N(\Lambda_b^0) + N(\bar{\Lambda}_b^0)} \approx \mathcal{A}_{CP}(\Lambda_b^0 \to pK^-\mu^+\mu^-) + \mathcal{A}_{\rm prod}(\Lambda_b^0) - \mathcal{A}_{\rm reco}(K^+) + \mathcal{A}_{\rm reco}(p).$$

The experimental contributions are effectively cancelled exploiting a control transition with negligible *CP* violation, *e.g.*, $\Lambda_b^0 \to pK^-J/\psi$, for the $\Lambda_b^0 \to pK^-\mu^+\mu^-$ decay, defining

$$\begin{aligned}\Delta\mathcal{A}_{CP} &\equiv \mathcal{A}_{\rm raw}(\Lambda_b^0 \to pK^-\mu^+\mu^-) - \mathcal{A}_{\rm raw}(\Lambda_b^0 \to pK^-J/\psi),\\ &= \mathcal{A}_{CP}(\Lambda_b^0 \to pK^-\mu^+\mu^-) - \mathcal{A}_{CP}(\Lambda_b^0 \to pK^-J/\psi).\end{aligned}$$

A different CPV observable can be obtained for four-body decays from triple products of final-state particle momenta in the mother particle rest frame, *e.g.*, defined as

$$C_{\widehat{T}} \equiv \vec{p}_{\mu^+} \cdot (\vec{p}_p \times \vec{p}_{K^-}), \qquad \overline{C}_{\widehat{T}} \equiv \vec{p}_{\mu^-} \cdot (\vec{p}_{\bar{p}} \times \vec{p}_{K^+})$$

and, denoting by $N(\overline{N})$ the number of Λ_b^0 ($\bar{\Lambda}_b^0$) signal candidates, taking the asymmetries

$$A_{\widehat{T}} \equiv \frac{N(C_{\widehat{T}} > 0) - N(C_{\widehat{T}} < 0)}{N(C_{\widehat{T}} > 0) + N(C_{\widehat{T}} < 0)}, \qquad \overline{A}_{\widehat{T}} \equiv \frac{\overline{N}(-\overline{C}_{\widehat{T}} > 0) - \overline{N}(-\overline{C}_{\widehat{T}} < 0)}{\overline{N}(-\overline{C}_{\widehat{T}} > 0) + \overline{N}(-\overline{C}_{\widehat{T}} < 0)}.$$

The difference between $A_{\widehat{T}}$ and $\overline{A}_{\widehat{T}}$, $a_{CP}^{\widehat{T}\text{-odd}} \equiv \left(A_{\widehat{T}} - \overline{A}_{\widehat{T}}\right)/2$ is a *CP*-odd observable [1], which is, by construction, largely insensitive to particle-antiparticle production and reconstruction asymmetries. The observables $\Delta\mathcal{A}_{CP}$ and $a_{CP}^{\widehat{T}\text{-odd}}$ are sensitive to distinct manifestations of CPV, depending on the interference of different decay amplitudes [2].

3. – Searches for *CP* violation in beauty baryons at LHCb

The LHCb Collaboration (LHCb) has performed six CPV searches in beauty baryon decays, the only search by other experiments was done by the CDF Collaboration in $\Lambda_b^0 \to p\pi^-, pK^-$ decays [3].

The $\Lambda_b^0 \to p\pi^-\pi^+\pi^-(K^+K^-)$ transitions are mediated by $b \to u$ quark-level tree and $b \to d$ loop amplitudes, characterized by different CPV components (*CP*-odd weak phases), making this decay sensitive to CPV from the CKM mechanism. LHCb observed these two transitions, with 6646 ± 105 $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ and 1030 ± 56 $\Lambda_b^0 \to p\pi^-K^+K^-$ events, measured $a_{CP}^{\widehat{T}\text{-odd}}$ integrated over all the events,

$$\begin{aligned}a_{CP}^{\widehat{T}\text{-odd}}(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) &= [+1.15 \pm 1.45\ (\text{stat}) \pm 0.32\ (\text{syst})] \times 10^{-2},\\ a_{CP}^{\widehat{T}\text{-odd}}(\Lambda_b^0 \to p\pi^-K^+K^-) &= [-0.93 \pm 4.54\ (\text{stat}) \pm 0.42\ (\text{syst})] \times 10^{-2},\end{aligned}$$

seeing no CPV evidence, and measured $a_{CP}^{\widehat{T}\text{-odd}}$ in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ phase-space intervals for two independent partitions, rejecting *CP* symmetry conservation at 3.3σ, representing the first evidence of CPV in a baryon decay [4].

The $b \to s$ neutral-current transition $\Lambda_b^0 \to pK^-\mu^+\mu^-$, prohibited at tree-level in the SM, has limited CPV expected from the SM, being CPV amplitudes suppressed compared

to CP-conserving ones due to CKM matrix hierarchy. Hence, this decay is particularly sensitive to CPV from physics beyond the SM, with new particles which may contribute to the loop amplitudes. LHCb observed this decay, finding 600 ± 31 events, measured $\Delta\mathcal{A}_{CP}$ with respect to $\Lambda_b^0 \to pK^- J/\psi$ decays, and $a_{CP}^{\widehat{T}\text{-odd}}$ [5],

$$\Delta\mathcal{A}_{CP} = [-3.5 \pm 5.0\ (\text{stat}) \pm 0.2\ (\text{syst})] \times 10^{-2},$$
$$a_{CP}^{\widehat{T}\text{-odd}} = [+1.2 \pm 5.0\ (\text{stat}) \pm 0.7\ (\text{syst})] \times 10^{-2},$$

both compatible with CP conservation

LHCb also observed the $b \to s$ transition $\Lambda_b^0 \to \Lambda(p\pi^-)\phi(K^+K^-)$, with a statistical significance of 5.9σ, and measured four observables analogous to triple product asymmetries [6]. These were defined as the asymmetry in the cosine (sine) of the helicity angle of the proton in the Λ rest frame, A_Λ^c (A_Λ^s), and of the helicity angle of the positive kaon in the ϕ rest frame, A_ϕ^c (A_ϕ^s). No significant asymmetry is seen:

$$A_\Lambda^c = -0.22 \pm 0.12\ (\text{stat}) \pm 0.06\ (\text{syst}), \quad A_\Lambda^s = +0.13 \pm 0.12\ (\text{stat}) \pm 0.05\ (\text{syst}),$$
$$A_\phi^c = -0.01 \pm 0.12\ (\text{stat}) \pm 0.03\ (\text{syst}), \quad A_\phi^s = -0.07 \pm 0.12\ (\text{stat}) \pm 0.01\ (\text{syst}).$$

The $\Lambda_b^0 \to \Lambda K^+\pi^-(K^-)$ decay is characterized by interfering $b \to u$ tree and $b \to d$ loop amplitudes, thus sensitive to SM CPV. LHCb observed these transitions, with 97 ± 14 $\Lambda_b^0 \to \Lambda K^+\pi^-$ and 185 ± 15 $\Lambda_b^0 \to \Lambda K^+K^-$ events, and measured $\Delta\mathcal{A}_{CP}$ with respect to the $\Lambda_b^0 \to \Lambda_c^+(\Lambda\pi^+)\pi^-$ transition [7], found compatible with CP conservation:

$$\Delta\mathcal{A}_{CP}(\Lambda_b^0 \to \Lambda K^+\pi^-) = -0.53 \pm 0.23\ (\text{stat}) \pm 0.11\ (\text{syst}),$$
$$\Delta\mathcal{A}_{CP}(\Lambda_b^0 \to \Lambda K^+K^-) = -0.28 \pm 0.10\ (\text{stat}) \pm 0.07\ (\text{syst}).$$

In the Cabibbo-suppressed $\Lambda_b^0 \to p\pi J/\psi$ decay, the contribution of loop diagrams, featuring CPV couplings, is comparable to tree amplitudes, with their interference potentially producing significant CPV effects. LHCb has measured the $\Delta\mathcal{A}_{CP}$ observable with respect to the $\Lambda_b^0 \to pK^- J/\psi$ decay on a sample of 2102 ± 61 events [8]:

$$\Delta\mathcal{A}_{CP} = [+5.7 \pm 2.3\ (\text{stat}) \pm 1.2\ (\text{syst})] \times 10^{-2}.$$

This result is compatible with CP symmetry at 2.2 standard deviations. No significant asymmetry was observed in the phase-space of the decay.

Last, LHCb observed the $\Lambda_b^0 \to K_s^0 p\pi^-$ decay, obtaining 106 ± 25 events, and measured $\Delta\mathcal{A}_{CP}$ with respect to $\Lambda_b^0 \to \Lambda_c^+(\to pK_s^0)\pi^-$ mode, with no evidence of CPV [9]:

$$\Delta\mathcal{A}_{CP} = +0.22 \pm 0.13\ (\text{stat}) \pm 0.03\ (\text{syst}).$$

4. – Summary and prospects

Exploiting the full LHC Run I dataset, the LHCb Collaboration found the first evidence of CPV in a baryon decay, $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$, while the other results were compatible with CP symmetry. These results are dominated by statistical uncertainties which, with the increase of beauty baryon decays expected with LHC Run II, should reduce by a factor ≈ 2.6, considering the rise in integrated luminosity (from 3 to 11 fb^{-1} in total) and in pp center-of-mass energy from 8 to 13 TeV. Forthcoming updates and new searches will lead to a better understanding of CP violation in the beauty baryon sector.

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