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CP Violation in Baryon Decays: Results from BESIII & LHCb

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The origin of baryon asymmetry of the Universe is one of the most fundamental open questions in physics. Charge-Parity (CP) violation is a key ingredient for explaining this asymmetry. While CP violation has been well established in meson systems for decades, the search for CP violation in baryon decays has drawn increasing attention in recent years. This proceeding summarizes the latest results on baryon CP violation from two major experiments: BESIII (Beijing Spectrometer III experiment) and LHCb (Large Hadron Collider beauty experiment). We review the experimental methods, key measurements, and the first observation of CP violation in baryon decays, highlighting their implications for testing the Standard Model and probing new physics.

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1. Introduction

The observed dominance of matter over antimatter in the Universe remains one of the most profound mysteries in modern physics [1]. This phenomenon results from the process called baryogenesis. According to Sakharov's conditions [2], three requirements must be satisfied for baryogenesis: (1) baryon number violation, (2) C and CP symmetry violation, and (3) departure from thermal equilibrium. While the Standard Model (SM) of particle physics incorporates CP violation through the Cabibbo-Kobayashi-Maskawa (CKM) mechanism [3, 4], the magnitude of CP violation in the SM is insufficient to explain the observed baryon asymmetry of the Universe [5]. Therefore, new forces or particles beyond the SM could provide additional contributions, making studies of CP violation crucial for probing new physics (NP).

CP violation has been extensively studied in meson systems. Milestone discoveries include the observation of CP violation in K^0 decays by Cronin-Fitch experiment in 1964 [6], the observation of CP violation in B^0 decays by BaBar and Belle experiments in 2001 [7, 8], and the observation of CP violation in D^0 decays by LHCb experiment in 2019 [9].

However, despite decays mediated by similar quark transitions as those in meson systems, baryon CP violation remained unobserved until 2025 [10]. In b-meson decays, large CP asymmetries have been observed, while the corresponding baryon decays mediated by same quark transition do not show such asymmetry. For instance, the b-meson decay $B_s^0 \to K^-\pi^+$ shows a $(23.6 \pm 1.7)\%$ CP asymmetry [11, 12], whereas the corresponding baryon decays $\Lambda_b^0 \to ph^-$, where h denotes a K or π meson, exhibit no such asymmetry with a precision of 0.7% [13, 14]. To understand the difference between meson and baryon decays, it is essential to study CP violation in baryon decays. Moreover, baryons offer unique sensitivity to new physics due to their complex decay dynamics and rich phase-space structures. This proceeding presents an overview of baryon CP violation searches at BESIII and LHCb experiments, focusing on hyperon studies at BESIII and b-baryon decays at LHCb.

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2. Hyperon CP violation results from BESIII

BESIII experiment operates at the BEPCII (Beijing Electron Positron Collider II), an e^+e^- collider. It can operate at the energy of J/ψ threshold and at excited ψ resonances peaks. With about 10^{10} J/ψ and about 3×10^9 $\psi(2S)$ decay events collected, BESIII recorded approximately 10^7 entangled hyperon-antihyperon pairs, enabling precise studies of hyperon decays [15].

With entangled hyperon pairs, the CP-violating signature in spin-1/2 nonleptonic hyperon decays can be described by the difference between hyperon and antihyperon decay distributions in their parity-violating two-body weak decays. In such decays, the angular distribution of the daughter baryon is proportional to $(1 + \alpha_Y \mathbf{P_Y} \cdot \hat{\mathbf{P}}_\mathbf{d})$, where α_Y is the hyperon decay parameter [16], and $\mathbf{P_Y}$ and $\hat{\mathbf{P}}_\mathbf{d}$ are the hyperon polarization and the unit vector in the direction of the daughter baryon momentum, respectively, both in the hyperon rest frame. The CP asymmetry is defined as $A_{CP}^{\alpha} = ([\alpha_Y + \overline{\alpha}_Y]/[\alpha_Y - \overline{\alpha}_Y])$ [17].

BESIII has searched for CP violation in multiple hyperon decay channels by measuring A_{CP}^{α}. Table 1 summarizes the expected number of entangled hyperon decay events from J/ψ and $\psi(2S)$

two-body decays. The large statistics allow for high-precision measurements of decay parameters and CP violation observables.

Table 2 presents the key results, which show no significant evidence of CP violation in hyperon decays, consistent with the SM expectation of small CP violation effects in hyperons.

Table 1: Hyperon production from J/ψ and $\psi(2S)$ decays at BESIII [15]. B is the branching fraction and N_B is the number of the expected hyperon events.

Decay mode	$B(\times 10^{-3})$	$N_B(\times 10^{6})$
$J/\psi \to \Lambda\bar{\Lambda}$	1.61 ± 0.15	16.1 ± 1.5
$J/\psi \to \Sigma^0\bar{\Sigma}^0$	1.29 ± 0.09	12.9 ± 0.9
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	1.50 ± 0.24	15.0 ± 2.4
$J/\psi \to \Sigma(1385)^-\bar{\Sigma}^+$(or c.c.)	0.31 ± 0.05	3.1 ± 0.5
$J/\psi \to \Sigma(1385)^-\bar{\Sigma}(1385)^+$(or c.c.)	1.10 ± 0.12	11.0 ± 1.2
$J/\psi \to \Xi^0\bar{\Xi}^0$	1.20 ± 0.24	12.0 ± 2.4
$J/\psi \to \Xi^-\bar{\Xi}^+$	0.86 ± 0.11	8.6 ± 1.0
$J/\psi \to \Xi(1530)^0\bar{\Xi}^0$	0.32 ± 0.14	3.2 ± 1.4
$J/\psi \to \Xi(1530)^-\bar{\Xi}^+$	0.59 ± 0.15	5.9 ± 1.5
$\psi(2S) \to \Omega^-\bar{\Omega}^+$	0.05 ± 0.01	0.15 ± 0.03

Table 2: CP asymmetries in hyperon decays at BESIII

Decay mode	$A_{\mathrm{CP}}(\%)$
$\psi \to \Sigma^+\bar{\Sigma}^-$	$-0.004 \pm 0.037 \pm 0.010$ [18]
$J/\psi \to \Lambda\bar{\Lambda}$	$-0.0025 \pm 0.0046 \pm 0.0012$ [19]
$J/\psi \to \Xi^-\bar{\Xi}^+$	$-0.006 \pm 0.013 \pm 0.006$ [20]
$\psi(2S) \to \Xi^-\bar{\Xi}^+$	$-0.015 \pm 0.051 \pm 0.010$ [21]
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	$-0.080 \pm 0.052 \pm 0.028$ [22]
$J/\psi \to \Xi^0\bar{\Xi}^0$	$-0.0054 \pm 0.0065 \pm 0.0031$ [23]

3. *b*-baryon CP violation results from LHCb

LHCb is a dedicated heavy-flavor experiment at the Large Hadron Collider (LHC). During its Run 1 and Run 2 operation periods, it has collected proton-proton collision data at center-of-mass energies of 7, 8, and 13 TeV, accumulating over 9 fb^{-1} of integrated luminosity. This large dataset, combined with its unique ability to trigger, reconstruct, and isolate decays with all types of charged particles, establishes LHCb as the leading experiment for baryon CPV searches in *b*-baryon decays.

In the past decade, numerous studies have been performed on the baryon CP violation searches [13, 14, 24–39].

In two-body baryon decays, the amount of CP violation does not depend on the phase space and could be described by a single A_{CP} value, which is defined as the asymmetry between the

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number of events from a baryon decay process and its corresponding antimatter decay process, subtracting the asymmetries arising from the baryon production and final state particle detection. As mentioned earlier, no large CP asymmetry has been observed in two-body baryon decays. The explanation for the small CP violation is not yet clear, some theories suggest that the S-wave and P-wave contributions to the CP violation in a two-body baryon decays may have opposite signs, thereby cancelling each other, making the total amount of CP violation small [40].

In multi-body baryon decays, CP violation could be described by not only A_{CP}, but also can vary across the decay phase space. The rich structure in the phase space also allows the use of various analysis methods, including direct CP asymmetry measurements, triple-product asymmetries [26], amplitude analysis, and Energy Test [41] techniques.

The first evidence of CP violation in baryon decays was found in the multi-body baryon decay of $\Lambda_b^0 \to \Lambda K^+ K^-$, which showed a CP asymmetry of $(8.3 \pm 2.3 \pm 1.6)\%$, with local asymmetry reaching about $(16.5 \pm 4.8 \pm 1.7)\%$ [37], however, this decay channel is limited by statistics, yielding a significance of 3.1 standard deviations and requiring further confirmation. Later, the first evidence of CP violation in b-baryons decays to charmonium was found in $\Lambda_b^0 \to J/\psi p h^-$ decays, with a significance of 3.9 standard deviations [39].

The most significant result from LHCb is the first observation of CP violation baryon decays in $\Lambda_b^0 \to p K^- \pi^+ \pi^-$ decays [10], with a significance of 5.2σ:

$$A_{\rm CP} = (2.45 \pm 0.46 \pm 0.10)\%.$$

This decay exhibits rich resonance structures, including $N^*(p\pi^+\pi^-)$, $K^{*-}(K^-\pi^+\pi^-)$, and $\Lambda(pK^-)$ intermediate states. Enhanced CP violation effects are observed in specific phase-space regions (see Table 3), with the largest asymmetry of $(5.4 \pm 0.9 \pm 0.1)\%$ in the $N^*(p\pi^+\pi^-)$ resonance region. In this region, a significance of 6.0 standard deviations is observed. The mass distributions in the $R(p\pi^+\pi^-)$ resonance phase space is shown in Figure 1.

Table 3: Local CP asymmetries in $\Lambda_b^0 \to p K^- \pi^+ \pi^-$ decays [10]

Decay topology	Mass region (GeV/c^2)	$A_{\rm CP}(\%)$
$\Lambda_b^0 \to R(pK^-)R(\pi^+\pi^-)$	$m_{pK^-} < 2.2$, $m_{\pi^+\pi^-} < 1.1$	$5.3 \pm 1.3 \pm 0.2$
$\Lambda_b^0 \to R(p\pi^-)R(K^-\pi^+)$	$m_{p\pi^-} < 1.7$, $m_{\pi^+K^-} \in (0.8, 1.0)$ or $(1.1, 1.6)$	$2.7 \pm 0.8 \pm 0.1$
$\Lambda_b^0 \to R(p\pi^+\pi^-)K^-$	$m_{p\pi^+\pi^-} < 2.7$	$5.4 \pm 0.9 \pm 0.1$
$\Lambda_b^0 \to R(K^-\pi^+\pi^-)p$	$m_{K^-\pi^+\pi^-} < 2.0$	$2.0 \pm 1.2 \pm 0.3$

4. Conclusions and outlook

The search for CP violation in baryon decays has entered a new era, with LHCb's recent discovery of baryon CP violation marking a major milestone. The observed baryon CP violation effects are broadly consistent with SM predictions, but the rich phase-space dependence and resonance structures highlight the need for more detailed theoretical calculations to fully understand the decay dynamics.

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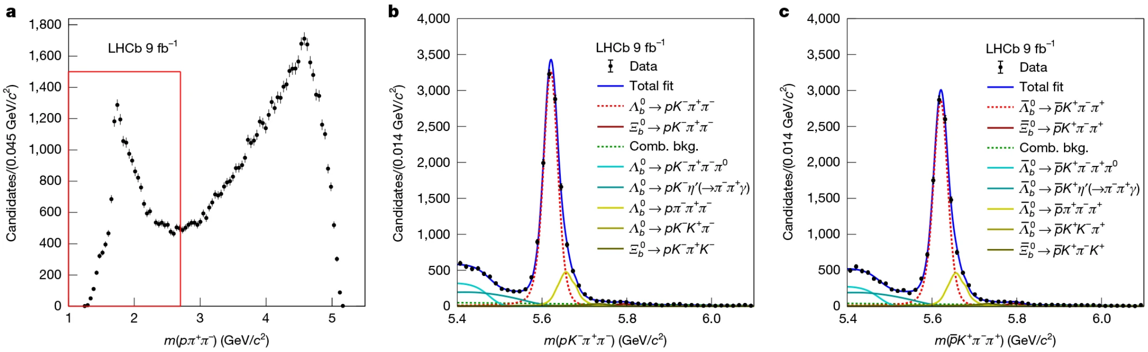

Figure 1: (a) Distribution of the $p\pi^+\pi^-$ mass including both Λ_b^0 and $\overline{\Lambda}_b^0$ candidates. The low-mass structure corresponds to excited nucleon resonances decaying to the $p\pi^+\pi^-$final state, whereas the broad structure at higher masses arises from other decay processes of the Λ_b^0 baryon. (b)(c) Mass distributions of candidates within the region delimited by the red box in (a) are shown for $\Lambda_b^0 \to pK^-\pi^+\pi^-$ (b) and its antimatter correspondent decays (c), together with the fitted projections and individual components.

Future prospects are promising. BESIII will continue to collect more charmonia threshold data following the upgrade of the BEPCII collider and BESIII inner tracker, enabling even more precise measurements of hyperon decay parameters and potential CP violataion effects [15].

LHCb's Run 3 program (2022–2026) is expected to collect an integrated luminosity over 20 fb^{-1}, more than twice the sum of Runs 1 and Run 2. The upgraded detector will enable higher precision measurements and searches for CP violation in new baryon decay channels, providing further insights into the origin of baryon CP violation and potential new physics contributions.

In the longer term, LHCb Upgrade II and future experiments, such as the proposed Super Tau-Charm Facility (STCF), Future Circular Collider (FCC-ee), and Circular Electron–Positron Collider (CEPC), will further expand the reach of baryon CP violation searches.

These efforts will not only test the SM's description of CP violation but also provide crucial clues for solving the baryon asymmetry of the Universe, bringing us closer to understanding one of the most fundamental questions in physics.

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