PROCEEDINGS OF SCIENCE

Beauty baryon decays at LHCb

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The beauty baryon spectroscopy exhibits a rich phenomenology, contributing to a deeper comprehension of fundamental interactions. The large sample of beauty baryons produced at the Large Hadron Collider offers an unprecedented opportunity to enhance our understanding of these particles through searching for new decay channels, measurement of b-baryon properties and decay parameters, and exploration of new states. This proceeding discusses recent results on beauty baryon decays based on proton-proton collision data samples, corresponding to an integrated luminosity of about $5\,\mathrm{fb}^{-1}$ or $9\,\mathrm{fb}^{-1}$, collected by the LHCb experiment at center-of-mass energies of 7, 8 and 13 TeV.

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1. Introduction

Heavy baryons are essential systems for studying both weak and strong interaction dynamics in the domain of flavor physics. While there has been significant progress in the study of beauty mesons, properties of beauty baryons remain largely unknown.

Given the large production rates of beauty baryons at the Large Hadron Collider (LHC), this enables improved precision of measurements and a better understanding of the underlying principles governing heavy flavor dynamics.

2. Recent results on beauty baryon decays at LHCb

2.1 Observation of $\Xi_b^0 \to \Xi_c^+ D_s^-$ and $\Xi_b^- \to \Xi_c^0 D_s^-$ decays

According to the quark model, the Λ_b^0, Ξ_b^0 and Ξ_b^- baryons form an SU(3) flavor multiplet, so do the Λ_c^+, Ξ_c^+ and Ξ_c^0. The heavy quark effective theory predicts that the partial decay widths of the three decay modes, $\Lambda_b^0 \to \Lambda_c^+ D_s^-$, $\Xi_b^0 \to \Xi_c^+ D_s^-$ and $\Xi_b^- \to \Xi_c^0 D_s^-$, are approximately the same [1]. Specifically, the $\Lambda_b^0 \to \Lambda_c^+ D_s^-$ decay has been measured with a branching fraction of $(1.10 \pm 0.10) \times 10^{-2}$ [2], while no prior measurements have been made for the decays $\Xi_b^0 \to \Xi_c^+ D_s^-$ and $\Xi_b^- \to \Xi_c^0 D_s^-$. Measuring these decays provides an opportunity to test the SU(3) flavor symmetry and further explore the dynamics of beauty-baryon weak decays.

The LHCb experiment has measured the relative production rates of the three decays using 5.1 fb^{-1} of proton-proton (pp) collision data collected during Run 2. These rates are defined as the product of the relative branching ratios and the corresponding ratios of beauty-hadron production cross-sections, as shown in Eq. 1. Final results of the relative production rates of the decays are [3]

$$\begin{aligned}
\mathcal{R}\left(\frac{\Xi_b^0}{\Lambda_b^0}\right) &\equiv \frac{\sigma\left(\Xi_b^0\right)}{\sigma\left(\Lambda_b^0\right)} \times \frac{\mathcal{B}\left(\Xi_b^0 \to \Xi_c^+ D_s^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ D_s^-\right)} = (15.8 \pm 1.1 \pm 0.6 \pm 7.7)\%, \\
\mathcal{R}\left(\frac{\Xi_b^-}{\Lambda_b^0}\right) &\equiv \frac{\sigma\left(\Xi_b^-\right)}{\sigma\left(\Lambda_b^0\right)} \times \frac{\mathcal{B}\left(\Xi_b^- \to \Xi_c^0 D_s^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ D_s^-\right)} = (16.9 \pm 1.3 \pm 0.9 \pm 4.3)\%, \\
\mathcal{R}\left(\frac{\Xi_b^0}{\Xi_b^-}\right) &\equiv \frac{\sigma\left(\Xi_b^0\right)}{\sigma\left(\Xi_b^-\right)} \times \frac{\mathcal{B}\left(\Xi_b^0 \to \Xi_c^+ D_s^-\right)}{\mathcal{B}\left(\Xi_b^- \to \Xi_c^0 D_s^-\right)} = (93.6 \pm 9.6 \pm 6.1 \pm 51.0)\%,
\end{aligned} \tag{1}$$

where the first uncertainties are statistical, the second systematic, and the third due to those of the branching fractions of Λ_c^+ , Ξ_c^+, and Ξ_c^0 decays. The results are consistent with SU(3) flavour symmetry and with predictions for relative production rates and decay branching fractions [1, 4, 5].

2.2 First observation of the $\Lambda_b^0 \to D^+ D^- \Lambda$ decay

The $\Lambda_b^0 \to D^+ D^- \Lambda$ decay is mediated by $b \to c\bar{c}s$ process, and it can decay via two types of two-body intermediate states. One is a Λ baryon and a charmonium resonance, the other one is a charmed baryon and a D meson. Thus it is predicted that there may exist resonances like charmonium $\psi(3770)$ and even pentaquark [6].

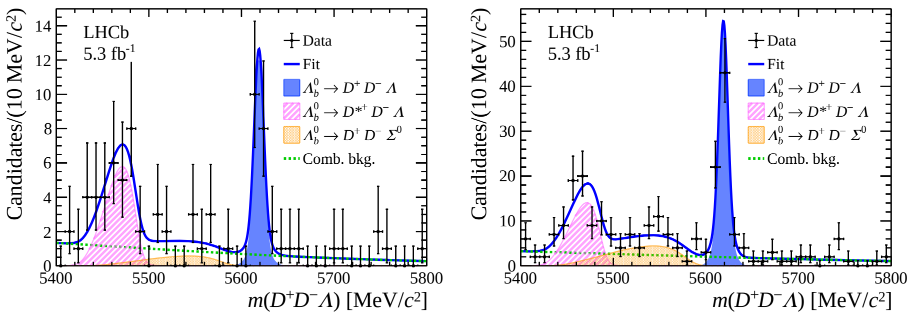

Figure 1: Invariant-mass distributions of $\Lambda_b^0 \to D^+D^-\Lambda$ candidates near the signal region with the fit results superimposed, for the (left) long-track and (right) downstream-track categories, respectively [7].

Using 5.3 fb^{-1} of pp collision data collected by LHCb during Run 2, the $\Lambda_b^0 \to D^+D^-\Lambda$ decay is observed experimentally for the first time. The invariant mass distributions and corresponding fit results are shown in Fig. 1. Its branching fraction is measured to be

$$\mathcal{B}(\Lambda_b^0 \to D^+D^-\Lambda) = (1.24 \pm 0.15 \pm 0.10 \pm 0.28 \pm 0.11) \times 10^{-4} \text{ [7]},$$

where the first uncertainty is statistical, the second is systematic, and the third and fourth come from the uncertainties on the $B^0 \to D^+D^-K_S^0$ branching fraction [8] and the beauty-hadron production cross-section ratio [9], respectively.

2.3 Observation and branching fraction measurement of the decay $\Xi_b^- \to \Lambda_b^0\pi^-$

Unlike many other decays of beauty baryons where the b quark decays, the $\Xi_b^- \to \Lambda_b^0\pi^-$ decay is mediated by $s \to u\bar{u}d$ where the b quark is a spectator. The $\Xi_b^- \to \Lambda_b^0\pi^-$ decay is observed for the first time at the LHCb experiment using pp collision data of Run 2, and the branching fraction is determined to be

$$\mathcal{B}(\Xi_b^- \to \Lambda_b^0\pi^-) = (0.89 \pm 0.10 \pm 0.07 \pm 0.29)\% \text{ [10]}, \tag{2}$$

where the uncertainties are statistical, systematic and from the fragmentation fractions of Ξ_b^- [11], respectively. The statistical precision is improved by a factor of three, compared to the result from Run 1 [12]. This extra contribution to the Ξ_b^- decay width should be considered when comparing the measured lifetime with theoretical predictions, where only the decays of the b quark are considered.

2.4 Precision measurement of the Ξ_b^- baryon lifetime

The heavy quark expansion (HQE) framework offers predictions for inclusive decay rates of beauty hadrons, allowing the calculation of b-hadron parameters, which are essential for determining elements of the CKM matrix. One critical test of the HQE is comparing its lifetime predictions for beauty baryons with experimental measurements. In particular, the ratio of $\tau_{\Xi_b^-}/\tau_{\Lambda_b^0}$ has an experimental uncertainty of 2.5% which exceeds the theoretical uncertainty of 1.9%, indicating the need for updated measurements [13].

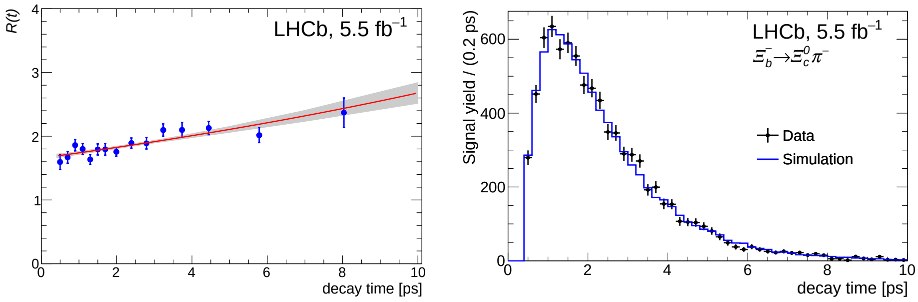

Figure 2: (Left) Corrected yield ratio $R(t)$ as a function of the decay time. The red line shows the fit result, and the gray band shows the 68% confidence level interval. (Right) Overlay of the decay-time spectrum of Ξ_b^- signal decays and simulation using the best fit lifetime of 1.575 ps [15].

The ratio of efficiency-corrected signal yields as a function of decay time, $R(t)$, defined as

$$R(t) \equiv \frac{N\left[\Xi_b^- \to \Xi_c^0 \pi^-\right](t)}{N\left[\Lambda_b^0 \to \Lambda_c^+ \pi^-\right](t)} \cdot \frac{\epsilon\left[\Lambda_b^0 \to \Lambda_c^+ \pi^-\right](t)}{\epsilon\left[\Xi_b^- \to \Xi_c^0 \pi^-\right](t)} = R_0 \exp(\lambda t), \tag{3}$$

where $\lambda \equiv 1/\tau_{\Lambda_b^0} - 1/\tau_{\Xi_b^-}$, is fitted to extract λ, and thus the lifetime ratio $\tau_{\Xi_b^-}/\tau_{\Lambda_b^0}$ can be determined, as shown in Fig. 2.

Using data samples collected during Run 2, the LHCb experiment provides the most precise measurement to date of the Ξ_b^- baryon lifetime, improving the precision of the world-average value by a factor of two [14]. Combining the Run 1 and Run 2 results measured by LHCb, we have

$$\frac{\tau_{\Xi_b^-}}{\tau_{\Lambda_b^0}} = (1.077 \pm 0.012 \pm 0.007)\ \text{ps}\ [15], \tag{4}$$

which is consistent with the HQE prediction of (1.078 ± 0.021) ps [13]. This result remains consistent with expectations, when accounting for the reduction (about 1%) in the HQE prediction due to the s-quark decay $\Xi_b^- \to \Lambda_b^0 \pi^-$ [10].

2.5 Measurement of Λ_b^0, Λ_c^+ and Λ decay parameters using $\Lambda_b^0 \to \Lambda_c^+ h^-$ decays

Decay parameters provide an excellent opportunity to enhance our understanding of the baryon decay dynamics and are also used to probe the matter–antimatter asymmetry. For a decay of a particle with spin-parity $\frac{1}{2}^+$ to a particle with spin-parity $\frac{1}{2}^+$ and a 0^- particle, the decay parameters α, β and γ are defined as functions of the S-wave and P-wave amplitudes

$$\alpha \equiv \frac{2\,\mathrm{Re}(s * p)}{|s|^2 + |p|^2}, \quad \beta \equiv \frac{2\,\mathrm{Im}(s * p)}{|s|^2 + |p|^2}, \quad \gamma \equiv \frac{|s|^2 - |p|^2}{|s|^2 + |p|^2}, \tag{5}$$

where $\alpha^2 + \beta^2 + \gamma^2 = 1$. CP violation can be quantified through these decay parameters by

$$A_\alpha = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} = -\tan\Delta\delta \tan\Delta\phi, \quad R_\beta = \frac{\beta + \bar{\beta}}{\alpha - \bar{\alpha}} = \tan\Delta\phi, \tag{6}$$

where $\bar{\alpha}$ and $\bar{\beta}$ are decay parameters of anti-baryon decay, and $\Delta\delta$ and $\Delta\phi$ are the differences in the strong and weak phase shifts between the S-wave and P-wave components.

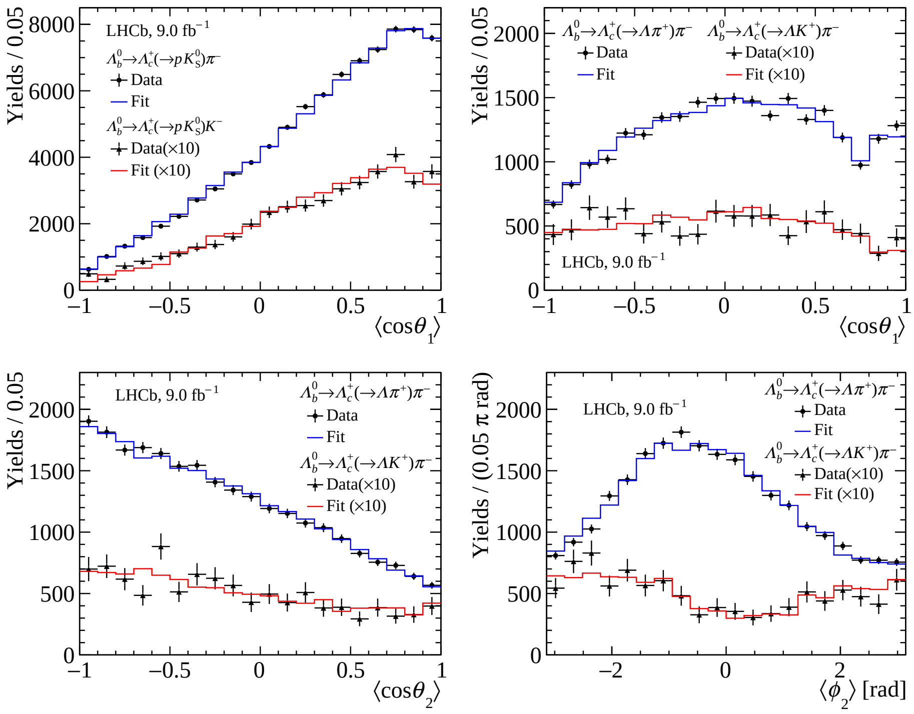

Figure 3: Distributions of (top left) the $\langle\cos\theta_1\rangle$ angle of the $\Lambda_b^0 \to \Lambda_c^+\left(\to pK_S^0\right)h^-$decays, and the (top right) $\langle\cos\theta_1\rangle$, (bottom left) $\langle\cos\theta_2\rangle$ and (bottom right) $\langle\phi_2\rangle$ angles of the $\Lambda_b^0 \to \Lambda_c^+(\to \Lambda h^+)\pi^-$decays. The angular brackets denote that the Λ_b^0 and $\overline{\Lambda}_b^0$ samples are merged [16].

Table 1: Measurements of α parameters and their *CP* asymmetries. The first uncertainties are statistical and the second are systematic.

Decay	α	$\bar{\alpha}$	$\langle\alpha\rangle$	A_α
$\Lambda_b^0 \to \Lambda_c^+\pi^-$	$-1.010 \pm 0.011 \pm 0.003$	$0.996 \pm 0.011 \pm 0.003$	$-1.003 \pm 0.008 \pm 0.005$	$0.007 \pm 0.008 \pm 0.005$
$\Lambda_b^0 \to \Lambda_c^+K^-$	$-0.933 \pm 0.042 \pm 0.014$	$0.995 \pm 0.036 \pm 0.013$	$-0.964 \pm 0.028 \pm 0.015$	$-0.032 \pm 0.029 \pm 0.006$
$\Lambda_c^+ \to \Lambda\pi^+$	$-0.782 \pm 0.009 \pm 0.004$	$0.787 \pm 0.009 \pm 0.003$	$-0.785 \pm 0.006 \pm 0.003$	$-0.003 \pm 0.008 \pm 0.002$
$\Lambda_c^+ \to \Lambda K^+$	$-0.569 \pm 0.059 \pm 0.028$	$0.464 \pm 0.058 \pm 0.017$	$-0.516 \pm 0.041 \pm 0.021$	$0.102 \pm 0.080 \pm 0.023$
$\Lambda_c^+ \to pK_S^0$	$-0.744 \pm 0.012 \pm 0.009$	$0.765 \pm 0.012 \pm 0.007$	$-0.754 \pm 0.008 \pm 0.006$	$-0.014 \pm 0.011 \pm 0.008$
$\Lambda \to p\pi^-$	$0.717 \pm 0.017 \pm 0.009$	$-0.748 \pm 0.016 \pm 0.007$	$0.733 \pm 0.012 \pm 0.006$	$-0.022 \pm 0.016 \pm 0.007$

The decay channels studied include $\Lambda_b^0 \to \Lambda_c^+h_1^-$, with subsequent decays of $\Lambda_c^+ \to \Lambda(\to p\pi^-)h_2^+$ or $\Lambda_c^+ \to pK_S^0$, where h_1^- and h_2^+ are either a pion or kaon. Using 9 fb^{-1} of full Run 1 and Run 2 pp collision data, the decay parameters are extracted from angular distributions, which are shown in Fig. 3, superimposed by fit results. Results of α parameters of Λ_b^0, Λ_c^+ and Λ are shown in Table 1. More results can be found in [16].

This is the first measurement of decay parameters of $\Lambda_b^0 \to \Lambda_c^+h^-$, and the precision of decay parameters in Λ_c^+ decays improves significantly. The results of Λ decays are consistent with previous BESIII results [17]. The CP-related parameters are also obtained, and no CP violation is found.

3. Summary

LHCb is a factory of beauty baryons, from which we can greatly improve knowledge about new decay modes and more precise parameters about b-baryons. These studies can help us open the door to search for exotic states, test and constrain theoretical models and search for new physics.

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