Measurement of Λ_b^0, Λ_c^+, and Λ Decay Parameters Using $\Lambda_b^0 \to \Lambda_c^+ h^-$ Decays

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A comprehensive study of the angular distributions in the bottom-baryon decays $\Lambda_b^0 \to \Lambda_c^+ h^- (h = \pi, K)$, followed by $\Lambda_c^+ \to \Lambda h^+$ with $\Lambda \to p\pi^-$ or $\Lambda_c^+ \to pK_S^0$ decays, is performed using a data sample of proton-proton collisions corresponding to an integrated luminosity of 9 fb^{-1} collected by the LHCb experiment at center-of-mass energies of 7, 8, and 13 TeV. The decay parameters and the associated charge-parity (CP) asymmetries are measured, with no significant CP violation observed. For the first time, the $\Lambda_b^0 \to \Lambda_c^+ h^-$ decay parameters are measured. The most precise measurements of the decay parameters α, β, and γ are obtained for Λ_c^+ decays and an independent measurement of the decay parameters for the strange-baryon Λ decay is provided. The results deepen our understanding of weak decay dynamics in baryon decays.

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Hadronic weak decays of baryons provide an excellent platform for studying baryon decay dynamics and the origin of the asymmetry between matter and antimatter [1–3]. Among them, the decay of a spin-half baryon to a spin-half baryon and a pseudoscalar meson is of special interest. For this type of decay, three decay parameters, first proposed by Lee and Yang to search for parity violation [4], can be defined as

$$\alpha \equiv \frac{2\Re(s^* p)}{|s|^2+|p|^2}, \quad \beta \equiv \frac{2\Im(s^* p)}{|s|^2+|p|^2}, \quad \gamma \equiv \frac{|s|^2-|p|^2}{|s|^2+|p|^2}, \qquad (1)$$

satisfying $\alpha^2+\beta^2+\gamma^2=1$, where s and p denote the parity-violating S-wave and parity-conserving P-wave amplitudes, respectively. The interference between the two amplitudes may generate differences between the differential decay rates of baryons and antibaryons, allowing CP-violation phenomena to be probed via angular analyses [5]. The amount of CP violation can be quantified by the asymmetries $A_\alpha = (\alpha+\bar{\alpha})/(\alpha-\bar{\alpha})$ and $R_\beta = (\beta+\bar{\beta})/(\alpha-\bar{\alpha})$, where $\bar{\alpha}$ and $\bar{\beta}$ denote the decay parameters of the antibaryons, and should have signs opposite to their baryonic counterparts. At leading order, these CP asymmetries are related to the weak and strong phase differences between the S- and P-wave amplitudes, $\Delta\phi$ and $\Delta\delta$, via the relations $A_\alpha = -\tan\Delta\delta \tan\Delta\phi$ and $R_\beta = \tan\Delta\phi$ [1].

Many phenomenological models have been used to calculate baryon decay parameters. For some two-body beauty-baryon decays, factorization is assumed to hold in model calculations [6–15], which predict that $\alpha \approx -1$, consistent with the $V-A$ nature of the weak current and maximal parity violation. For charm-baryon decays, model calculations are complicated by the presence of nonfactorizable contributions and often do not agree with each other [16–27]. For strange-baryon decays, nonfactorizable contributions may dominate, making theoretical calculations even more challenging [1].

Decay parameters have been measured for several hyperon and charm-baryon decays [28], while beauty decays are much less explored. The α parameter of the $\Lambda \to p\pi^-$ decay was recently updated by the BESIII [29,30] and CLAS [31] Collaborations, which resulted in a significantly larger value compared to the previous world average [32]. The α parameters of several Λ_c^+ decays were precisely measured by the FOCUS [33], BESIII [34], and Belle [35] Collaborations, while the precision of the β and γ measurements is still very limited [34,36]. To date, there is no decay parameter measurement for any Λ_b^0 decay to a baryon and a pseudoscalar meson, despite the observation of many such decay modes. The decay parameter of the $\Lambda_b^0 \to J/\psi\Lambda$ decay was measured in proton-proton (pp) collisions at the LHC [37–40], together with the Λ_b^0 polarization, which is found to be consistent with zero. Moreover, the photon polarization of the $\Lambda_b^0 \to \Lambda\gamma$ decay was measured by LHCb [41], suggesting the dominance of left-handed photons.

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In this Letter, the decay parameters and CP asymmetries of $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ and $\Lambda_b^0 \to \Lambda_c^+ K^-$ decays are measured through an angular analysis. Three Λ_c^+ decays are analyzed: $\Lambda_c^+ \to p K_S^0$, $\Lambda_c^+ \to \Lambda \pi^+$, and $\Lambda_c^+ \to \Lambda K^+$ with the subsequent decays $\Lambda \to p \pi^-$ and $K_S^0 \to \pi^+ \pi^-$. The decay parameters and associated CP asymmetries of the Λ_b^0, Λ_c^+, and Λ decays are determined simultaneously. The analysis is performed using data from pp collisions at center-of-mass energies of $\sqrt{s} = 7$, 8, and 13 TeV, corresponding to an integrated luminosity of 9 fb^{-1} collected with the LHCb detector. Inclusion of charge-conjugate processes is implied, unless otherwise stated.

The LHCb detector, designed for the study of particles containing b or c quarks, is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, described in detail in Refs. [42,43]. The online event selection for Λ_b^0 decays is performed by a trigger [44], which consists of a hardware stage followed by a software stage [45–48]. The hardware trigger is based on information from the calorimeter and muon systems. The software trigger requires a secondary vertex with a significant displacement from any primary vertex (PV).

Simulated samples of Λ_b^0 decays are produced to optimize event selection, study potential backgrounds and model the detector acceptance. These samples are generated using the software described in Refs. [49–54]. The products of each decay in the Λ_b^0 cascades are distributed uniformly in the allowed phase space.

In the offline selection, all tracks in the final state are required to have a large transverse momentum and be inconsistent with being directly produced from any PV. The Λ and K_S^0 candidates are reconstructed using $\Lambda \to p\pi^-$ and $K_S^0 \to \pi^- \pi^+$ decays, where the final-state tracks are required to form a vertex with a good fit quality that is significantly displaced from any PV and their invariant mass is consistent with the known value [28]. The Λ (K_S^0) candidate is combined with a kaon or pion (proton) track to form the Λ_c^+ candidate. The Λ_c^+ invariant mass is required to be within $\pm 26(20) \mathrm{MeV}/c^2$ of the known value [28] for the $\Lambda_c^+ \to p K_S^0$ and $\Lambda_c^+ \to \Lambda \pi^+$ ($\Lambda_c^+ \to \Lambda K^+$) decays. The smaller mass region for the $\Lambda_c^+ \to \Lambda K^+$ decay is used to suppress the $\Lambda_c^+ \to \Sigma^0 (\to \Lambda \gamma) \pi^+$ background, where the photon is not reconstructed. The Λ_b^0 candidate is formed by combining a Λ_c^+ candidate with a kaon or pion. The Λ_b^0 invariant mass, $m(\Lambda_c^+ h^-)$, is required to be larger than 5500 MeV/c^2 to reject background due to partially reconstructed Λ_b^0 decays.

Two types of background peaking in the signal mass region are identified. For the first type, D^0 or J/ψ mesons are observed in the invariant-mass distributions of the two charged companion tracks of Λ_b^0 and Λ_c^+ decays. The second type involves a genuine K_S^0 (Λ) decay reconstructed as the Λ (K_S^0) decay. These background candidates are suppressed using information from particle identification (PID) detectors or rejected by specific vetoes in the corresponding mass spectra. A boosted decision tree (BDT) classifier implemented in the TMVA toolkit [55] is then used to separate the Λ_b^0 signal from the background of random combinations of final-state particles. The BDT analysis is performed independently for $\Lambda_c^+ \to p K_S^0$ and $\Lambda_c^+ \to \Lambda h^+$ decays. Each BDT classifier is trained on simulated signal decays and background from data in the high-mass region $m(\Lambda_c^+ h^-) > 5900$ MeV/c^2, using a combination of kinematic, topological, and isolation variables of the Λ_b^0, Λ_c^+, Λ, or K_S^0 hadrons. In the final stage of the event selection, a simultaneous optimization of the final-state PID and BDT classifier requirements is performed to maximize the figure of merit, $N_S^2/(N_S + N_B)^{3/2}$, chosen to favor a high signal purity with small decay-parameter uncertainties. Here, N_S and N_B represent the signal and background yields in the signal region chosen to be ± 32 MeV/c^2 around the known Λ_b^0 mass [28], estimated with simulated signal decays and data in the high-mass region. The Λ_b^0 invariant mass is calculated with a kinematic fit [56] constraining the masses of all intermediate particles to their known values and the Λ_b^0 momentum to point back to its best-matched PV.

The invariant-mass distributions of the five significant Λ_b^0 cascade decays to $(pK_S^0)\pi^-$, $(pK_S^0)K^-$, $(\Lambda\pi^+)\pi^-$, $(\Lambda\pi^+)K^-$, and $(\Lambda K^+)\pi^-$ final states, where Λ_c^+ decay products are shown in brackets, are shown in Fig. 1 for candidates passing all selection criteria. The signal yields of the five decays are determined to be $(8.635 \pm 0.032) \times 10^4$, $(4.16 \pm 0.07) \times 10^3$, $(2.475 \pm 0.017) \times 10^4$, $(1.19 \pm 0.04) \times 10^3$, and $(1.010 \pm 0.034) \times 10^3$, respectively, from unbinned maximum-likelihood fits performed to the Λ_b^0 mass distributions. The signal component is described by a Hypatia function [57] and the combinatorial background by an exponential function. The $\Lambda_b^0 \to \Lambda_c^+ K^-$ decay misidentified as $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ decay, or vice versa, is also modeled by a Hypatia function, whose parameters are fixed to those obtained from the simulated samples. The relative yields of these cross-feed contributions are constrained using relative experimental efficiencies. For every decay mode, the fit result is used to determine the *sPlot* weight for each candidate [58], applied to subtract the background for the subsequent angular analysis.

The decay parameters are determined by analyzing the angular distributions of the Λ_b^0 cascade decays. The angular variables are calculated with the Λ_b^0 invariant mass constrained to the known value [28]. The kinematics of the three-step cascade $\Lambda_b^0 \to \Lambda_c^+[\to \Lambda(\to p\pi^-)h_1^+]h_2^-$ decays are fully described by five angular variables $\vec{\Omega} \equiv (\theta_0, \theta_1, \phi_1, \theta_2, \phi_2)$, depicted in Fig. 2. The variable θ_0 is the polar angle between the normal $\vec{P}_z$ of the production plane formed by the beam and Λ_b^0 momenta in the laboratory frame, and the Λ_c^+ momentum $\vec{p}_{\Lambda_c^+}$ in the Λ_b^0 rest frame. The variable θ_1 (θ_2) is the polar angle between $\vec{p}_{\Lambda_c^+}$ ($\vec{p}_p$) and $\vec{p}_\Lambda$, where particle

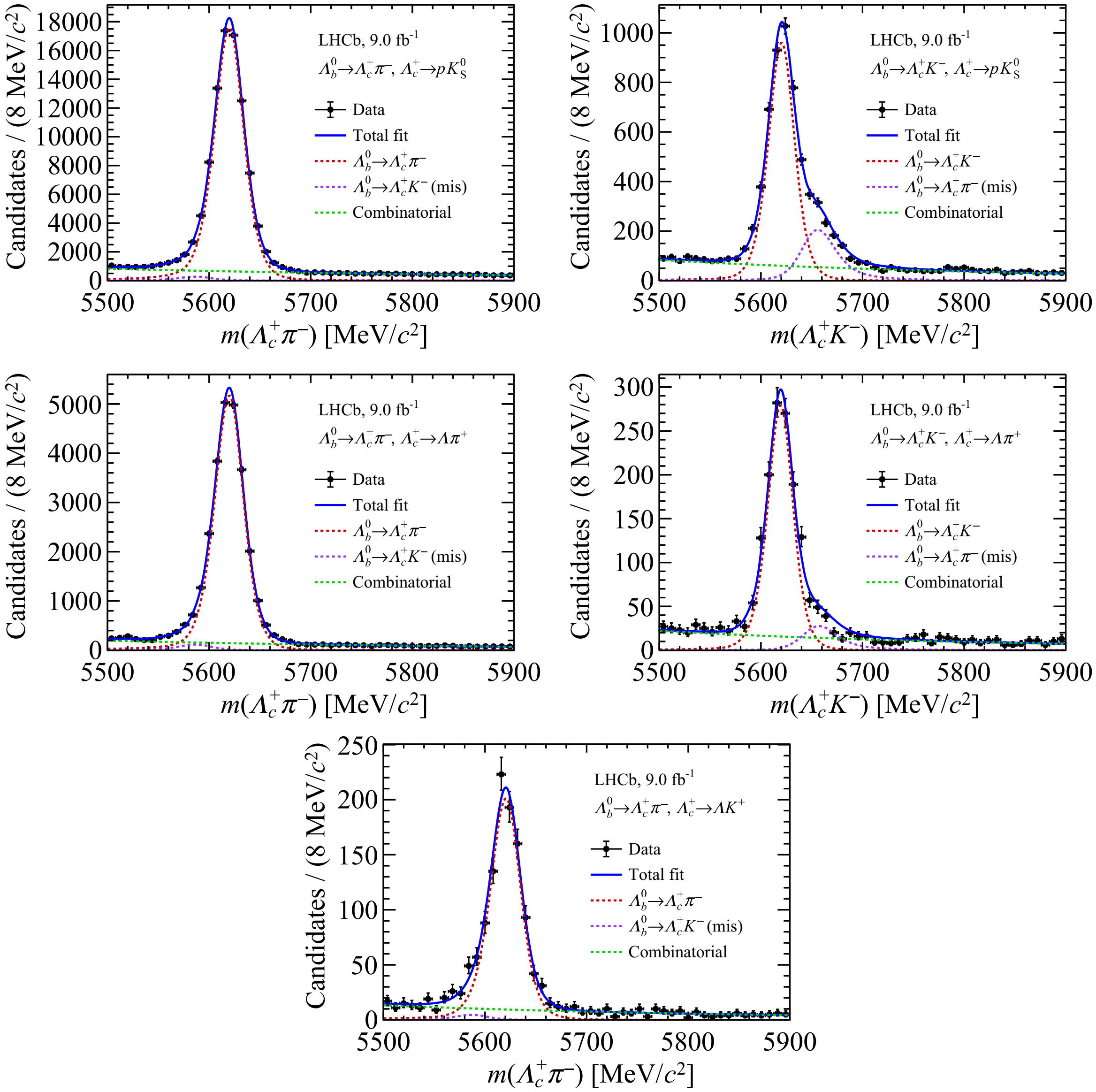

FIG. 1. The invariant-mass distributions of Λ_b^0 candidates reconstructed in the (top left) $\Lambda_b^0 \to \Lambda_c^+(\to pK_S^0)\pi^-$, (top right) $\Lambda_b^0 \to \Lambda_c^+(\to pK_S^0)K^-$, (middle left) $\Lambda_b^0 \to \Lambda_c^+(\to \Lambda\pi^+)\pi^-$, (middle right) $\Lambda_b^0 \to \Lambda_c^+(\to \Lambda\pi^+)K^-$, and (bottom) $\Lambda_b^0 \to \Lambda_c^+(\to \Lambda K^+)\pi^-$ decays, with the fit results drawn.

momenta are defined in the rest frames of the Λ_b^0 (Λ) and Λ_c^+ baryons, respectively. The variable ϕ_1 (ϕ_2) is the angle between the Λ_b^0 (Λ) decay plane and the Λ_c^+ decay plane, spanned by the momenta of their respective decay products. Similarly, for the two-step cascade decays, $\Lambda_b^0 \to \Lambda_c^+(\to pK_S^0)h_2^-$, the kinematics are described by three angular variables $\vec{\Omega} \equiv (\theta_0, \theta_1, \phi_1)$, which are the same as the first three variables of the three-step cascade.

The angular distributions can be expanded through the helicity formalism [59]. Based on previous studies at the LHC [37–40], the Λ_b^0 baryon is considered to be unpolarized, in which case the angular distributions become uniform in θ_0 and ϕ_1. The impact of Λ_b^0 polarization is considered as a source of systematic uncertainty. The reduced angular distributions are thus expressed as

$$\frac{\mathrm{d}^3\Gamma}{\mathrm{d}\cos\theta_1 \mathrm{d}\cos\theta_2 \mathrm{d}\phi_2} \propto (1 + \alpha_{\Lambda_b^0}\alpha_{\Lambda_c^+}\cos\theta_1 + \alpha_{\Lambda_c^+}\alpha_\Lambda\cos\theta_2 + \alpha_{\Lambda_b^0}\alpha_\Lambda\cos\theta_1\cos\theta_2 - \alpha_{\Lambda_b^0}\gamma_{\Lambda_c^+}\alpha_\Lambda\sin\theta_1\sin\theta_2\cos\phi_2 + \alpha_{\Lambda_b^0}\beta_{\Lambda_c^+}\alpha_\Lambda\sin\theta_1\sin\theta_2\sin\phi_2), \tag{2}$$

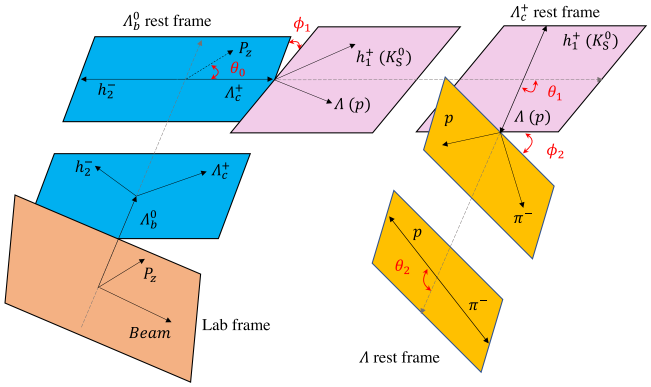

FIG. 2. Definition of the helicity angles for $\Lambda_b^0 \to (\Lambda_c^+ \to \Lambda h_1^+) h_2^-$ and $\Lambda_b^0 \to (\Lambda_c^+ \to pK_S^0)h^-$ decays, where h_1^+, h_2^- denote the kaon or pion.

for $\Lambda_b^0 \to \Lambda_c^+[\to \Lambda(\to p\pi^-)h_1^+]h_2^-$ decays, and

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_1} \propto 1 + \alpha_{\Lambda_b^0}\alpha_{\Lambda_c^+}\cos\theta_1, \tag{3}$$

for $\Lambda_b^0 \to \Lambda_c^+(\to pK_S^0)h_2^-$ decays, where the subscript of the decay parameters denotes the decaying particle. The decay parameters in this analysis are determined from simultaneous unbinned maximum-likelihood fits to the five Λ_b^0 $(\bar{\Lambda}_b^0)$ cascade decays, imposing the constraint $(\alpha_{\Lambda_c^+})^2 + (\beta_{\Lambda_c^+})^2 + (\gamma_{\Lambda_c^+})^2 = 1$. The $\beta_{\Lambda_c^+}$ and $\gamma_{\Lambda_c^+}$ parameters are related to the $\alpha_{\Lambda_c^+}$ and $\Delta_{\Lambda_c^+}$ parameters by $\beta_{\Lambda_c^+} = \sqrt{1-(\alpha_{\Lambda_c^+})^2}\sin\Delta_{\Lambda_c^+}$, $\gamma_{\Lambda_c^+} = \sqrt{1-(\alpha_{\Lambda_c^+})^2}\cos\Delta_{\Lambda_c^+}$, where $\Delta_{\Lambda_c^+}$ is the phase difference between the two helicity amplitudes of the $\Lambda_c^+ \to \Lambda h^+$ decay. This leads to two equivalent sets of fit parameters for a $\Lambda_c^+ \to \Lambda h^+$ decay. The fit is performed for each set of parameters independently to directly determine their values and uncertainties. To test *CP* violation, an additional joint fit of Λ_b^0 and $\bar{\Lambda}_b^0$ samples is applied with *CP*-related fit parameters, which are the *CP* asymmetries A_α, R_β, and *CP* averages $\langle\alpha\rangle \equiv (\alpha - \bar{\alpha})/2$, $R'_\beta \equiv (\beta - \bar{\beta})/(\alpha - \bar{\alpha})$. At leading order, the weak and strong phase differences are determined using $R_\beta = \tan\Delta\phi$ and $R'_\beta = \tan\Delta\delta$ [1], and the quadrant of phases can be determined using Eq. (45) in Ref. [60].

The logarithm of the likelihood function ($\log\mathcal{L}$) is constructed as

$$\log\mathcal{L}(\vec{\nu}) = \sum_{k=1}^{5}\left(\mathcal{C}_k \sum_{i=1}^{N_k} w_{k,i} \times \log\left[\mathcal{P}_k(\vec{\Omega}_k^i|\vec{\nu})\right]\right), \tag{4}$$

where $\vec{\nu}$ is the set of decay parameters, $\vec{\Omega}$ is the set of angular variables, and $\mathcal{P}(\vec{\Omega}|\vec{\nu})$ represents the signal probability density function (PDF). The subscript k runs over the five Λ_b^0 cascade decays, and the subscript i runs over all the N_k candidates of the kth decay. The *sPlot* weight $w_{k,i}$ in the $\log\mathcal{L}$ is used to remove the contribution of background candidates [58], while the constants $\mathcal{C}_k \equiv \sum_{i\in\mathrm{data}_k} w_{k,i}/\sum_{i\in\mathrm{data}_k} w_{k,i}^2$ are scale factors needed to correct the obtained statistical uncertainties [61]. The signal PDF $\mathcal{P}_k(\vec{\Omega}_k|\vec{\nu})$ is formulated as

$$\mathcal{P}_k(\vec{\Omega}_k|\vec{\nu}) = \frac{\epsilon_k(\vec{\Omega}_k)\cdot f_k(\vec{\Omega}_k|\vec{\nu})}{\int \mathrm{d}\vec{\Omega}_k \epsilon_k(\vec{\Omega}_k)\cdot f_k(\vec{\Omega}_k|\vec{\nu})}, \tag{5}$$

where $f_k(\vec{\Omega}_k|\vec{\nu})$ represents the angular distribution given in Eqs. (2) or (3), and $\epsilon_k(\vec{\Omega}_k)$ is the angular acceptance. The denominator is calculated numerically using the Monte Carlo integration method beginning with the corresponding simulated signal decays after full selection [62,63]. The distributions of the Λ_b^0 transverse momentum and pseudorapidity, and the number of tracks per event in the simulation samples are corrected to match those in data. In Fig. 3, the angular distributions of $\Lambda_b^0 \to \Lambda_c^+(\to pK_S^0)h^-$ and $\Lambda_b^0 \to \Lambda_c^+(\to \Lambda h^+)\pi^-$ decays are shown, superimposed by the fit result. Distributions for all decays are provided in Ref. [64]. A binned χ^2 test between the data and the fit gives a p value of 28%.

Various sources of systematic uncertainty on the decay parameters are studied. Possible biases introduced by the angular fit method are evaluated using pseudoexperiments. Mass and angular distributions of pseudosamples, including possible correlations, are generated according to the baseline fit results, and then the whole fit procedure is repeated to extract decay parameters. The parameter's systematic uncertainty is taken to be the mean of its pull distribution times its nominal statistical uncertainty. The *sPlot* method is used to subtract the background, hence the choice of the invariant-mass fit model introduces systematic uncertainties. These are estimated by repeating the invariant-mass fit with alternative fit models, including alternative descriptions of mass-shape functions and removing the constraints on yields, then using the corresponding updated *sPlot* weights to determine decay parameters. As the PID variables in simulation samples are calibrated to match data [65,66], the uncertainty on the calibration procedure introduces systematic uncertainties which are estimated with alternative calibration configurations. The limited size of simulation samples introduces an uncertainty on the efficiency propagated to the decay parameters, which is estimated with bootstrapped pseudoexperiments [67]. The influence of the production asymmetry for Λ_b^0 baryons and detection asymmetries on the final-state particles [68–70] are taken into account. Following the prescription of *CP* measurements [71,72], these asymmetries are introduced in the angular acceptance, and the angular fit is repeated to verify their impact on the measurements. The polarization of Λ_b^0 baryons is

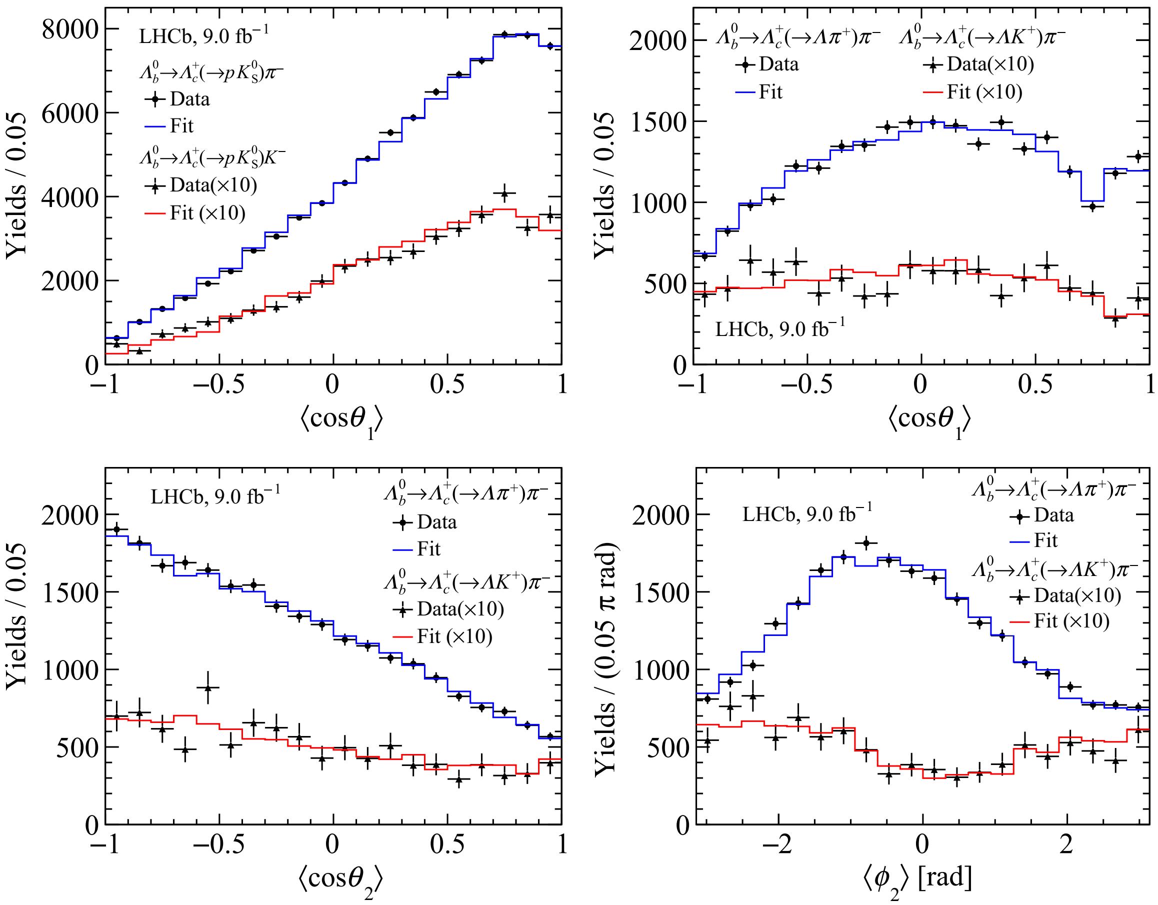

FIG. 3. Distributions of (top left) the $\langle\cos\theta_1\rangle$ angle of the $\Lambda_b^0\to\Lambda_c^+(\to pK_S^0)h^-$ decays, and the (top right) $\langle\cos\theta_1\rangle$, (bottom left) $\langle\cos\theta_2\rangle$, and (bottom right) $\langle\phi_2\rangle$ angles of the $\Lambda_b^0\to\Lambda_c^+(\to\Lambda h^+)\pi^-$ decays. The angular brackets denote that the Λ_b^0 and $\bar{\Lambda}_b^0$ samples are merged, where the ϕ_2 signs are also flipped for $\bar{\Lambda}_b^0$ samples. Points with error bars correspond to background-subtracted data using the *sPlot* technique.

considered as a source of systematic uncertainty. The angular fit is repeated with additional terms in the PDF incorporating the transverse polarization measured by LHCb [38] (see Appendix for details on this PDF). The impact of the experimental angular resolution is considered as a systematic uncertainty and found to be negligible. The spin of the Λ baryon undergoes a precession in the magnetic field of the detector, which modifies its angular distribution depending on the decay length [73]. The systematic uncertainty arising from the precession is examined using pseudoexperiments, and found to be negligible. A summary of the contributions from the various sources is given in Ref. [64]. The systematic uncertainties from different sources are added in quadrature, resulting in totals that are smaller than the statistical uncertainties.

The results are listed in Table I for the α parameters of Λ_b^0, Λ_c^+ and Λ decays, and in Table II for the β and γ

TABLE I. Measurements of α parameters and their CP asymmetries for $\Lambda_b^0\to\Lambda_c^+\pi^-$, $\Lambda_b^0\to\Lambda_c^+K^-$, $\Lambda_c^+\to\Lambda\pi^+$, $\Lambda_c^+\to\Lambda K^+$, $\Lambda_c^+\to pK_S^0$, and $\Lambda\to p\pi^-$ decays. The first uncertainties are statistical and the second are systematic.

Decay	α	$\bar{\alpha}$	$\langle\alpha\rangle$	A_α
$\Lambda_b^0\to\Lambda_c^+\pi^-$	$-1.010\pm0.011\pm0.003$	$0.996\pm0.011\pm0.003$	$-1.003\pm0.008\pm0.005$	$0.007\pm0.008\pm0.005$
$\Lambda_b^0\to\Lambda_c^+K^-$	$-0.933\pm0.042\pm0.014$	$0.995\pm0.036\pm0.013$	$-0.964\pm0.028\pm0.015$	$-0.032\pm0.029\pm0.006$
$\Lambda_c^+\to\Lambda\pi^+$	$-0.782\pm0.009\pm0.004$	$0.787\pm0.009\pm0.003$	$-0.785\pm0.006\pm0.003$	$-0.003\pm0.008\pm0.002$
$\Lambda_c^+\to\Lambda K^+$	$-0.569\pm0.059\pm0.028$	$0.464\pm0.058\pm0.017$	$-0.516\pm0.041\pm0.021$	$0.102\pm0.080\pm0.023$
$\Lambda_c^+\to pK_S^0$	$-0.744\pm0.012\pm0.009$	$0.765\pm0.012\pm0.007$	$-0.754\pm0.008\pm0.006$	$-0.014\pm0.011\pm0.008$
$\Lambda\to p\pi^-$	$0.717\pm0.017\pm0.009$	$-0.748\pm0.016\pm0.007$	$0.733\pm0.012\pm0.006$	$-0.022\pm0.016\pm0.007$

TABLE II. Measurements of the decay parameters β and γ, the phase difference Δ, the CP asymmetry R_β and the CP average R'_β for $\Lambda_c^+ \to \Lambda\pi^+$, $\Lambda_c^+ \to \Lambda K^+$ decays and their charge-conjugated decays. The first uncertainties are statistical and the second are systematic.

Decay	$\Lambda_c^+ \to \Lambda\pi^+$	$\Lambda_c^+ \to \Lambda K^+$
β	$0.368 \pm 0.019 \pm 0.008$	$0.35 \pm 0.12 \pm 0.04$
$\bar{\beta}$	$-0.387 \pm 0.018 \pm 0.010$	$-0.32 \pm 0.11 \pm 0.03$
γ	$0.502 \pm 0.016 \pm 0.006$	$-0.743 \pm 0.067 \pm 0.024$
$\bar{\gamma}$	$0.480 \pm 0.016 \pm 0.007$	$-0.828 \pm 0.049 \pm 0.013$
Δ (rad)	$0.633 \pm 0.036 \pm 0.013$	$2.70 \pm 0.17 \pm 0.04$
$\bar{\Delta}$ (rad)	$-0.678 \pm 0.035 \pm 0.013$	$-2.78 \pm 0.13 \pm 0.03$
R_β	$0.012 \pm 0.017 \pm 0.005$	$-0.04 \pm 0.15 \pm 0.02$
R'_β	$-0.481 \pm 0.019 \pm 0.009$	$-0.65 \pm 0.17 \pm 0.07$

parameters of $\Lambda_c^+ \to \Lambda h^+$ decays. The CP-related parameters are also obtained, and no CP violation is found. This is the first measurement of the parity-violating parameters of two-body Λ_b^0 decays into a spin-half baryon and a pseudoscalar meson. The results of the $\alpha_{\Lambda_b^0}$ decay parameters are close to -1, suggesting that Λ_c^+ baryons in $\Lambda_b^0 \to \Lambda_c^+ h^-$ decays are almost fully longitudinally polarized, which corresponds to the $V - A$ nature of weak decays and supports the factorization hypothesis in theoretical calculations [74]. The Λ_c^+ decay parameters are consistent with, and more precise than, the Belle [35] and BESIII [34] results. The $\alpha_{\Lambda_c^+}$ parameters are found to significantly deviate from -1, which may suggest that nonfactorizable contributions are substantial in hadronic decays of charm baryons. The β, γ, and Δ parameters of $\Lambda_c^+ \to \Lambda h^+$ decays are precisely measured for the first time, and will serve as essential inputs to theoretical models [60]. The weak and strong phase differences are determined to be $\Delta\phi = 0.01 \pm 0.02$ and $\Delta\delta = 2.693 \pm 0.017$ rad for the $\Lambda_c^+ \to \Lambda\pi^+$ decay, and $\Delta\phi = -0.03 \pm 0.15$ and $\Delta\delta = 2.57 \pm 0.19$ rad for the $\Lambda_c^+ \to \Lambda K^+$ decay. The α parameter and the corresponding CP asymmetry of the $\Lambda \to p\pi^-$ decay in this analysis are consistent with the BESIII results [29,30].

In conclusion, based on pp collision data collected by the LHCb experiment, corresponding to an integrated luminosity of 9 fb^{-1}, a comprehensive study of the angular distributions in Λ_b^0 cascade decays is performed. The analysis provides the first measurements of the decay parameters for $\Lambda_b^0 \to \Lambda_c^+ h^-$ decays, and the most precise measurements for the Λ_c^+ decay parameters. The weak and strong phase differences for $\Lambda_c^+ \to \Lambda h^+$ decays are also determined. The CP asymmetries are studied between the decay parameters of baryon and antibaryon decays, and no hint of CP violation is observed. The results provide valuable insights into the weak decay dynamics of baryons.

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End Matter

Appendix: Angular distributions—The helicity formalism is employed to describe the angular distributions of the decays in this Letter. For the decay of a spin-half baryon to a spin-half baryon and a pseudoscalar meson, two helicity amplitudes are involved with the respective couplings $H_\pm$, where the subscript represents the sign of the helicity of the final-state spin-half baryon. The helicity couplings are related to the S-wave (s) and P-wave (p) couplings as $s = (H_+ + H_-)/\sqrt{2}$ and $p = (H_+ - H_-)/\sqrt{2}$. The decay parameters are defined using the helicity amplitudes as

$$\alpha = \frac{|H_+|^2 - |H_-|^2}{|H_+|^2 + |H_-|^2}, \qquad \beta = \sqrt{1-\alpha^2}\sin\Delta,$$
$$\gamma = \sqrt{1-\alpha^2}\cos\Delta, \tag{A1}$$

where $\Delta = \arg(H_+/H_-)$ is the phase angle difference between the two helicity amplitudes.

The angular distribution is determined by the sum of all possible helicity amplitudes as

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\Omega} \propto |M|^2 = \sum_{\lambda_0,\lambda_0',\lambda_n} \rho_{\lambda_0,\lambda_0'} M_{\lambda_0,\lambda_n} M^*_{\lambda_0',\lambda_n}, \tag{A2}$$

where $\lambda_0^{(\prime)}$ and λ_n run over the helicities of the initial and final baryons, $\rho_{\lambda_0,\lambda_0'}$ is the polarization density matrix of the decaying baryon, and M_{λ_0,λ_n}, $M^*_{\lambda_0',\lambda_n}$ are the amplitude matrix elements.

For the Λ_b^0 baryon promptly produced in pp collisions, the possible polarization is expected to be perpendicular to the production plane due to parity conservation in strong interactions. Defining the polarization axis as the z axis, and the magnitude of the polarization as P_z, the polarization density matrix is expressed as

$$\rho = \begin{pmatrix} 1+P_z & 0 \\ 0 & 1-P_z \end{pmatrix}. \tag{A3}$$

Angular distribution for $\Lambda_b^0 \to \Lambda_c^+(\to pK_S^0)h^-$ decays: For $\Lambda_b^0 \to \Lambda_c^+(\to pK_S^0)h^-$ decays, the helicity amplitude is determined as

$$M_{\lambda_b,\lambda_p} = \sum_{\lambda_c} H^b_{\lambda_c} d^{\frac{1}{2}}_{\lambda_b,\lambda_c}(\theta_0) \cdot H^c_{\lambda_p} e^{i\lambda_c\phi_1} d^{\frac{1}{2}}_{\lambda_c,\lambda_p}(\theta_1), \tag{A4}$$

where $d^J_{\lambda,\lambda'}(\theta)$ is the Wigner d matrix, λ_b, λ_c and λ_p refer to the helicities of Λ_b^0, Λ_c^+ and p baryons, and $H^b_{\lambda_c}$ and $H^c_{\lambda_p}$ are the helicity couplings of Λ_b^0 and Λ_c^+ decays. The total amplitude squared is calculated by

$$|M|^2 \propto \sum_{\lambda_p} [(1+P_z)\cdot|M_{1/2,\lambda_p}|^2 + (1-P_z)\cdot|M_{-1/2,\lambda_p}|^2], \tag{A5}$$

which leads to

$$\begin{aligned}\frac{\mathrm{d}^3\Gamma}{\mathrm{d}\cos\theta_0 \mathrm{d}\cos\theta_1 \mathrm{d}\phi_1} \propto\ & 1 + \alpha_{\Lambda_b^0}\alpha_{\Lambda_c^+}\cos\theta_1 + P_z\cdot(\alpha_{\Lambda_b^0}\cos\theta_0 + \alpha_{\Lambda_c^+}\cos\theta_0\cos\theta_1 \\ & - \gamma_{\Lambda_b^0}\alpha_{\Lambda_c^+}\sin\theta_0\sin\theta_1\cos\phi_1 + \beta_{\Lambda_b^0}\alpha_{\Lambda_c^+}\sin\theta_0\sin\theta_1\sin\phi_1),\end{aligned} \tag{A6}$$

where $\alpha_{\Lambda_b^0}, \beta_{\Lambda_b^0}, \gamma_{\Lambda_b^0}$ are the Λ_b^0 decay parameters defined by $H^b_\pm$, and $\alpha_{\Lambda_c^+}$ is the Λ_c^+ decay parameter related to $H^c_\pm$.

Angular distribution for $\Lambda_b^0 \to \Lambda_c^+[\to \Lambda(\to p\pi^-)h_1^+]h_2^-$ decays: For $\Lambda_b^0 \to \Lambda_c^+[\to \Lambda(\to p\pi^-)h_1^+]h_2^-$ decays, the relevant angles are $(\theta_0, \theta_1, \phi_1, \theta_2, \phi_2)$, which are defined in Fig. 2. The helicity amplitude is expressed as

$$M_{\lambda_b,\lambda_p} = \sum_{\lambda_c} H^b_{\lambda_c} d^{\frac{1}{2}}_{\lambda_b,\lambda_c}(\theta_0) \cdot H^c_{\lambda_s} e^{i\lambda_c\phi_1} d^{\frac{1}{2}}_{\lambda_c,\lambda_s}(\theta_1) \cdot H^s_{\lambda_p} e^{i\lambda_s\phi_2} d^{\frac{1}{2}}_{\lambda_s,\lambda_p}(\theta_2), \tag{A7}$$

where λ_s refers to the helicity of Λ baryons, and $H^c_{\lambda_s}$ and $H^s_{\lambda_p}$ are the helicity couplings of Λ_c^+ and Λ decays. The total amplitude is calculated by Eq. (A5), which leads to

$$\begin{aligned}\frac{\mathrm{d}^5\Gamma}{\mathrm{d}\cos\theta_0 \mathrm{d}\cos\theta_1 \mathrm{d}\phi_1 \mathrm{d}\cos\theta_2 \mathrm{d}\phi_2} \propto\ & (1 + \alpha_{\Lambda_b^0}\alpha_{\Lambda_c^+}\cos\theta_1 + \alpha_{\Lambda_c^+}\alpha_\Lambda\cos\theta_2 + \alpha_{\Lambda_b^0}\alpha_\Lambda\cos\theta_1\cos\theta_2 \\ & - \alpha_{\Lambda_b^0}\gamma_{\Lambda_c^+}\alpha_\Lambda\sin\theta_1\sin\theta_2\cos\phi_2 + \alpha_{\Lambda_b^0}\beta_{\Lambda_c^+}\alpha_\Lambda\sin\theta_1\sin\theta_2\sin\phi_2) \\ & + P_z\cdot(\alpha_{\Lambda_b^0}\cos\theta_0 + \alpha_{\Lambda_c^+}\cos\theta_0\cos\theta_1 + \alpha_{\Lambda_b^0}\alpha_{\Lambda_c^+}\alpha_\Lambda\cos\theta_0\cos\theta_2 \\ & + \alpha_\Lambda\cos\theta_0\cos\theta_1\cos\theta_2 - \gamma_{\Lambda_b^0}\alpha_{\Lambda_c^+}\sin\theta_0\sin\theta_1\cos\phi_1 + \beta_{\Lambda_b^0}\alpha_{\Lambda_c^+}\sin\theta_0\sin\theta_1\sin\phi_1 \\ & - \gamma_{\Lambda_c^+}\alpha_\Lambda\cos\theta_0\sin\theta_1\sin\theta_2\cos\phi_2 + \beta_{\Lambda_c^+}\alpha_\Lambda\cos\theta_0\sin\theta_1\sin\theta_2\sin\phi_2 \\ & - \gamma_{\Lambda_b^0}\alpha_\Lambda\sin\theta_0\sin\theta_1\cos\theta_2\cos\phi_1 + \beta_{\Lambda_b^0}\alpha_\Lambda\sin\theta_0\sin\theta_1\cos\theta_2\sin\phi_1 \\ & + \beta_{\Lambda_b^0}\beta_{\Lambda_c^+}\alpha_\Lambda\sin\theta_0\sin\theta_2\cos\phi_1\cos\phi_2 + \beta_{\Lambda_b^0}\gamma_{\Lambda_c^+}\alpha_\Lambda\sin\theta_0\sin\theta_2\cos\phi_1\sin\phi_2 \\ & + \gamma_{\Lambda_b^0}\beta_{\Lambda_c^+}\alpha_\Lambda\sin\theta_0\sin\theta_2\sin\phi_1\cos\phi_2 + \gamma_{\Lambda_b^0}\gamma_{\Lambda_c^+}\alpha_\Lambda\sin\theta_0\sin\theta_2\sin\phi_1\sin\phi_2 \\ & - \gamma_{\Lambda_b^0}\gamma_{\Lambda_c^+}\alpha_\Lambda\sin\theta_0\cos\theta_1\sin\theta_2\cos\phi_1\cos\phi_2 \\ & + \gamma_{\Lambda_b^0}\beta_{\Lambda_c^+}\alpha_\Lambda\sin\theta_0\cos\theta_1\sin\theta_2\cos\phi_1\sin\phi_2 \\ & + \beta_{\Lambda_b^0}\gamma_{\Lambda_c^+}\alpha_\Lambda\sin\theta_0\cos\theta_1\sin\theta_2\sin\phi_1\cos\phi_2 \\ & - \beta_{\Lambda_b^0}\beta_{\Lambda_c^+}\alpha_\Lambda\sin\theta_0\cos\theta_1\sin\theta_2\sin\phi_1\sin\phi_2),\end{aligned} \tag{A8}$$

where α_Λ is the Λ decay parameter related to $H^s_\pm$.

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