

Establishing CP Violation in b -Baryon Decays

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It is a long-standing puzzle why the CP violation (CPV) in the baryon system has not yet been definitively established as in the meson one. We demonstrate that individual partial-wave CPV in the $\Lambda_b \rightarrow p\pi^-$ and pK^- decays can exceed 10%, but the destruction between the partial waves (the suppression by the small partial-wave weight) results in a small net direct CPV in the former (the latter) as measured currently. Our finding highlights the different dynamics responsible for CPVs in baryon and meson decays. We propose to probe the CPV observables associated with the angular distributions of the $\Lambda_b \rightarrow pa_1(1260)$, $pK_1(1270)$ decay products, which are large enough for being identified experimentally.

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Introduction—The CP violation (CPV) plays a crucial role in explaining the matter-antimatter asymmetry in the Universe. CPVs in the standard model (SM) originate from an irreducible phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix, which is, however, much smaller than those required by the matter-antimatter asymmetry. It is important to explore new CPV sources from physics beyond the SM. Currently, the experimentally observed CPVs are all in the meson systems, such as K [1], B [2,3], and D [4] mesons. However, CPVs in baryon systems have not yet been firmly established [5–14]. Given that the visible matter in the Universe is predominantly composed of baryons, it is natural to investigate CPVs in baryon decays. Recently, the LHCb Collaboration reported evidence of CPV in $\Lambda_b^0 \rightarrow \Lambda^0 K^+ K^-$ [14], which motivates timely theoretical studies of baryonic CPV.

Unlike mesons, baryons cannot undergo mixing and, thus, exhibit only CPVs in decays, known as direct CPVs. Bottom hadron decays allow large direct CPV at the order of 10%, in principle, owing to the relatively large CKM

weak phase between the first and third generations of quarks. This expectation has been confirmed in B meson decays with the measured direct CPVs ($-8.31 \pm 0.31\%$ for $B^0 \rightarrow K^+ \pi^-$, $(22.4 \pm 1.2)\%$ for $B_s^0 \rightarrow K^- \pi^+$, $(-31.4 \pm 3.0)\%$ for $B^0 \rightarrow \pi^+ \pi^-$, and $(16.2 \pm 3.5)\%$ for $B_s^0 \rightarrow K^+ K^-$ [15]. By contrast, CPVs in the baryon system have not been identified. For example, the measured direct CPVs [13]

$$\begin{aligned} A_{CP}^{\text{dir}}(\Lambda_b^0 \rightarrow p\pi^-) &= (0.2 \pm 0.8 \pm 0.4)\%, \\ A_{CP}^{\text{dir}}(\Lambda_b^0 \rightarrow pK^-) &= (-1.1 \pm 0.7 \pm 0.4)\% \end{aligned} \quad (1)$$

are compatible with null asymmetries within the precision of 1%. That is, CPVs in Λ_b baryon decays are much lower than those in similar B meson decays, although both occur through the $b \rightarrow u\bar{u}q$ transitions, $q = d, s$. Why baryon CPVs are so small and have not been established two decades after the observation of meson CPVs remains a puzzle in particle physics.

The dynamics in baryon and meson processes differ dramatically. The half-integer spin of baryons induces at least two partial-wave amplitudes, such as S - and P -wave amplitudes in $\Lambda_b \rightarrow p\pi^-$, pK^- , while there is only one partial-wave amplitude in B meson decays into two pseudoscalars. The analysis of the former is more intricate because of additional quarks involved in baryon modes and at least two hard gluons to share momentum transfer, which may enhance higher-power contributions and modify the behavior of power expansions [16,17]. There also exist more topological diagrams, including color-commensurate W -emission and W -exchange diagrams, which provide abundant sources of strong phases required for direct CPVs. A precise evaluation of strong phases in these

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topological diagrams poses a theoretical challenge. If the dynamical origin disparate from meson decays is not understood, CPVs in baryon processes cannot be predicted accurately.

We will demonstrate in a full QCD calculation that CPVs in partial waves of bottom baryon decays can be as large as those in B meson decays actually, greater than 10%, but the destruction between partial waves (the suppression by the small P -wave weight) turns in a small net CPV for the $\Lambda_b \rightarrow p\pi^-$ ($\Lambda_b \rightarrow pK^-$) decay. We further analyze the $\Lambda_b \rightarrow p\rho^-$, pK^{*-} , $pa_1^-(1260)$ and $pK_1^-(1270)$ modes, whose partial-wave CPVs, overall speaking, also reach 10% but cancel each other, giving rise to small total direct CPVs. Our study manifests the different dynamics responsible for CPVs in bottom baryon and meson decays and suggests to detect the former through partial-wave-related CPV observables. In particular, the magnitudes of CPVs via the up-down asymmetries in the angular distributions of the $\Lambda_b \rightarrow pa_1(1260)$, $pK_1(1270)$ decay products are higher than 20%, granting a great chance to establish baryon CPVs.

CP asymmetries in $\Lambda_b \rightarrow p\pi^-$, pK^- —A baryon decay amplitude, such as the one for $\Lambda_b \rightarrow ph$ with $h = \pi^-$ or K^- , is decomposed into

$$\mathcal{A}(\Lambda_b \rightarrow ph) = i\bar{u}_p(S + P\gamma_5)u_{\Lambda_b}, \quad (2)$$

where u_p (u_{Λ_b}) is the proton (Λ_b) spinor and S (P) denotes the parity-violating S -wave (parity-conserving P -wave) amplitude. The direct CPV is defined as

$$A_{CP}^{\text{dir}}(\Lambda_b \rightarrow ph) \equiv \frac{\Gamma(\Lambda_b \rightarrow ph) - \bar{\Gamma}(\bar{\Lambda}_b \rightarrow \bar{p}\bar{h})}{\Gamma(\Lambda_b \rightarrow ph) + \bar{\Gamma}(\bar{\Lambda}_b \rightarrow \bar{p}\bar{h})}, \quad (3)$$

with $\Gamma \propto |S|^2 + \kappa|P|^2$, $\bar{\Gamma} \propto |\bar{S}|^2 + \kappa|\bar{P}|^2$, and $\kappa = [(m_{\Lambda_b} - m_p)^2 - m_h^2]/[(m_{\Lambda_b} + m_p)^2 - m_h^2] \approx 0.51$, $\bar{S}$ and $\bar{P}$ being the CP -conjugate amplitudes. We also define the partial-wave CPVs:

$$A_{CP}^{S\text{-wave}} \equiv \frac{|S|^2 - |\bar{S}|^2}{|S|^2 + |\bar{S}|^2}, \quad A_{CP}^{P\text{-wave}} \equiv \frac{|P|^2 - |\bar{P}|^2}{|P|^2 + |\bar{P}|^2}. \quad (4)$$

The total direct CPV can be expressed as the weighted sum of the partial-wave CPVs:

$$A_{CP}^{\text{dir}} = \kappa_S A_{CP}^{S\text{-wave}} + \kappa_P A_{CP}^{P\text{-wave}}, \quad (5)$$

with the coefficients $\kappa_S = |S|^2/(|S|^2 + \kappa r_{CP}|P|^2)$ and $\kappa_P = \kappa|P|^2/(|S|^2/r_{CP} + \kappa|P|^2)$, where $r_{CP} = (1 + A_{CP}^{S\text{-wave}})/(1 + A_{CP}^{P\text{-wave}})$.

CPVs are generated by the interference between the contributions of the *tree* operators $\mathcal{T}$ and the *penguin* operators $\mathcal{P}$. The S - and P -wave amplitudes are then decomposed into

$$\begin{aligned} S &= \lambda_T |S_T| e^{i\delta_T^S} + \lambda_P |S_P| e^{i\delta_P^S}, \\ P &= \lambda_T |P_T| e^{i\delta_T^P} + \lambda_P |P_P| e^{i\delta_P^P}, \end{aligned} \quad (6)$$

respectively, where δ 's represent the strong phases and $\lambda_T = V_{ub}V_{ud(s)}^*$ and $\lambda_P = V_{tb}V_{td(s)}^*$ are the products of the CKM matrix elements for the $\Lambda_b \rightarrow p\pi^-$ (K^-) decay. The $b \rightarrow d\bar{u}u$ ($b \rightarrow s\bar{u}u$) transitions are dominated by tree (penguin) contributions with $|V_{td}^*V_{tb}/V_{ud}^*V_{ub}|(\alpha_s/\pi) \sim 0.1$ [$|V_{ts}^*V_{tb}/V_{us}^*V_{ub}|(\alpha_s/\pi) \sim 2$]. Considering the above ratios, we expect that the CPVs in these modes are of the order of 10%. The small measured CPVs in $\Lambda_b \rightarrow p\pi^-$, pK^- hint either that the strong-phase differences between the tree and penguin components in Eq. (6) diminish in the dominant partial wave or that the CPVs in the S - and P -wave amplitudes cancel in Eq. (5).

Topological diagrams, useful for assessing hadronic heavy-flavor decays [18–20], are classified according to weak currents and quark flows. The topological diagrams for the $\Lambda_b \rightarrow ph$ decays, h being a meson formed by the quarks $\bar{u}d$ or $\bar{u}s$, are displayed in Fig. 1. There are four tree diagrams: the color-allowed external W -emission T , the W -exchange E_2 , the color-commensurate W -emission C_2 , and the bow-tie W -exchange B . The other diagrams PC_1 , PC_2 , PE_1^u , PE_1^d , PE_2 , and PB are from the QCD and electroweak penguin operators. The diagrams T , E_2 , PC_1 , PE_1^u , and PE_1^d contribute to the modes with the final states $\bar{u}d$ and $\bar{u}s$, while C_2 , B , PC_2 , PB , and PE_2 contribute only to the former.

The diagram T , dominating the heavy-quark expansion [21], yields the S -wave amplitude $S_T = a_1(m_{\Lambda_b} - m_p)f_1(m_h^2)$ and the P -wave amplitude $P_T = a_1(m_{\Lambda_b} + m_p)g_1(m_h^2)$ [22], where a_1 is the Wilson coefficient and $f_1 \approx g_1$ [17,23–26] are the $\Lambda_b \rightarrow p$ transition form factors. Therefore, the tree contributions to the S - and P -wave amplitudes are of the same sign, $S_T \approx P_T$. To acquire the relative sign between the S - and P -wave penguin

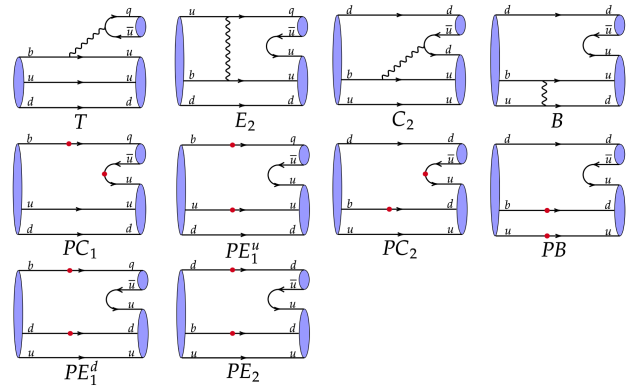


FIG. 1. Topological diagrams contributing to the $\Lambda_b \rightarrow ph$ decays with the light quark $q = d, s$, where the wavy line represents a W boson and the red dots represent the insertion of the penguin operators.

contributions, we convolute a topological diagram naively with the effective weak operators and the dominant combination of distribution amplitudes (DAs) of initial and final states. For example, the PC_2 and PE_1^u amplitudes are expressed as $\bar{u}_p(1+\gamma_5)(\gamma_5 \not{p}_\pi)(\not{p}_{\Lambda_b} \gamma_5) \not{p}_p(1-\gamma_5)u_{\Lambda_b}$ and $(\bar{u}_p \gamma_\lambda)(\not{p}_{\Lambda_b} \gamma_5)(1+\gamma_5)(\not{p}_\pi \gamma_5)(\gamma_\lambda \not{p}_p)(1-\gamma_5)u_{\Lambda_b}$, respectively, where the weak vertex assumes the $(S-P)(S+P)$ form and the pion momentum p_π , the proton momentum p_p , and the unit vector v_{Λ_b} along the minus direction in light-cone coordinates are associated with the twist-2 pion, twist-4 proton, and twist-4 Λ_b DAs [17], respectively. It is trivial to simplify the expressions into $\bar{u}_p(1-\gamma_5)u_{\Lambda_b}$, whose comparison with Eq. (2) then implies $S_{PC_2} \approx -P_{PC_2}$ and $S_{PE_1^u} \approx -P_{PE_1^u}$, i.e., the cancellation between the S - and P -wave amplitudes and small total direct CP asymmetries. Such cancellation does not appear in B meson decays into two pseudoscalar mesons, which involve only a single partial wave and no PC_2 and PE_1^u diagrams.

The above crude argument by means of the structure of topological diagrams needs to be justified by comprehensive QCD calculations. Three popular theoretical approaches have been developed to study hadronic B meson decays, known as the QCD factorization [27,28], the soft-collinear-effective theory [29–31], and the perturbative QCD (PQCD) factorization [32–34]. The PQCD approach is based on the k_T factorization theorem and free of end-point singularities, in which the factorizable and nonfactorizable emission, W -exchange, and annihilation diagrams are all calculable. CPVs of two-body hadronic B meson decays have been successfully predicted in PQCD [32–34]. Recently, this formalism was extended to the $\Lambda_b \rightarrow p$ transition form factors with reasonable high-twist hadron DAs, and the results agree with those from lattice QCD and other nonperturbative methods [17]. Exclusive heavy baryon decays can, thus, be analyzed systematically in this framework.

We compute the contributions from all diagrams to the $\Lambda_b \rightarrow p\pi^-, pK^-$ decays in the PQCD approach (see Supplemental Material [35]), where an amplitude is written as a convolution of hard kernels and hadron DAs. It is worth mentioning that several topological diagrams, especially the nonfactorizable ones from PC_2 and PE_1^u , are evaluated for the first time. The hard kernel contains the weak vertices and two off-shell gluons. The DAs for the Λ_b baryon, proton, and pseudoscalar mesons are input from Refs. [36–41]. We summarize the predictions in Table I, where $\mathcal{T}$ and $\mathcal{P}$ are the total tree and penguin amplitudes, respectively, and only the central values are given for clarity. It is seen that the imaginary S - and P -wave amplitudes from the $\mathcal{T}$ diagrams are of the same sign, but those from the dominant penguin diagrams PC_2 and PE_1^u are opposite in sign, consistent with our argument.

The obtained direct CPVs and partial-wave CPVs of the $\Lambda_b \rightarrow p\pi^-, pK^-$ decays are presented in Table II, with $\kappa_{S,P}$, shown as the percentages in parentheses, being the

TABLE I. Results of the topological amplitudes for the $\Lambda_b \rightarrow p\pi^-, pK^-$ decays in unit of 10^{-9} , which do not include the CKM matrix elements.

Amplitudes	Re(S)	Im(S)	Re(P)	Im(P)
$\Lambda_b \rightarrow p\pi^-$				
$\mathcal{T}$	701.19	−51.38	967.54	−265.17
C_2	−26.61	12.43	−41.51	0.14
E_2	−55.01	−38.14	−36.23	62.89
B	−4.00	9.60	−12.73	−19.93
Tree $\mathcal{T}$	615.57	−67.49	877.08	−222.06
PC_1	57.90	−1.12	1.88	−11.11
PC_2	−5.88	−12.00	4.62	14.20
PE_1^u	0.39	−9.47	−3.65	8.04
PB	0.85	−1.06	−1.46	−0.53
$PE_1^d + PE_2$	−0.55	−3.83	1.37	−0.31
Penguin $\mathcal{P}$	52.71	−27.49	2.77	10.28
$\Lambda_b \rightarrow pK^-$				
$\mathcal{T}$	853.60	−52.08	1190.21	−340.84
E_2	−66.28	−59.48	−50.31	79.56
Tree $\mathcal{T}$	787.31	−111.55	1139.90	−261.28
PC_1	75.64	−0.82	−4.35	−13.81
PE_1^u	0.10	−11.80	−4.76	9.93
PE_1^d	−1.50	−7.38	1.66	2.09
Penguin $\mathcal{P}$	74.23	−20.00	−7.45	−1.79

proportions of S - and P -wave contributions to the direct CPV. Theoretical uncertainties arise mainly from the variation of the parameters involved in the DAs. It is noticed that the partial-wave CPVs can exceed 10%, i.e., $A_{CP}^{S\text{-wave}}(\Lambda_b \rightarrow p\pi) = 0.17$ and $A_{CP}^{P\text{-wave}}(\Lambda_b \rightarrow pK) = -0.21$, similar to those in B meson decays. However, the destruction between the S -wave CPV (0.17) and the P -wave CPV (−0.06) in $\Lambda_b \rightarrow p\pi^-$ reduces the magnitude of direct CPV to $0.05^{+0.02}_{-0.03}$, which agrees with the data in Eq. (1). This demonstrates the previous discussion on the cancellation of partial-wave CPVs using topological diagrams. In the penguin-dominated decay of $\Lambda_b \rightarrow pK^-$, the S -wave CPV is small (−0.05) due to the small strong phase $\delta^{S\text{-wave}} = \delta_P^S - \delta_T^S = -7^\circ$, while the P -wave CPV is highly suppressed by the proportion $\kappa_P = 6\%$ due to $|P| \ll |S|$. Hence, its direct CPV (−0.06 $^{+0.03}_{-0.02}$) reveals no obvious deviation from zero either.

The large partial-wave CPVs can be probed by measuring the decay asymmetry parameters α , β , and γ , which were first proposed by Lee and Yang [65]. These observables, related to the partial-wave amplitudes via $\alpha \propto \text{Re}(S^*P)$, $\beta \propto \text{Im}(S^*P)$, and $\gamma \propto |S|^2 - |P|^2$, are also predicted and listed in Table II. It is found that the β -induced CPVs are significant but difficult to observe in current experiments; it is hard to determine experimentally the polarization of a final-state proton.

CP violations in $\Lambda_b \rightarrow pA, pV$ —The large partial-wave CPVs can certainly exist in other hadronic Λ_b baryon

TABLE II. CPV observables associated with (quasi-)two-body hadronic Λ_b decays. The percentages in the parentheses indicate the proportions of partial-wave CPVs to the direct CPVs.

	A_{CP}^{dir}	$A_{CP}^{S\text{-wave}}(\kappa_S)$	$A_{CP}^{P\text{-wave}}(\kappa_P)$	A_{CP}^a	A_{CP}^b	A_{CP}^c
$\Lambda_b \rightarrow p\pi^-$	$0.05_{-0.03}^{+0.02}$	$0.17_{-0.09}^{+0.05}$ (49%)	$-0.06_{-0.05}^{+0.04}$ (51%)	$0.02_{-0.02}^{+0.01}$	$0.22_{-0.05}^{+0.08}$	$0.11_{-0.06}^{+0.05}$
$\Lambda_b \rightarrow pK^-$	$-0.06_{-0.02}^{+0.03}$	$-0.05_{-0.04}^{+0.05}$ (94%)	$-0.21_{-0.46}^{+0.39}$ (6%)	$0.04_{-0.04}^{+0.03}$	$-0.44_{-0.04}^{+0.08}$	$0.02_{-0.05}^{+0.06}$
	A_{CP}^{dir}	$A_{CP}^{S^T\text{-wave}}(\kappa_{S^T})$	$A_{CP}^{(D+S^L)\text{-wave}}(\kappa_{D+S^L})$	$A_{CP}^{P_1\text{-wave}}(\kappa_{P_1})$	$A_{CP}^{P_2\text{-wave}}(\kappa_{P_2})$	$A_{CP}^{\mathcal{J}}$
$\Lambda_b \rightarrow p\rho^-$	$0.03_{-0.05}^{+0.03}$	$0.01_{-0.04}^{+0.01}$ (7%)	$0.02_{-0.03}^{+0.07}$ (44%)	$0.03_{-0.12}^{+0.04}$ (45%)	$0.17_{-0.06}^{+0.04}$ (4%)	$-0.01_{-0.01}^{+0.01}$
$\Lambda_b \rightarrow pK^{*-}$	$-0.05_{-0.16}^{+0.10}$	$-0.15_{-0.06}^{+0.12}$ (6%)	$0.27_{-0.27}^{+0.09}$ (33%)	$-0.23_{-0.18}^{+0.10}$ (55%)	$-0.14_{-0.10}^{+0.02}$ (6%)	$0.02_{-0.05}^{+0.04}$
	A_{CP}^{dir}	$A_{CP}^{S^T\text{-wave}}(\kappa_{S^T})$	$A_{CP}^{(D+S^L)\text{-wave}}(\kappa_{D+S^L})$	$A_{CP}^{P_1\text{-wave}}(\kappa_{P_1})$	$A_{CP}^{P_2\text{-wave}}(\kappa_{P_2})$	A_{CP}^{UD}
$\Lambda_b \rightarrow pa_1^-(1260)$	$-0.01_{-0.03}^{+0.04}$	$-0.22_{-0.10}^{+0.10}$ (6%)	$-0.11_{-0.07}^{+0.03}$ (46%)	$0.18_{-0.06}^{+0.11}$ (40%)	$-0.24_{-0.13}^{+0.07}$ (8%)	$-0.24_{-0.13}^{+0.08}$
$\Lambda_b \rightarrow pK_1^-(1270) (\theta_K = 30^\circ)$	$0.09_{-0.05}^{+0.08}$	$0.34_{-0.06}^{+0.02}$ (8%)	$-0.11_{-0.08}^{+0.12}$ (42%)	$0.19_{-0.15}^{+0.17}$ (42%)	$0.33_{-0.05}^{+0.04}$ (8%)	$0.26_{-0.10}^{+0.04}$
$\Lambda_b \rightarrow pK_1^-(1270) (\theta_K = 60^\circ)$	$0.07_{-0.06}^{+0.05}$	$0.46_{-0.09}^{+0.02}$ (9%)	$0.06_{-0.08}^{+0.11}$ (37%)	$-0.07_{-0.10}^{+0.09}$ (45%)	$0.46_{-0.07}^{+0.06}$ (9%)	$0.40_{-0.09}^{+0.04}$

decays. We further examine the modes $\Lambda_b \rightarrow pA$ with the axial-vector meson $A = a_1^-(1260)$ or $K_1^-(1270)$ and $\Lambda_b \rightarrow pV$ with the vector meson $V = \rho$ or K^{*-} . They share the same topological diagrams with $\Lambda_b \rightarrow p\pi^-, pK^-$ but with distinct meson DAs.

The longitudinal and transverse polarized $\Lambda_b \rightarrow pA$ decay amplitudes are parametrized as

$$\begin{aligned} \mathcal{A}^L(\Lambda_b \rightarrow pA) &= \bar{u}_p \epsilon_{L\mu}^* \left(A_1^L \gamma^\mu \gamma_5 + A_2^L \frac{p_p^\mu}{m_{\Lambda_b}} \gamma_5 \right. \\ &\quad \left. + B_1^L \gamma^\mu + B_2^L \frac{p_p^\mu}{m_{\Lambda_b}} \right) u_{\Lambda_b}, \\ \mathcal{A}^T(\Lambda_b \rightarrow pA) &= \bar{u}_p \epsilon_{T\mu}^* (A_1^T \gamma^\mu \gamma_5 + B_1^T \gamma^\mu) u_{\Lambda_b}, \end{aligned} \quad (7)$$

where $\epsilon_{L,T}$ are the longitudinal and transverse polarization vectors of the axial-vector meson and the polarization amplitudes $A_1^{L,T}, A_2^L, B_1^{L,T}$, and B_2^L form the partial-wave amplitudes $S^L = -A_1^L$, $S^T = -A_1^T$, $P_1 \approx -2B_1^L - B_2^L$, $P_2 \approx B_1^T$, and $D \approx -A_1^L + A_2^L$. The corresponding partial-wave CPVs are defined as in Eq. (4), in terms of which the direct CPVs can be evaluated:

$$A_{CP}^{\text{dir}} \approx \kappa_{S^T} A_{CP}^{S^T} + \kappa_{P_1} A_{CP}^{P_1} + \kappa_{P_2} A_{CP}^{P_2} + \kappa_{D+S^L} A_{CP}^{D+S^L}, \quad (8)$$

with $\kappa_{S^T} = 2|S^T|^2/\Pi$, $\kappa_{P_1} = (E_h^2|P_1|^2)/(m_h^2\Pi)$, $\kappa_{P_2} = 2|P_2|^2/\Pi$, $\kappa_{D+S^L} = (E_h^2|D+S^L|^2)/(m_h^2\Pi)$, and $\Pi \equiv 2|S^T|^2 + 2|P_2|^2 + E_h^2/m_h^2|D+S^L|^2 + E_h^2/m_h^2|P_1|^2$. The parametrization in Eq. (7) and the above formulation also apply to the $\Lambda_b \rightarrow pV$ modes.

The predictions for the CPVs in the $\Lambda_b \rightarrow pV, pA$ decays are collected in Table II. As the $K_1(1270)$ - $K_1(1400)$ mixing angle θ_K is not yet well determined [42], we take the typical values $\theta_K = 30^\circ$ and 60° for illustration. Most of the results

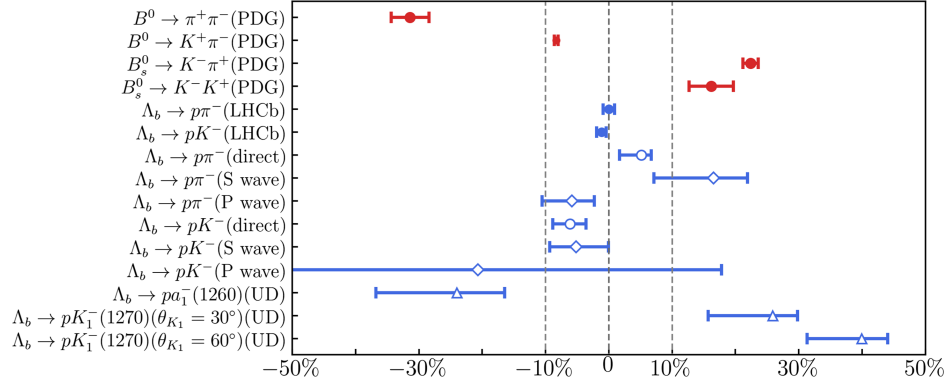
are not very sensitive to θ_K . It is found that the $D + S^L$ and P_1 components dominate the direct CPVs because of the relativistic enhancement factor E_h/m_h . The partial-wave CPVs of the $\Lambda_b \rightarrow pV, pA$ decays also exceed 10%; the P_2 -wave CPVs of $\Lambda_b \rightarrow p\rho^-$ and $pa_1^-(1260)$ are 17% and -24%, respectively; the $(D + S^L)$ -wave CPV of $\Lambda_b \rightarrow pK^{*-}$ is 27%; the partial-wave CPVs of $\Lambda_b \rightarrow pK_1^-(1270)$ even reach the order of 30%. However, the direct CPVs of these modes are all small. The relative sign of the partial-wave amplitudes involved in the $\Lambda_b \rightarrow pK^{*-}$, $pa_1^-(1260)$, and $pK_1(1270)$ decays can be argued in the same manner. Their tiny direct CPVs trace back to the strong cancellation of the major $(D + S^L)$ - and P_1 -wave CPVs, similar to the $\Lambda_b \rightarrow p\pi^-$ case.

Motivated by the sizable partial-wave CPVs, we construct promising observables associated with angular distributions of final states in multibody Λ_b decays, which can be measured in future experiments. With θ as the angle between the normal of the $A \rightarrow h_1 h_2 h_3$ decay plane and the momentum of A in the Λ_b rest frame, the angular distribution for the $\Lambda_b \rightarrow pA \rightarrow ph_1 h_2 h_3$ decay reads

$$\frac{d\Gamma}{d\cos\theta} \supset R \text{Re}(S^T P_2^*) \cos\theta. \quad (9)$$

The nonperturbative factor R parametrizes the effect and kinematics of the strong decay $A \rightarrow h_1 h_2 h_3$ [66], which will be canceled in the proposed CPV observable below. The full expression of the angular distribution is referred to [67], which contains additional pieces proportional to 1 and $\cos^2\theta$. We consider the up-down asymmetry for four-body decays:

$$A_{UD} \equiv \frac{\Gamma(\cos\theta > 0) - \Gamma(\cos\theta < 0)}{\Gamma(\cos\theta > 0) + \Gamma(\cos\theta < 0)} = R \text{Re}(S^T P_2^*), \quad (10)$$


 FIG. 2. CPVs measured in B meson and $\Lambda_b \rightarrow p\pi^-, pK^-$ decays and our predictions.

from which the R -independent CPV is defined:

$$A_{CP}^{UD} = \frac{A_{UD} + \bar{A}_{UD}}{A_{UD} - \bar{A}_{UD}}, \quad (11)$$

with $\bar{A}_{UD}$ denoting the charge conjugate of A_{UD} . Note that this CPV is induced by the partial-wave amplitudes S^T and P_2 . The angular distribution in the $\Lambda_b \rightarrow pV \rightarrow ph_1h_2$ decay is described by $1 + \mathcal{J}(3\cos^2\theta - 1)/2$ [67], where θ is the angle between h_1 in the V rest frame and the momentum of V in the Λ_b rest frame. Likewise, the asymmetry $A_{CP}^{\mathcal{J}} = (\mathcal{J} - \bar{\mathcal{J}})/(\mathcal{J} + \bar{\mathcal{J}})$ for $\Lambda_b \rightarrow pV$ can be defined.

The predictions for A_{CP}^{UD} are given in Table II, which exceed 20% in the $\Lambda_b \rightarrow pA$ decays owing to large strong phase difference between the S - and P -wave amplitudes. Hence, A_{CP}^{UD} with controllable uncertainties serves as an ideal observable for establishing CPVs in Λ_b decays experimentally. The measurements of A_{CP}^{UD} are based on the four-body decays $\Lambda_b \rightarrow p\pi^+\pi^-\pi^-$ and $pK^-\pi^+\pi^-$ for $pa_1(1260)$ and $pK_1(1270)$, respectively, both of which have large data samples at LHCb. The LHCb has reported the direct CPVs of the above modes from the Run 1 data corresponding to the integrated luminosity 3 fb^{-1} at the center-of-mass energies $\sqrt{s} = 7$ and 8 TeV [11]. The sum of particle and antiparticle channels gives the signal yields of $\Lambda_b \rightarrow pa_1$ and pK_1 around 800 and 1000, respectively. The yields would be enhanced by 4 times with the Run 2 data from twice the integrated luminosity of 6 fb^{-1} and twice the cross section at a higher collision energy of $\sqrt{s} = 13 \text{ TeV}$. According to the plan with 50 fb^{-1} at the end of Run 4 [68], the signal yields of Run 3 + 4 would be greater than those of Run 2 by a factor of $(50 - 9) \text{ fb}^{-1} / 6 \text{ fb}^{-1} \times 2 \sim 14$, where the factor of 2 comes from the enhancement of trigger efficiencies starting from Run 3 [69]. The total events with the full Run 1 + 2 + 3 + 4 data are expected to be a factor of 60 compared to the Run 1 data, as large as 48 000 and 60 000 for $\Lambda_b \rightarrow pa_1$ and pK_1 , respectively. With $A_{UD}[\Lambda_b \rightarrow pa_1] = -0.09 \pm 0.02$, $A_{UD}[\Lambda_b \rightarrow pK_1(\theta_K = 30^\circ)] = -0.19 \pm 0.04$,

and $A_{UD}[\Lambda_b \rightarrow pK_1(\theta_K = 60^\circ)] = -0.24^{+0.06}_{-0.05}$, the statistical uncertainties of A_{CP}^{UD} are then roughly 5% for $\Lambda_b \rightarrow pa_1$ and 4% for $\Lambda_b \rightarrow pK_1$ at the end of LHCb Run 4. The systematic uncertainties of A_{CP}^{UD} are smaller based on the control sample of $\Lambda_b^0 \rightarrow \Lambda_c^+(\rightarrow pK^-\pi^+)\pi^-$ as reported in [12]. Therefore, the up-down asymmetric CPVs in $\Lambda_b \rightarrow pa_1$ and pK_1 of the order of 20%–40% have a large possibility of being identified in the near future. Such measurements could establish CP violations in baryon decays.

Conclusion—The rich data samples and complicated dynamics in multibody bottom baryon decays offer high prospects for exploring baryon CPVs. This Letter presented the first full QCD analysis on two-body hadronic Λ_b decays in the PQCD approach. Our predictions for the total and partial-wave CPVs of the considered modes are summarized and compared with the available data for bottom hadron decays in Fig. 2. The study elucidates the mechanism responsible for the measured small CPVs in $\Lambda_b \rightarrow p\pi^-, pK^-$, in contrast to the sizable CPVs in the similar B meson decays. The partial-wave CPVs in $\Lambda_b \rightarrow p\pi^-$ reach 10% potentially, but the destruction between them leads to the tiny CPV. The direct CPV of $\Lambda_b \rightarrow pK^-$ is primarily attributed to the modest S -wave CPV. We have also extended our investigation to the CPVs in the modes with vector and axial-vector final states. Our work suggests that certain partial-wave CPVs in bottom baryon decays, especially those related to angular distributions, can be sufficiently significant and probed experimentally to establish baryon CPVs. It opens up avenues for deeply understanding the dynamics in heavy baryon decays and their CPVs.

Note added—The LHCb Collaboration has reported the first observation of the direct CPV in Λ_b baryon decays [70] recently. This discovery undoubtedly marks a significant milestone in the relevant fields.

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