

Large CP violation in $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$ and its U -spin partner decays

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The LHCb Collaboration has recently found a large CP -violating rate asymmetry in the b -baryon decay $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$. This is the first observation of CP violation in baryon processes, opening a new window to test its standard model (SM) origin. Many more baryon decays are expected to exhibit observable signals of CP violation. We show that there also exists large CP violation in the U -spin partner decay mode, $\Xi_b^0 \rightarrow \Sigma^+\pi^-K^+K^-$, with rate asymmetry $A_{CP}(\Xi_b^0 \rightarrow \Sigma^+\pi^-K^+K^-) = -A_{CP}(\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-) \frac{\text{Br}(\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-)}{\text{Br}(\Xi_b^0 \rightarrow \Sigma^+\pi^-K^+K^-)} \frac{\tau_{\Xi_b^0}}{\tau_{\Lambda_b^0}}$ in the U -spin symmetry limit. By neglecting a subleading contribution in the amplitudes, $A_{CP}(\Lambda_b^0 \rightarrow p\pi^+\pi^-\pi^-) = -(12 \pm 6)\%$. These predictions can be tested in the near future.

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Introduction. Recently the LHCb Collaboration [1] has reported its finding of sizable CP violation in the rate asymmetry of $\Lambda_b^0 \rightarrow p\pi^+K^-\pi^-$ decay given by

$$A_{CP} = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} = (2.45 \pm 0.46 \pm 0.10)\%,$$

with Γ and $\bar{\Gamma}$ being the rates of the particle and antiparticle modes, respectively. This is the first CP violation observed in baryon decay processes. In the standard model (SM), CP violation arises from the mixing of different generations of fermions [2], predicting CP violation in both meson and baryon decays. It has been a longstanding puzzle that CP violation has been discovered only in meson decays and mixing. Therefore, the ground-breaking LHCb measurement constitutes a significant progress in the pursuit of understanding. This opens a new window to test the SM and search for new physics beyond it.

We propose new baryonic decay modes with large CP violation to further test the SM. We focus on processes

involving final-state mesons (K and π) that are all electrically charged. The initial baryons are beauty baryons that form a doublet under U -spin symmetry: Λ_b^0 and Ξ_b^0 . The final-state baryons also belong to a U -spin doublet: p and Σ^+ . We find that there exists large CP violation in the U -spin partner decay mode $\Xi_b^0 \rightarrow \Sigma^+K^+K^-\pi^-$, with the relation

$$A_{CP}(\Xi_b^0 \rightarrow \Sigma^+\pi^-K^+K^-) = -A_{CP}(\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-) \frac{\text{Br}(\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-)}{\text{Br}(\Xi_b^0 \rightarrow \Sigma^+\pi^-K^+K^-)} \frac{\tau_{\Xi_b^0}}{\tau_{\Lambda_b^0}}. \quad (1)$$

This holds in the U -spin limit. Here, Br and τ denote the branching ratio and lifetime. We also find large CP violation in several other related processes when subleading contributions are neglected.

Theoretical studies of four-body decays of a beauty baryon are difficult due to the nonperturbative nature of quantum chromodynamics (QCD) at the relevant low energy scale. However, for certain processes, perturbative QCD calculations can provide reasonable guidance. We utilize a light-quark flavor subgroup, the U -spin symmetry [3,4] (invariance under the exchange of d and s quarks), as our guide [5–10]. This symmetry is broken by the mass difference (several tens of MeV) between the d and s quarks. However, since this mass difference is much smaller than the beauty-baryon mass scale (about 5 GeV), the breaking effects are expected to be of order 10%–20% [10]. This expectation is supported by comparisons between

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predictions and data in beauty-meson charmless decays into two pseudoscalar octet mesons. For example, U-spin symmetry successfully predicts CP asymmetries in decays such as $B_d \rightarrow K^+\pi^-$ and $B_s \rightarrow K^-\pi^+$ [10].

We should note that this approach does not predict the magnitudes of decay amplitudes. However, once sufficient data are collected, the relevant amplitudes can be obtained. Even without all the amplitudes being determined, there exist direct relations that can guide the search for decay modes with large CP violation in four-body decays of beauty baryons, thus testing the model.

The specific processes to be studied are

$$\begin{aligned} \Lambda_b^0 \rightarrow pK^-\pi^+\pi^-, \quad pK^+K^-K^-, \quad \Sigma^+K^+K^-\pi^-, \\ \Sigma^+K^+\pi^-\pi^-, \quad \Sigma^+\pi^+\pi^-\pi^-, \quad pK^+K^-\pi^-, \quad p\pi^+\pi^-\pi^-, \end{aligned} \quad (2)$$

and their corresponding U-spin partners

$$\begin{aligned} \Xi_b^0 \rightarrow \Sigma^+K^+K^-\pi^-, \quad \Sigma^+\pi^+\pi^-\pi^-, \quad p\pi^+K^-\pi^-, \\ p\pi^+K^-K^-, \quad pK^+K^-K^-, \quad \Sigma^+\pi^+K^-\pi^-, \quad \Sigma^+K^+K^-K^-. \end{aligned} \quad (3)$$

U-spin symmetry implies several relations in these partner decay channels, similarly to Eq. (1).

For U-spin partner processes with strangeness changes $\Delta S = 0$ and $\Delta S = -1$, the amplitudes $\mathcal{A}^{\Delta S=0}$ and $\mathcal{A}^{\Delta S=-1}$ take the form

$$\begin{aligned} \mathcal{A}^{\Delta S=0} &= V_{ud}^* V_{ub} \langle \mathcal{J} \rangle + V_{td}^* V_{tb} \langle \mathcal{P} \rangle, \\ \mathcal{A}^{\Delta S=-1} &= V_{us}^* V_{ub} \langle \mathcal{J} \rangle + V_{ts}^* V_{tb} \langle \mathcal{P} \rangle, \end{aligned} \quad (4)$$

where V_{ij} are the Cabibbo–Kobayashi–Maskawa (CKM) matrix elements. Here, $\langle \mathcal{J} \rangle$ and $\langle \mathcal{P} \rangle$ denote the CP -conserving amplitudes of the tree and penguin contributions, respectively, which are generally complex due to the presence of strong phases. The $\Delta S = 0$ and $\Delta S = 1$ decays share the same $\langle \mathcal{J} \rangle$ and $\langle \mathcal{P} \rangle$ owing to the U-spin

symmetry. The CP asymmetries are obtained by computing $A_{CP} \propto \int (|\mathcal{A}|^2 - |\bar{\mathcal{A}}|^2) = 4 \text{Im}(\lambda_t \lambda_u^*) \int \text{Im}(\langle \mathcal{J} \rangle \langle \mathcal{P} \rangle^*)$, where the integral symbol stands for phase space integration and summing over spins, and $\lambda_q = V_{qd}^* V_{qb}$ and $\lambda_q = V_{qs}^* V_{qb}$ for the $\Delta S = 0$ and $\Delta S = 1$ decays, respectively. From this expression, it is evident that a nonzero strong-phase difference between $\langle \mathcal{J} \rangle$ and $\langle \mathcal{P} \rangle$ is a necessary condition for a nonvanishing A_{CP} . From the unitarity of the CKM matrix, it follows that $\text{Im}(\lambda_t \lambda_u^*)$ has opposite signs for the $\Delta S = 0$ and $\Delta S = 1$ transitions and we obtain the following CP -violation relation

$$A_{CP}(\Delta S=0) = -A_{CP}(\Delta S=-1) \frac{\text{Br}(\Delta S=-1) \tau^{\Delta S=0}}{\text{Br}(\Delta S=0) \tau^{\Delta S=-1}}. \quad (5)$$

When applied to $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$ and $\Xi_b^0 \rightarrow \Sigma^+K^+K^-\pi^-$, this gives Eq. (1).

Decay amplitudes. The Λ_b baryon is a baryon that contains a heavy b quark and two light quarks, u and d , forming the udb state. It is one of the light quark flavor $SU(3)_F$ triplet b -baryons, $(\Xi_b^0, -\Xi_b^-, \Lambda_b^0)$, whose corresponding quark contents are (dsb, usb, udb) . The U-spin symmetry group is a subgroup $SU(2)_U$ of the flavor $SU(3)_F$, taking d and s as the fundamental building blocks. Λ_b^0 and Ξ_b^0 form a doublet of U-spin: $\mathbf{B}_b^i = (\Lambda_b^0, \Xi_b^0)$. The upper component has $U = 1/2$, $U_3 = +1/2$, and the lower component has $U = 1/2$, $U_3 = -1/2$.

For the particle fields in the final states (Σ^+ , p , $K^\pm$, and $\pi^\pm$), the proton and Σ^+ form a U-spin doublet $\mathbf{B}^i = (p, \Sigma^+)$, and π^- and K^- also form a U-spin doublet $(P^-)^i = (P_1, P_2) = (\pi^-, K^-)$. For the complex conjugate of these doublets, we adopt the expressions $\bar{\mathbf{B}}_i = (\bar{p}, \bar{\Sigma}^+)$ and $P_i^+ = (\pi^+, K^+)$.

We concentrate on processes related to $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$ through the U-spin symmetry. The leading effective Hamiltonian responsible for these decays in the SM is given by [11]

$$\begin{aligned} \mathcal{H}_{\text{eff}} &= \frac{G_F}{\sqrt{2}} \left[V_{uq}^* V_{ub} (C_1 Q_1^q + C_2 Q_2^q) - V_{tq}^* V_{tb} \sum_{i=3}^{10} C_i Q_i^q \right] + \text{H.c.}, \\ Q_1^q &= (\bar{u}\gamma^\mu(1-\gamma_5)u)(\bar{q}\gamma_\mu(1-\gamma_5)b), \quad Q_2^q = (\bar{q}\gamma^\mu(1-\gamma_5)u)(\bar{u}\gamma_\mu(1-\gamma_5)b), \end{aligned} \quad (6)$$

where $q = d, s$, G_F is the Fermi constant, $C_{1,2}$ are the Wilson coefficients for the tree-level operators, $C_{3,\dots,10}$ are the Wilson coefficients for the strong and electroweak penguin operators, and V_{ij} are the elements of the CKM matrix.

For $q = d$, $\mathcal{H}_{\text{eff}}$ has U-spin quantum numbers $U = 1/2$, $U_3 = +1/2$. We use $\mathcal{H}^i = (1, 0)$ to indicate this, with the understanding that the CKM elements are to be added to the amplitudes it induces. Similarly, for $q = s$, we use $\mathcal{H}^i = (0, 1)$. The transition operators, defined by

$\mathcal{H}_{\text{eff}} = V_{uq}^* V_{ub} \mathcal{T} + V_{tq}^* V_{tb} \mathcal{P}$, at the hadron level are parametrized as

$$\begin{aligned} \mathcal{T} = & \bar{\mathbf{B}}_i a_T \mathbf{B}_b^i \mathcal{H}_T^j (P^-)^k (P_1^+ P_2^+)_{\{jk\}} + \bar{\mathbf{B}}_i b_T \mathbf{B}_b^k \mathcal{H}_T^j (P^-)^i (P_1^+ P_2^+)_{\{jk\}} + \bar{\mathbf{B}}_i c_T \mathbf{B}_b^k \mathcal{H}_T^i (P^-)^j (P_1^+ P_2^+)_{\{jk\}} \\ & + \bar{\mathbf{B}}_i b_T^A \mathbf{B}_b^k \mathcal{H}_T^j (P^-)^i (P_1^+ P_2^+)_{[jk]} + \bar{\mathbf{B}}_i c_T^A \mathbf{B}_b^k \mathcal{H}_T^i (P^-)^j (P_1^+ P_2^+)_{[jk]} \end{aligned} \quad (7)$$

where $(P_1^+ P_2^+)_{\{ij\}} = [(P_1^+)_i (P_2^+)_j + (P_1^+)_j (P_2^+)_i]/2$ and $(P_1^+ P_2^+)_{[ij]} = [(P_1^+)_i (P_2^+)_j - (P_1^+)_j (P_2^+)_i]/2$, with $P_{1,2}^+$ representing the P^+ mesons with momenta $p_{1,2}$, respectively. The $SU(3)_F$ quantities $a_T, b_T^{(A)}$, and $c_T^{(A)}$ have Lorentz structures and depend on both momenta and spins. Writing the Lorentz structure of a_T in series of Λ^{-1} gives

$$\begin{aligned} a_T = & (S^{(0)} + P^{(0)} \gamma_5) + \frac{1}{\Lambda} \sum_{h \neq \mathbf{B}_b, \mathbf{B}} p_h^\mu \gamma_\mu (V_i^{(0)} + A_i^{(0)} \gamma_5) + \sum_{h \neq h'} \frac{p_h \cdot p_{h'}}{\Lambda^2} (S_{hh'}^{(1)} + P_{hh'}^{(1)} \gamma_5) \\ & + \frac{i}{\Lambda^2} \sum_{h, h' \neq \mathbf{B}_b, \mathbf{B}} p_h^\mu p_{h'}^\nu \sigma_{\mu\nu} (H_{hh'}^{(0)} + D_{hh'}^{(0)} \gamma_5) + \mathcal{O}(\Lambda^{-3}). \end{aligned} \quad (8)$$

Here, Λ is an energy scale whose value is naturally expected to be around m_b , and may also approximately coincide with the width of a resonance if the decay phase space lies nearby. The quantities $h^{(i)}$ denote sums over the initial and final hadrons. To avoid large $1/\Lambda$ power corrections and to obtain CP asymmetries that can be experimentally compared with theoretical predictions in a cleaner manner, one should avoid using data points in resonant regions, since small U-spin violations may be magnified near such regions. In general, the form factors depend on the momentum; however, here we expand them with respect to Λ and separate out the momentum dependence. For instance, $S_{hh'}^{(1)}$ can be regarded as the momentum-dependent correction to the leading term $S^{(0)}$. As a result, the quantities $S^{(0),(1)}, P^{(0),(1)}, V^{(0)}, A^{(0)}, H^{(0)}$, and $D^{(0)}$ defined here are all constants, independent of momenta and spins. We require $h \neq \mathbf{B}_b, \mathbf{B}$ in V_h and A_h to avoid double counting when the equations of motion are considered. A similar reasoning applies to the dipole moment terms. The same expansions of the Lorentz structure can also be performed for $b_T^{(A)}$ and $c_T^{(A)}$. However, when expanding b_T^A and c_T^A , the constant terms $S^{(0)}$ and $P^{(0)}$ do not contribute as $S^{(0)}(P_1^+ P_2^+)_{[jk]} = S^{(0)}(P^+ P^+)_{[jk]} = 0$. The momentum labeling was omitted, since $S^{(0)}$ and $P^{(0)}$ are constants.

Similarly, one expands the penguin amplitudes ($\mathcal{P}$) by replacing the subscripts T with P in the foregoing. Explicitly including the Dirac spinors $u_{\mathbf{B}_b}$ and $u_{\mathbf{B}}$ of $\mathbf{B}_b$ and $\mathbf{B}$, respectively for each of the processes listed above, we have the U-spin partner pair decay amplitudes given by

$$\begin{aligned} 1) \quad & \mathcal{A}(\Lambda_b^0 \rightarrow p\pi^+ K^- \pi^-) = \bar{u}_{\mathbf{B}} [V_{us}^* V_{ub} (a_T + b_T + b_T^A) + V_{ts}^* V_{tb} (a_P + b_P + b_P^A)] u_{\mathbf{B}_b}, \\ & \mathcal{A}(\Xi_b^0 \rightarrow \Sigma^+ K^+ \pi^- K^-) = \bar{u}_{\mathbf{B}} [V_{ud}^* V_{ub} (a_T + b_T + b_T^A) + V_{td}^* V_{tb} (a_P + b_P + b_P^A)] u_{\mathbf{B}_b}; \\ 2) \quad & \mathcal{A}(\Lambda_b^0 \rightarrow pK^+ K^- K^-) = 2\bar{u}_{\mathbf{B}} [V_{us}^* V_{ub} a_T + V_{ts}^* V_{tb} a_P] u_{\mathbf{B}_b}, \\ & \mathcal{A}(\Xi_b^0 \rightarrow \Sigma^+ \pi^+ \pi^- \pi^-) = 2\bar{u}_{\mathbf{B}} [V_{ud}^* V_{ub} a_T + V_{td}^* V_{tb} a_P] u_{\mathbf{B}_b}; \\ 3) \quad & \mathcal{A}(\Xi_b^0 \rightarrow p\pi^+ \pi^- K^-) = \bar{u}_{\mathbf{B}} [V_{us}^* V_{ub} (b_T + c_T + b_T^A + c_T^A) + V_{ts}^* V_{tb} (b_P + c_P + b_P^A + c_P^A)] u_{\mathbf{B}_b}, \\ & \mathcal{A}(\Lambda_b^0 \rightarrow \Sigma^+ K^+ K^- \pi^-) = \bar{u}_{\mathbf{B}} [V_{ud}^* V_{ub} (b_T + c_T + b_T^A + c_T^A) + V_{td}^* V_{tb} (b_P + c_P + b_P^A + c_P^A)] u_{\mathbf{B}_b}; \\ 4) \quad & \mathcal{A}(\Xi_b^0 \rightarrow p\pi^+ K^- K^-) = 2\bar{u}_{\mathbf{B}} [V_{us}^* V_{ub} b_T + V_{ts}^* V_{tb} b_P] u_{\mathbf{B}_b}, \\ & \mathcal{A}(\Lambda_b^0 \rightarrow \Sigma^+ K^+ \pi^- \pi^-) = 2\bar{u}_{\mathbf{B}} [V_{ud}^* V_{ub} b_T + V_{td}^* V_{tb} b_P] u_{\mathbf{B}_b}; \\ 5) \quad & \mathcal{A}(\Lambda_b^0 \rightarrow \Sigma^+ \pi^+ \pi^- \pi^-) = 2\bar{u}_{\mathbf{B}} [V_{us}^* V_{ub} c_T + V_{ts}^* V_{tb} c_P] u_{\mathbf{B}_b}, \\ & \mathcal{A}(\Xi_b^0 \rightarrow pK^+ K^- K^-) = 2\bar{u}_{\mathbf{B}} [V_{ud}^* V_{ub} c_T + V_{td}^* V_{tb} c_P] u_{\mathbf{B}_b}; \\ 6) \quad & \mathcal{A}(\Xi_b^0 \rightarrow \Sigma^+ \pi^+ K^- \pi^-) = \bar{u}_{\mathbf{B}} [V_{us}^* V_{ub} (a_T + c_T + c_T^A) + V_{ts}^* V_{tb} (a_P + c_P + c_P^A)] u_{\mathbf{B}_b}, \\ & \mathcal{A}(\Lambda_b^0 \rightarrow pK^+ K^- \pi^-) = \bar{u}_{\mathbf{B}} [V_{ud}^* V_{ub} (a_T + c_T + c_T^A) + V_{td}^* V_{tb} (a_P + c_P + c_P^A)] u_{\mathbf{B}_b}; \\ 7) \quad & \mathcal{A}(\Xi_b^0 \rightarrow \Sigma^+ K^+ K^- K^-) = 2\bar{u}_{\mathbf{B}} [V_{us}^* V_{ub} (a_T + b_T + c_T) + V_{ts}^* V_{tb} (a_P + b_P + c_P)] u_{\mathbf{B}_b}, \\ & \mathcal{A}(\Lambda_b^0 \rightarrow p\pi^+ \pi^- \pi^-) = 2\bar{u}_{\mathbf{B}} [V_{ud}^* V_{ub} (a_T + b_T + c_T) + V_{td}^* V_{tb} (a_P + b_P + c_P)] u_{\mathbf{B}_b}. \end{aligned} \quad (9)$$

Each of the pairs has the form given in Eq. (4), and therefore, similar CP asymmetry relations hold as in Eq. (1). By using Eq. (5), the direct U-spin relation in the previous section implies the predictions

$$\begin{aligned}
1) \quad & A_{CP}(\Xi_b^0 \rightarrow \Sigma^+ K^+ K^- \pi^-) = -A_{CP}(\Lambda_b^0 \rightarrow p \pi^+ K^- \pi^-) \frac{\text{Br}(\Lambda_b^0 \rightarrow p \pi^+ K^- \pi^-) \tau^{\Xi_b}}{\text{Br}(\Xi_b^0 \rightarrow \Sigma^+ K^+ K^- \pi^-) \tau^{\Lambda_b}}, \\
2) \quad & A_{CP}(\Xi_b^0 \rightarrow \Sigma^+ \pi^+ \pi^- \pi^-) = -A_{CP}(\Lambda_b^0 \rightarrow p K^+ K^- K^-) \frac{\text{Br}(\Lambda_b^0 \rightarrow p K^+ K^- K^-) \tau^{\Xi_b}}{\text{Br}(\Xi_b^0 \rightarrow \Sigma^+ \pi^+ \pi^- \pi^-) \tau^{\Lambda_b}}, \\
3) \quad & A_{CP}(\Lambda_b^0 \rightarrow \Sigma^+ K^+ K^- \pi^-) = -A_{CP}(\Xi_b^0 \rightarrow p \pi^+ K^- \pi^-) \frac{\text{Br}(\Xi_b^0 \rightarrow p \pi^+ K^- \pi^-) \tau^{\Lambda_b}}{\text{Br}(\Lambda_b^0 \rightarrow \Sigma^+ K^+ \pi^- \pi^-) \tau^{\Xi_b}}, \\
4) \quad & A_{CP}(\Lambda_b^0 \rightarrow \Sigma^+ K^+ \pi^- \pi^-) = -A_{CP}(\Xi_b^0 \rightarrow p \pi^+ K^- K^-) \frac{\text{Br}(\Xi_b^0 \rightarrow p \pi^+ K^- K^-) \tau^{\Lambda_b}}{\text{Br}(\Lambda_b^0 \rightarrow \Sigma^+ K^+ \pi^- \pi^-) \tau^{\Xi_b}}, \\
5) \quad & A_{CP}(\Xi_b^0 \rightarrow p K^+ K^- K^-) = -A_{CP}(\Lambda_b \rightarrow \Sigma^+ \pi^+ \pi^- \pi^-) \frac{\text{Br}(\Lambda_b^0 \rightarrow \Sigma^+ \pi^+ \pi^- \pi^-) \tau^{\Xi_b}}{\text{Br}(\Xi_b^0 \rightarrow p K^+ K^- K^-) \tau^{\Lambda_b}}, \\
6) \quad & A_{CP}(\Lambda_b^0 \rightarrow p K^+ K^- \pi^-) = -A_{CP}(\Xi_b^0 \rightarrow \Sigma^+ \pi^+ K^- \pi^-) \frac{\text{Br}(\Xi_b^0 \rightarrow \Sigma^+ \pi^+ K^- \pi^-) \tau^{\Lambda_b}}{\text{Br}(\Lambda_b^0 \rightarrow p K^+ K^- \pi^-) \tau^{\Xi_b}}, \\
7) \quad & A_{CP}(\Lambda_b^0 \rightarrow p \pi^+ \pi^- \pi^-) = -A_{CP}(\Xi_b^0 \rightarrow \Sigma^+ K^+ K^- K^-) \frac{\text{Br}(\Xi_b^0 \rightarrow \Sigma^+ K^+ K^- K^-) \tau^{\Lambda_b}}{\text{Br}(\Lambda_b^0 \rightarrow p \pi^+ \pi^- \pi^-) \tau^{\Xi_b}}. \tag{10}
\end{aligned}$$

From the above, if one of the A_{CP} values is measured, the CP violation of its U-spin partner can then be predicted, provided that the branching ratios in both channels are known. We would like to mention that if U-spin is violated, modifications will arise. It has been shown that, for B and B_s decays, the U-spin breaking effects are at the level of about 20% [10]. The relations discussed above should therefore be expected to hold at a similar level of accuracy. Consequently, one should keep in mind that the numerical values obtained below carry an uncertainty of roughly 20%.

As mentioned earlier, the natural energy scales Λ of the system are expected to correspond to the heavy quark mass m_b and to the resonance decay widths. If we focus on the phase space away from resonances, then $\Lambda = m_b$, and higher-order terms in the Λ^{-1} expansion may be neglected. Since the contributions of b_T^A and c_T^A start at order Λ^{-1} , they can be omitted in the nonresonant region. Resonances can generate sizable antisymmetric amplitudes, and in such cases, higher-order terms in Λ^{-1} must be retained. For instance, $\rho^0 \rightarrow \pi^+ \pi^-$ is antisymmetric in the two final-state mesons. However, no doubly charged, spin-integer bosons without heavy quarks are currently known, implying that P_1^+ and P_2^+ cannot be collectively produced from a single resonance.¹

Discussions and conclusions. We have the following related experimental information about the lifetimes and branching ratios [12]

$$\begin{aligned}
\tau^{\Lambda_b^0} &= (1.47 \pm 0.09) \times 10^{-12} \text{ s}, & \tau^{\Xi_b^0} &= (1.480 \pm 0.03) \times 10^{-12} \text{ s}; \\
\text{Br}(\Lambda_b^0 \rightarrow p \pi^+ \pi^- \pi^-) &= (2.08 \pm 0.21) \times 10^{-5}, & \text{Br}(\Lambda_b^0 \rightarrow p K^+ K^- \pi^-) &= (4.0 \pm 0.6) \times 10^{-6}, \\
\text{Br}(\Lambda_b^0 \rightarrow p \pi^+ K^- \pi^-) &= (5.0 \pm 0.5) \times 10^{-5}, & \text{Br}(\Lambda_b^0 \rightarrow p K^+ K^- K^-) &= (1.25 \pm 0.13) \times 10^{-5}. \tag{11}
\end{aligned}$$

For Ξ_b^0 decays, the experimental measurements are $\text{Br}(\Xi_b^0 \rightarrow p K^+ K^- K^-) \mathcal{R} = (1.7 \pm 0.9) \times 10^{-7}$, $\text{Br}(\Xi_b^0 \rightarrow p \pi^+ K^- K^-) \mathcal{R} = (1.7 \pm 0.3) \times 10^{-6}$, and $\text{Br}(\Xi_b^0 \rightarrow p \pi^+ K^- \pi^-) \mathcal{R} = (1.9 \pm 0.4) \times 10^{-6}$ [12]. Here, $\mathcal{R} = \text{Br}(b \rightarrow \Xi_b)/\text{Br}(b \rightarrow \Lambda_b)$, and $\text{Br}(b \rightarrow \mathbf{B}_b)$ denotes the fraction of a b quark hadronizing into a baryon $\mathbf{B}_b$. The hierarchy of $\text{Br}(\Xi_b^0 \rightarrow p \pi^+ K^- \pi^-) \approx \text{Br}(\Xi_b^0 \rightarrow p \pi^+ K^- K^-) \gg \text{Br}(\Xi_b^0 \rightarrow p K^+ K^- K^-)$ implies that $a_{T,P}, b_{T,P} \gg c_{T,P}$.

Efforts for CP violation searches have also been made. Besides the recently measured CP violation $A_{CP}(\Lambda_b \rightarrow p \pi^+ K^- \pi^-) = (2.45 \pm 0.46 \pm 0.10)\%$, for other decay modes discussed here, the precision is at the level of a few percent, but no confirmed results have been reported.

¹It should be noted that one of the P_1^+ and P_2^+ could be produced from baryonic and neutral mesonic resonance, which may contribute to b_T^A and c_T^A and be free from m_b^{-1} suppression. For instance, $\Lambda_b \rightarrow \Lambda(1520) \rho^0 \rightarrow (p K^-)(\pi^+ \pi^-)$.

From (1) in Eq. (10), we would obtain

$$A_{CP}(\Xi_b^0 \rightarrow \Sigma^+ K^+ K^- \pi^-) = -(2.45 \pm 0.47) \times 10^{-2} \frac{(5.0 \pm 0.5) \times 10^{-5}}{\text{Br}(\Xi_b^0 \rightarrow \Sigma^+ K^+ K^- \pi^-)}. \quad (12)$$

Unfortunately, experimentally the branching ratio $\text{Br}(\Xi_b^0 \rightarrow \Sigma^+ K^+ K^- \pi^-)$ has not been measured. If $\text{Br}(\Xi_b^0 \rightarrow \Sigma^+ K^+ K^- \pi^-)$ is similar to $\text{Br}(\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-)$, then sizeable CP violation may arise, potentially measurable in the near future.

In general, all the form factors—namely $S^{(0)}, P^{(0)}, \dots$ in Eq. (8)—are free parameters in the flavor symmetry

approach. As the series can continue indefinitely, a large number of terms would need to be included, making an overall fit impractical. Therefore, a cutoff in the Λ -expansion is necessary. As argued, b_T^A and c_T^A start at order Λ^{-1} , and P_1^+ and P_2^+ cannot originate from a single resonance. In light of this, we take $b_T^A = c_T^A = 0$ in the following and confront the assumption with the experimental data. Since interference terms between (a_T, b_T, c_T) and (b_T^A, c_T^A) vanish in the total decay width, $b_{T,P}^A$ and $c_{T,P}^A$ contribute only at order m_b^{-2} . In the following, we omit $b_{T,P}^A$ and $c_{T,P}^A$, as well as $c_{T,P}$, which has been shown to be small in the data. By taking these subleading contribution of $c_{T,P}, b_{T,P}^A, c_{T,P}^A$ to be zero, more predictions can be made [12]

$$\begin{aligned} \text{Br}(\Lambda_b^0 \rightarrow p\pi^+\pi^-\pi^-) &\simeq 2 \frac{\tau^{\Lambda_b^0}}{\tau^{\Xi_b^0}} \text{Br}(\Xi_b^0 \rightarrow \Sigma^+ K^+ K^- \pi^-) = (2.08 \pm 0.21 \pm 0.83) \times 10^{-5}, \\ \text{Br}(\Lambda_b^0 \rightarrow p\pi^+ K^- \pi^-) &\simeq \frac{1}{2} \frac{\tau^{\Lambda_b^0}}{\tau^{\Xi_b^0}} \text{Br}(\Xi_b^0 \rightarrow \Sigma^+ K^+ K^- K^-) = (5.0 \pm 0.5 \pm 2.0) \times 10^{-5}, \\ -A_{CP}(\Lambda_b^0 \rightarrow p\pi^+ K^- \pi^-) &\frac{2\text{Br}(\Lambda_b^0 \rightarrow p\pi^+ K^- \pi^-)}{\text{Br}(\Lambda_b^0 \rightarrow p\pi^+\pi^-\pi^-)} \simeq A_{CP}(\Lambda_b^0 \rightarrow p\pi^+\pi^-\pi^-) = (-12 \pm 3 \pm 5)\%, \end{aligned} \quad (13)$$

and $A_{CP}(\Xi_b^0 \rightarrow \Sigma^+ K^+ K^- \pi^-) \simeq A_{CP}(\Lambda_b^0 \rightarrow p\pi^+\pi^-\pi^-)$ from (1) and (7). We would like to comment that, if one naively applies the U-spin symmetry results by removing the second error in the above, the prediction deviates by more than 2σ from the latest measured range, $A_{CP}(\Lambda_b^0 \rightarrow p\pi^+\pi^-\pi^-) = (1.1 \pm 2.6)\%$ [13]. However, as mentioned earlier, since U-spin symmetry holds only up to the 20% level and an additional 20% uncertainty is associated with the cutoff scale Λ^{-1} , a larger error bar is expected. The second error quoted above reflects these effects. This leads

to a combined error of 6%. Taking these uncertainties into account, one finds that although the central values of the theoretical and experimental results appear to differ significantly, the deviation reduces to only 1.5σ . Interestingly, a model calculation incorporating the effects of final-state rescattering has indicated that $A_{CP}(\Lambda_b^0 \rightarrow p\pi^+\pi^-\pi^-)$ would also be negative [14]. Thus, more precise data are needed verify our approximate calculation. Moreover, it is premature to conclude the need for physics beyond the SM or even to invoke U-spin breaking effects.

On the other hand, (2) and (6) lead to

$$\begin{aligned} \text{Br}(\Lambda_b^0 \rightarrow pK^+ K^- K^-) &= 2 \frac{\tau^{\Lambda_b^0}}{\tau^{\Xi_b^0}} \text{Br}(\Xi_b^0 \rightarrow \Sigma^+ \pi^+ K^- \pi^-) = (1.25 \pm 0.13) \times 10^{-5}, \\ \text{Br}(\Lambda_b^0 \rightarrow pK^+ K^- \pi^-) &= \frac{1}{2} \frac{\tau^{\Lambda_b^0}}{\tau^{\Xi_b^0}} \text{Br}(\Xi_b^0 \rightarrow \Sigma^+ \pi^+ \pi^- \pi^-) = (4.0 \pm 0.6) \times 10^{-6}, \\ -A_{CP}(\Lambda_b^0 \rightarrow pK^+ K^- K^-) &\frac{\text{Br}(\Lambda_b^0 \rightarrow pK^+ K^- K^-)}{2\text{Br}(\Lambda_b^0 \rightarrow pK^+ K^- \pi^-)} = A_{CP}(\Lambda_b^0 \rightarrow pK^+ K^- \pi^-) = (-0.3 \pm 3.0)\%, \end{aligned} \quad (14)$$

where the last line is consistent with the experimental value of the asymmetry sum $A_{CP}(\Lambda_b^0 \rightarrow pK^+ K^- \pi^-) - A_{CP}(\Lambda_b^0 \rightarrow (\Lambda_c^+ \rightarrow p\pi^+\pi^-)\pi^-) = (-7 \pm 5)\%$ [12,13]. This prediction can also be tested by experiments in the near future. Note that baryonic and mesonic resonances may introduce a new energy scale, thereby breaking the power counting hierarchy $a_{T,P}, b_{T,P}, c_{T,P} \gg b_{T,P}^A, c_{T,P}^A$. In this

case, the relations in Eqs. (13) and (14) can still hold if the experiments bypass the resonance region, although the numerical values may differ.

It is worth emphasizing that the most robust results of this work—such as the relations in Eqs. (1) and (12)—arise directly from U-spin symmetry and do not depend on any additional power-counting assumptions. These model-

independent relations serve as clear benchmarks for future experimental tests of CP violation in baryon decays and for probing the validity of U-spin symmetry in b -baryon processes.

Note added. While we were finishing our work, a preprint by Zhang and Wang appeared [arXiv:2503.21885], which also considers the U-spin for related decays.

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Data availability. No data were created or analyzed in this study.

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