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Implications of recent LHCb data on CPV in b-baryon four body decays

Zhi-Peng Xing

work with **Qi Chen, Wu Xin, Ruilin Zhu**

Phys. Rev. D 112, no.3, 3 (2025)

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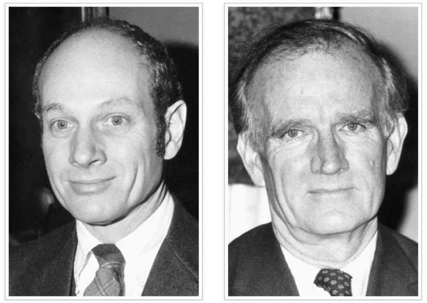
河南师范大学

- Introduction
- U-spin analysis of b-baryon decays
- Simple dynamic analysis
- Numerical results and conclusion

Introduction: 重子CP破坏

- 1956, Parity violation in weak interaction
- 1964, Observation of CP violation in Kaon
- 1973, Kobayashi-Maskawa mechanism
- 2004, Observation of direct CPV in B meson
- 2019, Observation of direct CPV in D meson
- 2025, Observation of direct CPV in b baryon



$$\Lambda_b^0 \to pK^-\pi^+\pi^-$$

$$\mathcal{A}_{CP} = (2.45 \pm 0.46 \pm 0.10)\% \,.$$

$$\begin{aligned}
\mathcal{A}_{CP}^{dir}(\Lambda_b^0 \to R(pK^-)R(\pi^+\pi^-)) &= (5.3 \pm 1.3 \pm 0.2)\%, \quad m_{pK^-} < 2.2\text{GeV}, \quad m_{\pi^-\pi^+} < 1.1\text{GeV}, \\
\mathcal{A}_{CP}^{dir}(\Lambda_b^0 \to R(p\pi^-)R(\pi^+K^-)) &= (2.7 \pm 0.8 \pm 0.1)\%, \quad m_{p\pi^-} < 1.7\text{GeV}, \\
& \quad 0.8\text{GeV} < m_{\pi^+K^-} < 1.0\text{GeV or } 1.1\text{GeV} < m_{\pi^+K^-} < 1.6\text{GeV}, \\
\mathcal{A}_{CP}^{dir}(\Lambda_b^0 \to R(p\pi^+\pi^-)K^-) &= (5.4 \pm 0.9 \pm 0.1)\%, \quad m_{p\pi^+\pi^-} < 2.7\text{GeV}, \\
\mathcal{A}_{CP}^{dir}(\Lambda_b^0 \to R(K^-\pi^+\pi^-)p) &= (2.0 \pm 1.2 \pm 0.3)\%, \quad m_{K^-\pi^+\pi^-} < 2.0\text{GeV}.
\end{aligned}$$

Introduction: 重子CP破坏

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Search for CP violation in $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$ decays

LHCb Collaboration

PHYSICAL REVIEW D **104,** 052010 (2021)

Search for CP violation in $\Xi_b^- \to pK^-K^-$ decays

R. Aaij *et al.*[*]
(LHCb Collaboration)

Article

Probing CP symmetry and weak phases with entangled double-strange baryons

https://doi.org/10.1038/s41586-022-04624-1

The BESIII Collaboration*✉

PHYSICAL REVIEW LETTERS **129,** 131801 (2022)

Precise Measurements of Decay Parameters and CP Asymmetry with Entangled Λ-$\bar{\Lambda}$ Pairs

PHYSICAL REVIEW LETTERS **133,** 101902 (2024)

Strong and Weak CP Tests in Sequential Decays of Polarized Σ^0 Hyperons

M. Ablikim *et al.*[*]
(BESIII Collaboration)

Stringent test of CP symmetry in Σ^+ hyperon decays

BESIII Collaboration • Medina Ablikim (Beijing, Inst. High Energy Phys.) Show All(703)

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PHYSICAL REVIEW LETTERS **134,** 101802 (2025)

estion Featured in Physics

Study of Λ_b^0 and Ξ_b^0 Decays to $\Lambda h^+h'^-$ and Evidence for CP Violation in $\Lambda_b^0 \to \Lambda K^+K^-$ Decays

R. Aaij *et al.*[*]
(LHCb Collaboration)

PHYSICAL REVIEW D **111,** 092004 (2025)

Measurement of CP asymmetries in $\Lambda_b^0 \to ph^-$ decays

R. Aaij *et al.*[*]
(LHCb Collaboration)

Observation of charge-parity symmetry breaking in baryon decays

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29 pages

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CP violation of baryon decays with $N\pi$ rescatterings*

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A novel strategy for searching for *CP* violations in the baryon sector

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PHYSICAL REVIEW LETTERS **134,** 221801 (2025)

Establishing *CP* Violation in *b*-Baryon Decays

Jia-Jie Han,[1] Ji-Xin Yu,[1,*] Ya Li,[2,†] Hsiang-nan Li,[3,‡] Jian-Peng Wang,[1,§] Zhen-Jun Xiao,[4,‖] and Fu-Sheng Yu[1,¶]
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The theoretical research on baryon CP violation has entered a new step

U-spin analysis of b-baryon decays

d $\Leftrightarrow$ s

$$\underbrace{\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}}\left[V_{ub}^{*}V_{uq}\left(\sum_{i=1}^{2} C_i Q_i^{uq} + \sum_{i=3}^{10} C_i Q_i^{q}\right) + V_{cb}^{*}V_{cq}\left(\sum_{i=1}^{2} C_i Q_i^{cq} + \sum_{i=3}^{10} C_i Q_i^{q}\right)\right], \quad q = d, s,}_{\text{Different strong phase and weak phase}}$$

- **The symmetry between u and (d,s) will change the structure of Hamiltonian**
- **The symmetry transformation of U-spin will not affect the generation mechanism of CPV: the weak phasedifference between tree level and penguin level.**

U-spin analysis of b-baryon decays

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$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}}\left[V_{ub}^* V_{uq}\left(\sum_{i=1}^{2} C_i Q_i^{uq} + \sum_{i=3}^{10} C_i Q_i^q\right) + V_{cb}^* V_{cq}\left(\sum_{i=1}^{2} C_i Q_i^{cq} + \sum_{i=3}^{10} C_i Q_i^q\right)\right], \quad q = d, s,$$

Omitting their Dirac structure

$$Q_{1,2}^{us} \sim (\bar{b}u)(\bar{u}s), \quad Q_{1,2}^{cs} \sim (\bar{b}c)(\bar{c}s), \quad Q_{1,2}^{ud} \sim (\bar{b}u)(\bar{u}d), \quad Q_{1,2}^{cd} \sim (\bar{b}c)(\bar{c}d),$$

$$Q_{3-10}^{s} \sim \bar{b}s \sum \bar{q}'q' \sim (b\bar{s})(u\bar{u}) + \boxed{(b\bar{s})(d\bar{d}) + (b\bar{s})(s\bar{s})}, \quad Q_{3-10}^{d} \sim \bar{b}d \sum \bar{q}'q' \sim (b\bar{d})(u\bar{u}) + \boxed{(b\bar{d})(d\bar{d}) + (b\bar{d})(s\bar{s})}.$$

$$2 \otimes \bar{2} \otimes 2 = 4 \oplus 2 \oplus 2$$

$$H_k^{ij} = \frac{1}{2} H(4)_k^{ij} - \frac{1}{3} H(2)_k^{ij} + \frac{2}{3} H(2')_k^{ij},$$

$$(H_4)_k^{ij} = -\frac{1}{3}\left(H_m^{im}\delta_k^j + H_m^{jm}\delta_k^i + H_m^{mi}\delta_k^j + H_m^{mj}\delta_k^i\right) + H_k^{ij} + H_k^{ji},$$

$$(H_2)_k^{ij} = H_m^{mi}\delta_k^j + H_m^{jm}\delta_k^i, \quad (H_2')_k^{ij} = H_m^{im}\delta_k^j + H_m^{mj}\delta_k^i.$$

U-spin analysis of b-baryon decays

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$$\mathcal{H}_{\rm eff}=\frac{G_F}{\sqrt{2}}\left[V_{ub}^*V_{uq}\left(\sum_{i=1}^{2}C_iQ_i^{uq}+\sum_{i=3}^{10}C_iQ_i^{q}\right)+V_{cb}^*V_{cq}\left(\sum_{i=1}^{2}C_iQ_i^{cq}+\sum_{i=3}^{10}C_iQ_i^{q}\right)\right],\quad q=d,s,$$

Omitting their Dirac structure

$$Q_{1,2}^{us}\sim(\bar{b}u)(\bar{u}s),\quad Q_{1,2}^{cs}\sim(\bar{b}c)(\bar{c}s),\quad Q_{1,2}^{ud}\sim(\bar{b}u)(\bar{u}d),\quad Q_{1,2}^{cd}\sim(\bar{b}c)(\bar{c}d),$$

$$Q_{3-10}^{s}\sim\bar{b}s\sum\bar{q}'q'\sim(b\bar{s})(u\bar{u})+\boxed{(b\bar{s})(d\bar{d})+(b\bar{s})(s\bar{s})},\quad Q_{3-10}^{d}\sim\bar{b}d\sum\bar{q}'q'\sim(b\bar{d})(u\bar{u})+\boxed{(b\bar{d})(d\bar{d})+(b\bar{d})(s\bar{s})}.$$

$$2\otimes\bar{2}\otimes 2=4\oplus 2\oplus 2$$

$$2(H_2)^{11}_1=3(H_2)^{21}_2=6(H_2)^{12}_2=2V_{ud}^*V_{ub}+2V_{cd}^*V_{cb},\quad 2(H_2)^{22}_2=3(H_2)^{12}_1=6(H_2)^{21}_1=2V_{us}^*V_{ub}+2V_{cs}^*V_{cb},$$

$$(H_2)^1=\frac{5}{3}(V_{ud}^*V_{ub}+V_{cd}^*V_{cb}),\quad (H_2)^2=\frac{5}{3}(V_{us}^*V_{ub}+V_{cs}^*V_{cb}),\qquad (H_4)=0,$$

$$(H_2)^i=(H_2)^{ji}_k\delta^k_j.$$

The Hamiltonian can form a doublet

U-spin analysis of b-baryon decays

$$B_b^1 = (\Xi_b^-),\ B_b^2 = (\Lambda_b^0, \Xi_b^0),\ B^1 = \frac{\sqrt{3}}{2}\Sigma^0 - \frac{1}{2}\Lambda^0, M^2 = (\pi^-, K^-),\ M^{\bar{2}} = (\pi^+, K^+),\ B_{\bar{2}}^2 = (\Sigma^-, \Xi^-),$$

$$M^3 = \begin{pmatrix} \frac{\sqrt{3}\eta_8}{2\sqrt{2}} - \frac{\pi^0}{2\sqrt{2}} & K^0 \\ \bar{K}^0 & \frac{\pi^0}{2\sqrt{2}} - \frac{\sqrt{3}\eta_8}{2\sqrt{2}} \end{pmatrix},\ B_1^2 = (p, \Sigma^+), B^3 = \begin{pmatrix} -\frac{\Sigma^0}{2\sqrt{2}} - \frac{\sqrt{3}\Lambda^0}{2\sqrt{2}} & n \\ \Xi^0 & \frac{\Sigma^0}{2\sqrt{2}} + \frac{\sqrt{3}\Lambda^0}{2\sqrt{2}} \end{pmatrix}$$

Taking triplet as an example

For the baryon system, the U-spin symmetry $2 \otimes 2 = 3 \oplus 1$, the wave functions can be expressed as:

$$\mathbf{3}: \begin{cases} U = 1, U_3 = +1: \quad \phi_3^{+1} = dd, \\ U = 1, U_3 = 0: \quad \phi_3^0 = \frac{1}{\sqrt{2}}(ds + sd), \\ U = 1, U_3 = -1: \quad \phi_3^{-1} = ss, \end{cases} \qquad \mathbf{1}: \quad U = 0, U_3 = 0: \quad \phi_1^0 = \frac{1}{\sqrt{2}}(ds - sd).$$

$$\Sigma^0 = \frac{1}{\sqrt{2}}[\frac{1}{\sqrt{12}}(2uds - usd - dsu + 2dus - sud - sdu)\frac{1}{\sqrt{6}}(2\uparrow\uparrow\downarrow - \uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow) + \frac{1}{2}(usd + dsu - sdu - sud)\frac{1}{\sqrt{2}}(\uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow)],$$

$$\Lambda^0 = \frac{1}{\sqrt{2}}[\frac{1}{\sqrt{12}}(2uds - dsu - sud - 2dus - sdu + usd)\frac{1}{\sqrt{2}}(\uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow)$$

$$\mathbf{3}: \begin{cases} U=1, U_3=+1: \quad \phi_3^{+1} = -\frac{1}{\sqrt{3}}[dd\frac{1}{\sqrt{2}}(\uparrow\downarrow + \downarrow\uparrow), u\uparrow]_p + \frac{\sqrt{2}}{\sqrt{3}}[dd\uparrow\uparrow, u\downarrow]_p, \\ U=1, U_3=0: \quad \phi_3^{0} = -\frac{1}{\sqrt{3}}[\frac{1}{\sqrt{2}}(ds+sd)\frac{1}{\sqrt{2}}(\uparrow\downarrow + \downarrow\uparrow), u\uparrow]_p + \frac{\sqrt{2}}{\sqrt{3}}[\frac{1}{\sqrt{2}}(ds+sd)\uparrow\uparrow, u\downarrow]_p, \\ U=1, U_3=-1: \quad \phi_3^{-1} = -\frac{1}{\sqrt{3}}[ss\frac{1}{\sqrt{2}}(\uparrow\downarrow + \downarrow\uparrow), u\uparrow]_p + \frac{\sqrt{2}}{\sqrt{3}}[ss\uparrow\uparrow, u\downarrow]_p, \end{cases} \tag{A12}$$

$$\mathbf{1}: \quad U=0, U_3=0: \quad \phi_1^{0} = -\frac{1}{\sqrt{3}}[\frac{1}{\sqrt{2}}(ds-sd)\frac{1}{\sqrt{2}}(\uparrow\downarrow + \downarrow\uparrow), u\uparrow]_p + \frac{\sqrt{2}}{\sqrt{3}}[\frac{1}{\sqrt{2}}(ds-sd)\uparrow\uparrow, u\downarrow]_p, \tag{A13}$$

where $[ds, u]_p$ is the permutation operation which is $[ds, u]_p = \frac{1}{\sqrt{3}}(uds + dus + dsu)$. Comparing the wave function under U-spin and $SU(3)_F$ in Eq.(A13), Eq.(A12) and Eq.(A6), we can derive

$$\phi_3^{+1} = n, \quad \phi_3^0 = -\frac{1}{2}\Sigma^0 - \frac{\sqrt{3}}{2}\Lambda^0, \quad \phi_3^{+1} = \Xi^0, \quad \phi_1^0 = -\frac{1}{2}\Lambda^0 + \frac{\sqrt{3}}{2}\Sigma^0. \tag{A14}$$

U-spin analysis of b-baryon decays

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$$\mathcal{A}^2_{222\bar{2}} = \sum_{q=u,c}\Big(c_{1q}(B^2_b)^i(H_q)^j(B^2_1)_i(M^2)_j(M^2)_k(M^{\bar{2}})^k + c_{2q}(B^2_b)^j(H_q)^i(B^2_1)_i(M^2)_j(M^2)_k(M^{\bar{2}})^k$$
$$+ c_{3q}(B^2_b)^j(H_q)^k(B^2_1)_i(M^2)_j(M^2)_k(M^{\bar{2}})^i\Big),$$

channel	amplitude	channel	amplitude
$\Lambda^0_b \to p\pi^-\pi^-\pi^+$	$\sum_q \lambda^q_d(c_1+c_2+c_3)$	$\Xi^0_b \to \Sigma^+K^-K^-K^+$	$\sum_q \lambda^q_s(c_1+c_2+c_3)$
$\Lambda^0_b \to pK^-\pi^-K^+$	$\sum_q \lambda^q_d(c_1+c_2)$	$\Xi^0_b \to \Sigma^+K^-\pi^-\pi^+$	$\sum_q \lambda^q_s(c_1+c_2)$
$\Xi^0_b \to pK^-\pi^-\pi^+$	$\sum_q \lambda^q_d(c_2+c_3)$	$\Lambda^0_b \to \Sigma^+K^-\pi^-K^+$	$\sum_q \lambda^q_s(c_2+c_3)$
$\Xi^0_b \to pK^-K^-K^+$	$\sum_q \lambda^q_d c_2$	$\Lambda^0_b \to \Sigma^+\pi^-\pi^-\pi^+$	$\sum_q \lambda^q_s c_2$
$\Lambda^0_b \to \Sigma^+\pi^-\pi^-K^+$	$\sum_q \lambda^q_d c_3$	$\Xi^0_b \to pK^-K^-\pi^+$	$\sum_q \lambda^q_s c_3$
$\Xi^0_b \to \Sigma^+\pi^-\pi^-\pi^+$	$\sum_q \lambda^q_d c_1$	$\Lambda^0_b \to pK^-K^-K^+$	$\sum_q \lambda^q_s c_1$
$\Xi^0_b \to \Sigma^+\pi^-K^-K^+$	$\sum_q \lambda^q_d(c_1+c_3)$	$\Lambda^0_b \to p\pi^-K^-\pi^+$	$\sum_q \lambda^q_s(c_1+c_3)$

U-spin symmetry channels

$$\Delta S = 0$$

$$\mathcal{A} = V_{ub}^* V_{ud} \mathcal{A}_u + V_{cb}^* V_{cd} \mathcal{A}_c,$$
$$\bar{\mathcal{A}} = V_{ub} V_{ud}^* \mathcal{A}_u + V_{cb} V_{cd}^* \mathcal{A}_c.$$

$$\Delta S = 1$$

$$\mathcal{A} = V_{ub}^* V_{us} \mathcal{A}_u + V_{cb}^* V_{cs} \mathcal{A}_c,$$
$$\bar{\mathcal{A}} = V_{ub} V_{us}^* \mathcal{A}_u + V_{cb} V_{cs}^* \mathcal{A}_c.$$

The squared amplitude is

$$|\mathcal{A}(B_b \to BMM)|^2 = |V_{ub}^* V_{uq}|^2 |\mathcal{A}_u|^2 + |V_{cb}^* V_{cq}|^2 |\mathcal{A}_c|^2 + 2\mathrm{Re}(V_{ub}^* V_{uq} \mathcal{A}_u \times V_{cb} V_{cq}^* \mathcal{A}_c^*),$$

$$|\mathcal{A}(\bar{B}_b \to \bar{B}\bar{M}\bar{M})|^2 = |V_{ub} V_{uq}^*|^2 |\mathcal{A}_u|^2 + |V_{cb} V_{cq}^*|^2 |\mathcal{A}_c|^2 + 2\mathrm{Re}(V_{ub} V_{uq}^* \mathcal{A}_u \times V_{cb}^* V_{cq} \mathcal{A}_c^*),$$

$$A_{CP}^{\mathrm{dir}} = -\frac{4\,\mathrm{Im}(V_{ub}^* V_{uq} V_{cb} V_{cq}^*)\,\mathrm{Im}(\mathcal{A}_u \mathcal{A}_c^*)}{|\mathcal{A}(B_b \to BMM)|^2 + |\mathcal{A}(\bar{B}_b \to \bar{B}\bar{M}\bar{M})|^2},$$

$$A_{CP}^{dir}(\Xi_b^0 \to \Sigma^+\pi^-K^-K^+) = -\mathcal{R}\left(\frac{\Lambda_b^0 \to p\pi^-K^-\pi^+}{\Xi_b^0 \to \Sigma^+\pi^-K^-K^+}\right) \times A_{CP}^{dir}(\Lambda_b^0 \to p\pi^-K^-\pi^+)$$

$$\mathcal{R}\left(\frac{B_b \to BMM}{B_b' \to B'M'M'}\right) = \frac{\mathcal{B}(B_b \to BMM)\cdot\tau(B_b')}{\mathcal{B}(B_b' \to B'M'M')\cdot\tau(B_b)}$$

CKM matrix unitarity relation

$$\boxed{\mathrm{Im}(V_{ub}^* V_{us} V_{cb} V_{cs}^*) = -\mathrm{Im}(V_{ub}^* V_{ud} V_{cb} V_{cd}^*)},$$

Detail discussion can be found in [Phys. Rev. D 111, no.5, 053006 (2025)]

U-spin analysis of b-baryon decays

Using the experimental data [12]

$$\mathcal{A}_{CP}^{dir}(\Lambda_b^0 \to p\pi^-\pi^+K^-) = (2.45 \pm 0.46 \pm 0.1)\%,$$

and [54]

$$\tau(\Lambda_b^0) = 1.468 \pm 0.009ps, \tau(\Xi_b^0) = 1.477 \pm 0.032ps, \tau(\Xi_b^-) = 1.578 \pm 0.021ps,$$

we can have

$$\begin{aligned} A_{CP}^{dir}(\Xi_b^0 \to \Sigma^+\pi^-K^-K^+) &= -\mathcal{R}\left(\frac{\Lambda_b^0 \to p\pi^-K^-\pi^+}{\Xi_b^0 \to \Sigma^+\pi^-K^-K^+}\right) \times A_{CP}^{dir}(\Lambda_b^0 \to p\pi^-K^-\pi^+) \\ &= -(2.45 \pm 0.46) \times \frac{(5.1 \pm 0.5) \times 10^{-5}}{Br(\Xi_b^0 \to \Sigma^+\pi^-K^-K^+)} \frac{\tau(\Xi_b)}{\tau(\Lambda_b)} = \frac{(-1.23 \pm 0.26) \times 10^{-4}}{Br(\Xi_b^0 \to \Sigma^+\pi^-K^-K^+)}. \end{aligned}$$

However, since the generation efficiency of Ξ_b^0 is not as high as that of Λ_b^0 in LHCb experiment, the prediction of Ξ_b^0 decay CPV may not be immediately useful for experimental CPV detection.

Simple dynamic analysis

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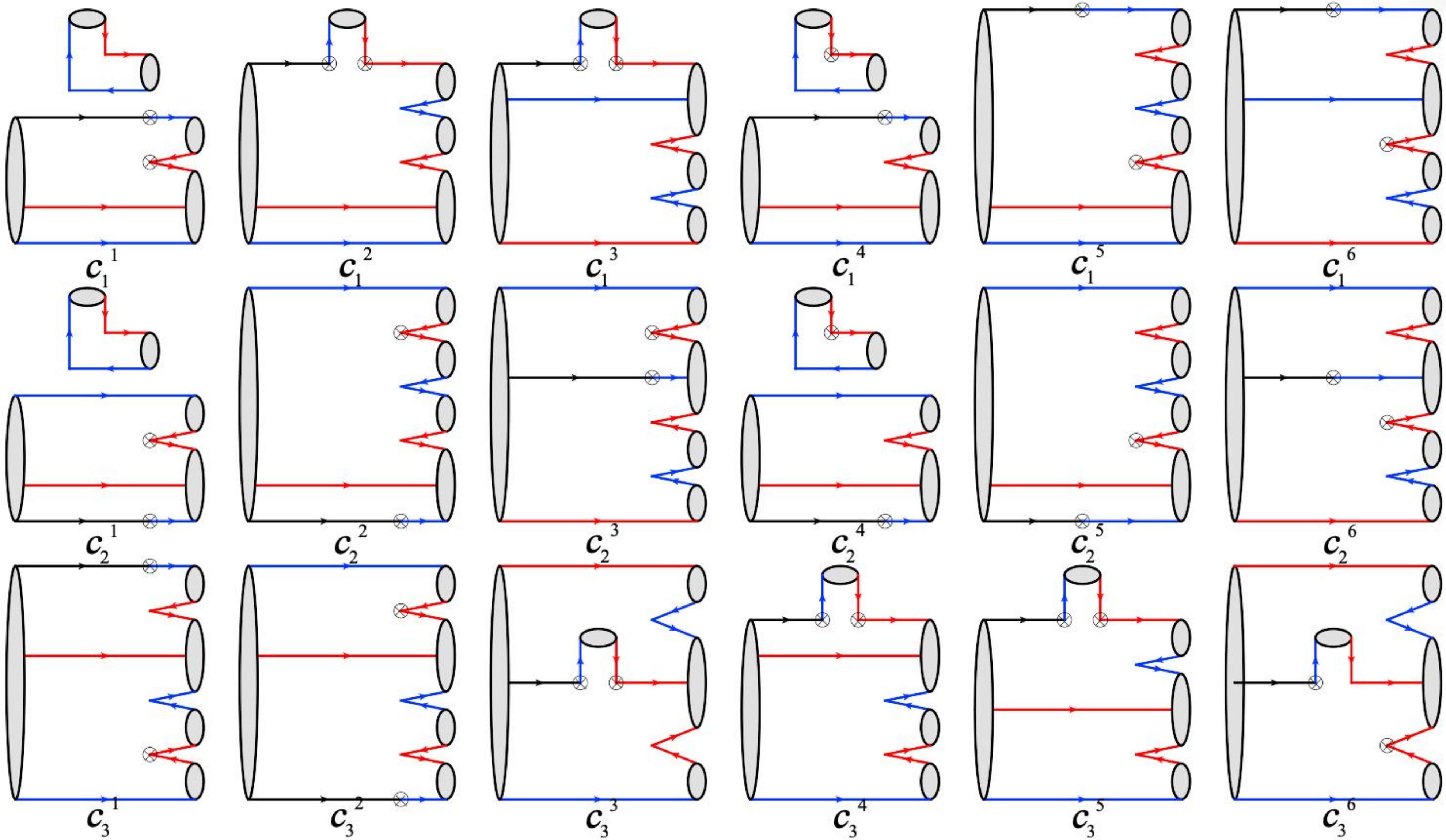
$$
\begin{aligned}
\mathcal{A}_{CP}^{dir}(\Lambda_b^0 \to R(pK^-)R(\pi^+\pi^-)) &= (5.3 \pm 1.3 \pm 0.2)\%, \quad m_{pK^-} < 2.2\text{GeV}, \quad m_{\pi^-\pi^+} < 1.1\text{GeV}, \\
\mathcal{A}_{CP}^{dir}(\Lambda_b^0 \to R(p\pi^-)R(\pi^+K^-)) &= (2.7 \pm 0.8 \pm 0.1)\%, \quad m_{p\pi^-} < 1.7\text{GeV}, \\
& \quad 0.8\text{GeV} < m_{\pi^+K^-} < 1.0\text{GeV or } 1.1\text{GeV} < m_{\pi^+K^-} < 1.6\text{GeV}, \\
\mathcal{A}_{CP}^{dir}(\Lambda_b^0 \to R(p\pi^+\pi^-)K^-) &= (5.4 \pm 0.9 \pm 0.1)\%, \quad m_{p\pi^+\pi^-} < 2.7\text{GeV}, \\
\mathcal{A}_{CP}^{dir}(\Lambda_b^0 \to R(K^-\pi^+\pi^-)p) &= (2.0 \pm 1.2 \pm 0.3)\%, \quad m_{K^-\pi^+\pi^-} < 2.0\text{GeV}.
\end{aligned}
$$

Can we determine the decay strcture by their topological diagram?

Simple dynamic analysis



Simple dynamic analysis

HQET&SCET $\lambda = \sqrt{\frac{\Lambda_{QCD}}{m_b}}.$

hard hard-collinear collinear soft

$$\psi = \xi_c + \eta_c + \xi_{hc} + \eta_{hc} + q_s$$
$$= \xi_c + \xi_{hc} + q_s - \frac{1}{in \cdot D_s}\frac{\not{n}}{2}((i\not{D}_\perp + m)(\xi_c + \xi_{hc}) + (g\not{A}_{\perp c} + g\not{A}_{\perp hc})q_s),$$

$$p_c^\mu \sim (1, \lambda^2, \lambda^4)$$

$$p_s^\mu \sim (\lambda^2, \lambda^2, \lambda^2)$$

$$\xi_c = \frac{\not{n}_-\not{n}_+}{4}\psi_c \sim \lambda^2, \quad h_v = \frac{1+\not{v}}{2}Q_v \sim \lambda^3, \quad q_s \sim \lambda^3,$$

QCD

$$O_{4q}(0) \to \sum_{i,j}\sum_{C=S,O}\left\{\int dr\, dt\, \widetilde{C}_{ij}^{(C)}(r,t,E,m_b,\mu)\, Q_{ij}^{(C)}(r,t) - \frac{1}{2}\int dr\, ds\, dt\, \widetilde{D}_{ij}^{(C)}(r,s,t,E,m_b,\mu)\, R_{ij}^{(C)}(r,s,t)\right\},$$

↓

$SCET_I$

↓

$SCET_{II}$

$$Q_{ij}^{(C)}(r,t) = [\bar{\xi}\,W](-r\bar{n})\,\Gamma_i T_1\,[W^\dagger\xi](r\bar{n})\,[\bar{h}\,S](0)\,\Gamma_j T_2\,[S^\dagger q_s](tn)\,,$$
$$R_{ij}^{(C)}(r,s,t) = [\bar{\xi}\,W](-r\bar{n})\,\Gamma_i T_1\,[W^\dagger\xi](r\bar{n})\,[\bar{h}\,S](0)\,\Gamma_j T_2\,\not{n}\,\not{A}_{c\perp}(s\bar{n})\,[S^\dagger q_s](tn)$$

$$[\bar{\xi}\,W]\,\Gamma_i\,[W^\dagger\xi]\,[\bar{h}\,S]\,\Gamma_j\,(\not{n}\,\not{A}_{c\perp})\,[S^\dagger q_s]$$
$$\text{or} \quad [\bar{\xi}\,W]\,\Gamma_i'\,(\not{n}\,\not{A}_{c\perp})\,[S^\dagger q_s]\,[\bar{h}\,S]\,\Gamma_j'\,[W^\dagger\xi]$$

See:Nucl. Phys. B 657, 229-256 (2003)

Simple dynamic analysis

HQET&SCET $\lambda = \sqrt{\frac{\Lambda_{QCD}}{m_b}}.$ hard hard-collinear collinear soft

$$[\bar{Q}\psi][\bar{\psi}\psi] \Rightarrow [\bar{h}_v q_s][\bar{\xi}_c\xi_c] \sim \lambda^{10}, \qquad [\bar{h}_v\xi_c][\bar{\xi}_c q_s] \sim \lambda^{10}, \qquad [\bar{h}_v\xi_c][\bar{q}_s\xi_c] \sim \lambda^{10}$$

A. In the rest frame of the b-baryon, the HQET indicates that the momentum of the light quark in b-baryon should be soft.

QCD → $\mathrm{SCET_I}$ → $\mathrm{SCET_{II}}$

B. The strictly analysis of matrix element in SCET need consider the strictly matching between four quark operator and several SCET operators in which the hard and hard-collinear gluon contribution will be integrated and therefore the hard scattering kernel will introduced. However, since the hard and hard-collinear gluon line can not be drawn in the topological diagram, we must omit the scattering kernel hand only analyze the contribution of SCET operator. That is the reason we called the dynamic analysis in our work is simply analysis.

C. The quark and anti-quark pair which come from the vacuum are seen as soft quark and anti-quark produced form a soft gluon in our work.

Simple dynamic analysis

HQET&SCET $\lambda = \sqrt{\frac{\Lambda_{QCD}}{m_b}}.$ hard hard-collinear collinear soft

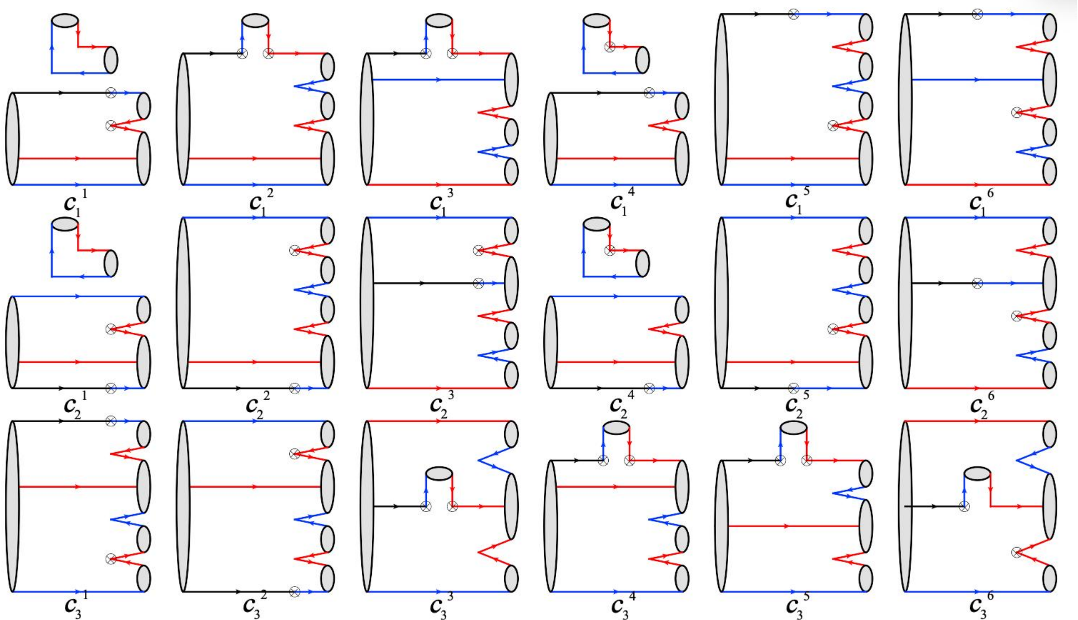
$[\bar{Q}\psi][\bar{\psi}\psi]$ ➡ $[\bar{h}_v q_s][\bar{\xi}_c \xi_c] \sim \lambda^{10}, \quad [\bar{h}_v \xi_c][\bar{\xi}_c q_s] \sim \lambda^{10}, \quad [\bar{h}_v \xi_c][\bar{q}_s \xi_c] \sim \lambda^{10}$

Since the kinematic region of soft and collinear are different, the wave function of hadron containing both soft quark and collinear quark is power suppressed.

QCD

SCET$_I$

SCET$_{II}$

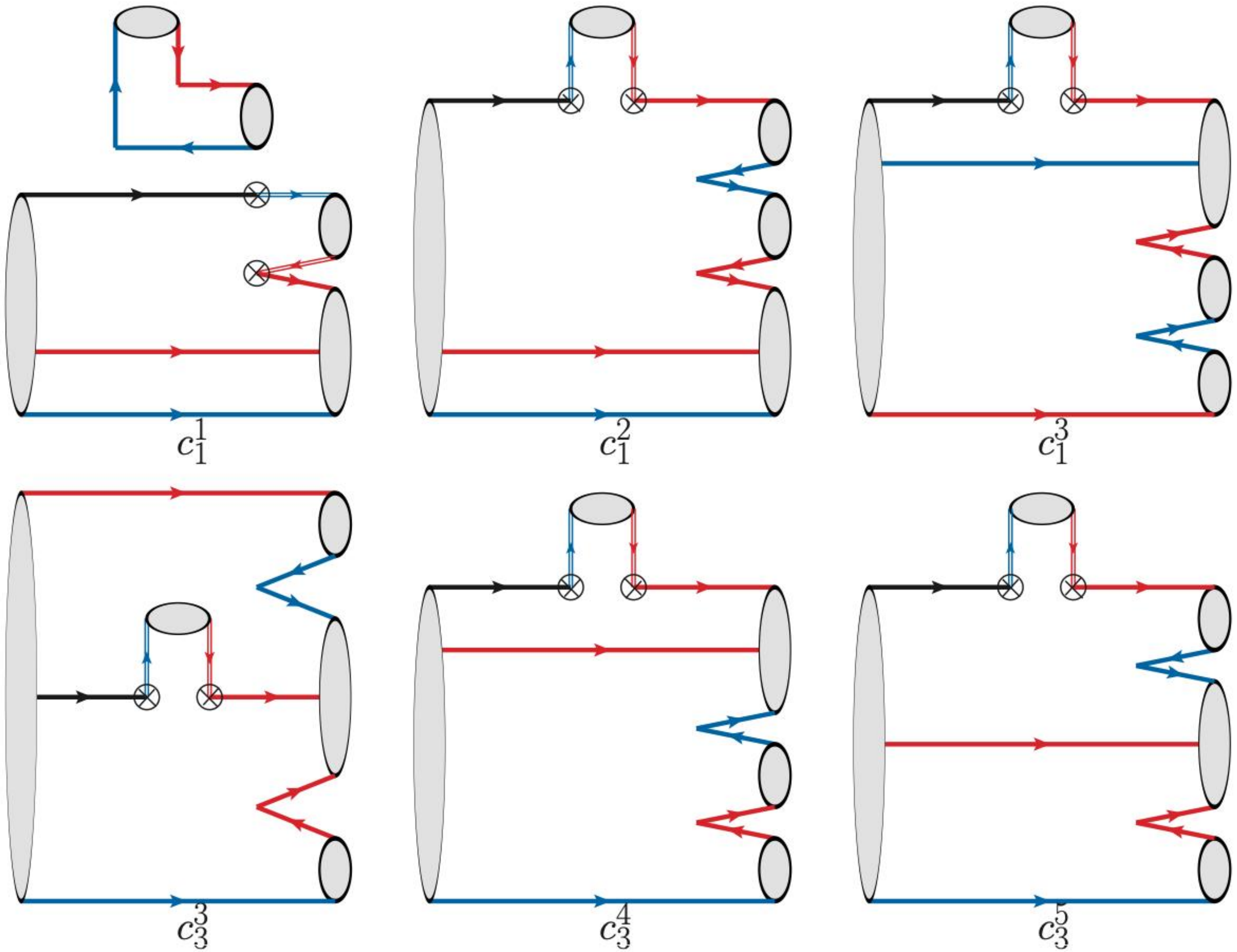


The strategy of find the leading power topological diagram is choosing the suitable leading power Hamiltonian and making the quark field in light hadron are all soft or collinear.

Simple dynamic analysis

HQET&SCET $\lambda = \sqrt{\frac{\Lambda_{QCD}}{m_b}}$.

$$\mathcal{A}^2_{222\bar{2}} = \sum_{q=u,c} \Big(c_{1q}(B_b^2)^i (H_q)^j (B_1^2)_i (M^2)_j (M^2)_k (M^{\bar{2}})^k + c_{2q}(B_b^2)^j (H_q)^i (B_1^2)_i (M^2)_j (M^2)_k (M^{\bar{2}})^k + c_{3q}(B_b^2)^j (H_q)^k (B_1^2)_i (M^2)_j (M^2)_k (M^{\bar{2}})^i \Big),$$



if we focus on the structure $B_b^2 \to R(B_1^2 M^2) R(M^{\bar{2}} M^2)$, only amplitude c_1 have contribution and if we focus on the structure $B_b^2 \to R(B_1^2 M^2 M^{\bar{2}}) M^2$, only amplitudes c_1 and c_3 can have contributions.

Numerical results and conclusion

Amplitude

$$\mathcal{A}(\Lambda_b^0 \to R(p\pi^-\pi^+)\pi^-) = \sum_q \lambda_d^q(c_1+c_3), \quad \mathcal{A}(\Xi_b^0 \to R(\Sigma^+K^-K^+)K^-) = \sum_q \lambda_s^q(c_1+c_3),$$

$$\mathcal{A}(\Xi_b^0 \to R(\Sigma^+K^-K^+)\pi^-) = \sum_q \lambda_d^q(c_1+c_3), \quad \mathcal{A}(\Lambda_b^0 \to R(p\pi^-\pi^+)K^-) = \sum_q \lambda_s^q(c_1+c_3),$$

$$\mathcal{A}(\Lambda_b^0 \to R(p\pi^-)R(\pi^-\pi^+)) = \sum_q \lambda_d^q c_1, \quad \mathcal{A}(\Xi_b^0 \to R(\Sigma^+K^-)R(K^-K^+)) = \sum_q \lambda_s^q c_1,$$

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$$\mathcal{A}(\Xi_b^0 \to R(\Sigma^+\pi^-)R(K^-K^+)) = \sum_q \lambda_d^q c_1, \quad \mathcal{A}(\Lambda_b^0 \to R(pK^-)(\pi^-\pi^+)) = \sum_q \lambda_s^q c_1.$$

Prediction

$$\boxed{A_{CP}^{dir}(\Lambda_b^0 \to R(p\pi^-\pi^+)\pi^-) = (-12.99 \pm 2.83_{\rm exp} \pm 2.59_{\rm U-spin} \pm 0.65_{\rm power})\%,}$$

$$A_{CP}^{dir}(\Lambda_b^0 \to R(p\pi^-)R(\pi^+\pi^-)) = (-12.75 \pm 3.63_{\rm exp} \pm 2.55_{\rm U-spin} \pm 0.64_{\rm power})\%,$$

$$A_{CP}^{dir}(\Lambda_b^0 \to R(p\pi^-)R(K^+K^-)) = (-65.93 \pm 20.06_{\rm exp} \pm 13.90_{\rm U-spin} \pm 3.30_{\rm power})\%,$$

$$A_{CP}^{dir}(\Lambda_b^0 \to R(pK^-)R(K^+K^-)) = (21.28 \pm 6.08_{\rm exp} \pm 4.26_{\rm U-spin} \pm 1.06_{\rm power})\%.$$

Numerical results and conclusion

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- **Our work provides a U-spin analysis on b-baryon four body decay CPV**
- **To improve the predicted power of our work, we also perform a simple dynamic analysis**

Prediction

$$A_{CP}^{dir}(\Lambda_b^0 \to R(p\pi^-\pi^+)\pi^-) = (-12.99 \pm 2.83_{\rm exp} \pm 2.59_{\rm U-spin} \pm 0.65_{\rm power})\%,$$
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$$A_{CP}^{dir}(\Lambda_b^0 \to R(pK^-)R(K^+K^-)) = (21.28 \pm 6.08_{\rm exp} \pm 4.26_{\rm U-spin} \pm 1.06_{\rm power})\%.$$