Charmless multi-body beauty-baryon decays

萧佑国
Yu-Kuo Hsiao
Shanxi Normal university

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2026.05.24@guangzhou.cn

In collaboration with
Kai-Lei Wang and Juan Wang

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Introduction

- CP violation, one of Sakharov's three essential conditions for explaining the matter–antimatter asymmetry of the Universe.

- Visible matter consists predominantly of baryons (protons and neutrons). Its manifestation in the baryon sector is therefore of particular significance.

- To this end, $\mathbf{B}_b \to \mathbf{B}M$ have been extensively studied, with $\mathcal{A}_{CP}$ extensively investigated:

1. C.D. Lu, Y.M. Wang, H. Zou, A. Ali and G. Kramer [PRD80, 034011 (2009)], "Anatomy of the pQCD Approach to the Baryonic Decays $\Lambda_b \to p\pi, pK$."
2. Y.K. Hsiao, C.Q. Geng [PRD91, 116007 (2015)], "Direct CP violation in Λ_b decays."
3. X.G. He and G.N. Li [PLB750, 82 (2015)], "Predictive CP violating relations for charmless two-body decays of beauty baryons $\Xi_b^{-,0}$ and Λ_b^0 with flavor $SU(3)$ symmetry."
4. J. Zhu, H.W. Ke and Z.T. Wei [EPJC76, 284 (2016)], "The decay of $\Lambda_b \to p\ K^-$ in QCD factorization approach."
5. Y.K. Hsiao, Y. Yao, C.Q. Geng [PRD95, 093001 (2017)], "Charmless two-body anti-triplet b-baryon decays."
6. S. Roy, R. Sinha and N.G. Deshpande [PRD102, 053007 (2020)], "Beauty baryon nonleptonic decays into decuplet baryons and CP -asymmetries based on an $SU(3)$ -flavor analysis."
7. A. Dery, M. Ghosh, Y. Grossman, S. Schacht [JHEP03, 165 (2020)], "$\mathrm{SU}(3)_F$ analysis for beauty baryon decays."
8. C.Q. Geng, C.W. Liu and T.H. Tsai [PLB815, 136125 (2021)], "Non-leptonic two-body decays of Λ_b^0 in light-front quark model."
9. R. Sinha, S. Roy and N. G. Deshpande [PRL128, 081803 (2022)], "Measuring CP Violating Phase in Beauty Baryon Decays."
10. J.J. Han, J.X. Yu, Y. Li, H.n. Li, J.P. Wang, Z.J. Xiao, F.S. Yu [PRL134, 221801 (2025)], "Establishing CP Violation in b-Baryon Decays."

• Measurements had not provided conclusive evidence:

$(\mathcal{A}_{CP}^{pK^-}, \mathcal{A}_{CP}^{p\pi^-}) = (-1.4 \pm 0.7 \pm 0.4, 0.4 \pm 0.9 \pm 0.4)\%$

LHCb [PRD111, 092004 (2025)]

$\mathcal{A}_{CP}^{pK^{*-}} \simeq (-0.6 \pm 4.0 \pm 1.9)\%$

LHCb [JHEP10, 169 (2025)]

• Situation changed with the observation:

$\mathcal{A}_{CP}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (2.45 \pm 0.46 \pm 0.10)\%$

LHCb, [Nature **643**, 1223 (2025)]

establishing the 1st discovery of baryonic CP violation.

Related theoretical investigations:

1. J.P. Wang and F.S. Yu [CPC48, 101002 (2024)],
"CP violation of baryon decays with $N\pi$ rescatterings."
2. Z.H. Zhang, J.Y. Yang and X.H. Guo [2504.19228],
"Full analysis of CP violation induced by the decay angular correlations in four-body cascade decays of heavy hadrons."
3. B.n. Zhang and D. Wang [PLB868, 139674 (2025)],
"U-spin conjugate CP violation relations in bottom baryon decays."
4. X.G. He, C.W. Liu, J. Tandean [PRD112, L111302 (2025)],
"Large CP violation in $\Lambda_b^0 \to pK^-\pi^+\pi^-$ and its U-spin partner decays."
5. Q. Chen, X. Wu, Z.P. Xing and R. Zhu [PRD112, 3 (2025)],
"Implications of recent LHCb data on CP violation in b-baryon four-body decays."
6. W. Wang, Z.P. Xing and Z.X. Zhao [PRD111, 053006 (2025)],
"Implications on the CP violation of charmless three body decays of bottom baryons from a U-spin analysis."

- The 1st baryonic CP asymmetry is in fact extracted from resonant subprocesses of $\Lambda_b^0 \to pK^-\pi^+\pi^-$, including

$\Lambda_b^0 \to R(p\pi^+\pi^-)K^-$,

$\Lambda_b^0 \to R(p\pi^-)R(K^-\pi^+)$,

$\Lambda_b^0 \to R(pK^-)R(\pi^+\pi^-)$,

interpreted in terms of the underlying two-body transitions

$\Lambda_b^0 \to N^{*+}K^-$, $\Lambda_b^0 \to N^{*0}\bar{K}_J^0$, $\Lambda_b^0 \to \Lambda^* M_J^0$,

followed by the strong decays:

$N^{*+} \to p\pi^+\pi^-$,

$N^{*0} \to p\pi^-$ together with $\bar{K}_J^0 \to K^-\pi^+$,

$\Lambda^* \to pK^-$ together with $M_J^0 \to \pi^+\pi^-$.

- N^* and Λ^*: the excited nucleon and hyperon states.
- Experimental kinematic selections suggest:

$M_J^0 = \rho^0$, ω, and $f_0/f_0(980)$

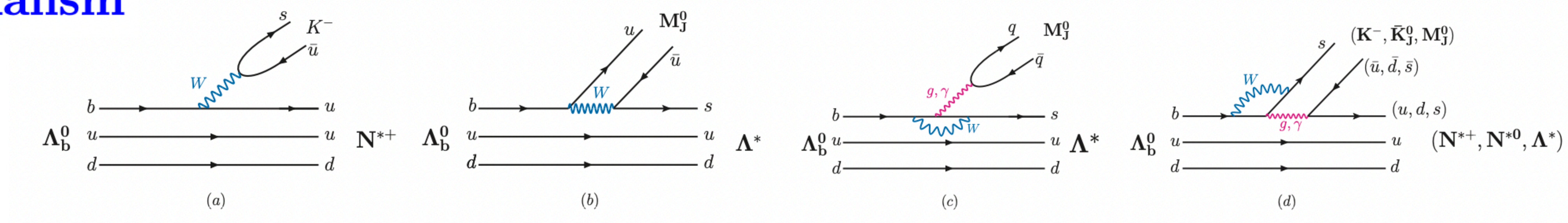
$\bar{K}_J^0 = \bar{K}^{*0}/\bar{K}^{*0}(892)$, $\bar{K}_0^{*0}/\bar{K}_0^{*0}(1430)$.

Decay topology	Mass region (GeV/c^2)	$\mathcal{A}_{CP}$
$\Lambda_b^0 \to R(pK^-)R(\pi^+\pi^-)$	$m_{pK^-} < 2.2$ $m_{\pi^+\pi^-} < 1.1$	$(5.3 \pm 1.3 \pm 0.2)\%$
$\Lambda_b^0 \to R(p\pi^-)R(K^-\pi^+)$	$m_{p\pi^-} < 1.7$ $0.8 < m_{\pi^+K^-} < 1.0$ or $1.1 < m_{\pi^+K^-} < 1.6$	$(2.7 \pm 0.8 \pm 0.1)\%$
$\Lambda_b^0 \to R(p\pi^+\pi^-)K^-$	$m_{p\pi^+\pi^-} < 2.7$	$(5.4 \pm 0.9 \pm 0.1)\%$
$\Lambda_b^0 \to R(K^-\pi^+\pi^-)p$	$m_{K^-\pi^+\pi^-} < 2.0$	$(2.0 \pm 1.2 \pm 0.3)\%$

- $\Lambda_b^0 \to N^* M$ and $\Lambda_b^0 \to \Lambda^* M$ play a key role; however, remaining largely unexplored.
- Limited understanding of the N^* and Λ^* resonances
- The constituent quark model (CQM), through its description of baryon spectroscopy, provides a much improved understanding of many excited baryon states.
- In particular, the CQM is applied to studies of $\Omega_{(c)}$ spectroscopy in Ω_b decays, Λ_c spectroscopy in Λ_b decays, Ω spectroscopy in Ω_c^0 decays.
- The CQM framework is well suited for studying $\Lambda_b^0 \to N^* M$ and $\Lambda_b^0 \to \Lambda^* M$.

1. H.H. Zhong, M.S. Liu, R.H. Ni, M.Y. Chen, X.H. Zhong, Q. Zhao, "Unified study of nucleon and Δ baryon spectra and their strong decays with chiral dynamics," [PRD110, 116034 (2024)].
2. K.L. Wang, Q.F. Lü, J.J. Xie, X.H. Zhong, "Toward discovering the excited Ω baryons through nonleptonic weak decays of Ω_c," [PRD107, 034015 (2023)].
3. K.L. Wang, J. Wang, Y.K. Hsiao, X.H. Zhong, "Excited Ω hyperon in charmful Ω_b weak decays," [PRD111, 114028 (2025)].
4. J. Wang, K.L. Wang, Y.K. Hsiao, "Investigating Ω_c spectroscopy in two-body Ω_b decays," arXiv:2603.13721 [hep-ph].

Formalism



Feynman diagrams for $(a,d)\ \Lambda_b^0 \to N^* K^-$, (d) $\Lambda_b^0 \to N^{*0}\bar{K}_J^0$, and $(b,c,d)\ \Lambda_b^0 \to \Lambda^* M_J^0$.

$$\hat{\mathcal{M}}(\Lambda_b^0 \to N^{*+}K^-) = (\alpha_1^s + \alpha_4^s)\langle K^-|(\bar{s}u)_{V-A}|0\rangle\langle N^{*+}|(\bar{u}b)_{V-A}|\Lambda_b^0\rangle$$

$$+\alpha_6^s\langle K^-|(\bar{s}u)_{S+P}|0\rangle\langle N^{*+}|(\bar{u}b)_{S-P}|\Lambda_b^0\rangle\ ,$$

$$\hat{\mathcal{M}}(\Lambda_b^0 \to N^{*0}\bar{K}_J^0) = \alpha_4^s\langle \bar{K}_J^0|(\bar{s}d)_{V-A}|0\rangle\langle N^{*0}|(\bar{d}b)_{V-A}|\Lambda_b^0\rangle$$

$$+\alpha_6^s\langle \bar{K}_J^0|(\bar{s}d)_{S+P}|0\rangle\langle N^{*0}|(\bar{d}b)_{S-P}|\Lambda_b^0\rangle\ ,$$

$$\hat{\mathcal{M}}(\Lambda_b^0 \to \Lambda^* M_J^0) = [\alpha_2^s\langle M_J^0|(\bar{u}u)_{V-A}|0\rangle + \alpha_3^s\langle M_J^0|(\bar{u}u+\bar{d}d+\bar{s}s)_{V-A}|0\rangle$$

$$+\alpha_4^s\langle M_J^0|(\bar{s}s)_{V-A}|0\rangle + \alpha_5^s\langle M_J^0|(\bar{u}u+\bar{d}d+\bar{s}s)_{V+A}|0\rangle$$

$$+\alpha_9^s\langle M_J^0|(2\bar{u}u-\bar{d}d-\bar{s}s)_{V-A}|0\rangle]\langle \Lambda^*|(\bar{s}b)_{V-A}|\Lambda_b^0\rangle$$

$$+\alpha_6^s\langle M_J^0|(\bar{s}s)_{S+P}|0\rangle\langle \Lambda|(\bar{s}b)_{S-P}|\Lambda_b^0\rangle\ .$$

- $R(p\pi^+\pi^-)$, $R(p\pi^-)$, and $R(pK^-)$

exhibit clear resonant structures in the region of (1.5–1.8) GeV

of the invariant mass spectra for the four-body decay $\Lambda_b^0 \to pK^-\pi^+\pi^-$.

- Within the CQM framework, the N^* and Λ^* resonances

are identified as members of the $1P$-wave baryon octet, including

$N(1535)/\Lambda(1670)$, $N(1520)/\Lambda(1690)$, $N(1650)$, $N(1700)$, and $N(1675)$,

with $J^P = (1/2^{-1}, 3/2^{-1}, 1/2^{-1}, 3/2^{-1}, 5/2^{-1})$, respectively,

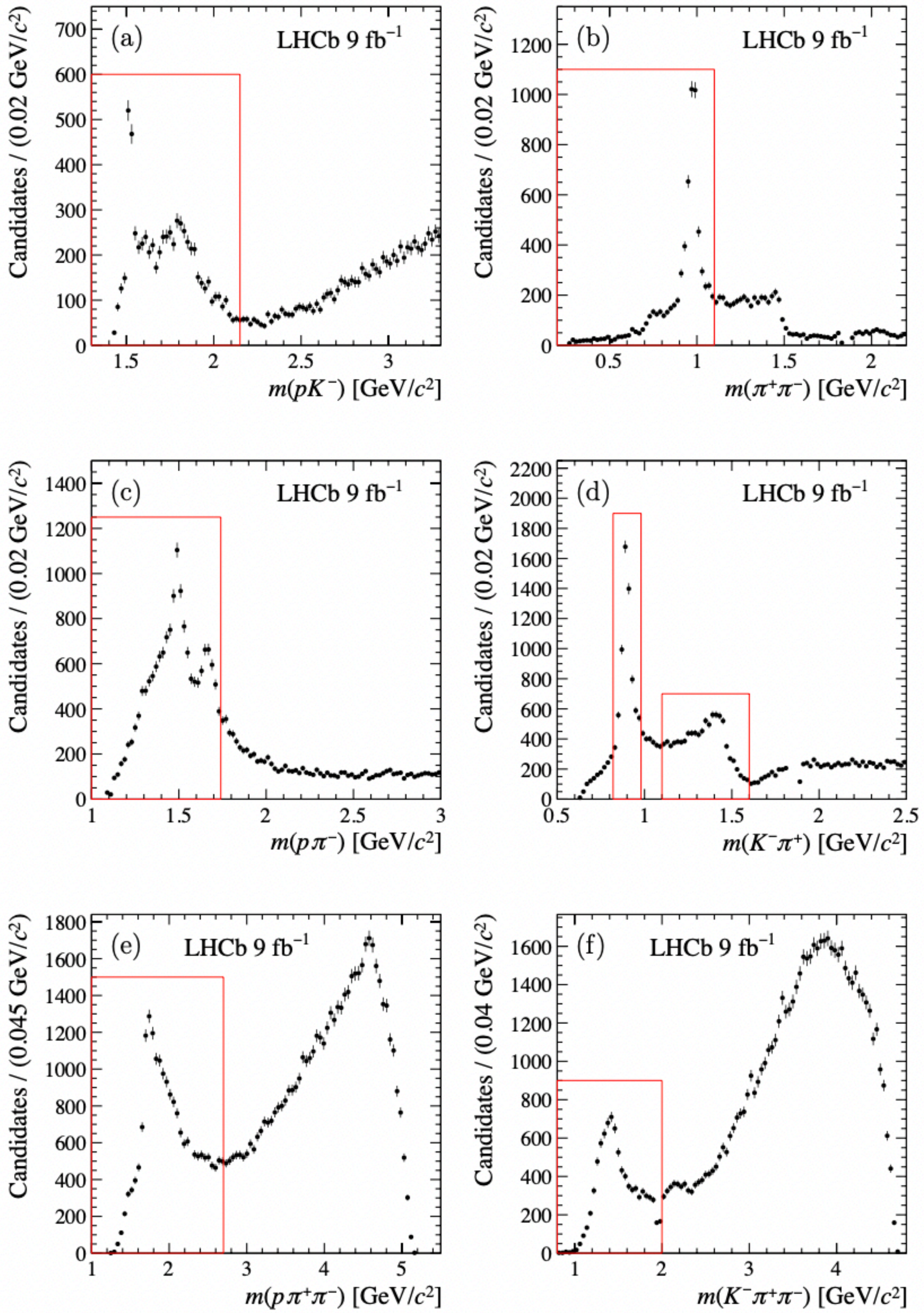
together with the $1P$-wave hyperon singlets

$\Lambda(1405)$ and $\Lambda(1520)$, carrying $J^P = (1/2^{-1}, 3/2^{-1})$, respectively.

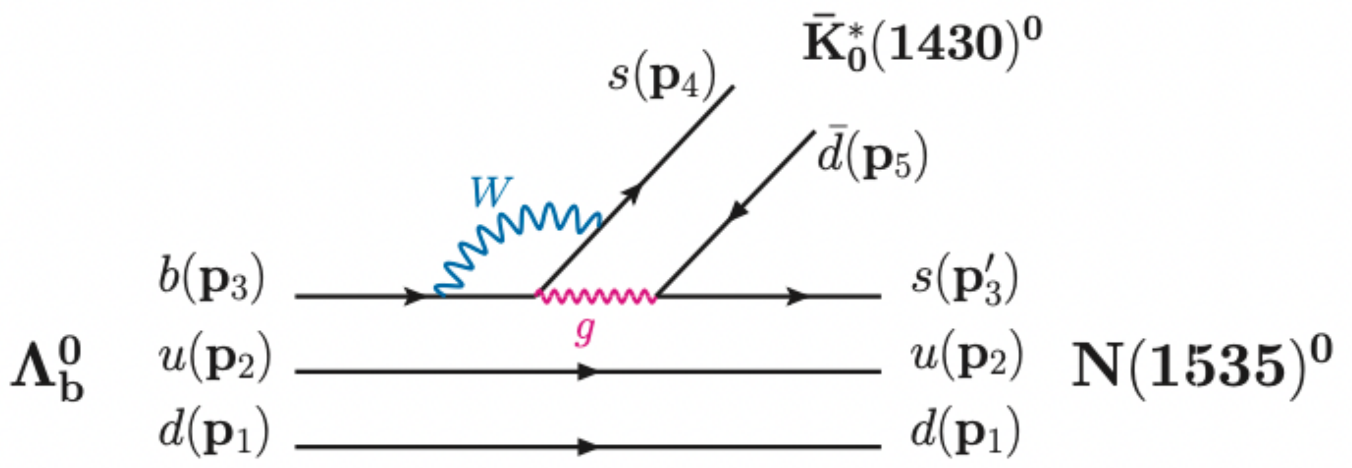
- A careful identification of the possible contributions

requires the evaluation of a total of 27 decay channels

in $\Lambda_b^0 \to N^{*+}K^-$, $N^{*0}\bar{K}_J^0$, and $\Lambda^* M_J^0$.



Using $\Lambda_b^0 \to N_{1535}^0 \bar{K}_0^{*0}$ as a example:



- The relevant effective Hamiltonian of the $b \to sd\bar{d}$ transitions:

$\mathcal{H}(b \to sd\bar{d}) = \Sigma_i c_i O_i \ (i = 1, 2, ..., 6)$,

$O_3 = \bar{\psi}_{\bar{s}_\alpha}\gamma_\mu(1-\gamma_5)\psi_{d_\beta}\bar{\psi}_{\bar{d}_\beta}\gamma^\mu(1-\gamma_5)\psi_{b_\alpha}$, $O_4 = \bar{\psi}_{\bar{s}_\beta}\gamma_\mu(1-\gamma_5)\psi_{d_\beta}\bar{\psi}_{\bar{d}_\alpha}\gamma^\mu(1-\gamma_5)\psi_{b_\alpha}$,

$O_5 = 2\bar{\psi}_{\bar{s}_\alpha}(1+\gamma_5)\psi_{d_\beta}\bar{\psi}_{\bar{d}_\beta}(1-\gamma_5)\psi_{b_\alpha}$, $O_6 = 2\bar{\psi}_{\bar{s}_\beta}(1+\gamma_5)\psi_{d_\beta}\bar{\psi}_{\bar{d}_\alpha}(1-\gamma_5)\psi_{b_\alpha}$.

- In the factorization, $O_{3(5)} \simeq O_{4(6)}/N_c^{eff}$.

$\alpha_4^s = -V_{tb}V_{ts}^* a_4$, $\alpha_6^s = V_{tb}V_{ts}^* 2a_6$, $a_{4(6)} = c_{4(6)}^{eff} + c_{3(5)}^{eff}/N_c^{eff}$.

- In the non-relativistic approximation:

$O_{4(6)} \simeq O_{4(6)}^{PC} + O_{4(6)}^{PV}$ [PC(PV), parity-conserving(violating)]:

$$O_4^{PC} = \delta^3(\mathbf{p}_3 - \mathbf{p}_3' - \mathbf{p}_4 - \mathbf{p}_5)/(2\pi)^3\hat{O}_f\hat{O}_c$$
$$\times\left\{\boldsymbol{\sigma}_4 \cdot \left[\left(\frac{\mathbf{p}_5}{2m_5} + \frac{\mathbf{p}_4}{2m_4}\right) - \left(\frac{\mathbf{p}_3'}{2m_3'} + \frac{\mathbf{p}_3}{2m_3}\right) + i\boldsymbol{\sigma}_3 \times \left(\frac{\mathbf{p}_3}{2m_3} - \frac{\mathbf{p}_3'}{2m_3'}\right)\right]\right.$$
$$\left.+\boldsymbol{\sigma}_3 \cdot \left[\left(\frac{\mathbf{p}_3'}{2m_3'} + \frac{\mathbf{p}_3}{2m_3}\right) - \left(\frac{\mathbf{p}_5}{2m_5} + \frac{\mathbf{p}_4}{2m_4}\right) + i\boldsymbol{\sigma}_4 \times \left(\frac{\mathbf{p}_4}{2m_4} - \frac{\mathbf{p}_5}{2m_5}\right)\right]\right\},$$
$$O_4^{PV} = \delta^3(\mathbf{p}_3 - \mathbf{p}_3' - \mathbf{p}_4 - \mathbf{p}_5)/(2\pi)^3\hat{O}_f\hat{O}_c(\boldsymbol{\sigma}_3 \cdot \boldsymbol{\sigma}_4 - 1),$$
$$O_6^{PC} = \delta^3(\mathbf{p}_3 - \mathbf{p}_3' - \mathbf{p}_4 - \mathbf{p}_5)/(2\pi)^3\hat{O}_f\hat{O}_c$$
$$\left\{\boldsymbol{\sigma}_4 \cdot \left(\frac{\mathbf{p}_4}{2m_4} - \frac{\mathbf{p}_5}{2m_5}\right) + \boldsymbol{\sigma}_3 \cdot \left(\frac{\mathbf{p}_3}{2m_3} - \frac{\mathbf{p}_3'}{2m_3'}\right)\right\},$$
$$O_6^{PV} = -\delta^3(\mathbf{p}_3 - \mathbf{p}_3' - \mathbf{p}_4 - \mathbf{p}_5)/(2\pi)^3\hat{O}_f\hat{O}_c,$$

$\hat{O}_f = b_5^\dagger(s)b_4^\dagger(\bar{d})b_3^\dagger(d)b_3(b)$: $b \to d$ transition+$s\bar{d}$ pair creation.

$\hat{O}_c = \delta_{c_4c_5}\delta_{c_3'c_3}$: color-singlet.

- $\mathcal{M}(\Lambda_b^0 \to N_{1535}^0 \bar{K}_0^{*0}) = \alpha_4^s(\mathcal{M}_4^{PC} + \mathcal{M}_4^{PV}) + \alpha_6^s(\mathcal{M}_6^{PC} + \mathcal{M}_6^{PV})$, where

$(\mathcal{M}_{4(6)}^{PC,PV})_{J_1,J_2,J_3}^{J_1^z,J_2^z,J_3^z} = \langle N_{1535}^0(\mathbf{P}_2, J_2, J_2^z)\bar{K}_0^{*0}(\mathbf{q}, J_3, J_3^z)|O_{4(6)}^{PC,PV}|\Lambda_b^0(\mathbf{P}_1, J_1, J_1^z)\rangle$,

$\Lambda_b(\mathbf{P}_1, J_1, J_1^z)$, $N_{1535}^0(\mathbf{P}_2, J_2, J_2^z)$. and $\bar{K}_0^{*0}(\mathbf{q}, J_3, J_3^z)$ denote the wave functions.

- Meson wave function: $M(\mathbf{P}_3, J, J_z) = \int d\mathbf{p}_4 d\mathbf{p}_5 \delta^3(\mathbf{p}_4 + \mathbf{p}_5 - \mathbf{P}_3)\Psi_M(\mathbf{p}_4, \mathbf{p}_5)$,

$\Psi_M(\mathbf{p}_4, \mathbf{p}_5)$: the momentum-space mock-state wave function.

In the Jacobi-momentum framework: $\mathbf{p}_M = (\mathbf{p}_4 - \mathbf{p}_5)/\sqrt{2}$,

internal motion of the meson as a **simple harmonic oscillation**,

$\Psi_M(\mathbf{p}_4, \mathbf{p}_5) = \sum_{m_M} \mathcal{C}_{m_M,S_z,J_3^z}^{l_M,S,J_3} \zeta_M \varphi_M \chi_{S_z}^S \psi_{n_M l_M m_M}(\mathbf{p}_M)$,

ζ_M, φ_M, and $\chi_{S_z}^S$, the color, flavor, spin wave functions, respectively.

$\psi_{n_M l_M m_M}(\mathbf{p}_M)$, the simple harmonic oscillation function:

$\psi_{nlm}(\mathbf{p}) = (i)^l(-1)^n \left[\frac{2n!}{(n+l+1/2)!}\right]^{1/2} \frac{1}{\alpha^{l+3/2}} \exp\left(-\frac{\mathbf{p}^2}{2\alpha^2}\right) L_n^{l+1/2}\left(\frac{\mathbf{p}^2}{\alpha^2}\right) \mathcal{Y}_{lm}(\mathbf{p})$

$L_n^{l+1/2}$, the associated Laguerre polynomial.

$\mathcal{Y}_{lm}(\mathbf{p}) = |\mathbf{p}|^l Y_{lm}(\hat{\mathbf{p}})$, the solid harmonic.

$Y_{lm}(\hat{\mathbf{p}})$, the spherical harmonic.

- Baryon wave function:

$$\mathbf{B}(\mathbf{P_B}, J, J_z) = \int d\mathbf{p}_1 d\mathbf{p}_2 d\mathbf{p}_3 \, \delta^3(\mathbf{p}_1 + \mathbf{p}_2 + \mathbf{p}_3 - \mathbf{P_B}) \Psi_\mathbf{B}(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3),$$

$\Psi_\mathbf{B}(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3)$, momentum-space mock-state baryon wave function.

In the Jacobi-momentum framework:

$$\mathbf{p}_\rho = (\mathbf{p}_1 - \mathbf{p}_2)/\sqrt{2},$$

$$\mathbf{p}_\lambda = \sqrt{3/2}[m_3(\mathbf{p}_1 + \mathbf{p}_2) - (m_1 + m_2)\mathbf{p}_3]/(m_1 + m_2 + m_3).$$

$\mathbf{p}_\rho$: the relative motion between q_1 and q_2.

$\mathbf{p}_\lambda$: the motion between q_3 and the $q_1 q_2$ subsystem.

the baryon is described by the ρ- and λ-mode oscillators,

such that $\Psi_\mathbf{B}$ contains $\psi^\rho_{n_\rho l_\rho m_\rho}(\mathbf{p}_\rho)$ and $\psi^\lambda_{n_\lambda l_\lambda m_\lambda}(\mathbf{p}_\lambda)$.

• In $\Lambda_b^0 \to N_{1535}^0 \bar{K}_0^{*0}$:

$\Psi_{\bar{K}_0^{*0}}(\mathbf{p}_4, \mathbf{p}_5) = \zeta_{\bar{K}_0^{*0}} \varphi_{\bar{K}_0^{*0}} [\chi_{-1}^1 \psi_{0\,1\,1}(\mathbf{p}_{\bar{K}_0^{*0}}) - \chi_0^1 \psi_{0\,1\,0}(\mathbf{p}_{\bar{K}_0^{*0}}) + \chi_1^1 \psi_{0\,1\,-1}(\mathbf{p}_{\bar{K}_0^{*0}})]/\sqrt{3}$,

$(\chi_1^1, \chi_0^1, \chi_{-1}^1) = (\uparrow\uparrow, (\uparrow\downarrow + \downarrow\uparrow)/\sqrt{2}, \downarrow\downarrow)$, $\zeta_{\bar{K}_0^{*0}} = (R\bar{R} + G\bar{G} + B\bar{B})/\sqrt{3}$, $\varphi_{\bar{K}_0^{*0}} = s\bar{d}$.

$\Psi_{\Lambda_b^0}(\mathbf{p}_\rho, \mathbf{p}_\lambda) = \zeta_{\Lambda_b^0} \phi_{\Lambda_b^0} \chi_{S_z=\pm 1/2, s_\rho=0}^{S=1/2} \psi_{000}^\rho(\mathbf{p}_\rho) \psi_{000}^\lambda(\mathbf{p}_\lambda)$,

$\zeta_{\Lambda_b^0} = (RGB - RBG + GBR - GRB + BRG - BGR)/\sqrt{6}$,

$\phi_{\Lambda_b^0} = (udb - dub)/\sqrt{2}$,

$\chi_{1/2, s_\rho=0}^{S=1/2} = -1/\sqrt{2}(\uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow)$, $\chi_{-1/2, s_\rho=0}^{S=1/2} = 1/\sqrt{2}(\uparrow\downarrow\downarrow - \downarrow\uparrow\downarrow)$.

$\Psi_{N_{1535}^0}(\mathbf{p}_\rho, \mathbf{p}_\lambda) = \sum_{M_L, S_z} \mathcal{C}_{M_L, S_z, J_z}^{L=1, S=1/2, J=1/2} \zeta_{N_{1535}^0} \frac{1}{\sqrt{2}}$

$[(\phi^\rho \chi_{S_z,1}^{1/2} + \phi^\lambda \chi_{S_z,0}^{1/2}) \psi_{01M_L}^\rho(\mathbf{p}_\rho) \psi_{000}^\lambda(\mathbf{p}_\lambda) + (\phi^\rho \chi_{S_z,0}^{1/2} - \phi^\lambda \chi_{S_z,1}^{1/2}) \psi_{000}^\rho(\mathbf{p}_\rho) \psi_{01M_L}^\lambda(\mathbf{p}_\lambda)]$,

$\phi^\rho = 1/\sqrt{2}(udd - dud)$, $\phi^\lambda = 1/\sqrt{6}(dud + udd - 2ddu)$, $\zeta_{N_{1535}^0} = \zeta_{\Lambda_b^0}$,

$\chi_{1/2, s_\rho=1}^{S=1/2} = -(\uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow - 2\uparrow\uparrow\downarrow)/\sqrt{6}$, and $\chi_{-1/2, s_\rho=1}^{S=1/2} = (\uparrow\downarrow\downarrow + \downarrow\uparrow\downarrow - 2\downarrow\downarrow\uparrow)/\sqrt{6}$.

The relevant CGCs satisfying $M_L + S_z = J_z$ are

$\mathcal{C}_{0,-1/2,-1/2}^{1,1/2,1/2} = -\mathcal{C}_{0,1/2,1/2}^{1,1/2,1/2} = \sqrt{1/3}$, $\mathcal{C}_{-1,1/2,-1/2}^{1,1/2,1/2} = -\mathcal{C}_{1,-1/2,1/2}^{1,1/2,1/2} = -\sqrt{2/3}$.

- $\mathcal{M}(\Lambda_b^0 \to N_{1535}^0 \bar{K}_0^{*0}) = \alpha_4^s(\mathcal{M}_4^{PC} + \mathcal{M}_4^{PV}) + \alpha_6^s(\mathcal{M}_6^{PC} + \mathcal{M}_6^{PV})$

$(\mathcal{M}_{4(6)}^{PC,PV})_{J_1,J_2,J_3}^{J_1^z,J_2^z,J_3^z} = \langle N_{1535}^0(\mathbf{P}_2, J_2, J_2^z)\bar{K}_0^{*0}(\mathbf{q}, J_3, J_3^z)|O_{4(6)}^{PC,PV}|\Lambda_b^0(\mathbf{P}_1, J_1, J_1^z)\rangle,$

$(\mathcal{M}_4^{PC})_{\frac{1}{2},\frac{1}{2},0}^{-\frac{1}{2},-\frac{1}{2},0} = \frac{2\sqrt{3}\alpha_{\lambda_2}^{5/2}q\alpha_3^{5/2}(\alpha_{\lambda_1}\alpha_{\rho_2}\alpha_{\rho_1})^{3/2}}{\pi^{9/4}\left(\alpha_{\lambda_1}^2+\alpha_{\lambda_2}^2\right)^{5/2}\left(\alpha_{\rho_1}^2+\alpha_{\rho_2}^2\right)^{3/2}}\frac{m_2}{2m_2+m_3'}\left(\frac{1}{m_4} - \frac{1}{m_5}\right),\ (\mathcal{M}_4^{PV})_{\frac{1}{2},\frac{1}{2},0}^{-\frac{1}{2},-\frac{1}{2},0} = 0,$

$(\mathcal{M}_6^{PC})_{\frac{1}{2},\frac{1}{2},0}^{-\frac{1}{2},-\frac{1}{2},0} = \frac{2\sqrt{3}\alpha_{\lambda_2}^{5/2}q\alpha_3^{5/2}(\alpha_{\lambda_1}\alpha_{\rho_2}\alpha_{\rho_1})^{3/2}}{\pi^{9/4}\left(\alpha_{\lambda_1}^2+\alpha_{\lambda_2}^2\right)^{5/2}\left(\alpha_{\rho_1}^2+\alpha_{\rho_2}^2\right)^{3/2}}\frac{m_2}{2m_2+m_3'}\left(\frac{1}{m_4} + \frac{1}{m_5}\right),\ (\mathcal{M}_6^{PV})_{\frac{1}{2},\frac{1}{2},0}^{-\frac{1}{2},-\frac{1}{2},0} = 0,$

$(\alpha_{\rho1}, \alpha_{\lambda1})$, $(\alpha_{\rho2}, \alpha_{\lambda2})$, and α_3 are the oscillator parameters, corresponding to the initial-state baryon, the final-state baryon, and the final-state meson, respectively.

The corresponding branching fraction is evaluated through

$\mathcal{B}(\Lambda_b^0 \to \mathbf{B}^* M) = 8\pi^2 \frac{|\mathbf{q}|\tau_1 E_2 E_3}{M_1} \sum_{J_1^z,J_2^z} |\mathcal{M}_{J_1,J_2,J_3}^{J_1^z,J_2^z,J_3^z}(\Lambda_b^0 \to \mathbf{B}^* M)|^2).$

All $\mathcal{B}(\Lambda_b^0 \to N^* M, \Lambda^* M)$ are evaluated in the same way.

Results

	N_{1535}	N_{1520}	N_{1650}	N_{1700}
$10^6\mathcal{B}(\Lambda_b^0\to N^{*+}K^-)$	$15.0^{+4.0+4.7}_{-1.8-4.1}$	$25.9^{+6.9+7.7}_{-3.2-7.0}$	$3.7^{+1.0+1.1}_{-0.5-1.0}$	$4.0^{+1.1+1.2}_{-0.5-1.0}$
$10^6\mathcal{B}(\Lambda_b^0\to N^{*0}\bar{K}^{*0})$	$6.8^{+2.6+2.0}_{-1.2-1.8}$	$12.4^{+4.8+3.6}_{-2.1-3.2}$	$1.7^{+0.7+0.5}_{-0.3-0.4}$	$1.9^{+0.7+0.5}_{-0.3-0.5}$
$10^6\mathcal{B}(\Lambda_b^0\to N^{*0}\bar{K}_0^{*0})$	$15.4^{+2.8+5.7}_{-1.3-4.8}$	$32.5^{+6.0+12.1}_{-2.8-10.2}$	$3.9^{+0.7+1.4}_{-0.3-1.2}$	$5.2^{+1.0+1.9}_{-0.5-1.6}$

	Λ_{1670}	Λ_{1690}	Λ_{1405}	Λ_{1520}
$10^7\mathcal{B}(\Lambda_b^0\to\Lambda^*\rho^0)$	$4.2^{+0.2+1.1}_{-0.2-1.0}$	$7.2^{+0.4+1.8}_{-0.4-1.7}$	$1.7^{+0.1+0.5}_{-0.1-0.4}$	$3.2^{+0.2+0.8}_{-0.2-0.8}$
$10^6\mathcal{B}(\Lambda_b^0\to\Lambda^*\omega)$	$0.9^{+0.5+0.2}_{-0.3-0.2}$	$1.5^{+0.8+0.4}_{-0.5-0.3}$	$0.4^{+0.2+0.1}_{-0.1-0.1}$	$0.7^{+0.4+0.2}_{-0.2-0.2}$
$10^6\mathcal{B}(\Lambda_b^0\to\Lambda^* f_0)$	$10.9^{+0.2+3.9}_{-0.2-3.3}$	$22.1^{+0.4+7.9}_{-0.5-6.7}$	$4.2^{+0.1+1.5}_{-0.1-1.3}$	$9.4^{+0.2+3.4}_{-0.2-2.9}$

- The $1P$-wave baryon resonances play a key role in $\Lambda_b^0\to\mathbf{B}^*M$, the underlying two-body transitions of $\Lambda_b^0\to pK^-\pi^+\pi^-$.
- $\mathcal{B}(\Lambda_b^0\to N^+_{1535,1520}K^-) > \mathcal{B}(\Lambda_b^0\to pK^-) = (5.5\pm1.0)\times10^{-6}$, providing a useful test of the CQM framework.
- The spin structure of the Λ_b^0 baryon has no overlap with that of N_{1675}, forbidding the transition and leading to $\mathcal{B}(\Lambda_b^0\to N_{1675}M)=0$.
- In the light scalar channel, f_0 with $J^{PC}=0^{++}$ only receives contributions from the $s\bar{s}$ scalar current associated with the α_6^s terms, leading to $\mathcal{B}(\Lambda_b^0\to\Lambda^* f_0)$ at the 10^{-5} level.

• Utilizing the approximate relations:

$\mathcal{B}(\Lambda_b^0 \to K^- p\pi^+\pi^-) \simeq$

$\mathcal{B}(\Lambda_b^0 \to N^{*+}K^-)\mathcal{B}(N^{*+} \to p\pi^+\pi^-)$,

$\mathcal{B}(\Lambda_b^0 \to N^{*0}\bar{K}_J^0)\mathcal{B}(N^{*0} \to p\pi^-)\mathcal{B}(\bar{K}_J^0 \to K^-\pi^+)$, and

$\mathcal{B}(\Lambda_b^0 \to \Lambda^* M_J^0)\mathcal{B}(\Lambda^* \to pK^-)\mathcal{B}(M_J^0 \to \pi^+\pi^-)$, with

the branching fractions of $N^*(\Lambda^*)$ decays in the table,

$\mathcal{B}(\bar{K}^{*0}, \bar{K}_0^{*0} \to K^-\pi^+) = (66.6, 62.0 \pm 6.7)\%$,

$\mathcal{B}(\rho^0, \omega, f_0 \to \pi^+\pi^-) = (100, 1.5 \pm 0.1, 35 \pm 8)\%$,

we estimate the resonant branching fractions of $\Lambda_b^0 \to pK^-\pi^+\pi^-$.

	N_{1535}	N_{1520}	N_{1650}	N_{1700}
$10^2\mathcal{B}(N^{*+} \to p\pi^+\pi^-)$	8.6 ± 5.2	24.5 ± 3.0	19.0 ± 7.0	56.7 ± 6.0
$10^2\mathcal{B}(N^{*0} \to p\pi^-)$	28.0 ± 6.7	40.0 ± 3.3	40.0 ± 6.7	8.0 ± 3.3

	Λ_{1670}	Λ_{1690}	Λ_{1405}	Λ_{1520}
$10^2\mathcal{B}(\Lambda^* \to pK^-)$	12.5 ± 2.5	12.5 ± 2.5	0	22.5 ± 0.5

• The direct CP asymmetry:

$$\mathcal{A}_{CP}(\Lambda_b^0 \to K^- p\pi^+\pi^-) \equiv \frac{\mathcal{B}(\Lambda_b^0 \to K^- p\pi^+\pi^-) - \mathcal{B}(\bar{\Lambda}_b^0 \to K^+\bar{p}\pi^-\pi^+)}{\mathcal{B}(\Lambda_b^0 \to K^- p\pi^+\pi^-) + \mathcal{B}(\bar{\Lambda}_b^0 \to K^+\bar{p}\pi^-\pi^+)}.$$

Results

resonant decay channel	$\mathcal{B}\times 10^6$	$\mathcal{A}_{CP}\times 10^2$
(measurement [14])		
$\Lambda_b^0\to K^-R(p\pi^+\pi^-)$	——	$5.4\pm0.9\pm0.1$
$\Lambda_b^0\to R(p\pi^-)R(K^-\pi^+)$	——	$2.7\pm0.8\pm0.1$
$\Lambda_b^0\to R(pK^-)R(\pi^+\pi^-)$	——	$5.3\pm1.3\pm0.2$
$\Lambda_b^0\to pK^-\pi^+\pi^-$	——	$2.45\pm0.46\pm0.10$
(our work)		
$\Lambda_b^0\to K^-(N^{*+}_{\rm sum}\to)p\pi^+\pi^-$	$10.6^{+1.8+2.1}_{-0.8-1.8}\pm1.2$	$7.40\pm0.21\pm0.22\pm0.20$
$\Lambda_b^0\to(N^{*0}_{\rm sum}\to)p\pi^-(\bar{K}^{*0}\to)K^-\pi^+$	$5.1^{+1.4+1.0}_{-0.6-0.9}\pm0.4$	$1.22\pm0.13\pm0.01\pm0.07$
$\Lambda_b^0\to(N^{*0}_{\rm sum}\to)p\pi^-(\bar{K}^{*0}_0\to)K^-\pi^+$	$11.9^{+1.6+3.2}_{-0.7-2.7}\pm1.3$	$0.95\pm0.14\pm0.19\pm0.14$
$\Lambda_b^0\to(N^{*0}_{\rm sum}\to)p\pi^-(\bar{K}^{0}_{\rm sum}\to)K^-\pi^+$	$17.1^{+2.1+3.4}_{-1.0-2.9}\pm1.4$	$1.03\pm0.16\pm0.14\pm0.19$
$\Lambda_b^0\to(\Lambda^*_{\rm sum}\to)pK^-(\rho^0\to)\pi^+\pi^-$	$0.21\pm0.01\pm0.03\pm0.02$	$1.37\pm0.00\pm0.08^{+0.14}_{-0.06}$
$\Lambda_b^0\to(\Lambda^*_{\rm sum}\to)pK^-(\omega\to)\pi^+\pi^-$	$(0.7^{+0.2}_{-0.1}\pm0.1\pm0.1)\times10^{-2}$	$6.29^{+0.31+0.03+0.06}_{-0.50-0.03-0.05}$
$\Lambda_b^0\to(\Lambda^*_{\rm sum}\to)pK^-(f_0\to)\pi^+\pi^-$	$2.2\pm0.0^{+0.5}_{-0.4}\pm0.4$	$0.94^{+0.01+0.99+0.05}_{-0.02-1.21-0.10}$
$\Lambda_b^0\to(\Lambda^*_{\rm sum}\to)pK^-(M^0_{\rm sum}\to)\pi^+\pi^-$	$2.4\pm0.0^{+0.5}_{-0.4}\pm0.4$	$0.99\pm0.08^{+0.97}_{-1.24}\pm0.11$
$\Lambda_b^0\to pK^-\pi^+\pi^-$	$30.0^{+2.8+4.0}_{-1.3-3.4}\pm1.8$	$3.18\pm0.11\pm0.13\pm0.11$

- $\mathcal{A}_{CP}(\Lambda_b^0\to K^-(N^{*+}_{\rm sum}\to)p\pi^+\pi^-)=(7.40\pm0.15\pm0.17\pm0.20)\%$, in good agreement with $\mathcal{A}_{CP}(\Lambda_b^0\to K^-R(p\pi^+\pi^-))$.
- $\mathcal{A}_{CP}(\Lambda_b^0\to(N^{*0}_{\rm sum}\to)p\pi^-(\bar{K}^0_{\rm sum}\to)K^-\pi^+)=(1.03\pm0.16\pm0.14\pm0.19)\%$, consistent with $\mathcal{A}_{CP}(\Lambda_b^0\to R(p\pi^-)R(K^-\pi^+))$.

Pure penguin-level processes, without interference from the tree-level amplitudes carrying the weak phase through V_{ub}.

- $\mathcal{A}_{CP}(\Lambda_b^0\to(\Lambda^*_{\rm sum}\to)pK^-(M^0_{\rm sum}\to)\pi^+\pi^-)=(0.99\pm0.08^{+0.97}_{-1.24}\pm0.11)\%$, showing a 2.6σ deviation from the current data.
- Summing over all resonant contributions, we obtain a significant branching fraction $\mathcal{B}(\Lambda_b^0\to pK^-\pi^+\pi^-)=(30.0^{+2.8+4.0}_{-1.3-3.4}\pm1.8)\times10^{-6}$. In particular, $\mathcal{A}_{CP}=(3.18\pm0.11\pm0.13\pm0.11)\%$ gives a natural interpretation of the 1st observed baryonic CP violation.

Summary

- $\Lambda_b^0 \to pK^-\pi^+\pi^-$ receives contributions from subprocesses, including $\Lambda_b^0 \to N^{*+}K^-$, $\Lambda_b^0 \to N^{*0}\bar{K}_J^0$, and $\Lambda_b^0 \to \Lambda^* M_J^0$.
- The participating N^* and Λ^* resonances are identified as $1P$-wave excited baryon states.
- The branching fractions $\mathcal{B}(\Lambda_b^0 \to \mathbf{B}^M)$ are investigated. In particular, $\mathcal{B}(\Lambda_b^0 \to N_{1535}^+ K^-, N_{1520}^+ K^-) = (15.0^{+4.0+4.7}_{-1.8-4.1}, 25.9^{+6.9+7.7}_{-3.2-7.0}) \times 10^{-6}$.
- Incorporating all relevant resonant contributions, we obtain $\mathcal{B}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (30.0^{+2.8+4.0}_{-1.3-3.4} \pm 1.8) \times 10^{-6}$, while the resulting $\mathcal{A}_{CP}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (3.18 \pm 0.11 \pm 0.13 \pm 0.11)\%$ is in good agreement with the current experimental measurement.

Thank You