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CP-violation study in b-baryon hadronic decays using $SU(3)$ symmetry

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Motivations

- CP violation (CPV) in B-meson decays: well established.
- Promising evidence of CPV in b-baryon decays:
  - ✓ CP asymmetry measurement (A_{CP}) in $\Lambda_b^0 \to p^+ K^-$, $\Lambda_b^0 \to p^+ \pi^-$ first at CDF and subsequently at LHCb.

    PRL 113 (2014) 24, 242001, PLB 787 (2018) 124-133
  - ✓ Results consistent with CP symmetry.
- Theory predicts sizable direct CP-asymmetry in bottom baryon decays.

  PRD 80 (2009) 034011, PRD 80 (2009) 094016, PRD 91 (2015) 11, 116007
- LHCb have also observed several multibody decays of b-baryons
  - ✓ Rich resonant structure leading to a common final state.
  - ✓ Analyze T-odd observables to look for CPV.

  Nature Physics 13 (2017) 391, JHEP 08 (2018) 039, EPJC 79 (2019) 745, PRD 102 (2020) 051101
- Large b-baryon production fraction at LHCb
- Provides an opportunity to measure the CKM parameters, complimentary to analogous B-meson decays.

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Overview

- Charmless b-baryon decays: Ideal place to look for CPV in b-baryons
- Two body decays of b-baryons:
  - ✓ Octet baryon and octet(singlet) meson.
  - ✓ Decuplet baryon and octet(singlet) meson.
- Several strangeness-changing ($\Delta S = -1$) and strangeness-conserving ($\Delta S = 0$) decays of b-baryons are possible.
- Similar studies in $B \to PP$, $B \to PV$ and $B \to VV$ decays have been well explored using various approaches.

Zeppenfeld (Z.Phys.C (1981)), Savage *et al.* (PRD (1989)), Gronau *et al.*(PRD (1994)), Grinstein *et al.*(PRD (1996)), Deshpande *et al.*(PRD (2000)), Hai-Yang Cheng *et al.* (PRD (2015)), Grossman *et al.* (JHEP (2014)), He *et al.* (EPJC(2020)) . . .

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Goal:

Identify amplitude relations and CP-asymmetry relations using $SU(3)$-symmetry.

Formalism

- Effective Hamiltonian($\mathcal{H}_{\text{eff}}$)=$\mathcal{H}_{eff}^{\text{T}} + \mathcal{H}_{eff}^{\text{QCDP}} + \mathcal{H}_{eff}^{\text{EWP}}$

Formalism

- $\mathcal{H}_{eff}^{\mathrm{T}}$

  $\epsilon\, \mathbf{15} \oplus \overline{\mathbf{6}} \oplus \mathbf{3}^{(6)} \oplus \mathbf{3}^{(\bar{3})}$

Tree operators

$$O_1^{(q=d,\,s)} = (\overline{u}_L^i \gamma^\mu b_L^j)(\overline{q}_L^j \gamma_\mu u_L^i), \quad O_2^{(q=d,\,s)} = (\overline{u}_L^i \gamma^\mu b_L^i)(\overline{q}_L^j \gamma_\mu u_L^j)$$

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QCD penguin operators

$$O_3^{(q_1=d,\,s)} = (\overline{q_1}_L^i \gamma^\mu b_L^i) \sum_{q=u,d,s} (\bar{q}_L^j \gamma_\mu q_L^j), \; O_4^{(q_1=d,\,s)} = (\overline{q_1}_L^i \gamma^\mu b_L^j) \sum_{q=u,d,s} (\bar{q}_L^j \gamma_\mu q_L^i)$$

$$O_5^{(q_1=d,\,s)} = (\overline{q_1}_L^i \gamma^\mu b_L^i) \sum_{q=u,d,s} (\bar{q}_R^j \gamma_\mu q_R^j), \; O_6^{(q_1=d,\,s)} = (\overline{q_1}_L^i \gamma^\mu b_L^j) \sum_{q=u,d,s} (\bar{q}_R^j \gamma_\mu q_R^i).$$

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Electroweak penguin operators

$$O_7^{(q_1=d,\,s)} = \frac{3}{2} (\overline{q_1}_L^i \gamma^\mu b_L^i) \sum_{q=u,d,s} e_q (\bar{q}_R^j \gamma_\mu q_R^j), \; O_8^{(q_1=d,\,s)} = \frac{3}{2} (\overline{q_1}_L^i \gamma^\mu b_L^j) \sum_{q=u,d,s} e_q (\bar{q}_R^j \gamma_\mu q_R^i)$$

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Formalism

- Effective Hamiltonian($\mathcal{H}_{\text{eff}}$)=$\mathcal{H}^{\text{T}}_{eff} + \mathcal{H}^{\text{QCDP}}_{eff} + \mathcal{H}^{\text{EWP}}_{eff}$

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}}\Big[\lambda_u^{(s)}\Big(C_1(O_1^{(u)} - O_1^{(c)}) + C_2(O_2^{(u)} - O_2^{(c)})\Big) - \lambda_t^{(s)}\sum_{i=1,2} C_i O_i^{(c)} - \lambda_t^{(s)}\sum_{i=3}^{10} C_i O_i^{(s)} + \lambda_u^{(d)}\Big(C_1(O_1^{(u)} - O_1^{(c)}) + C_2(O_2^{(u)} - O_2^{(c)})\Big) - \lambda_t^{(d)}\sum_{i=1,2} C_i O_i^{(c)} - \lambda_t^{(d)}\sum_{i=3}^{10} C_i O_i^{(d)}\Big],$$

Rev. Mod. Phys. **68** (1996) 1125

$V_{ub}V^*_{us} = \lambda^s_u$, $V_{ub}V^*_{ud} = \lambda^d_u$, $V_{tb}V^*_{ts} = \lambda^s_t$, $V_{tb}V^*_{td} = \lambda^d_t$ are the CKM elements and C_i s are the Wilson coefficients.

- Decompose the decay amplitude in terms of $SU(3)$-reduced amplitudes.

$\mathcal{B}_b(\overline{3}) \to \mathcal{O}(8)\mathcal{M}(8)$

✓ Final state: $1 \oplus 8_1 \oplus 8_2 \oplus 10 \oplus \overline{10} \oplus 27$

✓ Number of independent $SU(3)$-reduced amplitudes: 10

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$\langle 10 \parallel \mathbf{15} \parallel \overline{3}\rangle$, $\langle \overline{10} \parallel \overline{\mathbf{6}} \parallel \overline{3}\rangle$, $\langle 8_1 \parallel \mathbf{15} \parallel \overline{3}\rangle$,
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R Sinha, N.G. Deshpande, **SR (Phys.Rev.D 101 (2020) 3, 036018)**

$\mathcal{B}_b(\overline{3}) \to \mathcal{D}(10)\mathcal{M}(8)$

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Amplitude and *CP* relations

- Tree and penguin parts of a decay amplitude follow the same amplitude relation.
- Decay amplitude is decomposed as,

$$\mathcal{A}^l = \lambda_u^q \mathcal{A}^l_{\text{tree}} + \lambda_t^q \mathcal{A}^l_{\text{penguin}}.$$

where $l = 0, 1, 2$ denote contributions from particular partial waves.

$$\delta^l_{\text{CP}}(\mathcal{B}_b \to \mathcal{B}\,\mathcal{M}) = -4\mathbf{J} \times \text{Im}\Big[\mathcal{A}^{l*}_{\text{tree}}(\mathcal{B}_b \to \mathcal{B}\,\mathcal{M})\mathcal{A}^l_{\text{penguin}}(\mathcal{B}_b \to \mathcal{B}\,\mathcal{M})\Big],$$

where $\mathbf{J}$ is the Jarlskog Invariant and $\mathcal{B}$ is a final state octet($\mathcal{O}$) or decuplet($\mathcal{D}$) baryon.

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Selected results

$\mathcal{B}_b(\overline{3}) \to \mathcal{D}(10)\mathcal{M}(8)$

$$\delta^I_{\rm CP}(\Lambda_b^0 \to \Delta^+ K^-) = \delta^I_{\rm CP}(\Lambda_b^0 \to \Delta^0 \overline{K^0})$$

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Future directions

- Conclusive measurement of CP-violation in b-baryon decays.
- Study $SU(3)$-breaking effects in two body decays of b-baryons.
- Identify the intermediate charmless states that lead to common multibody electrically charged final states.
- Analyze the angular distribution of final states to isolate individual partial wave contributions to the total CP asymmetry.

Stay tuned for updated results from LHCb

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