$\Lambda_b \to \Lambda^{(*)}\nu\bar{\nu}$ decays and the recent $B^+ \to K^+\nu\bar{\nu}$ results from Belle-II

Dargi Shameer
Collaborators: Diganta Das Ria Sain

Center for Computational Natural Sciences and Bioinformatics, International Institute of Information Technology, Hyderabad

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Introduction

- The flavor-changing neutral current (FCNC) transitions such as the $b \to s\ell\ell$ and the $b \to s\nu\bar{\nu}$ are among the most sensitive probes for physics beyond the Standard Model (SM).
- The Belle-II experiment has recently reported the first measurement of $B^+ \to K^+\nu\bar{\nu}$ decay and it exceeds the Standard Model prediction by 2.7σ.
- The deviation may be an indication of new physics beyond the Standard Model in the $b \to s\nu\bar{\nu}$ sector.
- The electromagnetic corrections and $c\bar{c}$ resonance effects are not present in $b \to s\nu\bar{\nu}$
- The implications of the Belle-II result on the baryonic decay modes $\Lambda_b \to \Lambda^{(*)}\nu\bar{\nu}$ are studied.
- The decays can be studied in Tera-Z factories such as FCC-ee

$b \to s\nu\bar{\nu}$ Feynman diagram

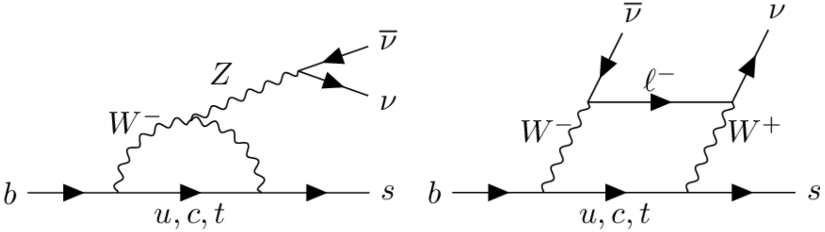

Figure: Lowest-order SM Feynman diagrams for $b \to s\nu\bar{\nu}$ transitions.

Effective Hamiltonian

The $b \to s\nu\nu$ Effective Hamiltonian in a low energy effective theory with additional right-handed neutrinos

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}}\frac{\alpha}{4\pi}\lambda_t\left[C^{\rm SM}\mathcal{O}^{\rm SM} + \sum_{A,B=L}^{R}\sum_{ij} C_{AB}^{ij}\mathcal{O}_{AB}^{ij}\right] \tag{1}$$

where the SM operator

$$O^{\rm SM} = (\bar{s}\gamma_\mu P_L b)(\bar{\nu}\gamma^\mu P_L \nu), \quad C^{SM} = -\frac{2\left(1.469 \pm 0.017\right)}{s_W^2},$$

The New Physics operators are

$$\mathcal{O}_{AB}^{ij} = (\bar{s}\gamma_\mu P_A b)(\bar{\nu}^i\gamma^\mu P_B \nu^j), \quad C_{AB}^{ij}, \quad A, B = L, R.$$

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Y. Liao, X.-D. Ma, and Q.-Y. Wang, JHEP 08, 162 (2020), 2005.08013.

Differential branching ratios

In case of lepton flavor conserving new physics the total differential branching ratios (SM+NP) for $\Lambda_b \to \Lambda\nu\bar{\nu}$ and $\Lambda_b \to \Lambda^*\nu\bar{\nu}$ are

$$\frac{d\mathcal{B}(\Lambda_b \to \Lambda\nu\bar{\nu})}{dq^2 d\cos\theta_\Lambda} = 2N_\Lambda^2\left[F_\Lambda^A \mathbb{C}_- + F_\Lambda^V \mathbb{C}_+ + \cos\theta_\Lambda F_\Lambda^{AV}\,\mathrm{Re}(\mathbb{C}')\right] \qquad (2)$$

$$\frac{d\mathcal{B}(\Lambda_b \to \Lambda^*\nu\bar{\nu})}{dq^2} = \frac{N_{\Lambda^*}^2}{3m_{\Lambda^*}^2}\left[G_{\Lambda^*}^A \mathbb{C}_- + G_{\Lambda^*}^V \mathbb{C}_+\right], \qquad (3)$$

Where the Wilson coefficients are

$$\mathbb{C}_- = \left|\delta_{ii} C^{\mathrm{SM}} + \delta_{ij}\left(C_{LL}^{ij} - C_{RL}^{ij}\right)\right|^2 + \left|\delta_{ij}\left(C_{LR}^{ij} - C_{RR}^{ij}\right)\right|^2 \qquad (4)$$

$$\mathbb{C}_+ = \left|\delta_{ii} C^{\mathrm{SM}} + \delta_{ij}\left(C_{LL}^{ij} + C_{RL}^{ij}\right)\right|^2 + \left|\delta_{ij}\left(C_{LR}^{ij} + C_{RR}^{ij}\right)\right|^2 \qquad (5)$$

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J. Brod, M. Gorbahn, and E. Stamou, Phys. Rev. D 83, 034030 (2011), 1009.0947

$$\begin{aligned}\mathbb{C}' &= \left(\delta_{ii}C^{\mathrm{SM}} + \delta_{ij}\left(C^{ij}_{LL} - C^{ij}_{RL}\right)\right)^* \times \left(\delta_{ii}C^{\mathrm{SM}} + \delta_{ij}\left(C^{ij}_{LL} + C^{ij}_{RL}\right)\right) \\ &+ \left(\delta_{ij}\left(C^{ii}_{LR} - C^{ii}_{RR}\right)\right)^* \left(\delta_{ij}\left(C^{ii}_{LR} + C^{ii}_{RR}\right)\right) \end{aligned} \tag{6}$$

The form factors are

$$F^A_\Lambda = \left(\left(m_{\Lambda_b} - m_\Lambda\right)^2 s_+ f_0^{A^2} + 2q^2 s_+ f_\perp^{A^2}\right) \tag{7}$$

$$F^V_\Lambda = \left(\left(m_{\Lambda_b} + m_\Lambda\right)^2 s_- f_0^{V^2} + 2q^2 s_- f_\perp^{V^2}\right) \tag{8}$$

$$F^{\mathrm{AV}}_\Lambda = -\alpha_\Lambda\left(2q^2\sqrt{s_- s_+} f_\perp^A f_\perp^V + \left(m^2_{\Lambda_b} - m^2_\Lambda\right)\sqrt{s_- s_+} f_0^A f_0^V\right) \tag{9}$$

$$G^A_{\Lambda^*} = \left(6 f_g^{A^2} m^2_{\Lambda^*} q^2 s_- + f_0^{A^2} s_+^2 s_- \left(m_{\Lambda_b} - m_{\Lambda^*}\right)^2 + 2 f_\perp^{A^2} q^2 s_- s_+^2\right) \tag{10}$$

$$G^V_{\Lambda^*} = \left(6 f_g^{V^2} m^2_{\Lambda^*} q^2 s_+ + f_0^{V^2} s_-^2 s_+ \left(m_{\Lambda_b} + m_{\Lambda^*}\right)^2 + 2 f_\perp^{V^2} q^2 s_+ s_-^2\right) \tag{11}$$

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LFV differential branching ratio

In case of lepton flavor violation new physics the differential branching ratios (only np) for $\Lambda_b \to \Lambda\nu\bar{\nu}$ and $\Lambda_b \to \Lambda^*\nu\bar{\nu}$ are

$$\frac{d\mathcal{B}(\Lambda_b \to \Lambda\nu\bar{\nu})}{dq^2} = 6N_\Lambda^2\Big[F_\Lambda^A(C^{SM} + \mathbb{C}_-^{LFV}) + F_\Lambda^V(C^{SM} + \mathbb{C}_+^{LFV})\Big] \quad (12)$$

$$\begin{aligned}\frac{d\mathcal{B}(\Lambda_b \to \Lambda^*\nu\bar{\nu})}{dq^2} &= 2N_{\Lambda^*}^2\Big[\big(G_{\Lambda^*}^A C^{SM} + F_{\Lambda^*}^A \mathbb{C}_-^{LFV}\big) \\ &+ \big(G_{\Lambda^*}^V C^{SM} + F_{\Lambda^*}^V \mathbb{C}_+^{LFV}\big)\Big] \quad (13)\end{aligned}$$

Where the wilson coefficients are

$$\mathbb{C}_-^{LFV} = \sum_{i\neq j}\Big[|C_{LL}^{ij} - C_{RL}^{ij}|^2 + |C_{LR}^{ij} - C_{RR}^{ij}|^2\Big], \quad (14)$$

$$\mathbb{C}_+^{LFV} = \sum_{i\neq j}\Big[|C_{LL}^{ij} + C_{RL}^{ij}|^2 + |C_{LR}^{ij} + C_{RR}^{ij}|^2\Big] \quad (15)$$

$$\mathbb{C}'^{LFV} = \sum_{i\neq j}(C_{LL}^{ij} - C_{RL}^{ij})^*(C_{LL}^{ij} + C_{RL}^{ij}) + \sum_{i\neq j}(C_{LR}^{ij} - C_{RR}^{ij})^*(C_{LR}^{ij} + C_{RR}^{ij}) \quad (16)$$

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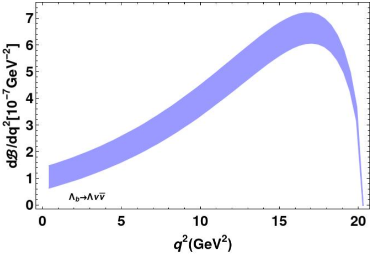
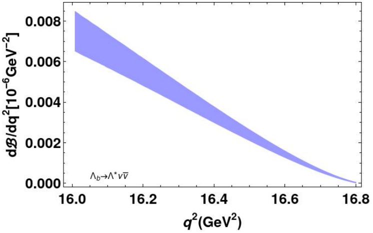
Differential branching ratio in Standard Model



(a) $\Lambda_b \to \Lambda\nu\bar{\nu}$



(b) $\Lambda_b \to \Lambda^*\nu\bar{\nu}$

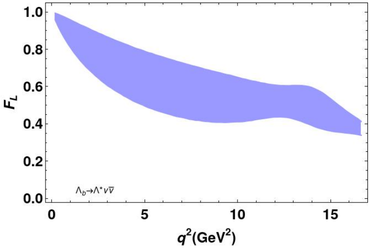
Figure: Standard Model prediction for $\Lambda_b \to \Lambda^{(*)}\nu\bar{\nu}$. The bands correspond to the uncertainties sourced by the form factors, EW correction, and CKM.

Longitudinal polarization fraction in Standard model

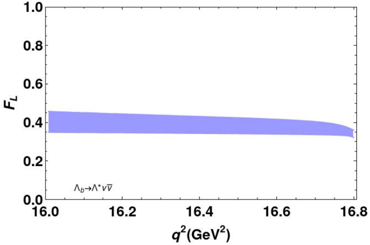
$$F_L^{\Lambda} = \frac{\left(m_{\Lambda_b} - m_{\Lambda}\right)^2 s_+ f_0^{A^2} \mathbb{C}_- + \left(m_{\Lambda_b} + m_{\Lambda}\right)^2 s_- f_0^{V^2} \mathbb{C}_+}{\left(F_{\Lambda}^A + F_{\Lambda}^V\right) C^{SM}} \tag{17}$$

$$F_L^{\Lambda^*} = \frac{\left(m_-^*\right)^2 s_+^2 s_- f_0^{A^2} \mathbb{C}_- + \left(m_+^*\right)^2 s_-^2 s_+ f_0^{V^2} \mathbb{C}_+}{\left(F_{\Lambda^*}^A + F_{\Lambda^*}^V\right) C^{SM}} \tag{18}$$

where we have defined $m_{\pm}^* = m_{\Lambda_b} \pm m_{\Lambda^*}$.



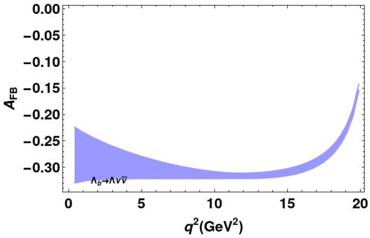
(a) F_L^{Λ} Vs q^2 in the Standard Model



(b) $F_L^{\Lambda^*}$ Vs q^2 in the Standard Model

forward-backward asymmetry in Standard model

$$A^{\Lambda}_{\rm FB} = -\alpha_{\Lambda}\sqrt{s_- s_+}\frac{2q^2 f_{\perp}^A f_{\perp}^V + (m^2_{\Lambda_b} - m^2_{\Lambda}) f_0^A f_0^V}{(F_{\Lambda}^A + F_{\Lambda}^V)\, C^{SM}} \mathrm{Re}(\mathbb{C}') \quad (19)$$



(c) A_{FB} Vs q^2 in the Standard Model

Standard Model predictions

	$\Lambda_b \to \Lambda \nu \bar{\nu}$	$\Lambda_b \to \Lambda^* \nu \bar{\nu}$
$Br \times 10^6$	(7.84 ± 0.94)	$(2.81 \pm 0.32) \times 10^{-9}$
F_L	0.52 ± 0.10	0.396 ± 0.066
A_{FB}	-0.29 ± 0.05	−

(d) : Standard Model predictions for $\Lambda_b \to \Lambda^{(*)}$ observables. The $\Lambda_b \to \Lambda^*$ observables are integrated from 16 GeV^2 to the end point

New Physics Scenarios

Lepton flavour structure New Physics in three scenarios

- Lepton Flavour Universality: The Hamiltonian being identical for all neutrino flavours, the total branching ratio is obtained by multiplying a factor of 3 to the branching ratio of an individual flavour.
- Lepton Flavor Universality violation with conserved Lepton Flavor: The Hamiltonian is not identical for all neutrino flavours; the sum of an individual flavour obtains the total branching ratio.
- Lepton Flavor Violation: In this case, neutrinos of different flavours appear in the NP operators, and the sum of a different flavour obtains the total branching ratio.

There are four New Physics Wilson coefficients $C^{ij}_{LL}, C^{ij}_{LR}, C^{ij}_{RL}, C^{ij}_{RR}$
Two scenarios for each Lepton flavour structure

- C^{ij}_{LL}, C^{ij}_{RL} are non-zero and $C^{ij}_{RL}, C^{ij}_{RR} = 0$
- C^{ij}_{RL}, C^{ij}_{RR} are non-zero and $C^{ij}_{LL}, C^{ij}_{RL} = 0$

Constraints on the $\Lambda_b \to \Lambda^{(*)}\nu\bar{\nu}$ branching ratios and $\mathcal{R}_{\nu\nu}^{\Lambda^{(*)}}$

	$C_{LL}>0$ $C_{RL}>0$	$C_{LL}<0$ $C_{RL}<0$	$C_{LL}>0$ $C_{RL}<0$	$C_{LL}<0$ $C_{RL}>0$
$\mathcal{B}(\Lambda_b \to \Lambda\nu\nu)$	1.20×10^{-5} 1.14×10^{-6}	2.79×10^{-5} 5.45×10^{-6}	8.64×10^{-6} 1.12×10^{-6}	3.66×10^{-5} 5.71×10^{-6}
$\mathcal{R}(\Lambda_b \to \Lambda\nu\nu)$	1.77 0.36	3.77 0.97	1.35 0.39	4.85 1.00
$\mathcal{B}(\Lambda_b \to \Lambda^*\nu\nu)_{16}$	6.13×10^{-9} 2.75×10^{-10}	7.18×10^{-9} 1.01×10^{-9}	2.32×10^{-9} 1.76×10^{-10}	2.22×10^{-9} 2.09×10^{-9}
$\mathcal{R}(\Lambda_b \to \Lambda^*\nu\nu)_{16}$	2.40 0.33	2.78 0.61	1.13 0.30	6.52 1.00

(e) Lepton flavour universal new physics with $LR=0$, $RR=0$

	$C_{LR}>0$ $C_{RR}>0$	$C_{LR}<0$ $C_{RR}<0$	$C_{LR}>0$ $C_{RR}<0$	$C_{LR}<0$ $C_{RR}>0$
$\mathcal{B}(\Lambda_b \to \Lambda\nu\nu)$	9.95×10^{-6} 5.48×10^{-6}	9.54×10^{-6} 5.48×10^{-6}	1.12×10^{-5} 5.49×10^{-6}	1.12×10^{-5} 5.49×10^{-6}
$\mathcal{R}(\Lambda_b \to \Lambda\nu\nu)$	1.50 1.00	1.50 1.00	1.66 1.00	1.66 1.00
$\mathcal{B}(\Lambda_b \to \Lambda^*\nu\nu)_{16}$	3.11×10^{-9} 1.93×10^{-9}	3.05×10^{-9} 1.96×10^{-9}	4.78×10^{-9} 1.99×10^{-9}	4.77×10^{-9} 1.95×10^{-9}
$\mathcal{R}(\Lambda_b \to \Lambda^*\nu\nu)_{16}$	1.29 1.00	1.29 1.00	1.92 1.00	1.92 1.00

(f) Lepton flavour universal new physics with $RL=0$, $LL=0$

	$[C_{LL}]^{ii}>0$ $[C_{RL}]^{ii}>0$	$[C_{LL}]^{ii}<0$ $[C_{RL}]^{ii}<0$	$[C_{LL}]^{ii}>0$ $[C_{RL}]^{ii}<0$	$[C_{LL}]^{ii}<0$ $[C_{RL}]^{ii}>0$
$\mathcal{B}(\Lambda_b \to \Lambda\nu\nu)$	1.07×10^{-5} 2.20×10^{-7}	2.55×10^{-5} 6.28×10^{-6}	7.87×10^{-6} 1.97×10^{-7}	3.08×10^{-5} 7.01×10^{-6}
$\mathcal{R}(\Lambda_b \to \Lambda\nu\nu)$	1.62 0.27	3.45 1.05	1.24 0.26	2.07 1.12
$\mathcal{B}(\Lambda_b \to \Lambda^*\nu\nu)_{16}$	5.51×10^{-9} 8.36×10^{-11}	7.87×10^{-9} 1.15×10^{-9}	1.90×10^{-9} 3.60×10^{-11}	1.44×10^{-8} 2.81×10^{-9}
$\mathcal{R}(\Lambda_b \to \Lambda^*\nu\nu)_{16}$	2.22 0.27	3.00 0.64	0.96 0.22	5.35 1.22

(g) Lepton Flavor Universality violation and conserved Lepton Flavor with $LR=0$, $RR=0$

	$[C_{LR}]^{ii}>0$ $[C_{RR}]^{ii}>0$	$[C_{LR}]^{ii}<0$ $[C_{RR}]^{ii}<0$	$[C_{LR}]^{ii}>0$ $[C_{RR}]^{ii}<0$	$[C_{LR}]^{ii}<0$ $[C_{RR}]^{ii}>0$
$\mathcal{B}(\Lambda_b \to \Lambda\nu\nu)$	9.94×10^{-6} 5.91×10^{-6}	1.00×10^{-5} 5.82×10^{-6}	1.14×10^{-5} 6.00×10^{-6}	1.14×10^{-5} 5.97×10^{-6}
$\mathcal{R}(\Lambda_b \to \Lambda\nu\nu)$	1.50 1.02	1.50 1.02	1.68 1.02	1.68 1.02
$\mathcal{B}(\Lambda_b \to \Lambda^*\nu\nu)_{16}$	3.07×10^{-9} 2.06×10^{-9}	3.00×10^{-9} 2.04×10^{-9}	4.91×10^{-9} 2.14×10^{-9}	4.95×10^{-9} 2.12×10^{-9}
$\mathcal{R}(\Lambda_b \to \Lambda^*\nu\nu)_{16}$	1.28 1.01	1.28 1.01	1.98 1.02	1.98 1.02

(h) Lepton Flavor Universality violation and conserved Lepton Flavor with $RL=0$, $LL=0$

Figure: Constraints on Wilson coefficients

Summary

- The branching ratios, F_L and A_{FB} of $\Lambda_b \to \Lambda \nu \bar{\nu}$ and $\Lambda_b \to \Lambda^* \nu \bar{\nu}$ are determined in the Standard Model
- Implications of the latest $B^+ \to K^+ \nu \bar{\nu}$ data on $\Lambda_b \to \Lambda \nu \bar{\nu}$ and $\Lambda_b \to \Lambda^* \nu \bar{\nu}$ are studied.
- Three New Physics scenarios considered: Lepton flavour universality, Lepton flavour universality violation with conserved lepton flavour and Lepton flavour violation are determined