Analysing $\Lambda_b \to \Lambda^{(*)}\nu\bar{\nu}$ decay in light of the recent Belle-II $B^+ \to K^+\nu\bar{\nu}$ data

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June 13, 2025
HPNP 2025, Osaka University

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Belle-II result

Recently, the Belle-II collaboration has presented the first evidence of the rare $B^+ \to K^+ \bar{\nu}\nu$ decay using two different measurement methods: a standard hadronic tag (had), and a novel inclusive tag (incl) [Belle-II:2023]. The branching ratios that the methods yield are

$$\begin{aligned} \mathrm{Br}(B^+ \to K^+ \bar{\nu}\nu)_{\mathrm{had}} &= (1.1^{+0.9+0.8}_{-0.8-0.5}) \times 10^{-5}\,, \\ \mathrm{Br}(B^+ \to K^+ \bar{\nu}\nu)_{\mathrm{incl}} &= (2.7 \pm 0.5 \pm 0.5) \times 10^{-5}\,, \end{aligned} \tag{1}$$

The combination of the two measurements

$$\mathrm{Br}(B^+ \to K^+ \bar{\nu}\nu)_{\mathrm{exp}} = (2.3 \pm 0.7) \times 10^{-5}\,, \tag{2}$$

is in excess of 2.7σ compared to the SM predictions

$$\mathrm{Br}(B^+ \to K^+ \bar{\nu}\nu)_{\mathrm{SM}} = (4.29 \pm 0.23) \times 10^{-6}\,. \tag{3}$$

The $b \to s\nu\bar{\nu}$ also mediates the $B^0 \to K^{*0}\nu\bar{\nu}$ transition and the upper limit on the branching ratio from the Belle collaboration is $\mathrm{Br}(B^0 \to K^{*0}\nu\bar{\nu})_{\mathrm{exp}} < 1.8 \times 10^{-5}$ [Belle:2017]. The excess over the SM rates can be expressed in terms of ratios [He et al:2023]

$$\begin{aligned} R_{\nu\nu}^{K} &= \frac{\mathrm{Br}(B^+ \to K^+\nu\bar{\nu})_{\mathrm{exp}}}{\mathrm{Br}(B^+ \to K^+\nu\bar{\nu})_{\mathrm{SM}}} = 5.4 \pm 1.6\,, \\ R_{\nu\nu}^{K^*} &= \frac{\mathrm{Br}(B \to K^*\nu\bar{\nu})_{\mathrm{exp}}}{\mathrm{Br}(B \to K^*\nu\bar{\nu})_{\mathrm{SM}}} < 2.7 \quad \text{or} \quad 1.9\,, \end{aligned} \tag{4}$$

Effective Hamiltonian

Keeping the possibility of light right-handed neutrinos, we work with an effective Hamiltonian for $b \to s\nu\bar{\nu}$ underlying decay

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}}\frac{\alpha}{4\pi}\lambda_t\left[C^{\rm SM}\mathcal{O}^{\rm SM} + \sum_{A,B=L/R}\sum_{ij} C^{ij}_{AB}\mathcal{O}^{ij}_{AB}\right], \qquad (5)$$

where the SM operator is $O^{\rm SM} = (\bar{s}\gamma_\mu P_L b)(\bar{\nu}\gamma^\mu P_L \nu)$ and the corresponding Wilson coefficient is [Buchalla, Brod]

$$C^{\rm SM} = -\frac{2X(x_t)}{s_W^2}, \quad X(x_t) = 1.469 \pm 0.017, \qquad (6)$$

which includes the NLO QCD corrections, and two-loop electroweak contributions. The lepton flavor specific NP operators are

$$\mathcal{O}^{ij}_{AB} = (\bar{s}\gamma_\mu P_A b)(\bar{\nu}^i\gamma^\mu P_B \nu^j). \qquad (7)$$

In the SM all the C^{ij}_{AB} vanish but they can be non-zero in physics

Motivation for similar baryonic decay

- As we are seeing anomaly in the B meson decay , similar decays with the same quark level decay should show similar behavior
- the most interesting cases are $\Lambda_b \to \Lambda(\to p\pi)\bar{\nu}\nu$ and $\Lambda_b \to \Lambda^*(\to N\bar{K})\bar{\nu}\nu$
- They provide complimentary information because of their spin
- Also for the ground state Λ decay to $p\pi$ being a weak decay, provides a forward backward asymmetry A_{FB}^h

Branching ratio in SM+NP in LFU

For Lepton flavor conserving case the decay rate becomes for

$$\frac{d^2\mathcal{B}_\Lambda}{dq^2 d\cos\theta_\Lambda} = N_\Lambda^2\Big[\Big((m_{\Lambda_b}-m_\Lambda)^2 s_+ f_0^{A^2} + 2q^2 s_+ f_\perp^{A^2}\Big)\mathbb{C}_- + \Big((m_{\Lambda_b}+m_\Lambda)^2 s_- f_0^{V^2} + 2q^2 s_- f_\perp^{V^2}\Big)\mathbb{C}_+ - 2\cos\theta_\Lambda \alpha_\Lambda \Big(2q^2\sqrt{s_- s_+} f_\perp^A f_\perp^V + (m_{\Lambda_b}^2 - m_\Lambda^2)\sqrt{s_- s_+} f_0^A f_0^V\Big)\mathrm{Re}(\mathbb{C}')\Big],$$

$$\frac{d^2\mathcal{B}_{\Lambda^*}}{dq^2 d\cos\theta_{\Lambda^*}} = \frac{N_{\Lambda^*}^2}{12 m_{\Lambda^*}^2}\Big[\Big((1+3\cos^2\theta_{\Lambda^*})(f_0^{A^2} s_+^2 s_- (m_{\Lambda_b}-m_{\Lambda^*})^2 + 2 f_\perp^{A^2} q^2 s_- s_+^2) + 18(1-\cos^2\theta_{\Lambda^*}) f_g^{A^2} m_{\Lambda^*}^2 q^2 s_-\Big)\mathbb{C}_- + \Big((1+3\cos^2\theta_{\Lambda^*})(f_0^{V^2} s_-^2 s_+ (m_{\Lambda_b}+m_{\Lambda^*})^2 + 2 f_\perp^{V^2} q^2 s_+ s_-^2) + 18(1-\cos^2\theta_{\Lambda^*}) f_g^{V^2} m_{\Lambda^*}^2 q^2 s_+\Big)\mathbb{C}_+\Big],$$

where $\alpha_\Lambda = 0.642 \pm 0.013$ [PDG] is a parameter related to the weak decay of Λ to $p\pi^-$, and N_X^2 are the normalization constants $f_i's$ are form-factors

The interference between the new physics and the SM is aptly captured by the Wilson coefficients

$$\begin{aligned}
\mathbb{C}_- &= \sum_i \left| C^{\rm SM} + (C^{ii}_{LL} - C^{ii}_{RL}) \right|^2 + \sum_i \left| (C^{ii}_{LR} - C^{ii}_{RR}) \right|^2 , \\
\mathbb{C}_+ &= \sum_i \left| C^{\rm SM} + (C^{ii}_{LL} + C^{ii}_{RL}) \right|^2 + \sum_i \left| (C^{ii}_{LR} + C^{ii}_{RR}) \right|^2 , \quad (8) \\
\mathbb{C}' &= \sum_i (C^{\rm SM} + (C^{ii}_{LL} - C^{ii}_{RL}))^* \times (C^{\rm SM} + (C^{ii}_{LL} + C^{ii}_{RL})) \\
&+ \sum_i ((C^{ii}_{LR} - C^{ii}_{RR}))^* ((C^{ii}_{LR} + C^{ii}_{RR})) . \quad (9)
\end{aligned}$$

The angular decay distribution provides 2 interesting observables:
Longitudinal polarisation fraction F_L

$$F_L^{\Lambda^*} = \frac{2}{3} \frac{\mathbb{C}_+ \mathbb{G}_1 + \mathbb{C}_- \mathbb{G}_2}{\mathbb{C}_+ \left(\mathbb{G}_1' + \mathbb{G}_1\right) + \mathbb{C}_- \left(\mathbb{G}_2' + \mathbb{G}_2\right)},$$

for Λ it comes out to be $\frac{1}{3}$
Then we define the forward-backward asymmetry :

$$A_{\mathrm{FB}}^{h,\Lambda} = \frac{\alpha_\Lambda \left(2q^2 \sqrt{s_- s_+} f_\perp^A f_\perp^V + \left(m_{\Lambda_b}^2 - m_\Lambda^2\right) \sqrt{s_- s_+} f_0^A f_0^V \right) \mathrm{Re}(\mathbb{C}')}{\left(\left(m_{\Lambda_b} - m_\Lambda\right)^2 s_+ f_0^{A^2} + 2q^2 s_+ f_\perp^{A^2} \right) \mathbb{C}_- + \left(\left(m_{\Lambda_b} + m_\Lambda\right)^2 s_- f_0^{V^2} + 2q^2 s_- f_\perp^{V^2} \right)}$$

LFV

For Lepton Flavor Violation (LFV) the decay rate becomes:

$$
\begin{aligned}
\frac{d^2\mathcal{B}_\Lambda}{dq^2 d\cos\theta_\Lambda} &= N_\Lambda^2\Bigg[\Big(\big(m_{\Lambda_b}-m_\Lambda\big)^2 s_+ f_0^{A^2} + 2q^2 s_+ f_\perp^{A^2}\Big)\mathbb{C}_-^{\mathrm{LFV}} + \Big(\big(m_{\Lambda_b}+m_\Lambda\big)^2 s_- f_0^{V^2} + 2q^2 s_- f_\perp^{V^2}\Big)\mathbb{C}_+^{\mathrm{LFV}} \\
&- 2\cos\theta_\Lambda \alpha_\Lambda\Big(2q^2\sqrt{s_- s_+} f_\perp^A f_\perp^V + \big(m_{\Lambda_b}^2 - m_\Lambda^2\big)\sqrt{s_- s_+} f_0^A f_0^V\Big)\mathrm{Re}(\mathbb{C}^{\prime\mathrm{LFV}})\Bigg], \\
\frac{d^2\mathcal{B}_{\Lambda^*}}{dq^2 d\cos\theta_{\Lambda^*}} &= \frac{N_{\Lambda^*}^2}{12 m_{\Lambda^*}^2}\Bigg[\mathbb{C}_+^{\mathrm{LFV}}\Big(18(1-\cos^2\theta_{\Lambda^*}) f_g^{V^2} m_{\Lambda^*}^2 q^2 s_+ + (1+3\cos^2\theta_{\Lambda^*})\big(f_0^{V^2}(m_{\Lambda_b}+m_{\Lambda^*})^2 + 2f_\perp^{V^2} q^2\big)\Big. \\
&+ \mathbb{C}_-^{\mathrm{LFV}}\Big(18(1-\cos^2\theta_{\Lambda^*}) f_g^{A^2} m_{\Lambda^*}^2 q^2 s_- + (1+3\cos^2\theta_{\Lambda^*})\big(f_0^{A^2}(m_{\Lambda_b}-m_{\Lambda^*})^2 + 2f_\perp^{A^2} q^2\big)s_+^2 s_-\Big)\Bigg],
\end{aligned}
$$

LFV

For Lepton Flavor Violation case, there is no interference between the new physics and the SM and the WC's come in the expression in the following way

$$\mathbb{C}_{-}^{\mathrm{LFV}} = \sum_{i\neq j}\left[\left|C_{LL}^{ij} - C_{RL}^{ij}\right|^2 + \left|C_{LR}^{ij} - C_{RR}^{ij}\right|^2\right],$$

$$\mathbb{C}_{+}^{\mathrm{LFV}} = \sum_{i\neq j}\left[\left|C_{LL}^{ij} + C_{RL}^{ij}\right|^2 + \left|C_{LR}^{ij} + C_{RR}^{ij}\right|^2\right],$$

$$\begin{aligned}\mathbb{C}'^{\mathrm{LFV}} = &\sum_{i\neq j}\left(C_{LL}^{ij} - C_{RL}^{ij}\right)^*\left(C_{LL}^{ij} + C_{RL}^{ij}\right)\\ &+\sum_{i\neq j}\left(C_{LR}^{ij} - C_{RR}^{ij}\right)^*\left(C_{LR}^{ij} + C_{RR}^{ij}\right).\end{aligned}$$

Figure 1: Enter Caption

SM prediction

SM prediction for $\Lambda_b \to \Lambda(\to p\pi)\bar{\nu}\nu$ and $\Lambda_b \to \Lambda^*(\to N\bar{K})\bar{\nu}\nu$ observables

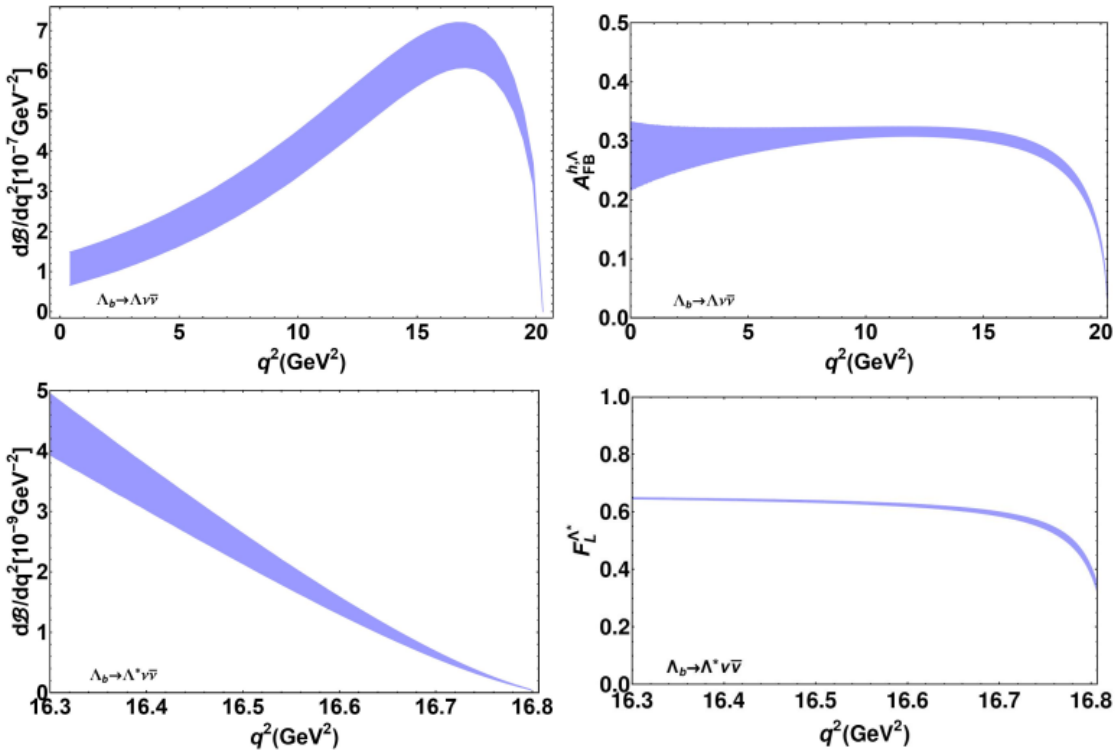


Figure 2: The bands correspond to the uncertainties sourced by the form factors, the SM Wilson coefficients, and the CKM elements.

1 Implications of Belle-II results

Implications of Belle-II results

To analyze the new physics implications of the Belle-II excess on the $\Lambda_b \to \Lambda^{(*)}\nu\bar{\nu}$ decays we utilize the the $R_K^{\nu\nu}$ and $R_{K^*}^{\nu\nu}$ data (4). The expressions of $R_K^{\nu\nu}$ and $R_{K^*}^{\nu\nu}$ following [He:2021, Browder:2021]

$$R_K^{\nu\nu} \approx 1 - 0.1\ \mathrm{Re}\sum_i \left(C_{LL}^{ii} + C_{RL}^{ii}\right) + 0.008 \sum_{ij} \left(\left| C_{LL}^{ij} + C_{RL}^{ij} \right|^2 + \left| C_{LR}^{ij} + C_{RR}^{ij} \right|^2 \right) ,$$

$$R_{K^*}^{\nu\nu} \approx 1 + \sum_i \mathrm{Re}\left(-0.1\ C_{LL}^{ii} + 0.07\ C_{RL}^{ii}\right) + \sum_{ij} \Big[0.008 \left(|C_{LL}^{ij}|^2 + |C_{RL}^{ij}|^2 + |C_{LR}^{ij}|^2 + |C_{RR}^{ij}|^2 \right)$$
$$- 0.01 \left(C_{LL}^{ij} C_{RL}^{ij} + C_{LR}^{ij} C_{RR}^{ij} \right) \Big] .$$

3 NP scenarios

Following, we discuss three New Physics scenarios:

1. Case-I:lepton flavor universal new physics: When the NP is lepton flavor universal, there is interference between the SM and the NP as seen in equation (8). The NP is described by the sets of new physics Wilson coefficients: C_{LL}^{ii}, C_{RL}^{ii}, C_{LR}^{ii}, and C_{RR}^{ii}.
2. Case-II: new physics with lepton flavor universality violation but conserved lepton number:
3. Case III: lepton flavor violating new physics where , there is no interference between the NP and the SM.

Case-I:LFU case

- We consider the following two cases: in the first case both $C_{LR}^{ii} = 0$ and $C_{RR}^{ii} = 0$ for all flavors, and in the second case both $C_{LL}^{ii} = 0$ and $C_{RL}^{ii} = 0$ for all flavors.
- the C_{LL}^{ii} and C_{RL}^{ii} coefficients are varied for one lepton flavor, while the coefficient for the other two flavors were kept SM-like.
- In table the C_{RR}^{ii} and the C_{LR}^{ii} were varied for one lepton flavor, while the two coefficients for the other flavors are SM like.

	$C_{LL}^{ii} > 0$ $C_{RL}^{ii} > 0$	$C_{LL}^{ii} < 0$ $C_{RL}^{ii} < 0$	$C_{LL}^{ii} > 0$ $C_{RL}^{ii} < 0$	$C_{LL}^{ii} < 0$ $C_{RL}^{ii} > 0$
$\mathcal{B}_\Lambda$	8.68×10^{-6}	1.09×10^{-5}	8.14×10^{-6}	1.00×10^{-5}
R_Λ	1.10 0.73	1.39 0.99	1.04 0.73	1.27 1.00
$\mathcal{B}_{\Lambda^*}$	1.06×10^{-8}	1.08×10^{-8}	8.44×10^{-9}	1.08×10^{-8}
R_{Λ^*}	1.25 0.73	1.28 0.83	1.0 0.69	1.28 1.00

	$C_{RR}^{ii} > 0$ $C_{LR}^{ii} > 0$	$C_{RR}^{ii} > 0$ $C_{LR}^{ii} < 0$
$\mathcal{B}_\Lambda$	8.98×10^{-6}	8.61×10^{-6}
R_Λ	1.14 1.00	1.1 1.00
$\mathcal{B}_{\Lambda^*}$	9.27×10^{-9}	9.32×10^{-9}
R_{Λ^*}	1.10 1.00	1.10 1.00

Same as in prev. table but $C_{LL}^{ii} = 0$, $C_{RL}^{ii} = 0$ for all choices of i, and C_{RR}^{ii}, C_{LR}^{ii} for a single choice of i are varied subject to the Belle-II constraints. As can be seen from (8), the case $C_{RR}^{ii} < 0, C_{LR}^{ii} < 0$ is identical to the case $C_{RR}^{ii} > 0, C_{LR}^{ii} > 0$, while $C_{RR}^{ii} < 0$, $C_{LR}^{ii} > 0$ is identical to the case $C_{RR}^{ii} > 0$, $C_{LR}^{ii} < 0$.

Lepton Flavor Universality violating new physics:

- Here we consider a scenario in which the lepton flavor universality is violated but the lepton flavor is still conserved
- first case both $C_{LR}^{ii} = 0$ and $C_{RR}^{ii} = 0$ for all flavors,
- second case both $C_{LL}^{ii} = 0$ and $C_{RL}^{ii} = 0$ for all flavors.
- The upper limit on branching ratios and upper and lower limits on $R_{\nu\nu}^{\Lambda^{(*)}}$ coming from the Belle-II data in different cases is shown in next tables

.

	$C_{LL}^{ii} > 0$ $C_{RL}^{ii} > 0$	$C_{LL}^{ii} < 0$ $C_{RL}^{ii} < 0$	$C_{LL}^{ii} > 0$ $C_{RL}^{ii} < 0$	$C_{LL}^{ii} < 0$ $C_{RL}^{ii} > 0$
$\mathcal{B}_\Lambda$	8.66×10^{-6}	1.13×10^{-5}	8.23×10^{-6}	1.02×10^{-5}
R_Λ	1.10 0.46	1.44 0.98	1.05 0.46	1.30 1.02
$\mathcal{B}_{\Lambda^*}$	1.09×10^{-8}	1.41×10^{-8}	1.42×10^{-8}	1.08×10^{-8}
R_{Λ^*}	1.29 0.47	1.67 0.75	1.68 0.47	1.28 0.76

Bounds on the $\Lambda_b \to \Lambda(\to p\pi)\bar{\nu}\nu$ and $\Lambda_b \to \Lambda^*(\to N\bar{K})\bar{\nu}\nu$ observables in different lepton flavor universality violating NP scenarios. Keeping $C_{RR}^{ii} = 0$, $C_{LR}^{ii} = 0$ for all three flavors $i = e, \mu, \tau$, while the C_{LL}^{ii}, C_{RL}^{ii} are varied for two lepton flavors subject to the Belle-II constraints.

Case-II:LFU case

	$C^{ii}_{\kappa R} > 0$ $C^{ii}_{LR} > 0$	$C^{ii}_{RR} > 0$ $C^{ii}_{LR} < 0$
$\mathcal{B}_\Lambda$	9.15×10^{-6}	8.60×10^{-6}
R_Λ	1.17 1.00	1.1 1.00
$\mathcal{B}_{\Lambda^*}$	9.27×10^{-9}	9.25×10^{-9}
R_{Λ^*}	1.10 1.00	1.10 1.00

Same as in prev. table but $C^{ii}_{LL} = 0$, $C^{ii}_{RL} = 0$ for all choices of i, and C^{ii}_{RR}, C^{ii}_{LR} for a two choices of i are varied subject to the Belle-II constraints. but $C^{ii}_{LL} = 0$, $C^{ii}_{RL} = 0$ for all choices of i, and C^{ii}_{RR}, C^{ii}_{LR} for a single choice of i are varied subject to the Belle-II constraints. As can be seen from (8), the case $C^{ii}_{RR} < 0, C^{ii}_{LR} < 0$ is identical to the case $C^{ii}_{RR} > 0, C^{ii}_{LR} > 0$, while $C^{ii}_{RR} < 0$, $C^{ii}_{LR} > 0$

Case-II:LFU case

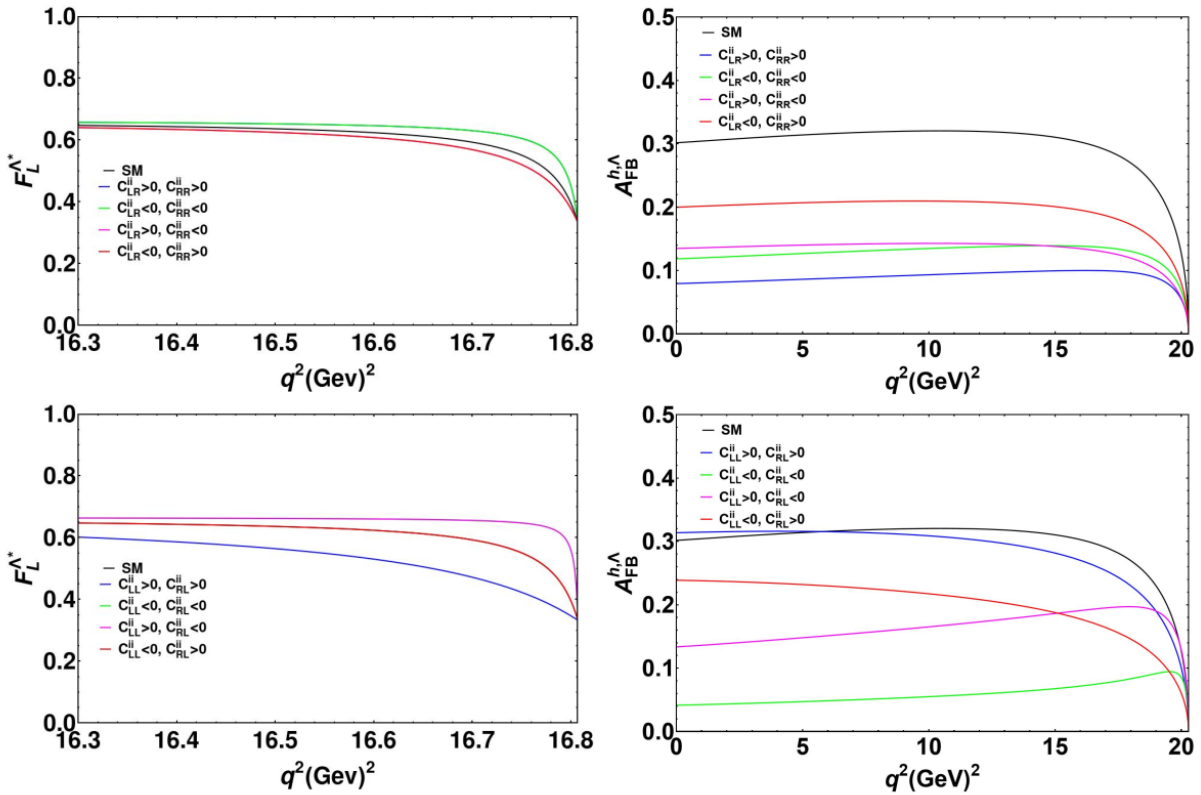


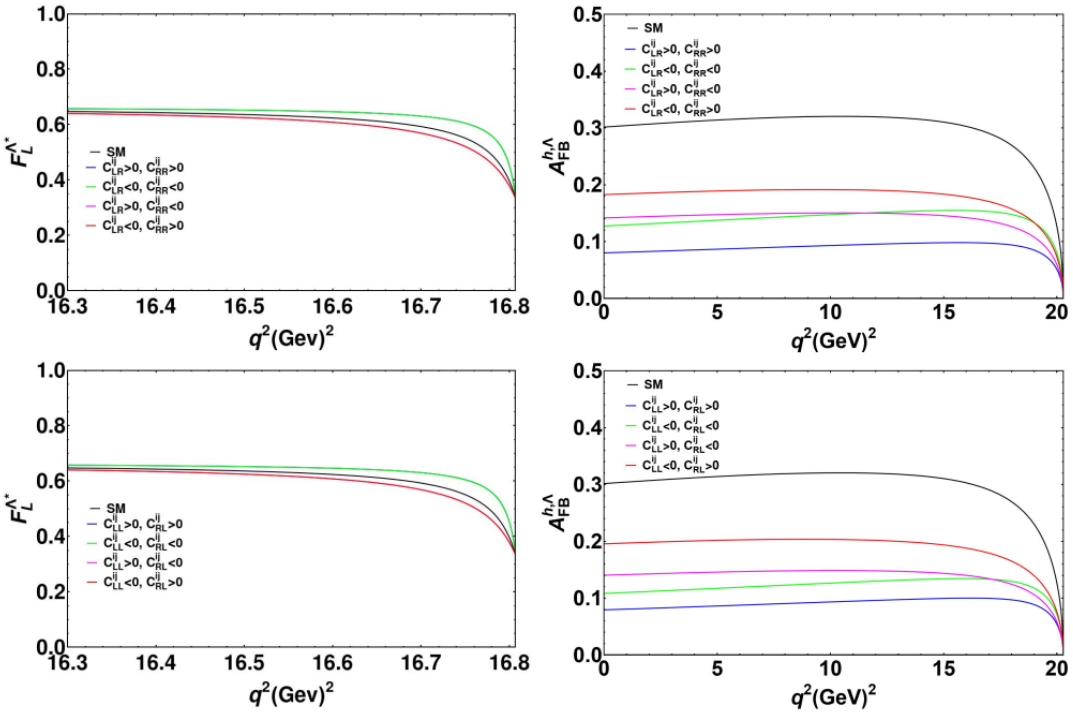
Figure 3: The observables $F_L^{\Lambda^*}$ and $A_{\rm FB}^{h,\Lambda}$ in the scenario with lepton flavor universality violation but conserved lepton number. The first two plots from the left correspond to scenario where $C_{LL}^{ii} = 0$, $C_{RL}^{ii} = 0$. The last two plots from the left correspond to scenario where $C_{LR}^{ii} = 0$ and

Lepton Flavor violation:

- If new physics is lepton flavor violating, there is no interference between the NP and the SM.
- We consider the scenario in which both $C_{LR}^{ij} = 0$ and $C_{RR}^{ij} = 0$ for all flavors and vary C_{RL}^{ij} and C_{LL}^{ij} for all flavors independently subject to the constraints set by the Belle-II data.
- To obtain the next table the C_{LL}^{ij} and C_{RL}^{ij} are varied for three lepton flavors independently.
- Keeping $C_{RR}^{ii} = 0, C_{LR}^{ii} = 0$ for all three flavors $i = e, \mu, \tau$, the C_{LL}^{ii}, C_{RL}^{ii} are varied for three lepton flavor i subject to the Belle-II constraints.
- The other scenario in which $C_{RL}^{ij} =$ and $C_{LL}^{ij} = 0$ yields the same table as can be understood from the prev. exp

	$C_{LL}^{ii} > 0$ $C_{RL}^{ii} > 0$	$C_{LL}^{ii} > 0$ $C_{RL}^{ii} < 0$
$\mathcal{B}_{\Lambda}$	7.38×10^{-6}	6.83×10^{-6}
R_{Λ}	1.17 1.00	1.09 1.00
$\mathcal{B}_{\Lambda^*}$	3.30×10^{-9}	3.32×10^{-9}
R_{Λ^*}	1.26 1.00	1.25 1.00

Upper bounds on the $\Lambda_b \to \Lambda(\to p\pi)\bar{\nu}\nu$ and $\Lambda_b \to \Lambda^*(\to N\bar{K})\bar{\nu}\nu$ observables in different lepton flavor violating NP scenarios. The upper limit on branching ratios and upper and lower limits on $R_{\nu\nu}^{\Lambda^{(*)}}$ are shown in tables.



The observables $F_L^{\Lambda^*}$ and $A_{\rm FB}^{h,\Lambda}$ in the scenario with lepton flavor violation. The first two plots from the left correspond to scenario where $C_{LL}^{ii} = 0$, $C_{RL}^{ii} = 0$. The last two plots from the left correspond to scenario where $C_{LR}^{ii} = 0$ and $C_{RR}^{ii} = 0$ In each plots the set of non-zero coefficients were randomly varied subject to $R_{K^*}^{\nu\nu}$ constraints.

Summary

- The $b \to s\nu\bar{\nu}$ transitions are theoretically cleaner in comparison with $b \to s\ell\ell$ transitions and serve as sensitive probe of physics beyond the Standard Model.
- Recently the Belle-II experiment presented their first measurement of $B^+ \to K^+\nu\bar{\nu}$ decay which deviates from the Standard Model by 2.7σ.
- Motivated by these results, in the present paper, we study the baryonic decay modes $\Lambda_b \to \Lambda(\to p\pi)\nu\bar{\nu}$ and $\Lambda_b \to \Lambda^*(\to N\bar{K})\nu\bar{\nu}$ that are expected to be observed in the proposed Tera-Z factory such as the FCC-ee and also in CEPC.

Summary

- The study is performed in a low-energy effective theory framework with additional right-handed neutrinos.
- We present upper limits on the branching ratios that are consistent with the recent Belle-II result.
- Additionally, we find that among the two observables studied – the longitudinal polarization fraction $F_L^{\Lambda^*}$ and the hadronic-side forward-backward asymmetry $A_{\mathrm{FB}}^{h,\Lambda}$
- The hadronic-side forward-backward asymmetry $A_{\mathrm{FB}}^{h,\Lambda}$ can be used to discriminate between the Standard Model and the New Physics scenarios considered.

Thanks For Your Attention!

Any questions?