PROBING HEAVY NEUTRINO THROUGH SEMILEPTONIC DECAYS

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based on arXiv:2603.15461, with D. Bečirević[a], S. Fajfer[b], N. Košnik[b], L. Pavičić[b]

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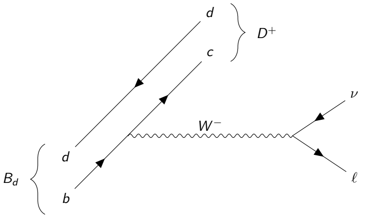
Semileptonic decays in the Standard Model

- In the Standard Model,



- **Experimentally**, what is measured is $\mathcal{B}(B_d \to D\,\ell\, E_{miss})$
  $\Rightarrow$ **any $B_d \to D\,\ell$'inv'** decay would contribute to the measurement

- we consider $b \to c\,\ell\, N$ transitions where N is a **neutral lepton field** because ...

- N is a key ingredient of many BSM models (neutrino mass, ...)
- $R_K^{\nu\nu} = \frac{\mathcal{B}(B \to K\nu\bar{\nu})^{exp}}{\mathcal{B}(B \to K\nu\bar{\nu})^{SM}}$=5.4±1.5 measured by Belle II [1]
- overall 3σ tension in $R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$ between SM predictions and measurements

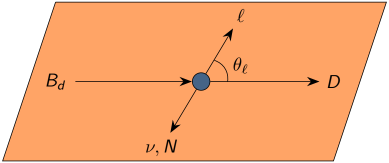
Framework

Particle content: (SM + N_L) **OR** (SM + N_R)

$$\mathcal{H}_{\rm eff}^{L/R} = \frac{4 G_F V_{q_u q_d}}{\sqrt{2}} \Big((\bar{u}\gamma^\mu d_L)(\bar{\ell}\gamma_\mu \nu_L) + \sum_{A\in\{L,R\}} C^V_{A,L/R} (\bar{u}\gamma^\mu d_A)(\bar{\ell}\gamma^\mu N_{L/R})$$
$$+ C^S_{A,L/R}(\bar{u}\, d_A)(\bar{\ell}\, N_{L/R}) + C^T_{A,L/R}(\bar{u}\,\sigma^{\mu\nu} d_A)(\bar{\ell}\sigma_{\mu\nu} N_{L/R}) \Big)$$

Differential branching ratio for a SL decay [2]:

$$\frac{d^2\mathcal{B}(B_d \to D\ell X)}{dq^2 d\cos\theta_\ell} = a(q^2) + b(q^2)\cos\theta_\ell + c(q^2)\cos^2\theta_\ell$$



Branching ratio:

$$\mathcal{B} = \int dq^2\ 2\left(a(q^2) + \frac{c(q^2)}{3} \right)$$

Forward-backward asymmetry:

$$\langle A_{FB} \rangle = \int dq^2 \frac{b(q^2)}{\mathcal{B}}$$

New observable !

▶ the lepton ℓ has a definite polarization $(\uparrow, \downarrow) = (+, -)$ $\rightarrow$ each decay is $B_d \rightarrow D\ell^{\uparrow}X$ or $B_d \rightarrow D\ell^{\downarrow}X$ $\rightarrow$ observables can be defined for both lepton helicities.

The **polarized foward-backward asymmetry**

$$\langle A_{FB}^{\pm} \rangle = \frac{1}{\mathcal{B}} \int dq^2 \left(\int_0^1 d\cos\theta_\ell - \int_{-1}^0 d\cos\theta_\ell \right) \frac{d^2\mathcal{B}^{\pm}}{dq^2\, d\cos\theta_\ell} = \frac{\int dq^2\, b^{\pm}(q^2)}{\mathcal{B}}$$

indicates the **preference in direction** of $\ell^{\uparrow\downarrow}$ in the dilepton rest frame.

In the SM, $\langle A_{FB}^{-} \rangle = 0$

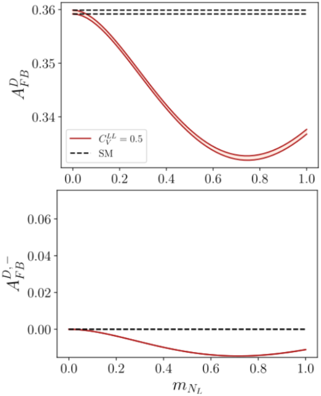
- $b^{-}(q^2) = 0$ & $b^{+}(q^2) \neq 0$
- True for **all semileptonic decays**
- In the SM, ℓ^{-} in the dilepton rest frame has no preferential direction

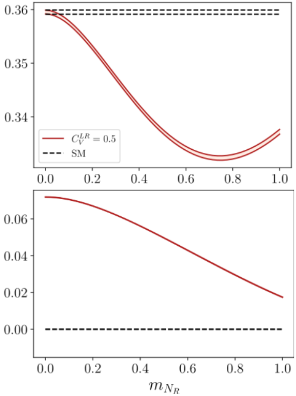
A_{FB}^{-} **is a great probe of new physics !**

$$\mathcal{H}_{\text{eff}} \supset (\bar{u}\gamma^{\mu} d_A)(\bar{\ell}\gamma_{\mu} \mathbf{N_L}) \quad \textbf{or} \quad \mathcal{H}_{\text{eff}} \supset (\bar{u}\gamma^{\mu} d_A)(\bar{\ell}\gamma_{\mu} \mathbf{N_R})$$

N_L	N_R
$\langle A_{FB}^{-} \rangle$ **Always negative !** (and null for $m_{N_L} = 0$)	$\langle A_{FB}^{-} \rangle$ **Always positive !** (and non-zero for $m_{N_R} = 0$)

$B \to D\tau(\nu + N_L)$





$B \to D\tau(\nu + N_R)$

Conclusion

- ⋆ Many **well motivated** BSM models involve neutral lepton fields (N_L, N_R) & and can impact semileptonic decays
- ⋆ In 3-body semileptonic decays, $\langle A_{FB}^{-} \rangle$ is **exactly zero** in the SM
- ⋆ A non-zero $\langle A_{FB}^{-} \rangle$ can indicate the presence of a neutral lepton field N and its sign can give a clue on the **chirality** of N
- ⋆ In 4-body semileptonic decays, similar conclusions can be drawn

References

[1] L. Allwicher et al. "Understanding the first measurement of $\mathcal{B}(B \to K\nu\bar{\nu})$". In: *Physics Letters B* (2024).

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[4] Alakabha Datta et al. "$B^- \to D^{(*)}\ell X$" decays in effective field theory with massive right-handed neutrinos". In: *Phys. Rev. D* (2022). arXiv: 2204.01818 [hep-ph].

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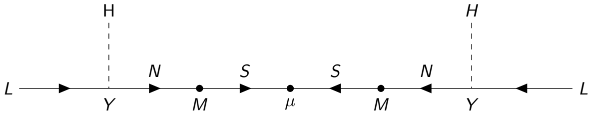
Back-up

Inverse Seesaw mechanism

- Particle content : SM + sterile RH neutral lepton field N_R + sterile LH neutral lepton field S_L [2]

$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} - Y_N \bar{L}\tilde{H}N_R - M_N \bar{N}_R S_L - \frac{1}{2}\mu \bar{S}_L^c S_L$$



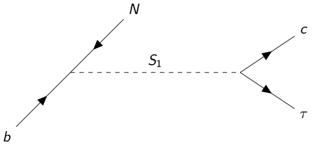
- generates dim 5 Weinberg operator and 'natural' small neutrino masses $m_\nu \approx \mu \frac{Y^2 v^2}{M^2}$
- S_L mixes with ν_L and therefore the interaction $W_\mu^- \bar{\ell}\gamma^\mu S_L'$ is generated

- a semileptonic transition is induced through mixing with the SM neutrinos
- we would then have the operator $(\bar{u}\gamma^\mu d_L)(\bar{\ell}\gamma^\mu N_L)$, with N **massive**

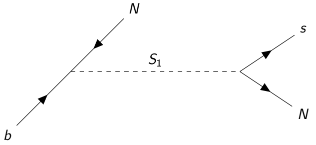
S_1 leptoquark for $R_{K^+}^{\nu\nu}$ and $R_{D^{(*)}}$

- Particle content : RH neutral lepton field N_R, S_1 $(\bar{3}, 1, -1/3)$ [3]

$$\mathcal{L} \supset y_{c\tau}^{R}\overline{c^c}P_R\tau S_1 + y_{sN}^{R}\overline{s^c}P_R N_R S_1 + y_{bN}^{R}\overline{b^c}P_R N_R S_1 + \text{ h.c.}$$



$\Rightarrow$ Generates $(\bar{c}\gamma^\mu b_R)(\bar{\tau}\gamma_\mu N_R)$ that contributes to $R_{D^{(*)}}$



$\Rightarrow$ Generates $(\bar{s}\gamma^\mu b_R)(\bar{N}\gamma_\mu N_R)$ that contributes to $R_{K^+}^{\nu\nu}$

This BSM model solves 2 'discrepancies' at once and generates a semileptonic transition with a **massive or massless** neutral lepton field N_R

Usual observables

Differential branching ratio for a semileptonic decay [4]:

$$\frac{d^2\mathcal{B}(M \to P\ell X)}{dq^2 d\cos\theta_\ell} = a(q^2) + b(q^2)\cos\theta_\ell + c(q^2)\cos^2\theta_\ell$$

The following observables have been previously defined :

- ⋆ Branching ratio:

$$\mathcal{B} = \int dq^2 d\cos\theta_\ell \frac{d^2\mathcal{B}}{dq^2 d\cos\theta_\ell} = \int dq^2\, 2\left(a(q^2) + \frac{c(q^2)}{3}\right)$$

- ⋆ Forward-backward asymmetry:

$$\langle A_{FB}\rangle = \frac{1}{\mathcal{B}}\int dq^2 \left(\int_0^1 d\cos\theta_\ell - \int_{-1}^0 d\cos\theta_\ell\right)\frac{d^2\mathcal{B}}{dq^2 d\cos\theta_\ell} = \int dq^2 \frac{b(q^2)}{\mathcal{B}}$$

Usual observables

Differential BR for a SL decay for a definite lepton polarization ($\uparrow = +, \downarrow = -$) :

$$\frac{d^2\mathcal{B}^{\pm}(M \to P\ell^{\pm}X)}{dq^2 d\cos\theta_\ell} = a_{\pm}(q^2) + b_{\pm}(q^2)\cos\theta_\ell + c_{\pm}(q^2)\cos^2\theta_\ell$$

The following observables have been previously defined :

- ⋆ Polarized Branching ratio:

$$\boxed{\mathcal{B}^{\pm} = \int dq^2 d\cos\theta_\ell \frac{d^2\mathcal{B}\pm}{dq^2 d\cos\theta_\ell} = \int dq^2\ 2\left(a_{\pm}(q^2) + \frac{c_{\pm}(q^2)}{3}\right)}$$

- ⋆ Lepton polarization asymmetry: $\boxed{P_\ell = \frac{\mathcal{B}^+ - \mathcal{B}^-}{\mathcal{B}^+ + \mathcal{B}^-}}$

We notice $\langle A_{FB}\rangle = \int dq^2 \frac{b(q^2)}{\mathcal{B}} = \int dq^2 \frac{b^+(q^2)+b^-(q^2)}{\mathcal{B}}$

What can $A_{FB}^{-} \neq 0$ mean ?

$\Rightarrow$ **Measuring a non-zero $\langle A_{FB}^{-} \rangle$ means measuring new physics**

Ingredients for a non-zero $\langle A_{FB}^{-} \rangle$:

- interactions with a **massive** N_L
- interactions with a **massless or massive** N_R

We explore the case of **vector interactions**:

- $C^S_{L/R,L/R} = C^T_{L/R,L/R} = 0$
- we keep $(C^V_{L,L}$ & $C^V_{R,L})$ **OR** $(C^V_{L,R}$ & $C^V_{R,R})$

If $\langle A_{FB}^{-} \rangle \neq 0$, could we probe the chirality of the neutral lepton field ?

N_L or N_R ?

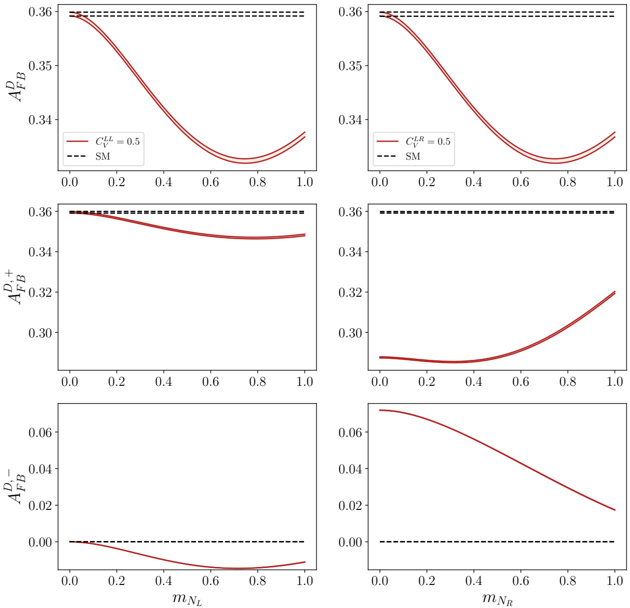
$$\mathcal{H}_{\text{eff}} \supset (\bar{u}\gamma^\mu d_A)(\bar{\ell}\gamma_\mu \mathbf{N_L}) \quad \textbf{or} \quad \mathcal{H}_{\text{eff}} \supset (\bar{u}\gamma^\mu d_A)(\bar{\ell}\gamma_\mu \mathbf{N_R})$$

N_L	N_R
$b^-(q^2) = - \tilde{\mathcal{N}}\lvert C^V_{LL}+C^V_{RL}\rvert^2 H^V_0 H^V_t (K^N_{--})^2$	$b^-(q^2) = \tilde{\mathcal{N}}\lvert C^V_{LR}+C^V_{RR}\rvert^2 H^V_0 H^V_t (K^N_{+-})^2$
Always negative ! (and null for $m_{N_L}=0$)	**Always positive !** (and non-zero for $m_{N_R}=0$)

Definitions:

- $H^V_0(q^2) = \frac{\sqrt{\lambda_{MP}}}{\sqrt{q^2}} f_+(q^2)$
- $H^V_t(q^2) = \frac{m_M^2 - m_P^2}{\sqrt{q^2}} f_0(q^2)$
- $\tilde{\mathcal{N}} = \frac{\lvert V_{q_u q_d}\rvert^2 G_F^2}{128\pi^3} \frac{\sqrt{\lambda_{MP}}\sqrt{\lambda_{\ell N}}}{4q^2 m_M^3}$
- $K_{\pm,\pm}(m_\ell, q, m_N) = \frac{(E_X+m_X \pm \lvert p_\ell\rvert)(E_\ell+m_\ell \pm \lvert p_\ell\rvert)}{\sqrt{(E_\ell+m_\ell)(E_X+m_X)}}$ [5]

$B \to D\tau(\nu + N_L)$ $B \to D\tau(\nu + N_R)$



$M \to P\,\ell\,E_{miss}$ & A_{FB}^{-}

- $A_{FB}^{\pm}$ describes the preference in direction of $\ell^{\pm}$
- In the Standard Model, $A_{FB}^{-} = 0$
- Non-zero A_{FB}^{-} for **any SL decay** suggests new physics
- while A_{FB}^{tot} does not say anything about the chirality of N, A_{FB}^{-} can in the case of vector interactions !
- $(\bar{b}\Gamma c)(\bar{\tau}\Gamma N)$ induce $B \to D\tau N$ but also $B \to D^{*}(\to D\pi)\tau N$

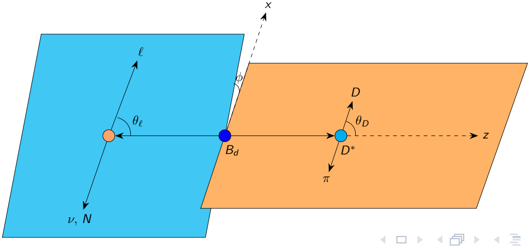
Can we draw similar conclusions for 4-body decays ?

Framework

- Particle content: (SM + N_L) **OR** (SM + N_R)

$$\mathcal{H}_{\text{eff}}^{L/R} = \frac{4 G_F V_{q_u q_d}}{\sqrt{2}} \Bigg((\bar{u}\gamma^\mu d_L)(\bar{\ell}\gamma_\mu \nu_L) + \sum_{A\in\{L,R\}} C^V_{A,L/R} (\bar{u}\,\gamma^\mu\, d_A)(\bar{\ell}\,\gamma^\mu\, N_{L/R})$$
$$+ C^S_{A,L/R}(\bar{u}\, d_A)(\bar{\ell}\, N_{L/R}) + C^T_{A,L/R}(\bar{u}\,\sigma^{\mu\nu}\, d_A)(\bar{\ell}\,\sigma_{\mu\nu}\, N_{L/R}) \Bigg)$$

- Process : $(B \to D^*(D\pi)\,\tau$ 'inv'), $(D \to K^*(K\pi)\mu$'inv'), etc..
  In general, $(M \to V(\to P\pi)\ell$'inv') measured as $\mathcal{B}(M \to V(\to P\pi)\ell E_{miss})$
- Kinematics : In the B_d meson rest frame,



Usual observables

Differential BR for a 4-body SL decay for ($\uparrow = +$, $\downarrow = -$) lepton polarization :

$$\frac{d^2\mathcal{B}^{\pm}(M \to V(P\pi)\ell^{\pm}X)}{dq^2 d\cos\theta_\ell d\cos\theta_D} = 2 \times \frac{d\mathcal{B}^{\pm}_{\mathcal{L}}}{dq^2 d\cos\theta_\ell}\cos^2\theta_D + \frac{d\mathcal{B}^{\pm}_{\mathcal{T}}}{dq^2 d\cos\theta_\ell}\sin^2\theta_D$$

with the **longitudinal** and **tranverse** polarizations defined as

$$\frac{dF^{\pm}_L}{dq^2 d\cos\theta_\ell} = \frac{1}{\mathcal{B}}\frac{d\mathcal{B}^{\pm}_{\mathcal{L}}}{dq^2 d\cos\theta_\ell} = \frac{\pi}{\mathcal{B}}\left(I^{\pm}_{1c} + I^{\pm}_{6c}\cos\theta_\ell + I^{\pm}_{2c}\cos 2\theta_\ell\right)$$

$$\frac{dF^{\pm}_T}{dq^2 d\cos\theta_\ell} = \frac{1}{\mathcal{B}}\frac{d\mathcal{B}^{\pm}_{\mathcal{T}}}{dq^2 d\cos\theta_\ell} = \frac{2\pi}{\mathcal{B}}\left(I^{\pm}_{1s} + I^{\pm}_{6s}\cos\theta_\ell + I^{\pm}_{2s}\cos 2\theta_\ell\right)$$

The **longitudinal/transverse polarized forward backward asymmetry**

$$\frac{dA^{\pm}_{FB,L}}{dq^2} = \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_\ell \, \frac{d^2 F^{\pm}_L}{dq^2\, d\cos\theta_\ell} = \frac{\pi}{\mathcal{B}} I^{\pm}_{6c}$$

$$\frac{dA^{\pm}_{FB,T}}{dq^2} = \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_\ell \, \frac{d^2 F^{\pm}_T}{dq^2\, d\cos\theta_\ell} = \frac{2\pi}{\mathcal{B}} I^{\pm}_{6s}$$

In the SM, $\langle A^{-}_{FB,L}\rangle = 0$

In the SM, $\langle A^{+}_{FB,T}\rangle = 0$

$A^{-}_{FB,L}$ & $A^{+}_{FB,T}$ are a great probe of new physics !

$\langle A^{-}_{FB,L} \rangle$: N_L or N_R ?

$$\mathcal{H}_{\rm eff} \supset (\bar{u}\gamma^{\mu} d_A)(\bar{\ell}\gamma_{\mu} \mathbf{N_L}) \quad \textbf{or} \quad \mathcal{H}_{\rm eff} \supset (\bar{u}\gamma^{\mu} d_A)(\bar{\ell}\gamma_{\mu} \mathbf{N_R})$$

N_L	N_R
$I^{-}_{6c}(q^2) = - 2\tilde{\mathcal{N}} \lvert C^V_{LL} - C^V_{RL} \rvert^2 H^V_0 H^V_t (K^N_{--})^2$	$I^{-}_{6c}(q^2) = 2\tilde{\mathcal{N}} \lvert C^V_{LR} - C^V_{RR} \rvert^2 H^V_0 H^V_t (K^N_{+-})^2$
Always negative ! (and null for $m_{N_L} = 0$)	**Always positive !** (and non-zero for $m_{N_R} = 0$)

Such a general conclusion can not be drawn for $A^{+}_{FB,T}$

$\langle A^{-}_{FB,L} \rangle$: N_L or N_R ?

$$\mathcal{H}_{\text{eff}} \supset (\bar{u}\gamma^{\mu} d_A)(\bar{\ell}\gamma_{\mu} \mathbf{N_L}) \quad \textbf{or} \quad \mathcal{H}_{\text{eff}} \supset (\bar{u}\gamma^{\mu} d_A)(\bar{\ell}\gamma_{\mu} \mathbf{N_R})$$

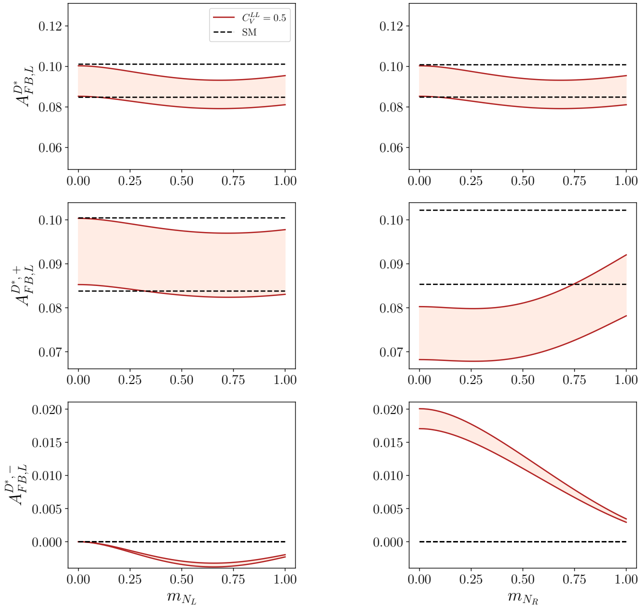
N_L	N_R
$I^{-}_{6c}(q^2) = - 2\tilde{\mathcal{N}} \lvert C^V_{LL} - C^V_{RL} \rvert^2 H^V_0 H^V_t (K^N_{--})^2$	$I^{-}_{6c}(q^2) = 2\tilde{\mathcal{N}} \lvert C^V_{LR} - C^V_{RR} \rvert^2 H^V_0 H^V_t (K^N_{+-})^2$
Always negative ! (and null for $m_{N_L} = 0$)	**Always positive !** (and non-zero for $m_{N_R} = 0$)

Definitions:

- $H^V_0(q^2) = \frac{m_M + m_V}{2m_V\sqrt{q^2}} \left[(m^2_M - m^2_V - q^2) A_1(q^2) - \frac{\lambda_V(q^2)}{(m_M + m_V)^2} A_2(q^2) \right]$
- $H^V_t(q^2) = \frac{\sqrt{\lambda_V(q^2)}}{\sqrt{q^2}} A_0(q^2)$
- $\tilde{\mathcal{N}} = \frac{3G^2_F V^2_{cb}}{4096\pi^4} \frac{\sqrt{\lambda_{MV}}\sqrt{\lambda_{\ell X}}}{m^3_M q^2} \mathcal{B}(V \to P\pi)$.

Such a general conclusion can not be drawn for $A^{+}_{FB,T}$

$B \to D^* \tau(\nu + N_L)$ $\qquad$ $B \to D^* \tau(\nu + N_R)$



νSMEFT answer to $\mathcal{B}(B \to K^+ E_{miss})$ excess

νSMEFT : SMEFT extended by N_R (1,1,1)

In this framework, the dim 6 operator that better explains the $\mathcal{B}(B \to K^+ E_{miss})$ measurement is the scalar operator :

$$\mathcal{O}^{LNQd} = \bar{L}^{\alpha} N \, \epsilon_{\alpha\beta} \, \bar{Q}_2^{\beta} d_1$$
$$= (\bar{\nu}_L N_R)(\bar{s} b_L) - (\bar{\ell} N_R)(\bar{c} b_L)$$

$(\bar{\nu}_L N_R)(\bar{s} b_L)$

can explain $\mathcal{B}(B \to K^+ E_{miss})$ measurement for all masses of N_R

$(\bar{\ell} N_R)(\bar{c} b_L)$

contributes to B_d semileptonic decays!