

PROBING HEAVY NEUTRINO THROUGH SEMILEPTONIC DECAYS

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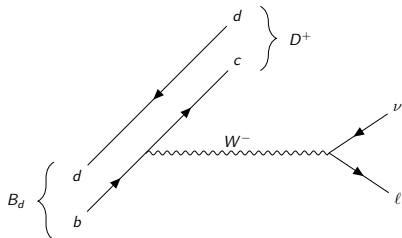
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Semileptonic decays in the Standard Model

- In the Standard Model, the electroweak transition induces $B_d \rightarrow D \tau \nu$ through



- Experimentally**, what is measured is $\mathcal{B}(B_d \rightarrow D \tau E_{miss})$
 $\Rightarrow$ **any $B_d \rightarrow D \tau$ 'inv' decay** would contribute to the measurement
- Here, we will consider additional $b \rightarrow c \ell N$ transitions where N is a **neutral lepton field**

- Why are neutral lepton fields of interest and how can they appear in semileptonic decays (SL) ?
- How can we probe neutral lepton fields in SL decays ?

Why should we go beyond the Standard Model?

Hints of new physics ...

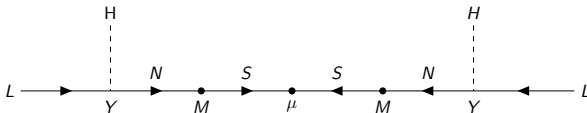
- In the Standard Model, neutrinos are **massless** but **neutrino oscillations** show that neutrinos are massive
⇒ **necessity of physics beyond the Standard Model (BSM)**
- $R_K^{\nu\nu} = \frac{\mathcal{B}(B \rightarrow K \nu \bar{\nu})^{\text{exp}}}{\mathcal{B}(B \rightarrow K \nu \bar{\nu})^{\text{SM}}} = 5.4 \pm 1.5$ measured by Belle II [1]
- overall 3σ tension in $R_{D^{(*)}} = \frac{\mathcal{B}(B \rightarrow D^{(*)} \tau \nu)}{\mathcal{B}(B \rightarrow D^{(*)} \ell \nu)}$ between SM predictions and measurements

Let's explore potential explanations that involve neutral lepton fields

Inverse Seesaw mechanism

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

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



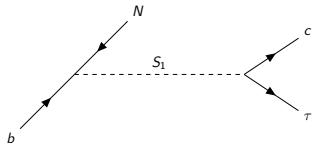
- generates dim 5 Weinberg operator and 'natural' small neutrino masses $m_\nu \approx \mu \frac{Y^2 v^2}{M^2}$
- S_L mixes with ν_L and therefore the interaction $W_\mu^- \bar{\ell} \gamma^\mu S'_L$ is generated

- 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**

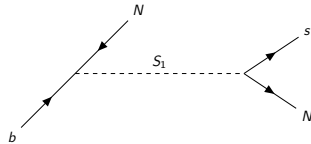
S_1 leptoquark for $R_{K^+}^{\nu\nu}$ and $R_{D^{(*)}}$

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

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



$\Rightarrow$ 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

Many BSM models contain NL fields (N_L , N_R) that contribute to SL decays :

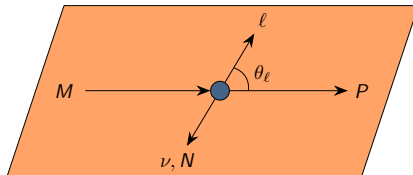
How to effectively probe the presence of N in SL decays ?

Framework

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

$$\mathcal{H}_{\text{eff}}^{L/R} = \frac{4G_F V_{qu} V_{qd}}{\sqrt{2}} \left((\bar{u} \gamma^\mu d_L) (\bar{\ell} \gamma_\mu \nu_L) + \sum_{A \in \{L, R\}} C_{A, L/R}^V (\bar{u} \gamma^\mu d_A) (\bar{\ell} \gamma^\mu N_{L/R}) + C_{A, L/R}^S (\bar{u} d_A) (\bar{\ell} N_{L/R}) + C_{A, L/R}^T (\bar{u} \sigma^{\mu\nu} d_A) (\bar{\ell} \sigma_{\mu\nu} N_{L/R}) \right)$$

- Process : $(K \rightarrow \pi \mu \text{'inv'})$, $(B \rightarrow D \tau \text{'inv'})$, $(D \rightarrow K \mu \text{'inv'})$, etc..
In general, $(M \rightarrow P \ell \nu) + (M \rightarrow P \ell N)$ measured as $\mathcal{B}(M \rightarrow P \ell E_{\text{miss}})$
- Kinematics : In the dilepton rest frame,



Differential branching ratio for a semileptonic decay [4]:

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

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 ($\uparrow = +$, $\downarrow = -$) :

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

The following observables have been previously defined :

★ Polarized Branching ratio:

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

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

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

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 $\ell^{\pm}$ 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 !

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**:

- $C_{L/R,L/R}^S = C_{L/R,L/R}^T = 0$
- we keep $(C_{L,L}^V \ \& \ C_{R,L}^V)$ **OR** $(C_{L,R}^V \ \& \ C_{R,R}^V)$

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

N_L or N_R ?

$$\mathcal{H}_{\text{eff}} \supset (\bar{u} \gamma^\mu d_A) (\bar{\ell} \gamma_\mu \mathbf{N}_L) \quad \text{or} \quad \mathcal{H}_{\text{eff}} \supset (\bar{u} \gamma^\mu d_A) (\bar{\ell} \gamma_\mu \mathbf{N}_R)$$

N_L

$$b^-(q^2) = -\tilde{\mathcal{N}} |C_{LL}^V + C_{RL}^V|^2 H_0^V H_t^V (K_{--}^N)^2$$

Always negative !
(and null for $m_{N_L} = 0$)

N_R

$$b^-(q^2) = \tilde{\mathcal{N}} |C_{LR}^V + C_{RR}^V|^2 H_0^V H_t^V (K_{+-}^N)^2$$

Always positive !
(and non-zero for $m_{N_R} = 0$)

N_L or N_R ?

$$\mathcal{H}_{\text{eff}} \supset (\bar{u}\gamma^\mu d_A)(\bar{\ell}\gamma_\mu \mathbf{N}_L) \quad \text{or} \quad \mathcal{H}_{\text{eff}} \supset (\bar{u}\gamma^\mu d_A)(\bar{\ell}\gamma_\mu \mathbf{N}_R)$$

N_L

N_R

$$b^-(q^2) = -\tilde{\mathcal{N}} |C_{LL}^V + C_{RL}^V|^2 H_0^V H_t^V (K_{--}^N)^2$$

$$b^-(q^2) = \tilde{\mathcal{N}} |C_{LR}^V + C_{RR}^V|^2 H_0^V H_t^V (K_{+-}^N)^2$$

Always negative !
(and null for $m_{N_L} = 0$)

Always positive !
(and non-zero for $m_{N_R} = 0$)

Definitions:

$$\bullet H_0^V(q^2) = \frac{\sqrt{\lambda_{MP}}}{\sqrt{q^2}} f_+(q^2)$$

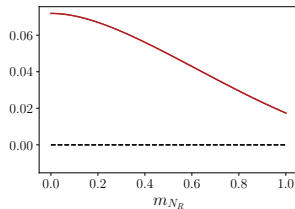
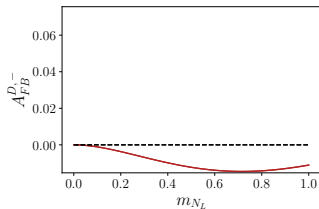
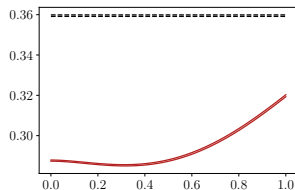
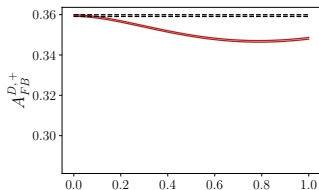
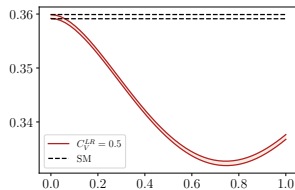
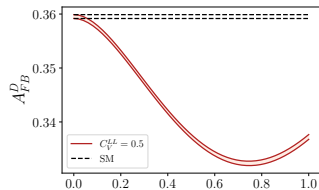
$$\bullet H_t^V(q^2) = \frac{m_M^2 - m_P^2}{\sqrt{q^2}} f_0(q^2)$$

$$\bullet \tilde{\mathcal{N}} = \frac{|V_{qu}q_d|^2 G_F^2}{128\pi^3} \frac{\sqrt{\lambda_{MP}}\sqrt{\lambda_{\ell N}}}{4q^2 m_M^3}$$

$$\bullet K_{\pm,\pm}(m_\ell, q, m_N) = \frac{(E_X + m_X \pm |p_\ell|)(E_\ell + m_\ell \pm |p_\ell|)}{\sqrt{(E_\ell + m_\ell)(E_X + m_X)}} \quad [5]$$

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

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



$$M \rightarrow P \ell E_{\text{miss}} \text{ \& } A_{FB}^-$$

- $A_{FB}^\pm$ 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 $B \rightarrow D\tau N$ but also $B \rightarrow D^*(\rightarrow D\pi)\tau N$

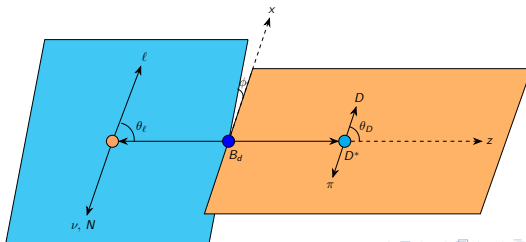
Can we draw similar conclusions for 4-body decays ?

Framework

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

$$\mathcal{H}_{\text{eff}}^{L/R} = \frac{4G_F V_{quqd}}{\sqrt{2}} \left((\bar{u}\gamma^\mu d_L)(\bar{\ell}\gamma_\mu \nu_L) + \sum_{A \in \{L,R\}} C_{A,L/R}^V (\bar{u}\gamma^\mu d_A)(\bar{\ell}\gamma^\mu N_{L/R}) \right. \\ \left. + C_{A,L/R}^S (\bar{u} d_A)(\bar{\ell} N_{L/R}) + C_{A,L/R}^T (\bar{u}\sigma^{\mu\nu} d_A)(\bar{\ell}\sigma_{\mu\nu} N_{L/R}) \right)$$

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



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

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

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

$$\begin{aligned} \frac{dF_L^\pm}{dq^2 d \cos \theta_\ell} &= \frac{1}{\mathcal{B}} \frac{d\mathcal{B}_\mathcal{L}^\pm}{dq^2 d \cos \theta_\ell} = \frac{\pi}{\mathcal{B}} (I_{1c}^\pm + I_{6c}^\pm \cos \theta_\ell + I_{2c}^\pm \cos 2\theta_\ell) \\ \frac{dF_T^\pm}{dq^2 d \cos \theta_\ell} &= \frac{1}{\mathcal{B}} \frac{d\mathcal{B}_\mathcal{T}^\pm}{dq^2 d \cos \theta_\ell} = \frac{2\pi}{\mathcal{B}} (I_{1s}^\pm + I_{6s}^\pm \cos \theta_\ell + I_{2s}^\pm \cos 2\theta_\ell) \end{aligned}$$

The longitudinal/transverse polarized forward backward asymmetry

$$\frac{dA_{FB,L}^{\pm}}{dq^2} = \left[\int_0^1 - \int_{-1}^0 \right] d\cos\theta_{\ell} \frac{d^2 F_L^{\pm}}{dq^2 d\cos\theta_{\ell}} = \frac{\pi}{\mathcal{B}} I_{6c}^{\pm}$$

$$\frac{dA_{FB,T}^{\pm}}{dq^2} = \left[\int_0^1 - \int_{-1}^0 \right] d\cos\theta_{\ell} \frac{d^2 F_T^{\pm}}{dq^2 d\cos\theta_{\ell}} = \frac{2\pi}{\mathcal{B}} I_{6s}^{\pm}$$

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 !

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

$$\mathcal{H}_{\text{eff}} \supset (\bar{u}\gamma^\mu d_A)(\bar{\ell}\gamma_\mu \mathbf{N}_L) \quad \text{or} \quad \mathcal{H}_{\text{eff}} \supset (\bar{u}\gamma^\mu d_A)(\bar{\ell}\gamma_\mu \mathbf{N}_R)$$

N_L

$$I_{6c}^-(q^2) = -2\tilde{\mathcal{N}}|C_{LL}^V - C_{RL}^V|^2 H_0^V H_t^V (K_{--}^N)^2$$

Always negative !
(and null for $m_{N_L} = 0$)

N_R

$$I_{6c}^-(q^2) = 2\tilde{\mathcal{N}}|C_{LR}^V - C_{RR}^V|^2 H_0^V H_t^V (K_{+-}^N)^2$$

Always positive !
(and non-zero for $m_{N_R} = 0$)

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

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

$$\mathcal{H}_{\text{eff}} \supset (\bar{u}\gamma^\mu d_A)(\bar{\ell}\gamma_\mu \mathbf{N}_L) \quad \text{or} \quad \mathcal{H}_{\text{eff}} \supset (\bar{u}\gamma^\mu d_A)(\bar{\ell}\gamma_\mu \mathbf{N}_R)$$

N_L

N_R

$$I_{6c}^-(q^2) = -2\tilde{\mathcal{N}}|C_{LL}^V - C_{RL}^V|^2 H_0^V H_t^V (K_{--}^N)^2$$

$$I_{6c}^-(q^2) = 2\tilde{\mathcal{N}}|C_{LR}^V - C_{RR}^V|^2 H_0^V H_t^V (K_{+-}^N)^2$$

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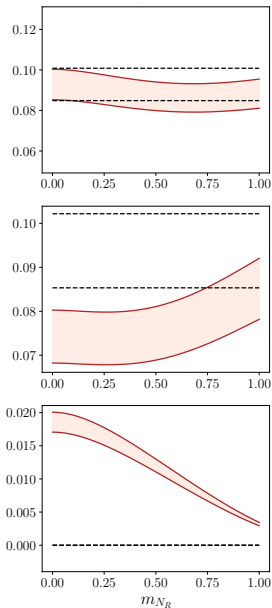
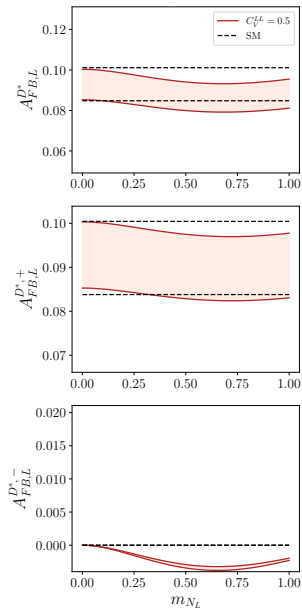
Definitions:

- $H_0^V(q^2) = \frac{m_M + m_V}{2m_V \sqrt{q^2}} \left[(m_M^2 - m_V^2 - q^2) A_1(q^2) - \frac{\lambda_V(q^2)}{(m_M + m_V)^2} A_2(q^2) \right]$
- $H_t^V(q^2) = \frac{\sqrt{\lambda_V(q^2)}}{\sqrt{q^2}} A_0(q^2)$
- $\tilde{\mathcal{N}} = \frac{3G_F^2 V_{cb}^2}{4096\pi^4} \frac{\sqrt{\lambda_{MV}} \sqrt{\lambda_{\ell X}}}{m_M^3 q^2} \mathcal{B}(V \rightarrow P\pi).$

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

$$B \rightarrow D^* \tau (\nu + N_L)$$

$$B \rightarrow D^* \tau (\nu + N_R)$$



Conclusion

- ★ Many **well motivated** BSM models involve neutral lepton fields (N_L, N_R) & 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, $\langle A_{FB,L}^- \rangle$ & $\langle A_{FB,T}^+ \rangle$ are **exactly zero** and are good probes of new physics

- [1] L. Allwicher et al. “Understanding the first measurement of $\mathcal{B}(B \rightarrow K\nu\bar{\nu})$ ”. In: *Physics Letters B* (2024).
- [2] M. B. Gavela et al. “Minimal Flavour Seesaw Models”. In: *JHEP* (2009). arXiv: 0906.1461 [hep-ph].
- [3] Damir Bečirević et al. “Right-handed interactions in puzzling B-decays”. In: *Phys. Lett. B* (2025). arXiv: 2410.23257 [hep-ph].
- [4] Damir Becirevic et al. “Angular distributions of $\bar{B} \rightarrow D^{(*)}\ell\bar{\nu}_\ell$ decays and search of New Physics”. In: *Nucl. Phys. B* (2019). arXiv: 1602.03030 [hep-ph].
- [5] Alakabha Datta et al. “ $B^- \rightarrow D^{(*)}\ell X$ ” decays in effective field theory with massive right-handed neutrinos”. In: *Phys. Rev. D* (2022). arXiv: 2204.01818 [hep-ph].

Back-up

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

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

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

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

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

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

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

contributes to B_d semileptonic decays!