PROBING THE NEUTRINO MASS 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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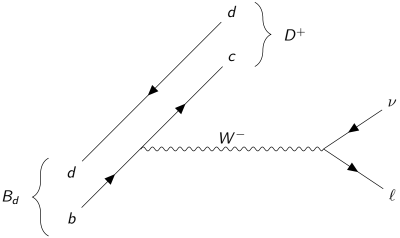
Semileptonic decays in the Standard Model

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



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

- Here, we will consider additional $b \to c\,\ell\,N$ 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 ...

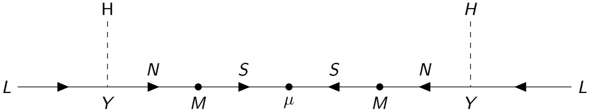
- In the Standard Model, neutrinos are **massless** but **neutrino oscillations** show that neutrinos are massive
  $\Rightarrow$ **necessity of physics beyond the Standard Model (BSM)**
- $R_K^{\nu\nu} = \frac{\mathcal{B}(B\to K\nu\bar{\nu})^{exp}}{\mathcal{B}(B\to K\nu\bar{\nu})^{SM}}$=5.4±1.5 measured 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

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]

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



- 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**

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

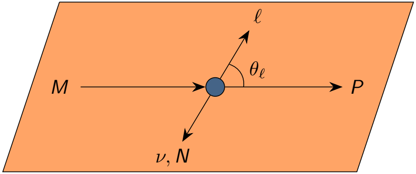
How to effectively probe the presence of N in SL decays ?

Framework

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

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

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



Usual observables

Differential branching ratio for a semileptonic decay [3]:

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

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

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**:

- $C^{S}_{L/R,L/R} = C^{T}_{L/R,L/R} = 0$
- 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 $m_{N_R} = 0$)

N_L or N_R ?

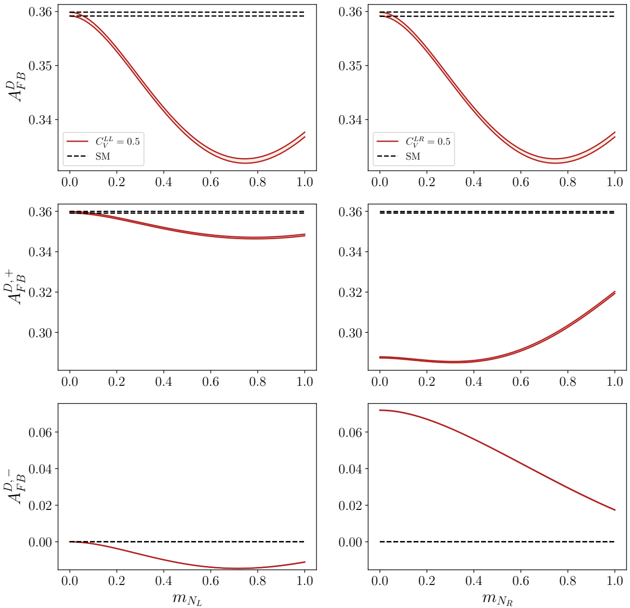
$$\mathcal{H}_{\text{eff}} \supset (\bar{u}\gamma^\mu d_A)(\bar{\ell}\gamma_\mu \mathbf{N_L}) \quad \textbf{or} \quad \mathcal{H}_{\text{eff}} \supset (\bar{u}\gamma^\mu d_A)(\bar{\ell}\gamma_\mu \mathbf{N_R})$$

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:

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

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



Conclusion

- Many **well motivated** BSM models involve neutral lepton fields (N_L, N_R) & and can impact semileptonic decays
- $A_{FB}^{\pm}$ describes the preference in direction of $\ell^{\uparrow}\downarrow$
- 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 $B \to D^*(\to D\pi)\tau N \;\Rightarrow$ similar conclusions can be drawn for 4-body semileptonic decays

References

[1] L. Allwicher et al. "Understanding the first measurement of $\mathcal{B}(B \to K\nu\bar{\nu})$". 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 Becirevic et al. "Angular distributions of $\bar{B} \to D^{(*)}\ell\bar{\nu}_\ell$ decays and search of New Physics". In: *Nucl. Phys. B* (2019). arXiv: 1602.03030 [hep-ph].

[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].

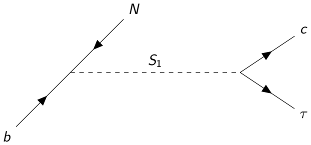
[5] Damir Bečirević et al. "Right-handed interactions in puzzling B-decays". In: *Phys. Lett. B* (2025). arXiv: 2410.23257 [hep-ph].

Back-up

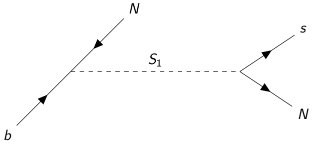
S_1 leptoquark for $R_{K^+}^{\nu\nu}$ and $R_{D^{(*)}}$

- Particle content : RH neutral lepton field N_R, S_1 $(\bar{3}, 1, -1/3)$ [5]

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



$\Rightarrow$ 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

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

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

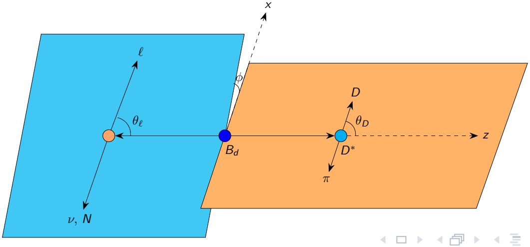
contributes to B_d semileptonic decays!

Framework

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

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

- 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 ?

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

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 $m_{N_R} = 0$)

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

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

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

Definitions:

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

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

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