Future collider sensitivities to νSMEFT interactions

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Outline

1. Motivation: SM Neutrino EFT (νSMEFT)

2. Lepton-trijet signals at LHeC

3. Lepton collider sensitivities to *N* signals

Masses in the standard model (SM)

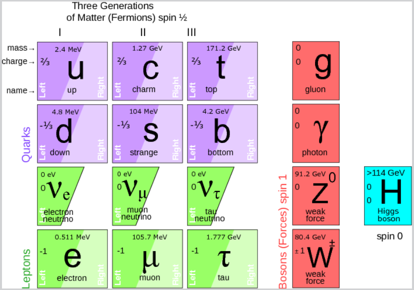
- Gauge symmetry breaking $[SU(2)_L \times U(1)_Y]_{EW} \Rightarrow U(1)_Q$

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \overset{SSB}{\Rightarrow} \langle\phi\rangle = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix}$$

- Dirac mass in Yukawa Lagrangian:

$$-\mathcal{L}_Y \supset \Gamma_\ell^{ij} \, \overline{L_L^i} \, \phi \, \ell_R^j \Rightarrow \frac{\Gamma_\ell^{ij} v}{\sqrt{2}} \overline{\ell_L^i} \, \ell_R^j$$

- Massless neutrinos $\nu_{\ell L}$...
- Lepton number is conserved...
- But it needs to be extended to include neutrino masses!



$$\ell^i = e,\ \mu,\ \tau$$

$$L_L = \begin{pmatrix} \nu_\ell \\ \ell \end{pmatrix}_L$$

$$\ell_R = \ell_R^-$$

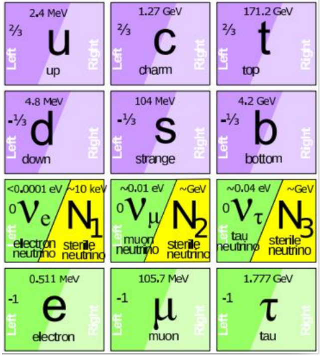
Seesaw Mechanism (Type I)

- Incorporate sterile $N_{i,R}$

$$\mathcal{L}_\nu = -\Gamma_{\ell j}\overline{L_{\ell,L}}\epsilon\tilde{\phi}^* N_{j,R} - \frac{1}{2}(N_{i,R})^T \mathcal{C} M_{ij} N_{j,R} + h.c.$$

SSB

$$\mathcal{L}_\nu = -\bar{\nu}_{\ell,L} M^D_{\ell j} N_{j,R} - \frac{1}{2}\overline{N^c_{i,R}} M^N_{ij} N_{j,R}$$



- 6 massive states: Majorana fermions
- 3 Light ν_m

$$m_\nu \sim (M^D)^2 (M^N)^{-1}$$

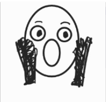
- 3 Heavy N

$$M_N \sim M^N$$

- Mixing of the active-massive states:

$$\nu_{\ell,L} = U_{\ell m}\,\nu_m + U_{\ell N}\,N$$

Heavy N undetectable



$$U_{\ell N} \lesssim 1 \times 10^{-6}\sqrt{\frac{100\ GeV}{M_N}}$$

TINY MIXINGS!

νSMEFT: Dim=6 simplified scenario [1]

what if there is something more ?

- EFT with N_R and SM fields

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_\nu + \mathcal{L}^5 + \mathcal{L}^6 + \cdots$$

} Encodes BSM physics with N_R as low-energy degree of freedom

1. Discard the mixing term in the renormalizable lagrangian:

$$\mathcal{L}_\nu \supset \Gamma_\ell \overline{L_{\ell,L}} \epsilon \tilde{\phi}^* N_R \to 0 \sim U_{\ell N} \to 0$$

2. Consider only one massive heavy N ($N \equiv N_R$) with a Majorana mass: it is a Majorana particle!
3. Only dim 5 interaction with ONE N is $\mathcal{O}^{(5)}_{N\phi} = \bar{N}_R \, N_R^c \, \phi^\dagger \phi$: reabsorb contribution to M_N in N physical mass m_N (See JHEP 09(2022)079, 2205.13550)

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d=6}^{\infty} \left(\frac{1}{\Lambda^{d-4}} \sum_{\mathcal{J}} \alpha_{\mathcal{J}} \mathcal{O}^d_{\mathcal{J}} + h.c. \right)$$

[1] F. del Aguila PLB (2009) 0806.0876, Liao PRD (2017) 1612.04527, Bhattacharya PRD (2016) 1505.05264

Dim $=6$ Operators with one heavy N [1]

Higgs dressed mixing

73 couplings counting different flavors!

$$\mathcal{O}_{LN\phi} = (\phi^\dagger \phi)(\bar{L}_i N \tilde{\phi}) \qquad (\alpha^{(i)}_{LN\phi}) \qquad \textit{SCALAR}$$

Boson currents

NC $\mathcal{O}_{NN\phi} = i(\phi^\dagger D_\mu \phi)(\bar{N}\gamma^\mu N) \quad \alpha_Z \quad (\alpha_{NN\phi})$

CC $\mathcal{O}_{Nl\phi} = i(\phi^T \epsilon D_\mu \phi)(\bar{N}\gamma^\mu l_i) \quad \alpha^{(i)}_W \quad (\alpha^{(i)}_{Nl\phi}) \quad \textit{VECTORIAL}$

4-fermions $(4-f)$

CC $\mathcal{O}_{duNl} = (\bar{d}_j \gamma^\mu u_j)(\bar{N}\gamma_\mu l_i) \quad \alpha^{(i,j)}_{duNl}$

BOTH:

$\mathcal{O}_{fNN} = (\bar{f}_i \gamma^\mu f_i)(\bar{N}\gamma_\mu N) \quad \alpha^{(i)}_{fNN} \quad f = u, d, l, Q, L$

$\mathcal{O}_{QuNL} = (\bar{Q}_i u_i)(\bar{N} L_j)\ \alpha^{(i,j)}_{QuNl}, \quad \mathcal{O}_{QNLd} = (\bar{Q}_i N)\epsilon(\bar{L}_j d_j)\ \alpha^{(i,j)}_{QNLd}$

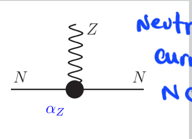
$\mathcal{O}_{LNQd} = (\bar{L}_i N)\epsilon(\bar{Q}_j d_j)\ \alpha^{(i,j)}_{LNQd}, \quad \mathcal{O}_{LNLl} = (\bar{L}_i N)\epsilon(\bar{L}_j l_j)\ \alpha^{(i,j)}_{LNLl}$

1-loop generated $(1-loop)$

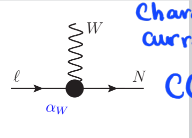
$$\alpha^{1-loop} = \frac{\alpha^{tree}}{16\pi^2}$$

$\mathcal{O}_{NB} = (\bar{L}_i \sigma^{\mu\nu} N)\tilde{\phi} B_{\mu\nu} \quad \alpha^{(i)}_{NB}$

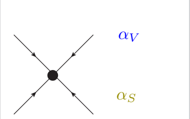
$\mathcal{O}_{NW} = (\bar{L}_i \sigma^{\mu\nu} \tau^I N)\tilde{\phi} W^I_{\mu\nu} \quad \alpha^{(i)}_{NW} \cdots \qquad \textit{TENSORIAL}$

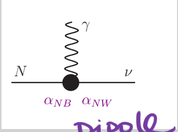


Neutral current NC



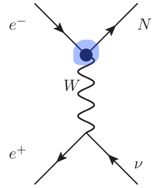
Charged current CC



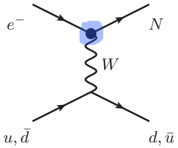


Dipole

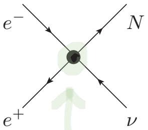
Dim$=6$ Operators with one heavy N [1]



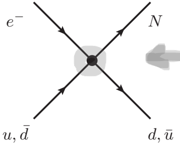
$\mathcal{O}_{Ne\phi}$



$\mathcal{O}_{LNLe}$



$\mathcal{O}_{duNe},\ \mathcal{O}_{QuNL},\ \mathcal{O}_{LNQd},\ \mathcal{O}_{QNLd}$



Tree-level generated :

- $\mathcal{O}^{i}_{Nl\phi} = i(\phi^T \epsilon D_\mu \phi)(\overline{N}\gamma^\mu l_i)$

$$\mathcal{O}^{i,j}_{duNl} = (\overline{d}_j \gamma^\mu u_j)(\overline{N}\gamma_\mu l_i)$$

$$\mathcal{O}^{i,j}_{LNQd} = (\overline{L}_i N)\epsilon(\overline{Q}_j d_j)$$

$$\mathcal{O}^{i,j}_{QuNL} = (\overline{Q}_i u_i)(\overline{N} L_j)$$

$$\mathcal{O}^{i,j}_{QNLd} = (\overline{Q}_i N)\epsilon(\overline{L}_j d_j)$$

$$\mathcal{O}^{i,j}_{LNLl} = (\overline{L}_i N)\epsilon(\overline{L}_j l_j)$$

[1] F. del Aguila PLB (2009) 0806.0876, Liao PRD (2017) 1612.04527, Bhattacharya PRD (2016) 1505.05264

Bounds on the couplings $\alpha_{\mathcal{J}}^{(i)}$ (νSMEFT)

• Effective CC

$$\mathcal{L}^{d=6}_{Nl\phi} \supset \frac{-v m_W}{\sqrt{2}} \frac{\alpha_W^{(i)}}{\Lambda^2} \bar{l}_i \gamma^\mu P_R N W^-_\mu$$

$$\mathcal{L}^{d=4}_{\nu} \supset \frac{-g}{\sqrt{2}} U_{l_i N} \bar{l}_i \gamma^\mu P_L N W^-_\mu$$

• seesaw CC

$$g = \frac{2 m_W}{v}$$

$$U_{l_i N} \simeq \frac{\alpha^{(i)} v^2}{2\Lambda^2}$$

Translate existing bounds on seesaw mixings!

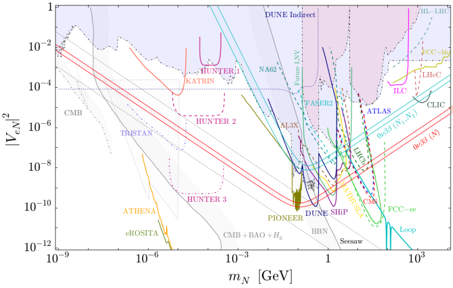
- $\alpha^{bound}_{0\nu\beta\beta} \lesssim 3.2 \times 10^{-2} \left(\frac{m_N}{100 GeV}\right)^{1/2}$

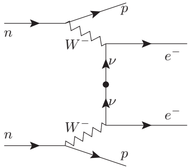
On first family operators

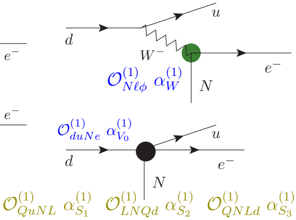
- Neutrinoless double beta decay:

  KamLAND-Zen $\tau_{0\nu\beta\beta} \geq 1.1 \times 10^{26} yr$

[*] FIPs Antel et. al. 2305.01715, EPJC (2023)







[**] Also see Fernández-Martínez 2304.06772, JHEP(2023) and R.Beltrán 2302.03216, JHEP (2023)

Our agnostic benchmark: every operator ON

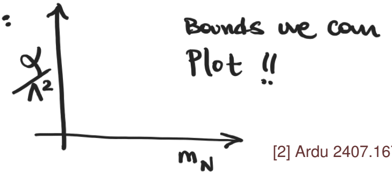
Why??

- ...Different operators mix under renormalization between scales [2]
- Allow N production and decay to depend on different physics

We consider

- Operators contributing to $0\nu\beta\beta-$decay (first family) set to $\alpha^{bound}_{0\nu\beta\beta} \lesssim 3.2 \times 10^{-2} \left(\frac{m_N}{100 GeV}\right)^{1/2}$
- Every other operator set to the same numerical value α: mostly second and third families flavors...
- Scan on m_N and α values:

$$\mathcal{L}^{d=6} = \frac{\alpha_J}{\Lambda^2} \mathcal{O}_J \rightarrow$$



[2] Ardu 2407.16751, JHEP (2024)

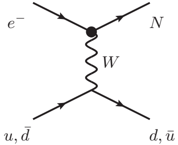
Lepton-trijet signals at the LHeC [3]

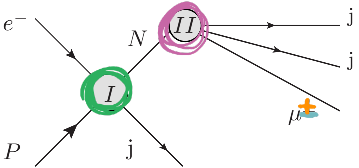
- Lepton Flavor violation: $pe^- \to \mathrm{j}N \to \mathrm{j}\ \mu^-\mathrm{jj}$
- Lepton Number violation: $pe^- \to \mathrm{j}N \to \mathrm{j}\ \mu^+\mathrm{jj}$

(and flavor)

(I)

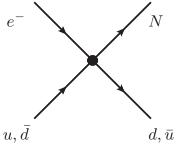
$\mathcal{O}_{Ne\phi}$

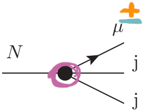


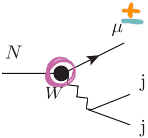


N production affected by 0νββ-decay bound

$\mathcal{O}_{duNe},\ \mathcal{O}_{QuNL},\ \mathcal{O}_{LNQd},\ \mathcal{O}_{QNLd}$





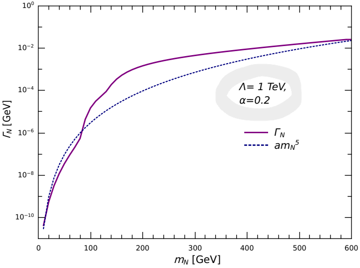


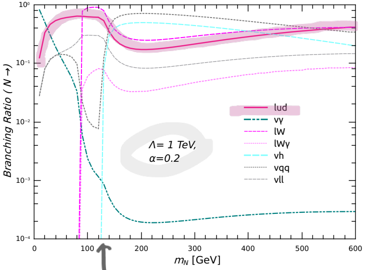
N decay to muons is less constrained

[3] G. Zapata, T.Urruzola, O.A. Sampayo, L. Duarte 2305.16991, EPJC (2024)

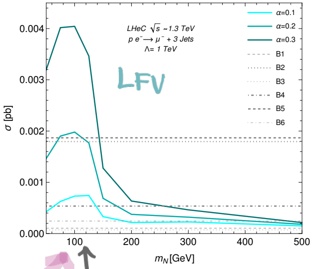
Lepton-trijet signals at the LHeC [3]

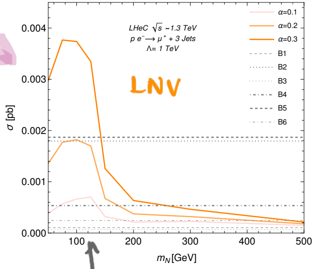
[4] N decays: L.Duarte 1603.08052, EPJC (2016)





N →μjj



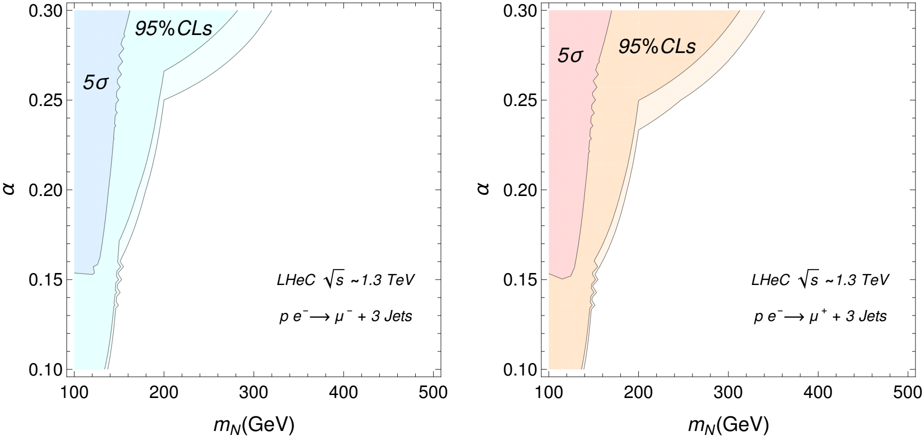


[3] G. Zapata, T. Urruzola, O.A. Sampayo, L. Duarte, 2305.16991, EPJC (2024)

νSMEFT Sensitivity prospects for LHeC: [3]

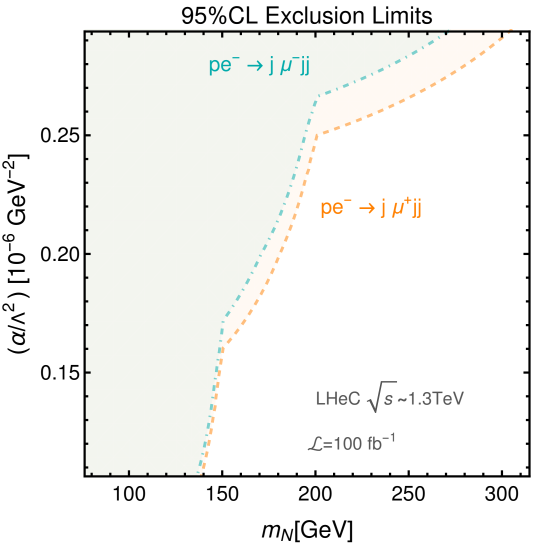
5σ-Discovery and 95% CLs limits at the LHeC: $\mathcal{L} = 100\ \mathrm{fb}^{-1}$ ($\Lambda = 1$ TeV) from lepton-trijet signals. (BDT analysis)

Bounds affect (mostly) to 2nd. family couplings



[3] G. Zapata, T. Urruzola, O.A. Sampayo, L. Duarte 2305.16991, EPJC (2024)

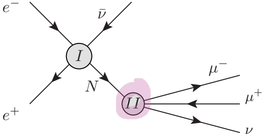
νSMEFT Sensitivity prospects for LHeC: [3]

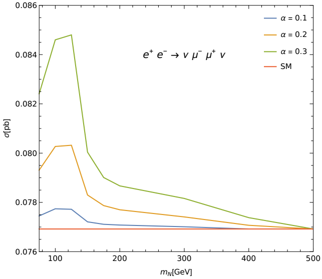


[3] G. Zapata, T.Urruzola, O.A. Sampayo, L. Duarte 2305.16991, EPJC (2024)

Lepton collider νSMEFT sensitivity prospects [4] Work in progress

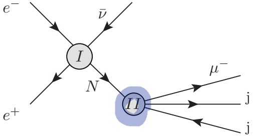
- Single N production and leptonic decay
- $e^+e^- \rightarrow \nu\mu^+\mu^-\nu$

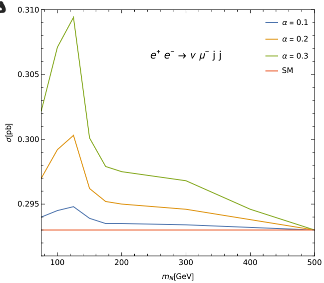




Much bigger cross section →

- Single N production and semi-leptonic decay
- $e^+e^- \rightarrow \nu\mu^-$jj

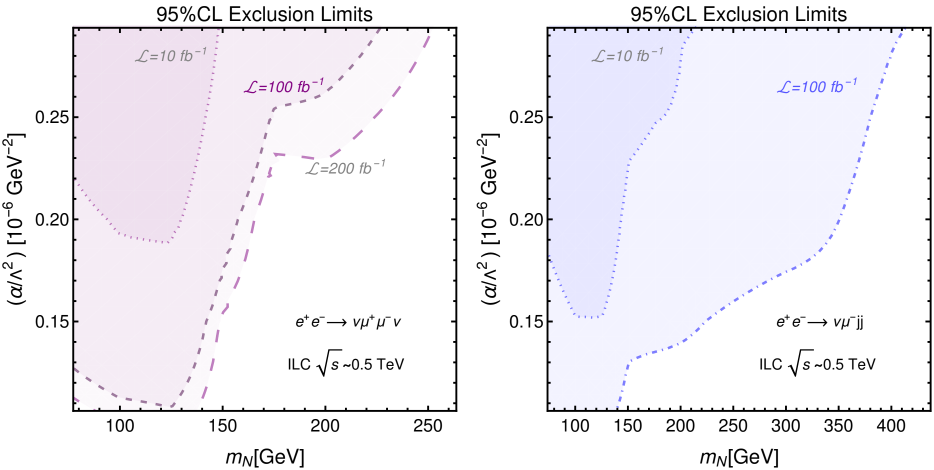




[4] L. Duarte, D. Chalencon, T. Urruzola 25XX.XXXXX: Work in progress

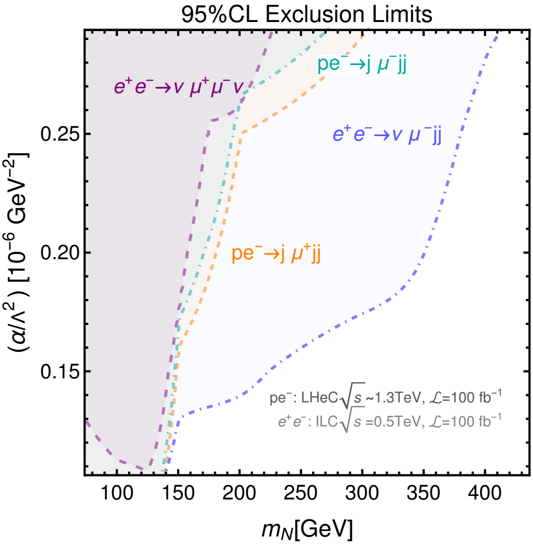
Lepton collider νSMEFT sensitivity prospects [4] Work in progress

Exclusion limits at the ILC: cut based analysis we already proposed in [5]



[5] G. Zapata, T. Urruzola, O.Sampayo and L. Duarte, 2201.02480, EPJC (2022)

Future collider νSMEFT sensitivity prospects [4] Work in progress



[4] L. Duarte, D. Chalencon, T. Urruzola 25XX.XXXXX: Work in progress

Take home message

- νSMEFT: model independent info on new physics contributions to heavy N (HNL) phenomenology (beyond seesaw mixing!)
- 95% CLs exclusion limits in $\mathcal{O}(EW)$ $m_N - \alpha$ plane show future LHeC and ILC (or FCC-ee) could constrain the effective couplings (muon family) to a region as tight as the bounds that are currently considered for $m_N \lesssim \mathcal{O}(10)$ GeV

  (See Fernández-Martínez 2304.06772, JHEP(2023) and R.Beltrán 2302.03216, JHEP (2023))
- Lots of parameter space to be explored yet!

¡Thanks for your attention!

Curiosity? lucia.duarte@fcien.edu.uy

νSMEFT: (Backup)

- EFT with N_R^i and SM fields

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_\nu + \mathcal{L}^5 + \mathcal{L}^6 + \cdots$$

- Non-renormalizable operators (dim > 5) [1]:

$$\mathcal{O}_W^{(5)} = \sum_{\ell\ell'} \frac{(\alpha_W)_{\ell\ell'}}{\Lambda} \bar{L}_{\ell,L} \; \tilde{\phi}^* \; \tilde{\phi}^\dagger \; L_{\ell',L} + h.c. \quad (\mathcal{O}_{LH})$$

Weinberg operator
ν_L Majorana mass

$$\mathcal{O}_{N\phi}^{(5)} = \sum_{ij} \frac{(\alpha_{N\phi})_{ij}}{\Lambda} \bar{N}_{i,R} \, N_{j,R}^c \, \phi^\dagger \phi + h.c. \quad (\mathcal{O}_{NNH})$$

N_R Majorana mass
+

$$\mathcal{O}_{NB}^{(5)} = \sum_{i \neq j} \frac{(\alpha_{NB})_{ij}}{\Lambda} \bar{N}_{i,R} \, \sigma_{\mu\nu} \, N_{j,R}^c \, B^{\mu\nu} + h.c. \quad (\mathcal{O}_{NNB})$$

N dipole Coupling

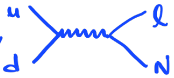
[*] See: Graesser PRD(2007) 0704.0438, Aparici (PRD 2009) 0904.3244 and Caputo (JHEP 2017) 1704.08721,

See Joel Jones's talk! Delgado JHEP 09(2022)079, 2205.13550 + 2311.17989 JHEP(2024)

Dim= 6 operators: renormalizable UV-realizations

$$\begin{aligned}\mathcal{L}^{tree} \supset \frac{1}{\Lambda^2}\sum_{i,j}\Big\{ & -\alpha_W^{(i)}\frac{v\,m_W}{\sqrt{2}}\,\bar{l}_i\gamma^\nu P_R N\, W^-_\mu \\
+ \; & \alpha_{duNl}^{(i,j)}\,(\bar{u}_j\gamma^\nu P_R d_j\; \bar{l}_i\gamma_\nu P_R N) \\
+ \; & \alpha_{LNLl}^{(i,j)}(\bar\nu_i P_R N\; \bar l_j P_R l_j - \bar\nu_j P_R l_j\; \bar l_i P_R N) \\
+ \; & \alpha_{QuNL}^{(i,j)}\,(\bar u_j P_L d_j\; \bar l_i P_R N + \bar u_j P_L u_j\; \bar\nu_i P_R N) \\
+ \; & \alpha_{LNQd}^{(i,j)}\,(\bar d_j P_R d_j\; \bar\nu_i P_R N - \bar u_j P_R d_j\; \bar l_i P_R N) \\
+ \; & \alpha_{QNLd}^{(i,j)}\,(\bar u_i P_R N\; \bar l_j P_R d_j - \bar d_i P_R N\; \bar\nu_j P_R d_j) \\
+ \; & \text{h.c.}\Big\}\end{aligned}$$

UV- mediator :



Charged vector

Charged and Neutral SCALARS

SCALAR LEPTOQUARKS

- A renormalizable UV-completion is needed for Majorana N 4f vertices to work in MadGraph5

See also: G.Zapata Eur.Phys.J.C 82(2022)6, 2201.02480 and G. Cottin JHEP 09(2021)039, 2105.13851