Models of Radiative Linear Seesaw with Electrically Charged Mediators

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The flavour structure of SM

- In the SM, three families of fermions groups in doublets of $SU(2)_L$:

$$Q_{Lj} = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} c_L \\ s_L \end{pmatrix}, \begin{pmatrix} t_L \\ b_L \end{pmatrix}$$
$$l_{jL} = \begin{pmatrix} e_L \\ \nu_e \end{pmatrix}, \begin{pmatrix} \mu_L \\ \nu_\mu \end{pmatrix}, \begin{pmatrix} \tau_L \\ \nu_\tau \end{pmatrix}$$

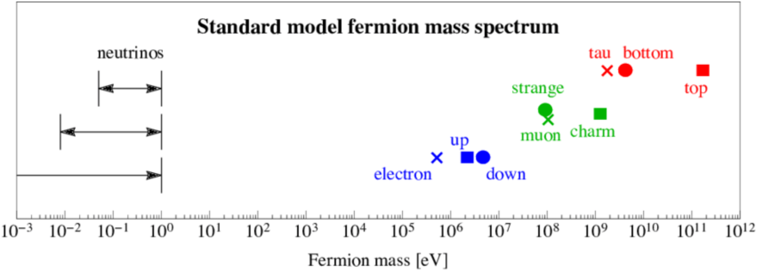
- Right-handed quarks and leptons are $SU(2)_L$ singlets.

The flavour structure of SM

- After EWSB, Yukawa couplings would give mass to fermions:

$$Y_{ij}\overline{\Psi}_{iL}H\Psi_{jR}$$

- But the masses have strong hierarchy!! $m_1 < m_2 < m_3$.
- And neutrinos are only left-handed!!



Ref. arXiv:2206.13449

Seesaw mechanism

New particle content $\longrightarrow$ new neutrino mass matrix:

$$\begin{pmatrix} \overline{\nu}_L & \overline{\nu}^c_R \end{pmatrix} \begin{pmatrix} 0 & m^D \\ (m^D)^T & M_R \end{pmatrix} \begin{pmatrix} \nu^c_L \\ \nu_R \end{pmatrix}$$

This neutrino mass matrix can be diagonalized as follows (assuming $M_R >> m^D$):

$$m^\nu = -m^D M_R^{-1} (m^D)^T$$

where m^ν is the light active neutrino mass matrix.

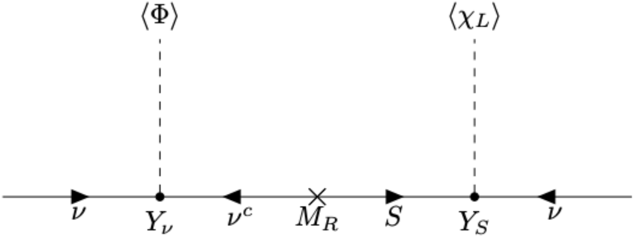
Seesaw mechanism main feature

The effective left-handed Majorana mass m^ν is naturally suppressed by the heavy scale of M_R, this is the main feature of *seesaw* mechanism, as M_R grow up m^ν decrease.

Tree and loop seesaw models

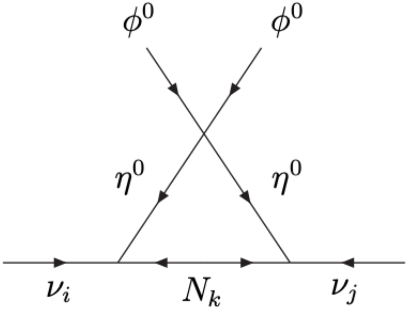
Tree level realisation of a linear seesaw model

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D & M_L \\ m_D^T & 0 & M_R \\ M_L^T & M_R^T & 0 \end{pmatrix}$$



Ref. arXiv:2305.00994

1 loop radiative seesaw mechanism (Scotogenic Model)



$$(\mathcal{M}_\nu)_{ij} = \sum_k \frac{h_{ik} h_{jk} M_k}{16\pi^2} \left[\frac{m_R^2}{m_R^2 - M_k^2} \ln \frac{m_R^2}{M_k^2} - \frac{m_I^2}{m_I^2 - M_k^2} \ln \frac{m_I^2}{M_k^2} \right]$$

Ref. arXiv:hep-ph/0601225

Models of Radiative Linear Seesaw with Electrically Charged Mediators

We propose a model with radiative linear seesaw. In the basis $\left(\nu_L, \nu_R^C, N_R^C\right)$, the neutrino mass matrix is:

$$M_\nu = \begin{pmatrix} 0_{3\times3} & \varepsilon & m \\ \varepsilon^T & 0_{2\times2} & M \\ m^T & M^T & 0_{2\times2} \end{pmatrix},$$

- The Lepton numbers of neutral fields are $L(\nu_L) = L(\nu_R) = -L(N_r) = 1$
- ε is a small submatrix in two realizations: 1-loop (Model 1) and 2-loop (Model 2).

Models of Radiative Linear Seesaw with Electrically Charged Mediators: **Particle content**

- Model 1 and 2 have two $SU(2)_L$ doublet:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad \eta = \begin{pmatrix} \eta^+ \\ \eta^0 \end{pmatrix}$$

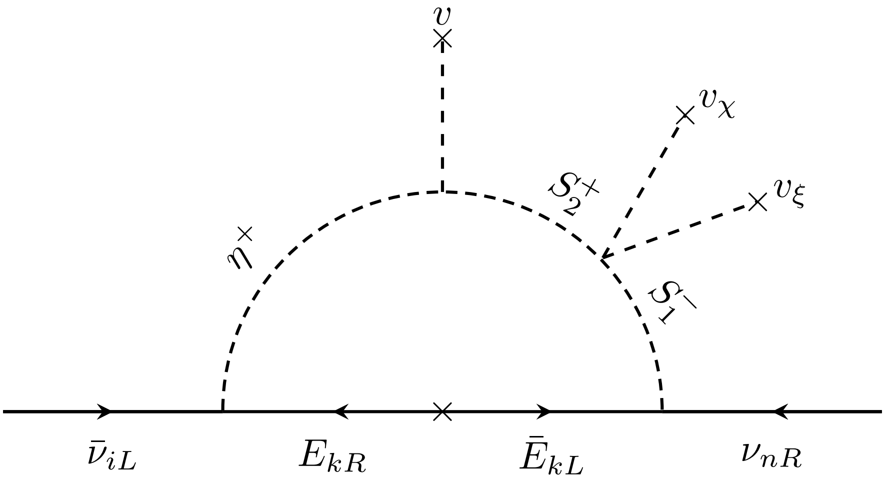
- Singlet scalars ρ, ξ, χ, $S_1^{\pm}$ and $S_2^{\pm}$
- Model 2 have new $SU(2)_L$ singlet scalar σ
- Vector-like leptons E_i $(i = 1,2,3)$

Models of Radiative Linear Seesaw with Electrically Charged Mediators: **Model 1**

$$
\begin{gathered}
SU(3)_C \times SU(2)_L \times U(1)_Y \times Z_2 \times Z_4 \\
\Downarrow v_\xi, v_\chi \\
SU(3)_C \times SU(2)_L \times U(1)_Y \times \widetilde{Z}_2 \\
\Downarrow v \\
SU(3)_C \times U(1)_{\text{em}} \times \widetilde{Z}_2
\end{gathered}
$$

- $SU(2)_L$ singlet scalars ξ and χ breaks $Z_2 \times Z_4$
- v is the usual EWSB vev
- $\widetilde{Z}_2$ is preserved

Models of Radiative Linear Seesaw with Electrically Charged Mediators: **Model 1**

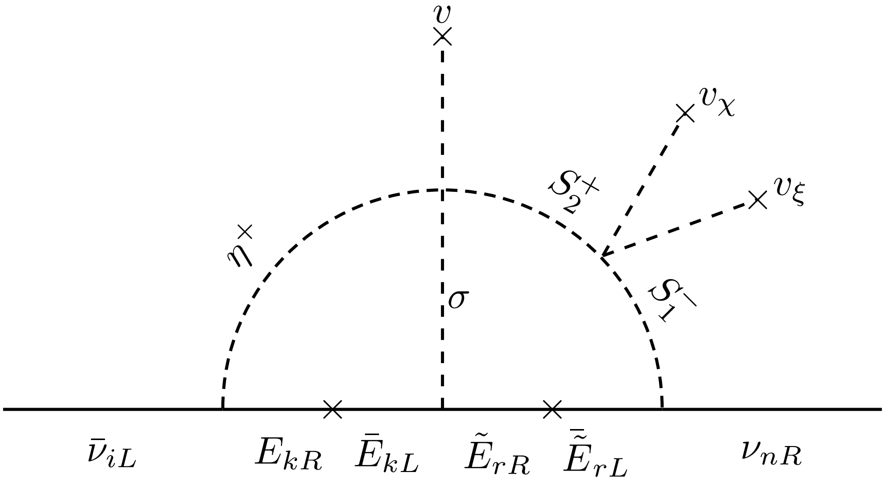


Models of Radiative Linear Seesaw with Electrically Charged Mediators: **Model 2**

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times Z_2^{(1)} \times Z_2^{(2)} \times Z_4$$
$$\Downarrow v_\xi, v_\chi$$
$$SU(3)_C \times SU(2)_L \times U(1)_Y \times Z_2^{(2)} \times \widetilde{Z}_2$$
$$\Downarrow v$$
$$SU(3)_C \times U(1)_{em} \times Z_2^{(2)} \times \widetilde{Z}_2$$

- $SU(2)_L$ singlet scalars ξ and χ breaks $Z_2 \times Z_4$
- v is the usual EWSB vev
- $Z_2^{(2)} \times \widetilde{Z}_2$ is preserved

Models of Radiative Linear Seesaw with Electrically Charged Mediators: **Model 2**

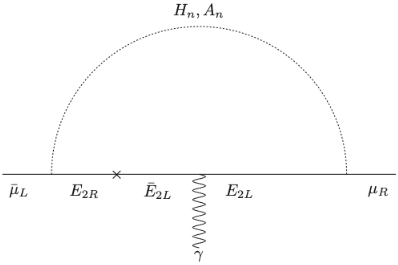


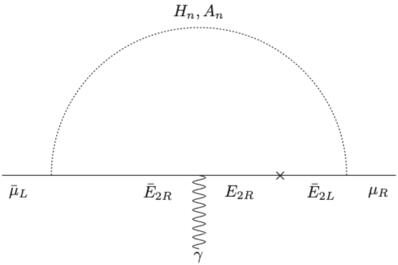
Models of Radiative Linear Seesaw with Electrically Charged Mediators: **Neutrino masses**

$$m_\nu \sim \begin{cases} \dfrac{\lambda y^3 v^2 \tilde{f} m_E}{16\pi^2 m_S^2 M} & \text{for the one loop model} \\ \\ \dfrac{\lambda^2 y^4 v^2 m_E^2}{256\pi^4 m_S^2 M} & \text{for the two loop model.} \end{cases}$$

- Model 1: $M \sim \mathcal{O}(10^3)$ TeV $\to m_\nu \sim 50$ meV
- Model 2: $M \sim \mathcal{O}(1)$ TeV $\to m_\nu \sim 50$ meV

Models of Radiative Linear Seesaw with Electrically Charged Mediators: **muon g-2 anomaly contribution**





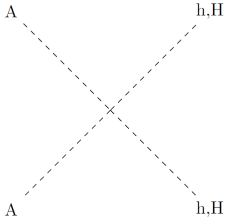
$m_{H_1} \approx 10164{,}1\,\text{GeV}$ $\quad m_{H_2} \approx 3782{,}1\,\text{GeV}$ $\quad m_{A_1} \approx 5860{,}1\,\text{GeV}$

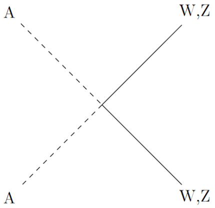
$m_{A_2} \approx 3781{,}9\,\text{GeV}$ $\quad m_{E_2} \approx 625\,\text{GeV}$

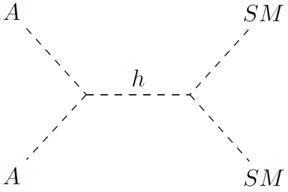
$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (2{,}49 \pm 0{,}48) \times 10^{-9}$$

Models of Radiative Linear Seesaw with Electrically Charged Mediators: **Dark Matter**

- Scalar Dark Matter scenario
- CP-odd physical state from ρ and η mixing.

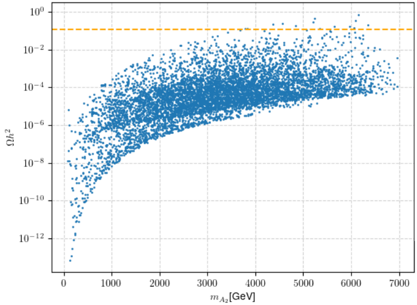


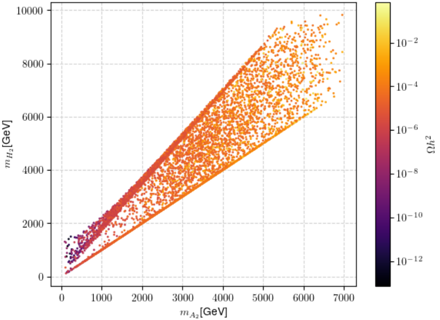




Models of Radiative Linear Seesaw with Electrically Charged Mediators: **Dark Matter**

- Scalar spectrum H_2 and A_2 nearly degenerate.

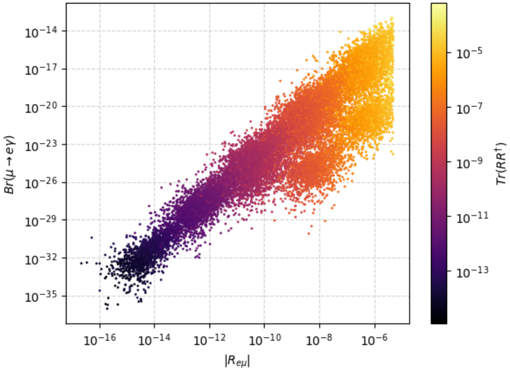


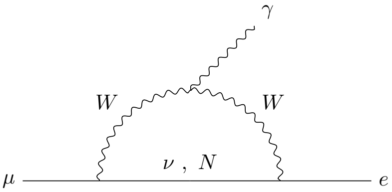


- DM reach relic abundance limit

Models of Radiative Linear Seesaw with Electrically Charged Mediators: **cLFV:** $\mu \to e\gamma$

- $\mu \to e\gamma$ contributions with ν and N in internal line.
- The model fits $Br(\mu \to e\gamma)$ limit.





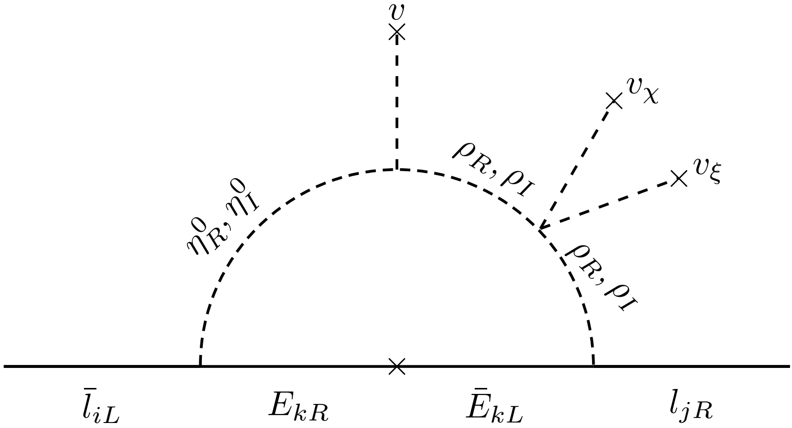
- $R = \dfrac{1}{\sqrt{2}} m M^{-1}$

Models of Radiative Linear Seesaw with Electrically Charged Mediators: **Summary**

- Radiative linear seesaw $\rightarrow$ dirac submatrix at one and two loop level
- Electrically charged mediators
- $\widetilde{Z}_2$ preserved guarantees DM stability
- Successfully comply constraints $\rightarrow (g-2)_\mu$, Ωh^2, cLFV

This presentation is based in "Models of Radiative Linear Seesaw With Electrically Charged Mediators", in collaboration with A. E. Cárcamo Hernández, Yocelyne Hidalgo Velásquez, Sergey Kovalenko and Iván Schmidt.

Models of Radiative Linear Seesaw with Electrically Charged Mediators: **Charged leptons mass matrix**



Models of Radiative Linear Seesaw with Electrically Charged Mediators: **Charged leptons mass matrix**

$$(M_l)_{ij} = \sum_{k=1}^{3} \frac{y_{ik}^{(E)} x_{kj}^{(l)} m_{E_k}}{16\pi^2} \left\{ \left[F\left(m_{H_1}^2, m_{E_k}^2\right) - F\left(m_{H_2}^2, m_{E_k}^2\right) \right] \sin 2\theta_H - \left[F\left(m_{A_1}^2, m_{E_k}^2\right) - F\left(m_{A_2}^2, m_{E_k}^2\right) \right] \sin 2\theta_A \right\},$$

where $F\left(m_1^2, m_2^2\right)$ is the function defined as,

$$F\left(m_1^2, m_2^2\right) = \frac{m_1^2}{m_1^2 - m_2^2} \ln\left(\frac{m_1^2}{m_2^2}\right).$$

m_{H_1} and m_{H_2} are the masses of the physical CP even inert scalars, whereas m_{A_1} and m_{A_2} are those of the inert pseudoscalars.

Models of Radiative Linear Seesaw with Electrically Charged Mediators: **Charged leptons mass matrix**

The SM charged lepton mass matrix can be parametrized as follows:

$$M_l = A_l J_E^{-1} B_l^T, \qquad J_E = \begin{pmatrix} \frac{1}{16\pi^2} m_{E_1} K_E^{(1)} & 0 & 0 \\ 0 & \frac{1}{16\pi^2} m_{E_2} K_E^{(2)} & 0 \\ 0 & 0 & \frac{1}{16\pi^2} m_{E_3} K_E^{(3)} \end{pmatrix}$$

where:

$$\begin{aligned} K_E^{(n)} &= \left[F\left(m_{H_1}^2, m_{E_n}^2\right) - F\left(m_{H_2}^2, m_{E_n}^2\right)\right]\sin 2\theta_H \\ &\quad - \left[F\left(m_{A_1}^2, m_{E_n}^2\right) - F\left(m_{A_2}^2, m_{E_n}^2\right)\right]\sin 2\theta_A, \qquad n = 1,2,3 \\ A_l &= V_L^{(l)} \widetilde{M}_l^{\frac{1}{2}} J_E^{\frac{1}{2}}, \qquad B_l = V_R^{(l)} \widetilde{M}_l^{\frac{1}{2}} J_E^{\frac{1}{2}}, \qquad \widetilde{M}_l = \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix} \end{aligned}$$

Models of Radiative Linear Seesaw with Electrically Charged Mediators: **Leptogenesis**

- M is diagonal and $|M_{11}| << |M_{22}|$
- Leptogenesis is dominated by $N_{\pm}$

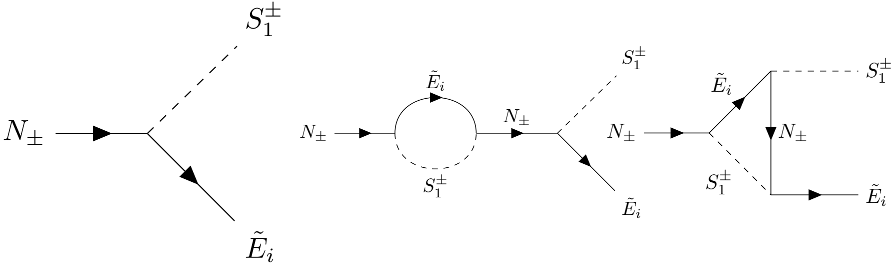
$$K^{eff} \simeq \left(K_{N^+} \delta_+^2 + K_{N^-} \delta_-^2 \right),$$

where:

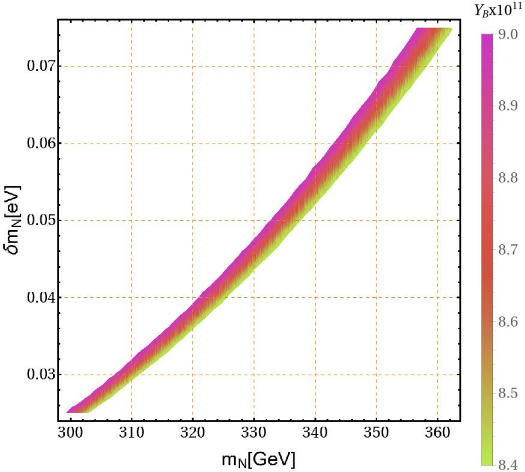
$$\delta_{\pm} = \frac{m_{N^+} - m_{N^-}}{\Gamma_{N^{\pm}}}, \qquad K_{N^{\pm}} = \frac{\Gamma_{\pm}}{H(T)}, \qquad H(T) = \sqrt{\frac{4\pi^3 g^*}{45}} \frac{T^2}{M_P}$$

$$\begin{aligned}
Y_{\Delta B} &= \frac{n_B - \overline{n}_B}{s} = -\frac{28}{79} \frac{\epsilon_+ + \epsilon_-}{g^*}, \qquad \text{for} \qquad K^{eff} \ll 1, \\
Y_{\Delta B} &= \frac{n_B - \overline{n}_B}{s} = -\frac{28}{79} \frac{0,3\left(\epsilon_+ + \epsilon_-\right)}{g^* K^{eff} \left(\ln K^{eff}\right)^{0,6}}, \qquad \text{for} \qquad K^{eff} \gg 1,
\end{aligned}$$

Models of Radiative Linear Seesaw with Electrically Charged Mediators: **Leptogenesis**



Models of Radiative Linear Seesaw with Electrically Charged Mediators: **Leptogenesis**



Models of Radiative Linear Seesaw with Electrically Charged Mediators: **cLFV:** $\mu \to e\gamma$

$$
\begin{aligned}
\mathrm{BR}\left(l_i \to l_j \gamma\right) &= \frac{\alpha_W^3 s_W^2 m_{l_i}^5}{256\pi^2 m_W^4 \Gamma_i} \left|G_{ij}\right|^2 \\
G_{ij} &\simeq \sum_{k=1}^{3} \left(\left[\left(1 - RR^\dagger\right) U_\nu\right]^*\right)_{ik} \left(\left(1 - RR^\dagger\right) U_\nu\right)_{jk} G_\gamma\left(\frac{m_{\nu_k}^2}{m_W^2}\right) \\
&\quad + 2\sum_{l=1}^{2} (R^*)_{il} (R)_{jl} G_\gamma\left(\frac{m_{N_{R_l}}^2}{m_W^2}\right), \\
G_\gamma(x) &= \frac{10 - 43x + 78x^2 - 49x^3 + 18x^3 \ln x + 4x^4}{12(1-x)^4},
\end{aligned}
$$

where

$$
R = \frac{1}{\sqrt{2}} m M^{-1},
$$