

Radiative inverse and linear seesaw models

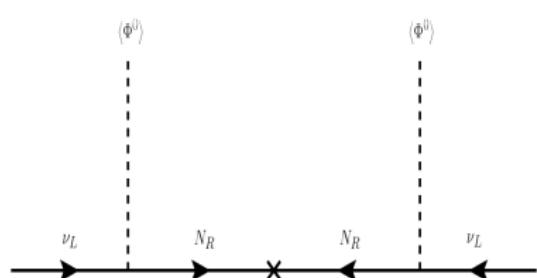
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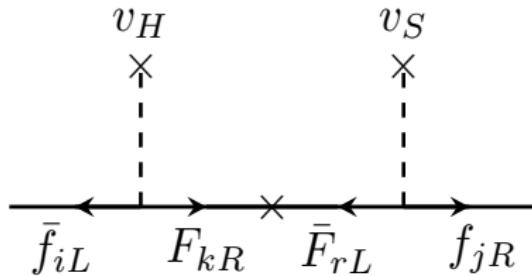
SUSY 2023 Conference, 17-07-2023.

Based on: C. Bonilla, AECH, S. Kovalenko, H. Lee, R. Pasechnik and
I. Schmidt, arxiv:hep-ph/2305.11967
AECH, V. K. N. and J. W. F. Valle, arxiv:hep-ph/2305.02273

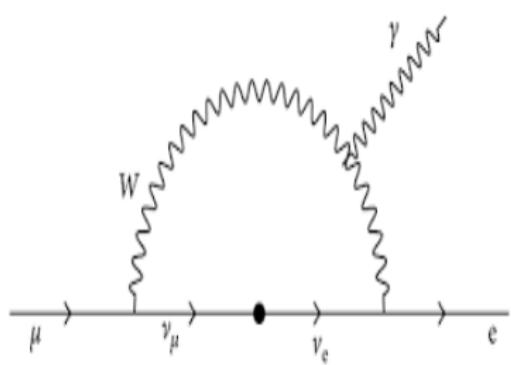
Introduction



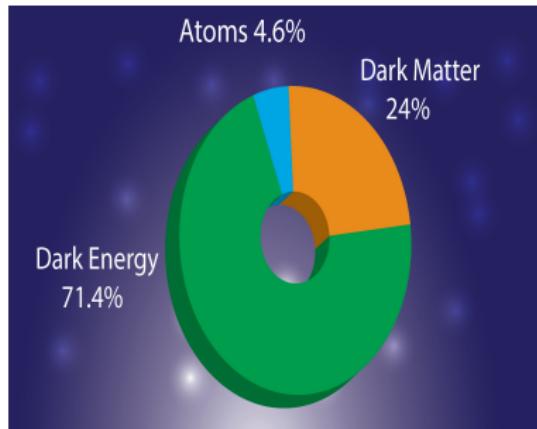
Type I seesaw mechanism

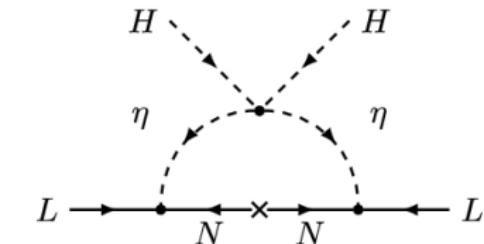
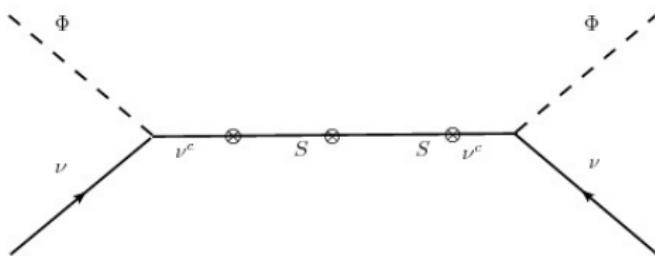


Universal seesaw mechanism



$$Br_{SM}(\mu \rightarrow e\gamma) \sim \mathcal{O}(10^{-54}), \quad Br_{exp}(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$$





Inverse seesaw

$$-\mathcal{L}_{\text{mass}}^{(\nu)} = \frac{1}{2} \begin{pmatrix} \overline{\nu_L} & \overline{N_R} & \overline{S_R} \end{pmatrix} \mathbf{M}_\nu \begin{pmatrix} \nu_L \\ N_R^C \\ S_R^C \end{pmatrix} + \text{H.c}$$

$$\mathbf{M}_\nu = \begin{pmatrix} 0_{3 \times 3} & \mathbf{M}_1 & \mathbf{M}_L \\ \mathbf{M}_1^T & 0_{3 \times 3} & \mathbf{M}_2 \\ \mathbf{M}_L^T & \mathbf{M}_2^T & \mu \end{pmatrix}$$

$$\mathbf{M}_L = 0_{3 \times 3}, \quad \mu_{ij} \ll (M_1)_{ij} \ll (M_2)_{ij}$$

$$Q_{\nu_L}^{U(1)_L} = Q_{S_R}^{U(1)_L} = -Q_{N_R}^{U(1)_L} = 1$$

$$\tilde{\mathbf{M}}_\nu = \mathbf{M}_1 (\mathbf{M}_2^T)^{-1} \mu \mathbf{M}_2^{-1} \mathbf{M}_1^T$$

$$\mathbf{M}_\nu^{(1)} = -\frac{1}{2} (\mathbf{M}_2 + \mathbf{M}_2^T) + \frac{1}{2} \mu$$

$$\mathbf{M}_\nu^{(2)} = \frac{1}{2} (\mathbf{M}_2 + \mathbf{M}_2^T) + \frac{1}{2} \mu$$

One loop Ma radiative seesaw model

η and N are odd under a preserved Z_2

$$L \tilde{\eta} N, \frac{\lambda_5}{2} (H^\dagger \cdot \eta)^2 + \text{h.c}$$



Linear seesaw:

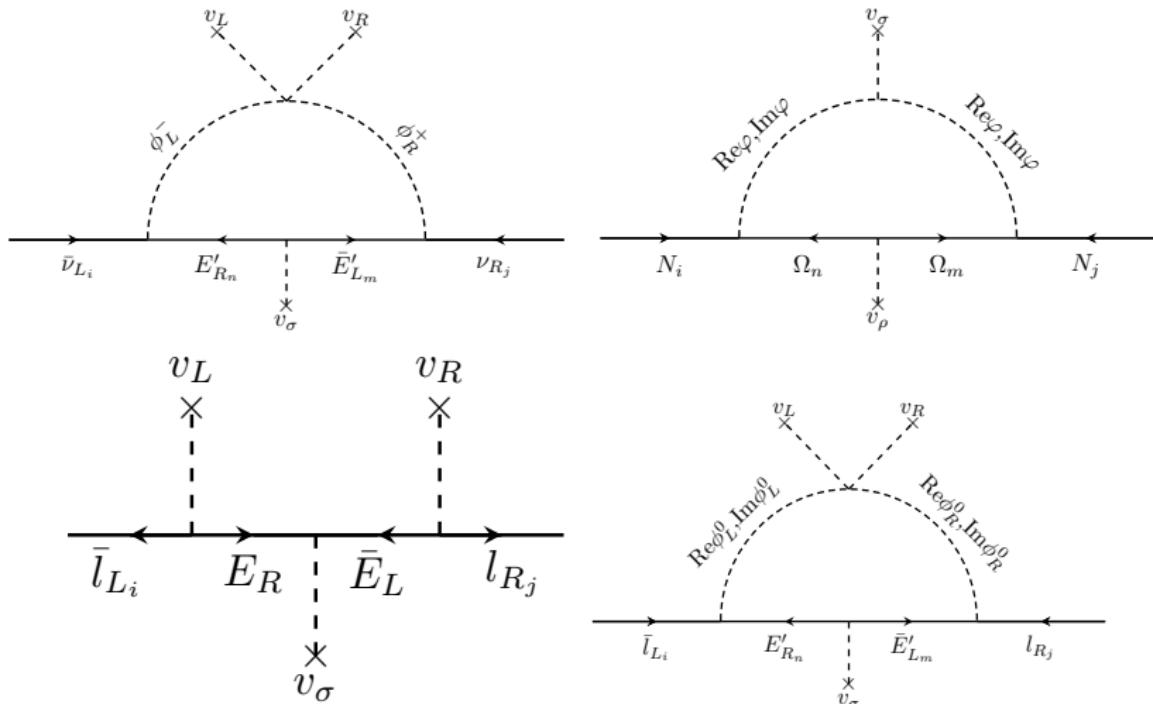
$$\mu = 0_{3 \times 3}$$

$$\tilde{\mathbf{M}}_\nu = -\mathbf{M}_L \mathbf{M}_2^{-1} \mathbf{M}_1^T - \mathbf{M}_1 (\mathbf{M}_2^T)^{-1} \mathbf{M}_L^T$$

An extended left-right symmetric model.

Model based on $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times U(1)_X$ with:

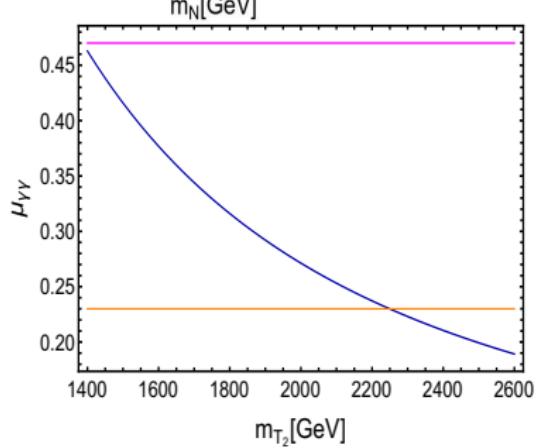
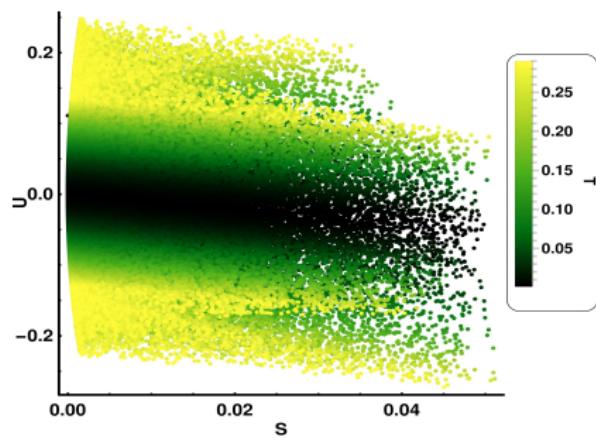
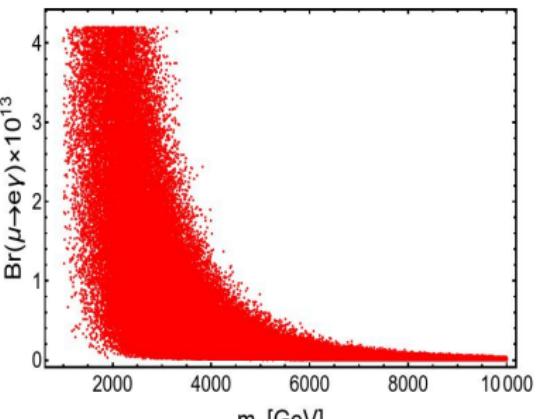
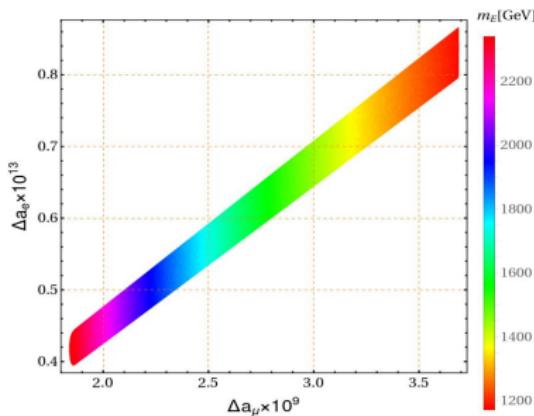
- ➊ Tree level masses for t, b, c, τ from Universal Seesaw.
- ➋ 1-loop masses for u, d, s, e, μ .
- ➌ 3-loop ν masses from inverse seesaw, with 1-loop Dirac and Majorana submatrices.
- ➍ Global $U(1)_X$ broken to preserved Z_2 , with $(-1)^{X+2s}$ being the Z_2 charges.
- ➎ No tree level FCNCs.



$$M_\nu = \begin{pmatrix} 0_{3 \times 3} & m_D & 0_{3 \times 3} \\ m_D^T & 0_{3 \times 3} & M \\ 0_{3 \times 3} & M & \mu \end{pmatrix}$$

	χ_L	χ_R	ϕ_L	ϕ_R	σ	ρ	φ
$SU(3)_C$	1	1	1	1	1	1	1
$SU(2)_L$	2	1	2	1	1	1	1
$SU(2)_R$	1	2	1	2	1	1	1
$U(1)_{B-L}$	1	1	1	1	0	0	0
$U(1)_X$	0	0	-1	-1	-2	-6	-1

Left (right) handed SM fermions are in $SU(2)_L$ ($SU(2)_R$) doublets.

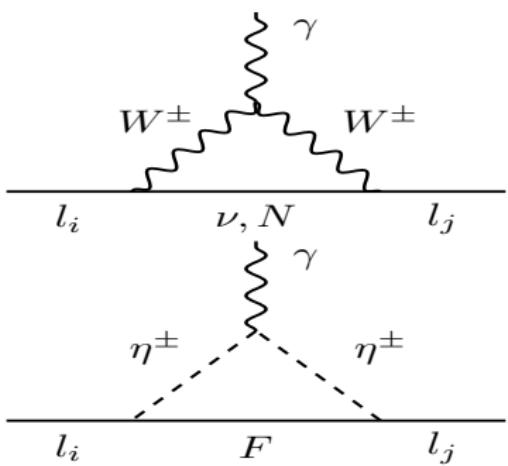
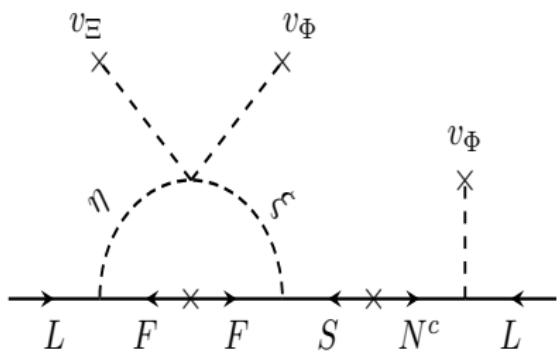


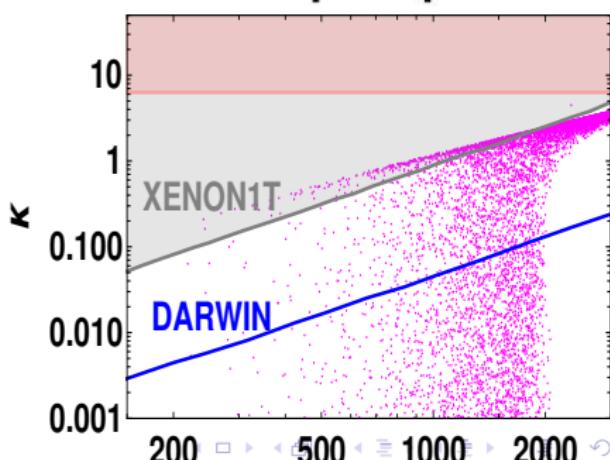
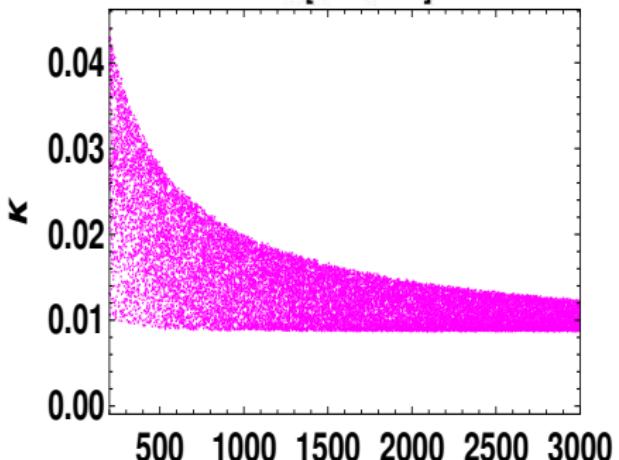
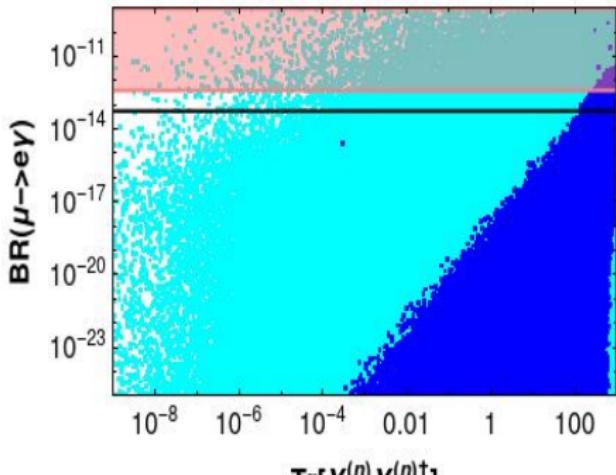
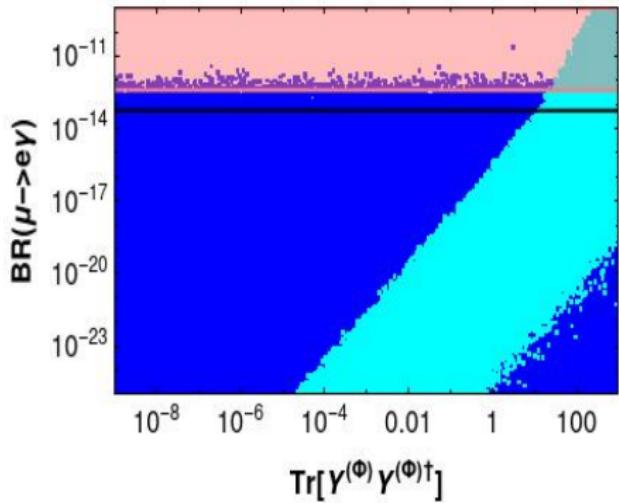
Extended IDM with radiative linear seesaw mechanism

	L_i	I_i^c	N_i^c	S_i	Φ	F_i	Ξ	η	ξ
$SU(2)_L \times U(1)_Y$	$(2, -\frac{1}{2})$	$(1, 1)$	$(1, 0)$	$(1, 0)$	$(2, \frac{1}{2})$	$(1, 0)$	$(3, 0)$	$(2, \frac{1}{2})$	$(1, 0)$
$U(1)_{\mathcal{L}}$	1	-1	-1	1	0	0	2	-1	-1

Table: Fields and their quantum numbers. Here $i = 1, 2, 3$. The global $U(1)_{\mathcal{L}}$ group breaks down to preserved \mathcal{Z}_2 , with $(-1)^{3\mathcal{B}+2\hat{\mathcal{L}}+2s} \in \mathcal{Z}_2$.

$$M_\nu = \begin{pmatrix} 0_{3 \times 3} & m_D & \varepsilon \\ m_D^T & 0_{3 \times 3} & M \\ \varepsilon^T & M & 0_{3 \times 3} \end{pmatrix}$$





Conclusions

- Both tree-level and radiative seesaw mechanisms can be implemented for explaining the SM fermion mass hierarchy.
- Neutrino masses can be generated via radiative inverse or linear seesaw.
- Fermion masses and mixings, DM, CLFV and $(g - 2)_{e,\mu}$ anomalies can be accounted for.

Acknowledgements

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Extra Slides

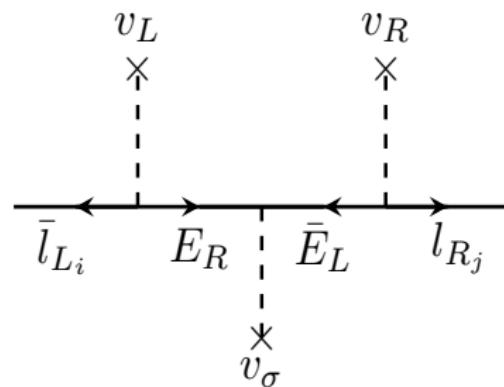
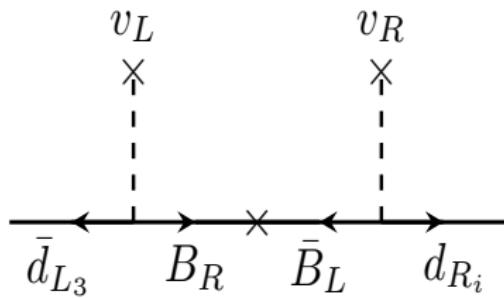
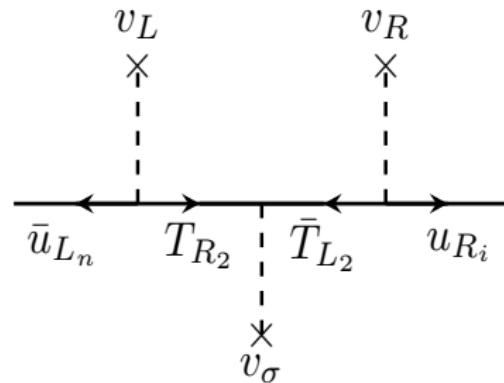
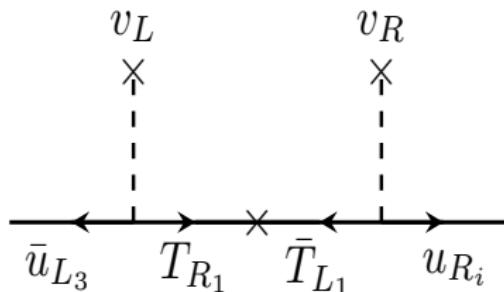
	Q_{L_n}	Q_{L_3}	Q_{R_i}	L_{L_j}	L_{R_i}	T_{L_n}	T_{R_1}	T_{R_2}	B_L	B_R	T'_L	T'_R	B'_{L_n}	B'_{R_n}	E_L	E_R	E'_{L_n}	E'_{R_n}	N_{R_i}	Ω_{R_n}
$SU(3)_C$	3	3	3	1	1	3	3	3	3	3	3	3	3	1	1	1	1	1	1	
$SU(2)_L$	2	2	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
$SU(2)_R$	1	1	2	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
$U(1)_{B-L}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	-1	-1	$\frac{4}{3}$	$\frac{4}{3}$	$\frac{4}{3}$	$-\frac{2}{3}$	$-\frac{2}{3}$	$\frac{4}{3}$	$\frac{4}{3}$	$-\frac{2}{3}$	$-\frac{2}{3}$	-2	-2	-2	0	0	
$U(1)_X$	2	0	0	0	-2	0	0	2	0	0	-1	1	1	3	-2	0	-1	1	2	-3

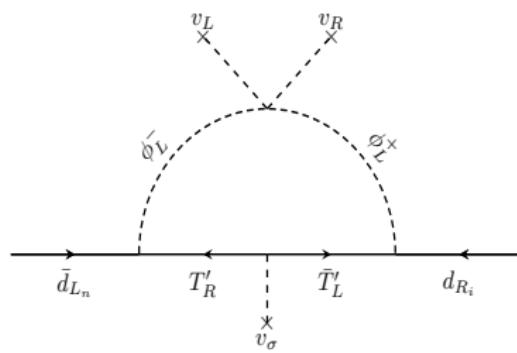
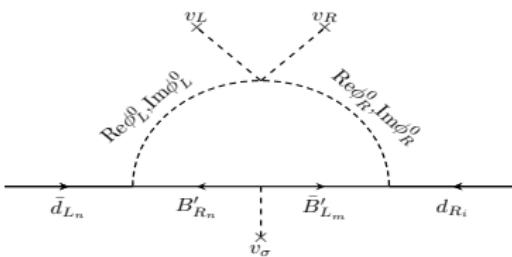
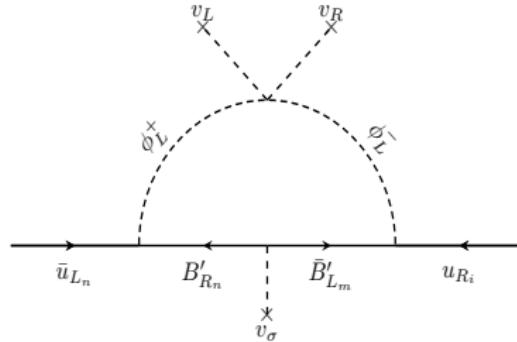
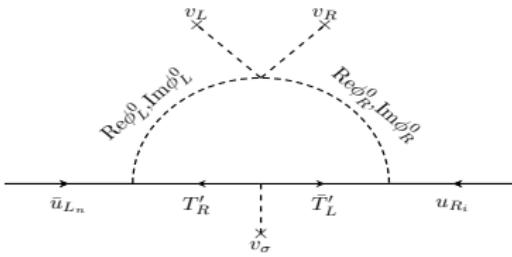
Table: Fermion charge assignments under the $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times U(1)_X$ symmetry.

	χ_L	χ_R	ϕ_L	ϕ_R	σ	ρ	φ
$SU(3)_C$	1						
$SU(2)_L$	2	1	2	1	1	1	1
$SU(2)_R$	1	2	1	2	1	1	1
$U(1)_{B-L}$	1	1	1	1	0	0	0
$U(1)_X$	0	0	-1	-1	-2	-6	-1

Table: Scalar boson charge assignments under the $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times U(1)_X$ symmetry.

The scalar dark matter candidate is the lightest among the $Re\varphi$, $Im\varphi$, $Re\phi_L^0$, $Re\phi_R^0$ fields.



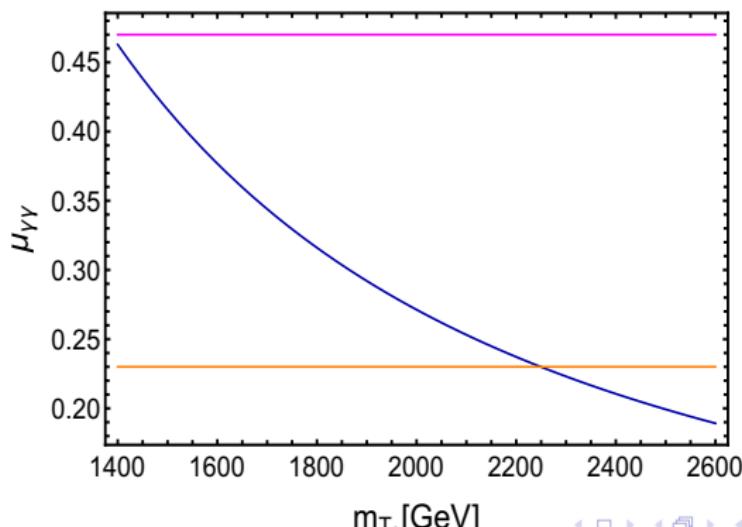


The 95 GeV diphoton excess has a signal strength given by:

$$\mu_{\gamma\gamma}^{(\text{exp})} = \frac{\sigma_{\text{exp}}(pp \rightarrow \sigma_R \rightarrow \gamma\gamma)}{\sigma_{SM}(pp \rightarrow h \rightarrow \gamma\gamma)} = 0.35 \pm 0.12, \quad (1)$$

For the sake of simplicity, we set:

$$\begin{aligned} m_{T'} &= m_{B'_1} = m_{B'_2} = m_{E'_1} = m_{E'_2} = 10 \text{ TeV}, & m_E &= 100 \text{ TeV}, \\ m_{H_1^\pm} &= m_{H_2^\pm} = 10 \text{ TeV}, & C_{\sigma H_1^\pm H_1^\mp} &= C_{\sigma H_2^\pm H_2^\mp} = 4.5 \text{ TeV}, \\ y_T &= y_{T'} = y_{B'_1} = y_{B'_2} = y_E = y_{E'_1} = y_{E'_2} = y_F. \end{aligned}$$



The one-loop contributions to the oblique parameters T , S and U are defined as:

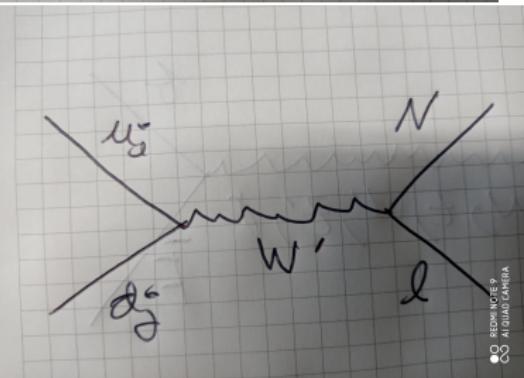
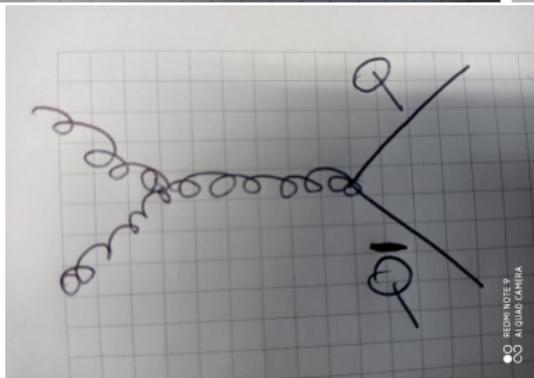
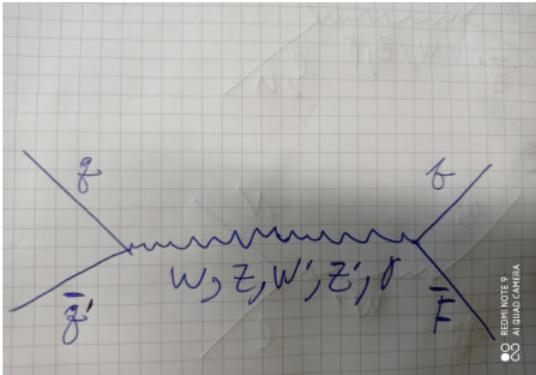
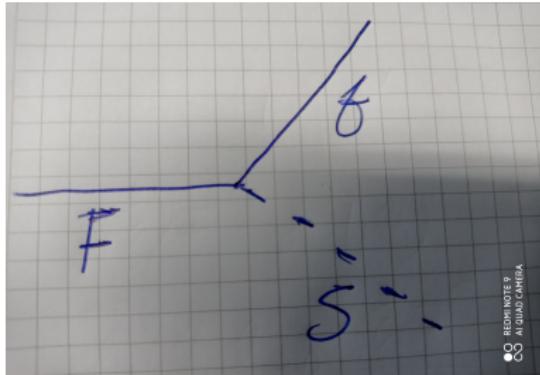
$$T = \frac{\Pi_{33}(q^2) - \Pi_{11}(q^2)}{\alpha_{EM}(M_Z) M_W^2} \Big|_{q^2=0}, \quad S = \frac{2 \sin 2\theta_W}{\alpha_{EM}(M_Z)} \frac{d\Pi_{30}(q^2)}{dq^2} \Big|_{q^2=0},$$

$$U = \frac{4 \sin^2 \theta_W}{\alpha_{EM}(M_Z)} \left(\frac{d\Pi_{33}(q^2)}{dq^2} - \frac{d\Pi_{11}(q^2)}{dq^2} \right) \Big|_{q^2=0}$$

where $\Pi_{11}(0)$, $\Pi_{33}(0)$, and $\Pi_{30}(q^2)$ are the vacuum polarization amplitudes with $\{W_\mu^1, W_\mu^1\}$, $\{W_\mu^3, W_\mu^3\}$ and $\{W_\mu^3, B_\mu\}$ external gauge bosons, respectively, and q is their momentum. The experimental values of T , S and U are:

$$T = -0.01 \pm 0.10, \quad S = 0.03 \pm 0.12, \quad U = 0.02 \pm 0.11. \quad (2)$$

The scalar sector yields the prediction $m_{H_i^0} = m_{A_i^0}$ ($i = 1, 2$) and $\theta_H = -\theta_A$. In our numerical analysis we have varied $m_{H_1^0}$, $m_{H_2^0}$, θ_H , θ in the ranges $1 \text{ TeV} \leq m_{H_i^0} \leq 3 \text{ TeV}$ ($i = 1, 2$), $0.9 \times 10^{-2} \text{ rad} \leq \theta_H \leq 1.1 \times 10^{-2} \text{ rad}$ and $0.9 \times 10^{-3} \text{ rad} \leq \theta \leq 1.1 \times 10^{-3} \text{ rad}$, respectively.



The sterile neutrinos have the following decay modes $N_a^\pm \rightarrow l_i^\pm W^\mp$, $N_a^\pm \rightarrow \nu_i Z$ and $N_a^\pm \rightarrow \nu_i S$, $N_a^\pm \rightarrow l_i^+ l_j^- \nu_k$, $N_a^\pm \rightarrow l_i^- u_j d_k$, $N_a^\pm \rightarrow b \bar{b} \nu_k$

Parameters	Y_{ij}^η	$Y_{ij}^{\tilde{c}} = y\delta_{ij}$	m_{F_i}	$M_{ij} = M_N\delta_{ij}$	$m_{D_1, D_2, D_{A_1}, D_{A_2}, \eta^\pm}$	θ_D	a, b, c
Range	$[10^{-10}, 4\pi]$	$[10^{-16}, 4\pi]$	$[200, 5000]$ GeV	$[200, 5000]$ GeV	$[200, 5000]$ GeV	0.01	[-20,20]

Table: The sampling region used in generating the plots of $Br(\mu \rightarrow e\gamma)$ in the extended IDM theory.

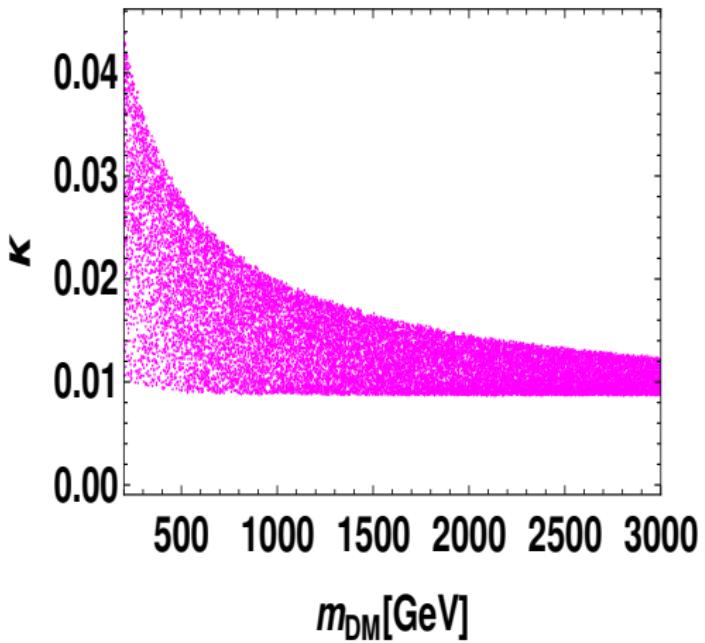
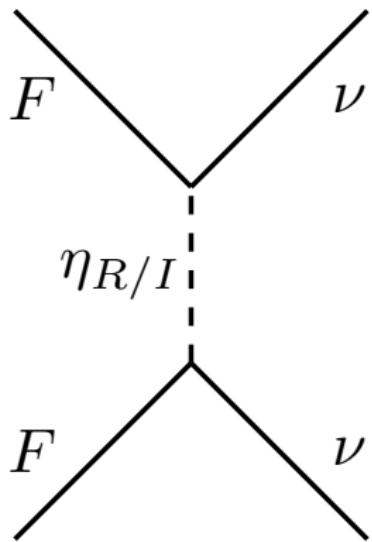


Figure: Annihilation of a pair of fermionic dark matter candidates into a pair of active neutrinos (left figure). Allowed parameter space in the $m_{F_1} - Y_{11}^{(\eta)}$ plane that reproduces the correct DM relic density in the case of the fermionic dark matter (right figure).

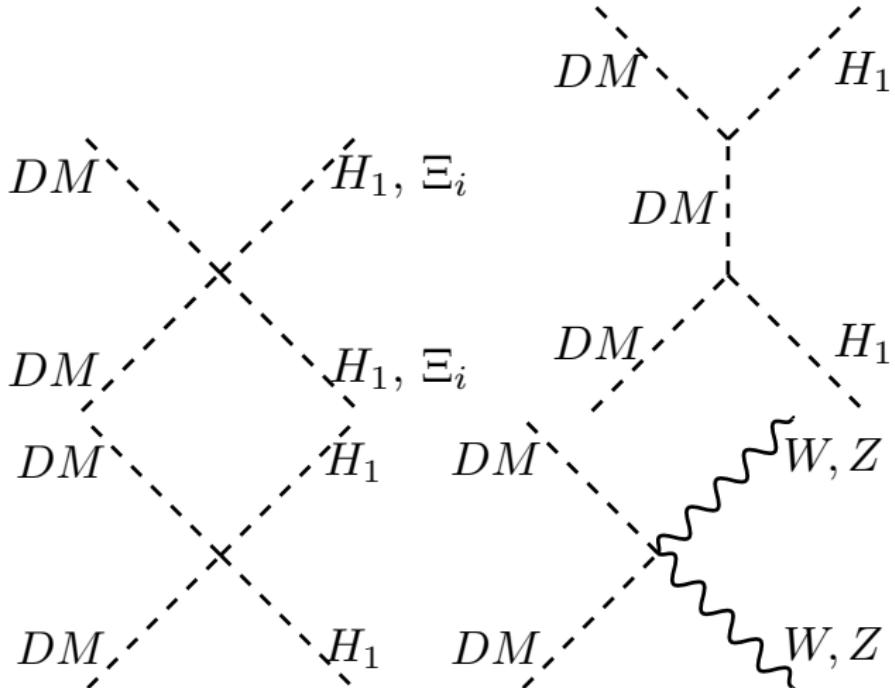


Figure: Dominant Feynman diagrams contributing to dark-matter annihilation into a pair of SM particles and the charged and the neutral components of the triplet scalar Ξ for the benchmark considered.