

Universal inverse seesaw and radiative neutrino masses.

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CompHep 2021 Workshop, 2nd December of 2021.

Based on: AECH, D. T. Huong and I. Schmidt, 2105.01731

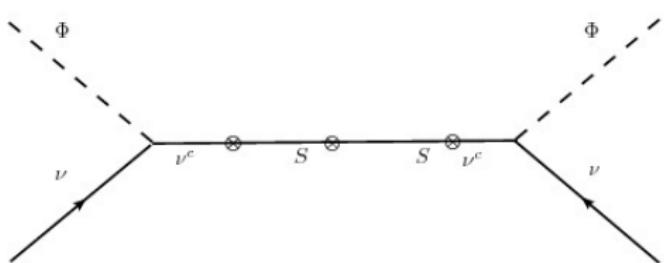
AECH, C. Hati, S. Kovalenko, J. W. F. Valle and
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Introduction

Some reasons to extend the SM are:

- ① Fermion mass hierarchy.
- ② Fermion mixing pattern.
- ③ Number of SM fermion families.
- ④ $(g - 2)_{\mu,e}$.
- ⑤ Dark matter.
- ⑥ Lepton and baryon asymmetry.
- ⑦ Hierarchy problem.



Inverse seesaw

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

$$\mathbf{M}_\nu = \left(\begin{array}{ccc} 0_{3 \times 3} & \mathbf{M}_1 & \mathbf{M}_L \\ \mathbf{M}_1^T & 0_{3 \times 3} & \mathbf{M}_2 \\ \mathbf{M}_L^T & \mathbf{M}_2^T & \mu \end{array} \right)$$

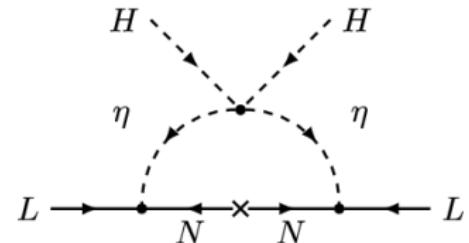
$$\mathbf{M}_L = 0_{3 \times 3}$$

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

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

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

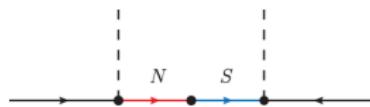
$$\mathbf{M}_\nu^{(2)} = \frac{1}{2} (\mathbf{M}_2 + \mathbf{M}_2^T) + \frac{1}{2} \mu$$



One loop Ma radiative seesaw model

η and N are odd under a preserved Z_2

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



Linear seesaw:

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

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

Universal Inverse seesaw mechanism.

The neutrino mass matrix for the IS in the basis (ν_L, ν_R^C, N_R^C) :

$$M_\nu = \begin{pmatrix} 0_{3 \times 3} & m_{\nu D} & 0_{3 \times 3} \\ m_{\nu D}^T & 0_{3 \times 3} & M \\ 0_{3 \times 3} & M^T & \mu \end{pmatrix}, \quad (1)$$

For charged fermions, in the basis

$(\bar{f}_{1L}, \bar{f}_{2L}, \bar{f}_{3L}, \bar{F}_L, \tilde{\bar{F}}_L) - (f_{1R}, f_{2R}, f_{3R}, F_R, \tilde{F}_R)$ we might have:

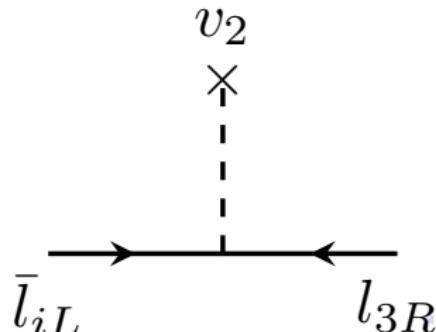
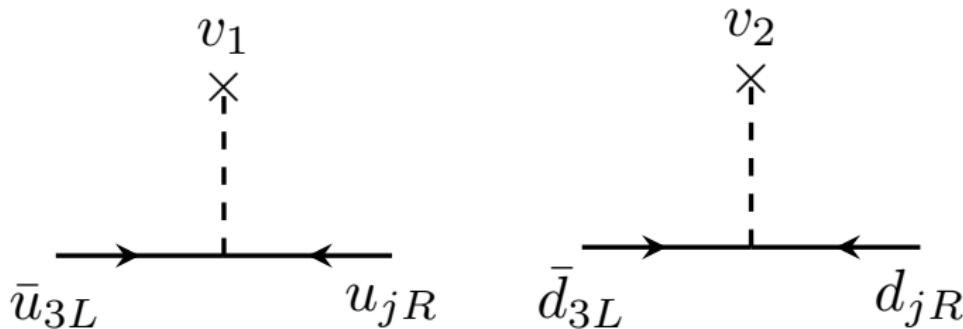
$$M_F = \begin{pmatrix} 0_{3 \times 3} & F_F & 0_{3 \times 1} \\ G_F^T & 0 & X_F \\ 0_{1 \times 3} & Y_F & m_F \end{pmatrix}, \quad (2)$$

In the limit $m_F \rightarrow 0$ ($F = T, D, E$)

$$\begin{aligned} Q_{U(1)}(f_{iL}) &= Q_{U(1)}(\tilde{F}_L) = Q_{U(1)}(F_R) = a, \\ Q_{U(1)}(f_{iR}) &= Q_{U(1)}(\tilde{F}_R) = Q_{U(1)}(F_L) = b, \quad a \neq b. \end{aligned} \quad (3)$$

Extending the IS to the first and second families of SM charged fermions:

$$M_F = \begin{pmatrix} C_F + \Delta_F & F_F & 0_{3 \times 1} \\ G_F^T & 0 & X_F \\ 0_{1 \times 3} & Y_F & m_F \end{pmatrix}, \quad (4)$$



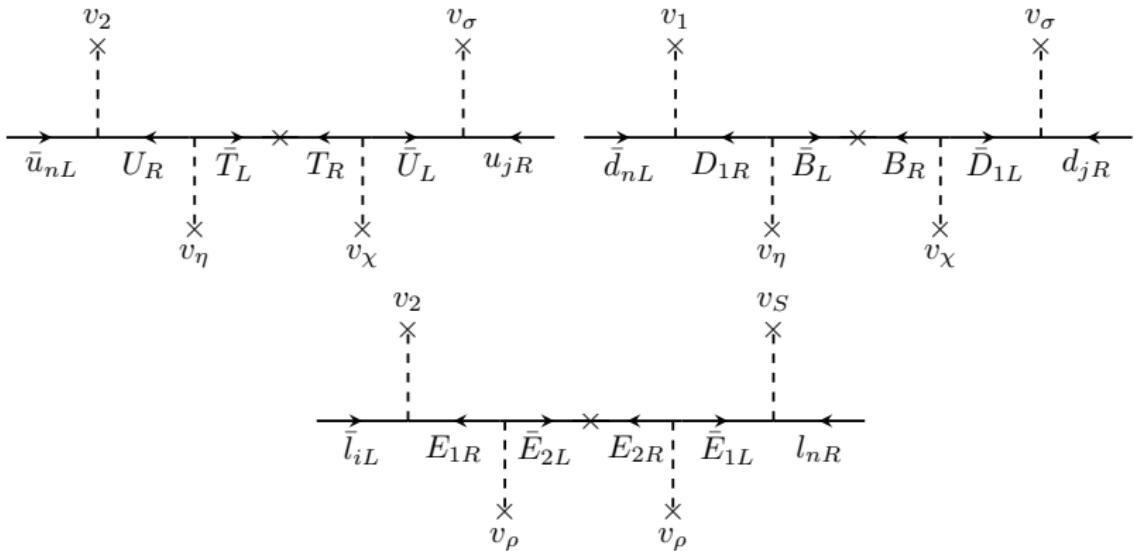


Figure: Tree level Feynman diagrams contributing to the entries of the SM charged fermion mass matrices. Here, $n = 1, 2$ and $i, j = 1, 2, 3$.

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$	Z_2	Z_4
ϕ_1	1	2	$\frac{1}{2}$	$\frac{1}{3}$	0	-1
ϕ_2	1	2	$\frac{1}{2}$	$\frac{2}{3}$	0	1
σ	1	1	0	$\frac{1}{3}$	0	-1
χ	1	1	0	$\frac{2}{3}$	0	-2
η	1	1	0	-1	0	2
ρ	1	1	0	2	0	-1
S	1	1	0	0	0	1
ζ_1^+	1	1	1	$\frac{2}{3}$	0	-1
ζ_2^+	1	1	1	1	0	0
ζ_3^+	1	1	1	$\frac{2}{3}$	0	1
φ_1	1	1	0	1	1	0
φ_2	1	1	0	0	1	1

Table: Scalar assignments under
 $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X \times Z_2 \times Z_4$.

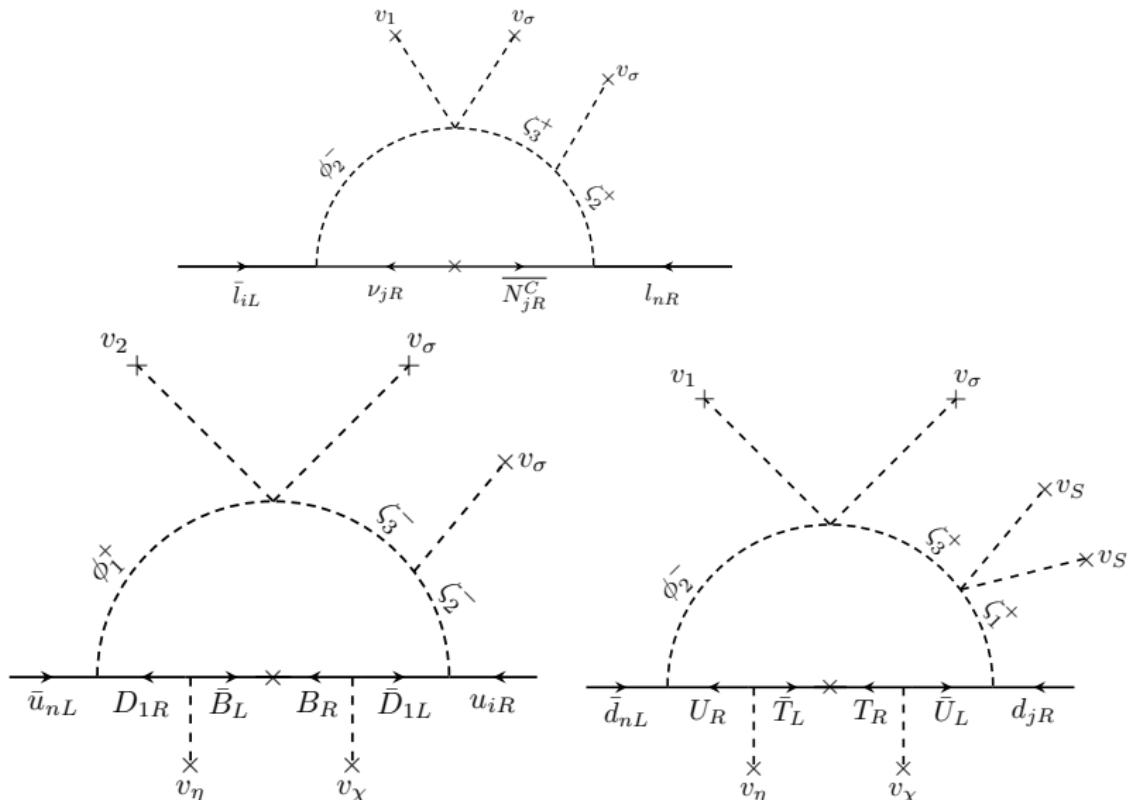


Figure: One loop Feynman diagrams contributing to the entries of the SM charged fermion mass matrices. Here, $n = 1, 2$ and $i, j = 1, 2, 3$.

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$	Z_2	Z_4
q_{nL}	3	2	$\frac{1}{6}$	0	0	1
q_{3L}	3	2	$\frac{1}{6}$	$\frac{1}{3}$	0	0
u_{iR}	3	1	$\frac{2}{3}$	$\frac{2}{3}$	0	1
d_{iR}	3	1	$-\frac{1}{3}$	$-\frac{1}{3}$	0	-1
U_L	3	1	$\frac{2}{3}$	$\frac{1}{3}$	0	2
U_R	3	1	$\frac{2}{3}$	$\frac{2}{3}$	0	2
T_L	3	1	$\frac{2}{3}$	$-\frac{1}{3}$	0	0
T_R	3	1	$\frac{2}{3}$	$-\frac{1}{3}$	0	0
D_{1L}	3	1	$-\frac{1}{3}$	0	0	2
D_{1R}	3	1	$-\frac{1}{3}$	$-\frac{1}{3}$	0	2
D_{2L}	3	1	$-\frac{1}{3}$	0	1	-1
D_{2R}	3	1	$-\frac{1}{3}$	$-\frac{1}{3}$	1	0
B_L	3	1	$-\frac{1}{3}$	$\frac{2}{3}$	0	0
B_R	3	1	$-\frac{1}{3}$	$\frac{2}{3}$	0	0

Table: Quark assignments under

$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X \times Z_2 \times Z_4$. Here $i = 1, 2, 3$.

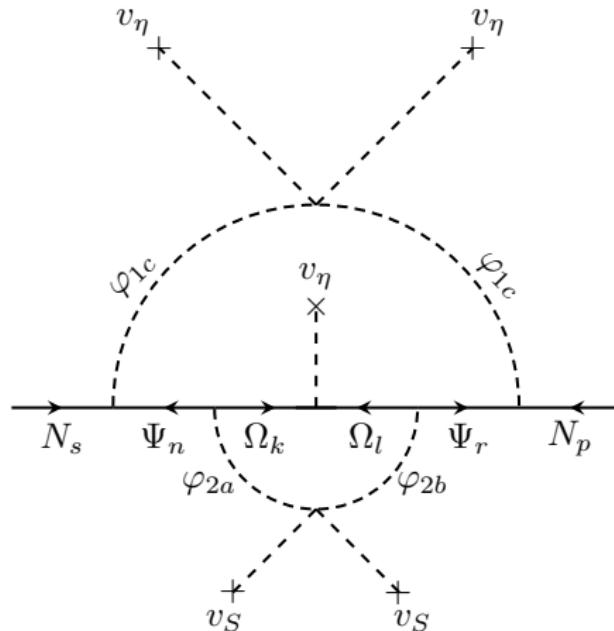


Figure: Two-loop Feynman diagram contributing to the Majorana neutrino mass submatrix μ . Here $n, k, l, r = 1, 2, s, p = 1, 2, 3, a, b, c = R, I$, with φ_{nR} and φ_{nl} corresponding to the CP even and CP odd parts of the scalar field φ_n , respectively.

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$	Z_2	Z_4
l_{iL}	1	2	$-\frac{1}{2}$	$-\frac{1}{3}$	0	1
l_{nR}	1	1	-1	-1	0	1
l_{3R}	1	1	-1	-1	0	0
E_{1L}	1	1	-1	-1	0	-2
E_{1R}	1	1	-1	-1	0	0
E_{2L}	1	1	-1	1	0	1
E_{2R}	1	1	-1	1	0	1
ν_{iR}^C	1	1	0	$-\frac{1}{3}$	0	0
N_{iR}	1	1	0	0	0	-1
Ψ_{nR}	1	1	0	1	1	1
Ω_{nR}	1	1	0	-1	0	0

Table: Lepton assignments under $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X \times Z_2 \times Z_4$. Here $i = 1, 2, 3$ and $n = 1, 2$.

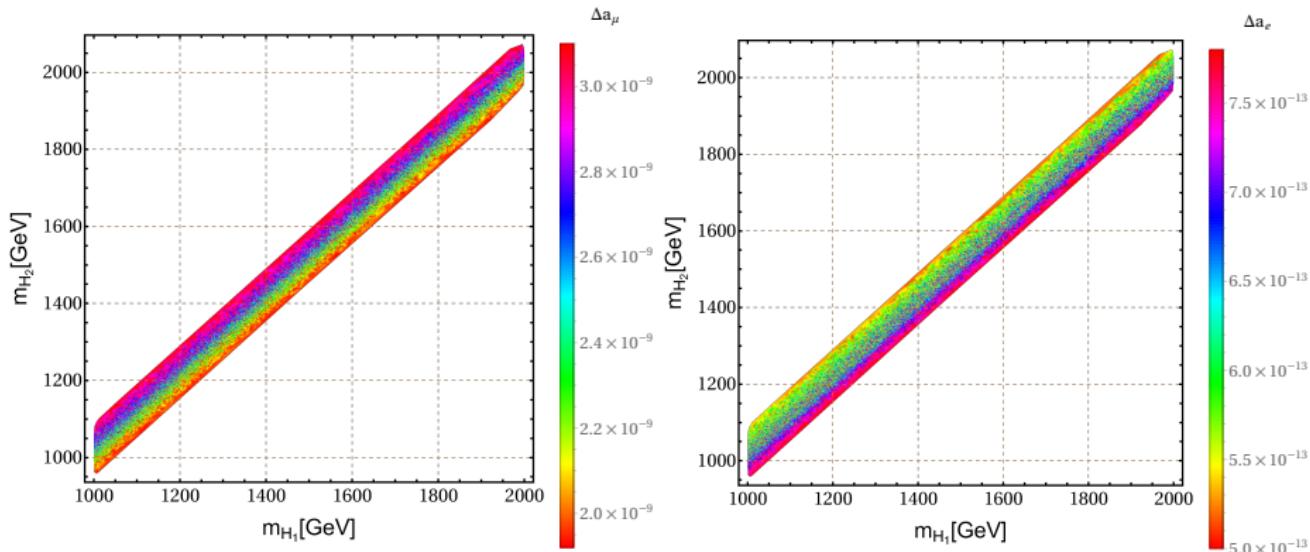


Figure: Correlation between the masses of the scalars H_1 and H_2 consistent with the muon and electron anomalous magnetic moments.

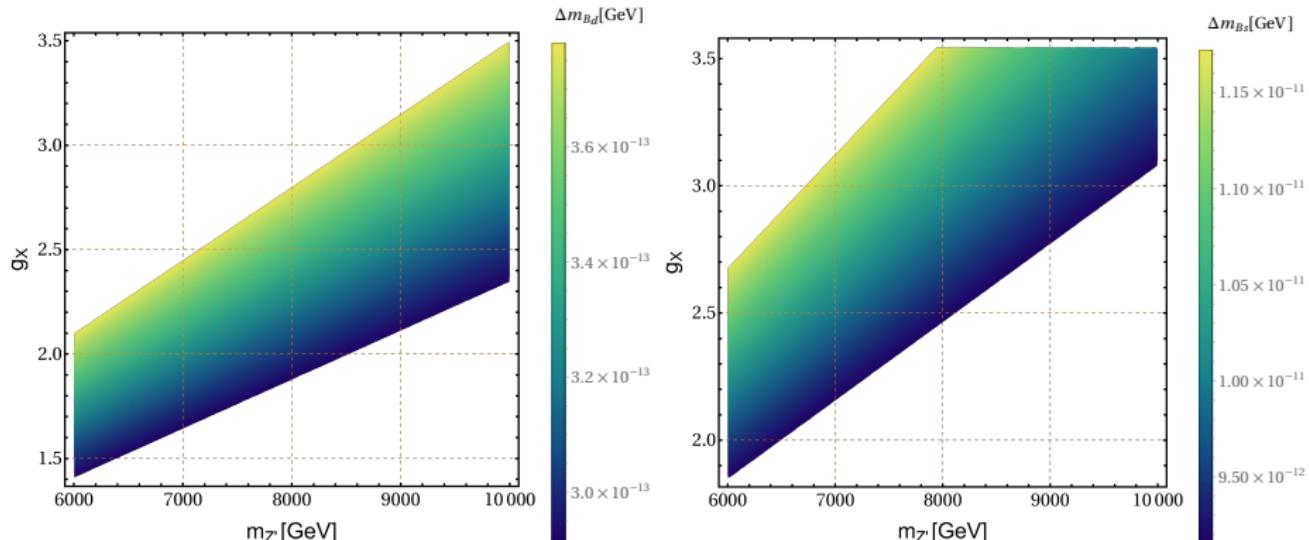


Figure: Allowed region in the $m_{Z'} - g_X$ plane consistent with the constraint arising from $B_d^0 - \bar{B}_d^0$ (left-plot) and $B_s^0 - \bar{B}_s^0$ (right-plot) mixings. Here we fix the couplings of the flavor violating neutral Yukawa interactions as 2×10^{-4} and 10^{-3} for the left and right plots, respectively. Furthermore, we have set $M_{H_1} = 1.2$ TeV, $M_{H_2} = 1.3$ TeV, $M_{A_1} = M_{A_2} = 1$ TeV.

$K^0 - \bar{K}^0$ mixing constraint is also fulfilled for a flavor violating Yukawa coupling of the order of 0.5×10^{-5}

The scalar DM φ_2 mainly annihilates into W^+W^- , ZZ , $t\bar{t}$, $b\bar{b}$, HH via a scalar portal interaction. The relic density is:

$$\Omega h^2 \simeq 0.1 \left(\frac{m_{\varphi_2}}{\lambda_{\text{eff}} \times 1.354 \text{TeV}} \right)^2, \quad (5)$$

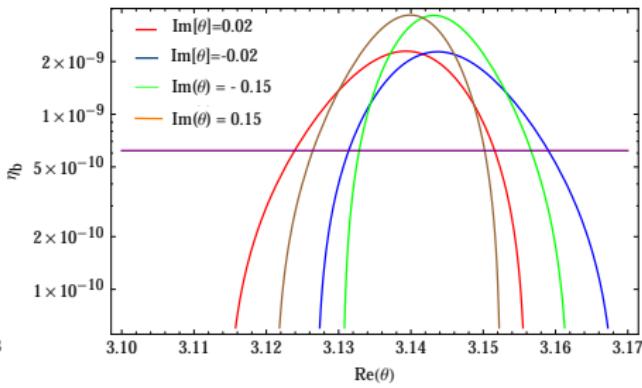
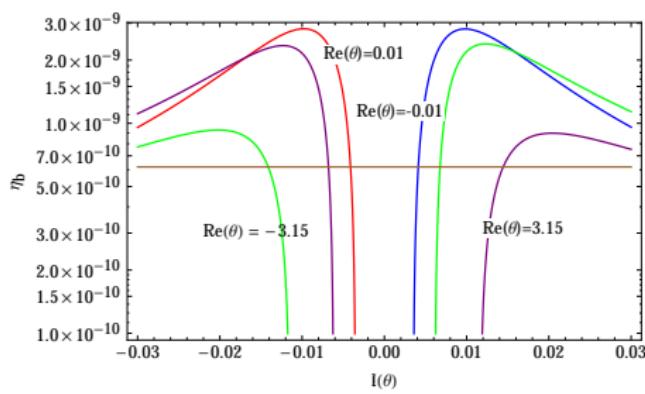
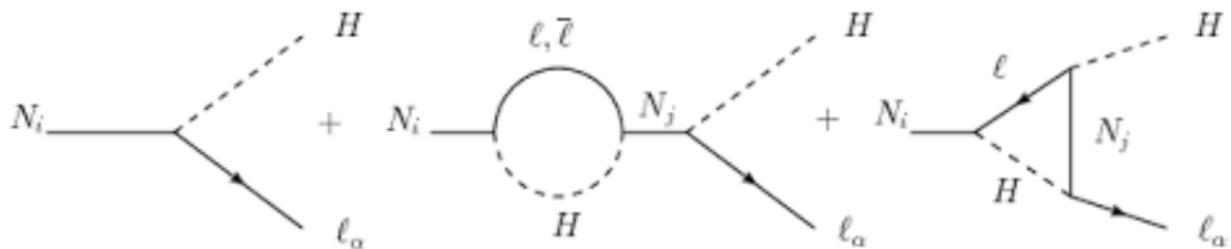
If the effective coupling is in the range $0.5 < \lambda_{\text{eff}} < 1.5$, the dark matter mass satisfies $0.75 \text{TeV} < m_{\varphi_2} < 2.25 \text{TeV}$.

Ψ_n annihilates into SM particles through the exchange of a new gauge boson. The relic density is given as

$$\Omega_\Phi h^2 \simeq 0.1 \text{pb} \left(\frac{\alpha}{150 \text{GeV}} \right)^{-2} \left(\frac{m_\Psi}{2.86 \text{TeV}} \right)^2, \quad (6)$$

where $\left(\frac{\alpha}{150 \text{GeV}} \right)^2 \simeq 1 \text{pb}$.

To study the lepton asymmetry we assume that the fermions Ψ_{nR} are heavier than the lightest pseudo-Dirac pair, (N^\pm) . Thus, the lepton asymmetry parameter, is induced by decay process of N^\pm .



Scotogenic neutrino masses with GCU

Field	$SU(3)_c$	$SU(3)_L$	$U(1)_X$	$U(1)_N$	Q	$M_P = (-1)^{3(B-L)+2s}$
q_{iL}	3	$\bar{3}$	0	0	$(-\frac{1}{3}, \frac{2}{3}, -\frac{1}{3})^T$	$(+++)^T$
q_{3L}	3	3	$\frac{1}{3}$	$\frac{2}{3}$	$(\frac{2}{3}, -\frac{1}{3}, \frac{2}{3})^T$	$(++-)^T$
μ_{aR}	3	1	$\frac{2}{3}$	$\frac{1}{3}$	$\frac{2}{3}$	+
d_{aR}	3	1	$-\frac{1}{3}$	$\frac{1}{3}$	$-\frac{1}{3}$	+
U_{3R}	3	1	$\frac{2}{3}$	$\frac{4}{3}$	$\frac{2}{3}$	-
D_{iR}	3	1	$-\frac{1}{3}$	$-\frac{2}{3}$	$-\frac{1}{3}$	-
I_{aL}	1	3	$-\frac{1}{3}$	$-\frac{2}{3}$	$(0, -1, 0)^T$	$(++-)^T$
e_{aR}	1	1	-1	-1	-1	+
ν_{iR}	1	1	0	-4	0	-
ν_{3R}	1	1	0	5	0	+
Ω_{aL}	1	8	0	0	$\begin{pmatrix} 0 & 1 & 0 \\ -1 & 0 & -1 \\ 0 & 1 & 0 \end{pmatrix}$	$\begin{pmatrix} - & - & + \\ - & - & + \\ + & + & - \end{pmatrix}$
η	1	3	$-\frac{1}{3}$	$\frac{1}{3}$	$(0, -1, 0)^T$	$(++-)^T$
ρ	1	3	$\frac{2}{3}$	$\frac{1}{3}$	$(1, 0, 1)^T$	$(++-)^T$
χ	1	3	$-\frac{1}{3}$	$-\frac{2}{3}$	$(0, -1, 0)^T$	$(---)^T$
ϕ	1	1	0	2	0	+
σ	1	1	0	1	0	-

Table: 3311 model field content ($a = 1, 2, 3$ and $i = 1, 2$ are family indices). ↗ ↘ ↙

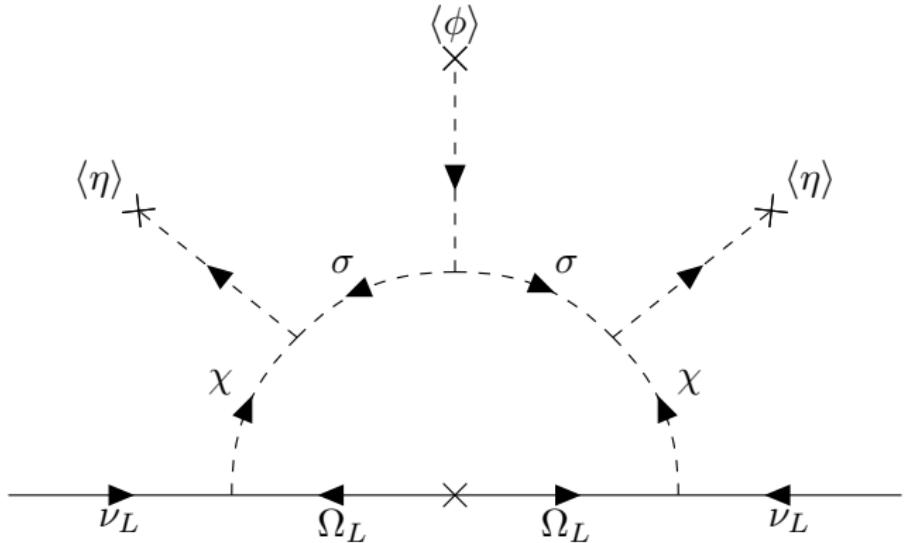


Figure: Feynman-loop diagram contributing to the light active Majorana neutrino mass matrix.

$$Q = T_3 - \frac{T_8}{\sqrt{3}} + X, \quad B - L = -\frac{2}{\sqrt{3}} T_8 + N, \quad (7)$$

$$q_{iL} = \begin{pmatrix} d_i \\ -u_i \\ D_i \end{pmatrix}_L \quad q_{3L} = \begin{pmatrix} u_3 \\ d_3 \\ U_3 \end{pmatrix}_L \quad l_{aL} = \begin{pmatrix} \nu_a \\ e_a \\ N_a \end{pmatrix}_L, \quad (8)$$

The gauged $B - L$ symmetry is spontaneously broken leaving a discrete remnant symmetry $M_P = (-1)^{3(B-L)+2s}$.

$$\begin{aligned} \langle \eta \rangle &= \frac{1}{\sqrt{2}}(\nu_1, 0, 0)^T, & \langle \rho \rangle &= \frac{1}{\sqrt{2}}(0, \nu_2, 0)^T, & \langle \chi \rangle &= (0, 0, w)^T, \\ \langle \phi \rangle &= \frac{1}{\sqrt{2}}\Lambda, & \langle \sigma \rangle &= 0. \end{aligned} \quad (9)$$

We assume $w, \Lambda \gg \nu_1, \nu_2$, such that the SSB pattern of the model is

$$\begin{array}{c} SU(3)_C \times SU(3)_L \times U(1)_X \times U(1)_N \\ \downarrow w, \Lambda \\ SU(3)_C \times SU(2)_L \times U(1)_Y \times M_P \\ \downarrow \nu_1, \nu_2 \\ SU(3)_C \times U(1)_Q \times M_P. \end{array} \quad (10)$$

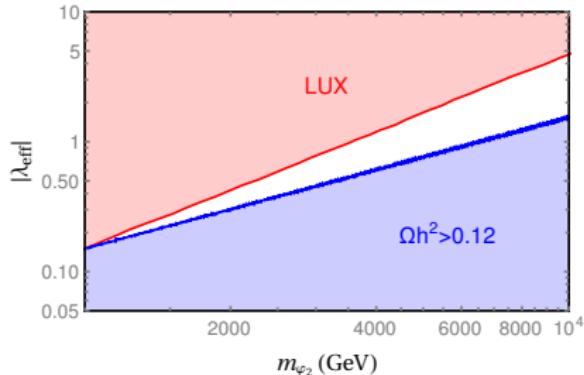
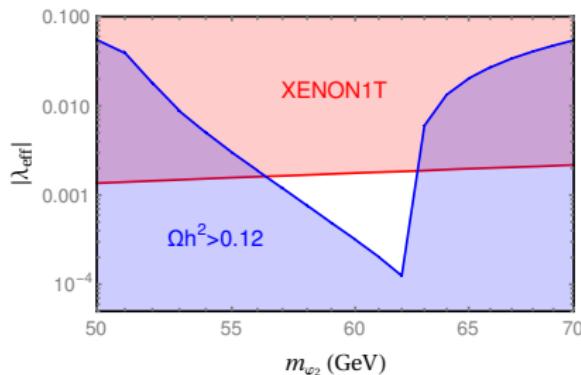


Figure: Viable mass regions where the field φ_2 of the simplified model described in the text behaves as a dark matter candidate. The red regions correspond to the current direct detection limits. The blue regions represent values of the effective coupling λ_{eff} where the corresponding relic density is incompatible with the Planck measurement.

For the case of fermionic DM candidate, one has:

$$\langle \sigma v \rangle \approx \left(\frac{\alpha}{150 \text{ GeV}} \right)^2 \left(\frac{M_\Omega}{3 \text{ TeV}} \right)^2 \approx \left(\frac{M_\Omega}{3 \text{ TeV}} \right)^2 \text{ pb}, \quad (11)$$

$$\Omega_{DM} h^2 = \frac{0.1 \text{ pb}}{\langle \sigma v \rangle}, \quad (12)$$

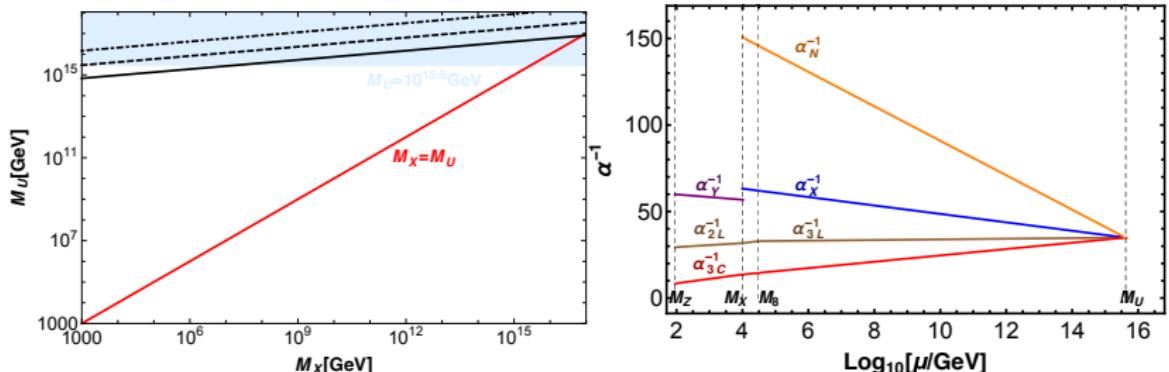


Figure: Left) Unification scale M_U as a function of the 3-3-1-1 symmetry breaking scale M_X , for three benchmark choices $M_8 = M_X$ (solid curve), $M_8 = 3M_X$ (dashed curve) and $M_8 = 10M_X$ (dot-dashed curve). (Right) An example of $SU(3)_c \times SU(3)_L \times U(1)_X \times U(1)_N$ unification for a phenomenologically accessible 3-3-1-1 symmetry breaking scale $M_X = 10$ TeV and $M_8 = 3M_X = 30$ TeV.

3-3-1 model with radiative linear seesaw mechanism.

	$SU(3)_C$	$SU(3)_L$	$U(1)_X$	$U(1)$
χ	1	3	$-\frac{1}{3}$	0
η	1	3	$-\frac{1}{3}$	4
ρ	1	3	$\frac{2}{3}$	-2
S^-	1	1	-1	0
σ	1	1	0	-2

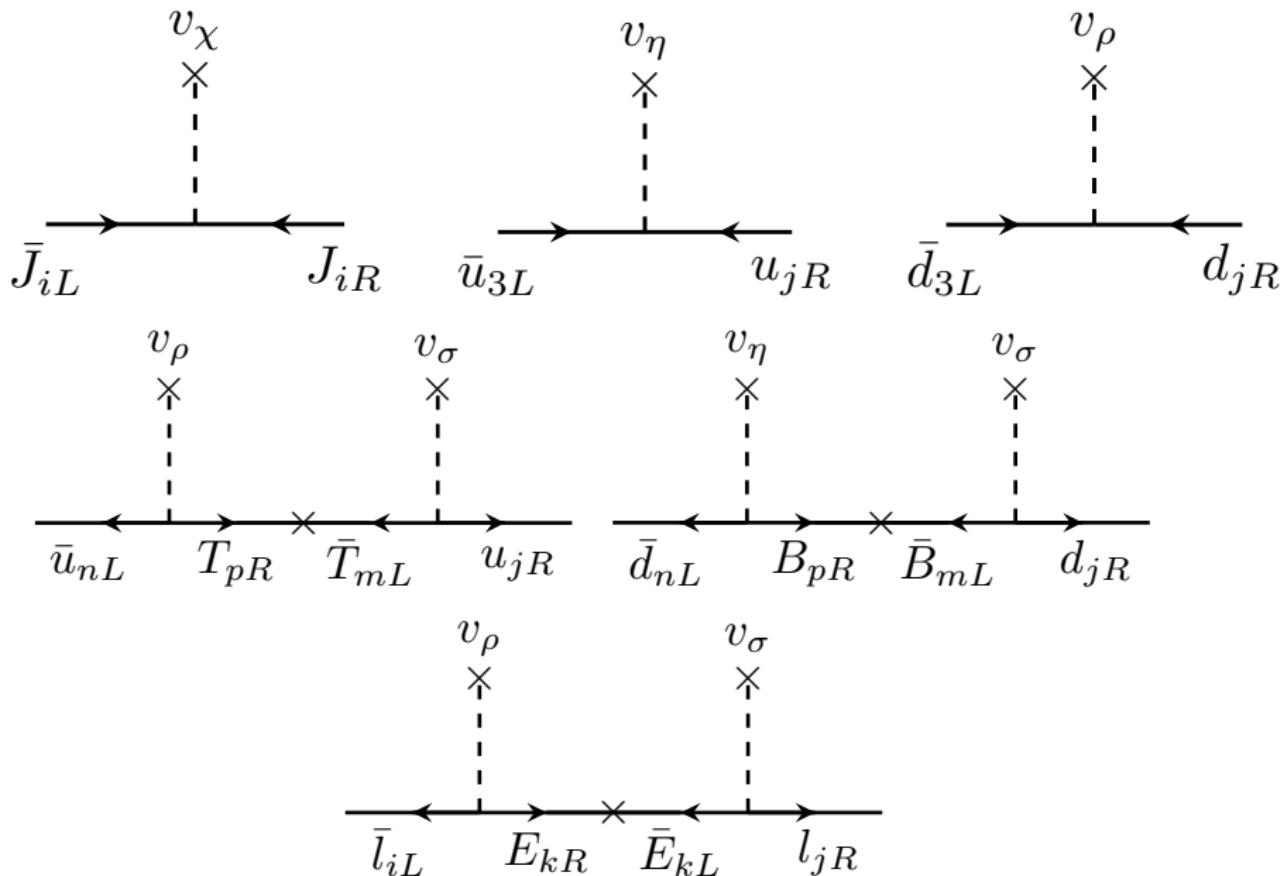
Table: Scalar assignments under $SU(3)_C \times SU(3)_L \times U(1)_X \times U(1)$.

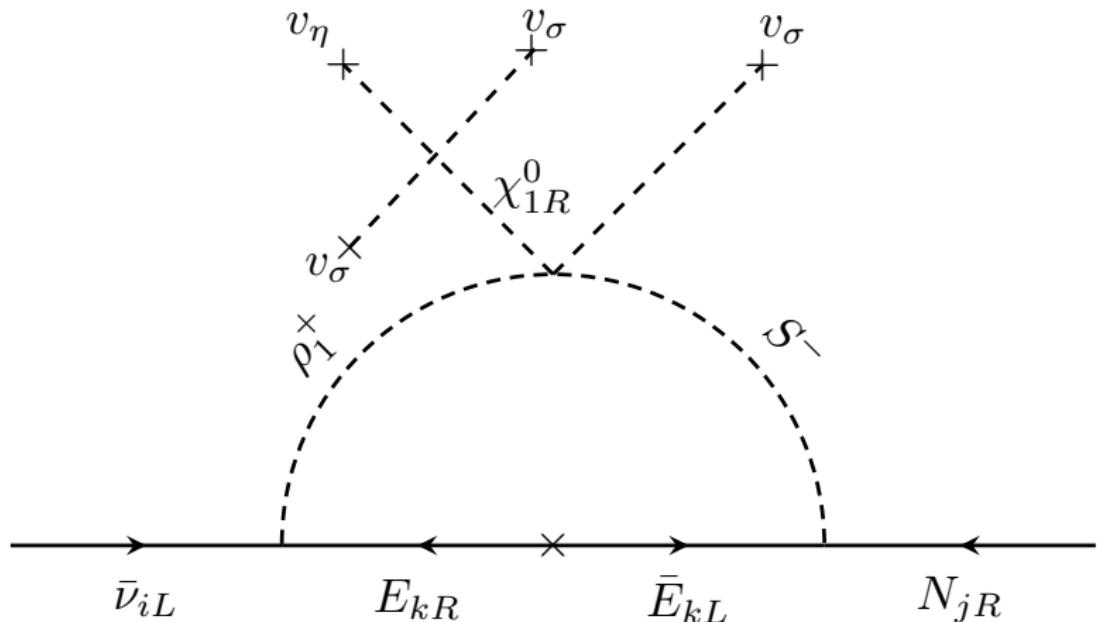
	$SU(3)_C$	$SU(3)_L$	$U(1)_X$	$U(1)$
L_{iL}	1	3	$-\frac{1}{3}$	1
e_{iR}	1	1	-1	1
N_{iR}	1	1	0	1
E_{iL}	1	1	-1	3
E_{iR}	1	1	-1	3

Table: Lepton assignments under $SU(3)_C \times SU(3)_L \times U(1)_X \times U(1)$. Here $i = 1, 2, 3$.

	$SU(3)_C$	$SU(3)_L$	$U(1)_X$	$U(1)$
Q_{nL}	3	3	0	0
Q_{3L}	3	3	$\frac{1}{3}$	0
u_{iR}	3	1	$\frac{2}{3}$	-4
d_{iR}	3	1	$-\frac{1}{3}$	2
J_{1R}	3	1	$\frac{2}{3}$	0
J_{nR}	3	1	$-\frac{1}{3}$	0
T_{nL}	3	1	$\frac{2}{3}$	-2
T_{nR}	3	1	$\frac{2}{3}$	-2
B_{nL}	3	1	$-\frac{1}{3}$	4
B_{nR}	3	1	$-\frac{1}{3}$	4

Table: Quark assignments under $SU(3)_C \times SU(3)_L \times U(1)_X \times U(1)$. Here $i = 1, 2, 3$ and $n = 1, 2$.





The neutrino mass matrix in the basis $(\nu_L, \nu_R^C, N_R^C)^T$ is:

$$M_\nu = \begin{pmatrix} 0_{3 \times 3} & m_{\nu D} & \varepsilon \\ m_{\nu D}^T & 0_{3 \times 3} & M \\ \varepsilon^T & M^T & 0_{3 \times 3} \end{pmatrix}, \quad (13)$$

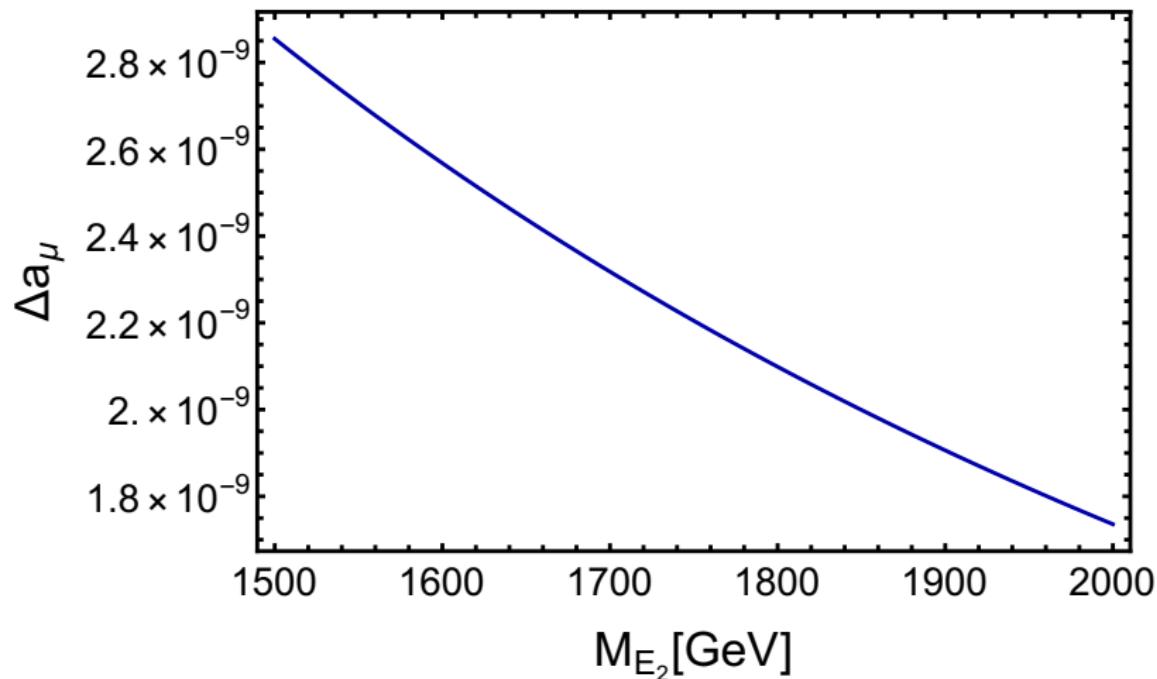


Figure: Muon anomalous magnetic moment as a function of the charged exotic lepton mass M_{E_2} .

We fixed $\theta = \frac{\pi}{4}$, $M_{A_1} = M_{H_1} = 0.5 \text{ TeV}$, $M_{A_2} = 0.6 \text{ TeV}$, $M_{H_2} = 2 \text{ TeV}$.

Conclusions

- Inverse seesaw mechanism can explain the SM fermion mass hierarchy.
- Fermion masses and mixings, DM, $(g - 2)_{e,\mu}$ anomalies, lepton and baryon asymmetries can be accounted for.
- Dark matter stability can arise from a residual matter-parity symmetry.
- Leptonic $SU(3)_L$ octets allow GCU and one loop scotogenic neutrino generation. DM can also be accounted for.
- Neutrino masses can be generated via one-loop linear seesaw with $g - 2$ accommodated in agreement with existing bounds.

Acknowledgements

Thank you very much to all of you for the attention.

A.E.C.H was supported by Fondecyt (Chile), Grant No. 1210378 and Milenio-ANID-ICN2019 044.

Extra Slides

Thus, the lepton asymmetry parameter, is induced by decay process of N^\pm :

$$\begin{aligned}\epsilon_\pm &= \sum_{\alpha=1}^3 \frac{\{\Gamma(N_\pm \rightarrow l_\alpha H^+) - \Gamma(N_\pm \rightarrow \bar{l}_\alpha H^-)\}}{\{\Gamma(N_\pm \rightarrow l_\alpha H^+) + \Gamma(N_\pm \rightarrow \bar{l}_\alpha H^-)\}} \\ &\simeq \frac{\Im[(y^\nu)^\dagger y^\nu (y^\nu)^\dagger y^\nu]_{11}}{8\pi A_\pm} \frac{r}{r^2 + \frac{\Gamma_\pm^2}{m_{N_\pm}^2}},\end{aligned}\quad (14)$$

where $r \equiv \frac{m_{N_+}^2 - m_{N_-}^2}{m_{N_+} m_{N_-}}$, $A_\pm = ((y^\nu)^\dagger y^\nu)_{11}$, $\Gamma_\pm \equiv \frac{A_\pm m_{N_\pm}}{8\pi}$.

$$\begin{aligned}\eta_B &= \frac{\epsilon_{N_\pm}}{g_*} \quad \text{for} \quad K_{N_\pm}^{\text{eff}} \ll 1, \\ \eta_B &= \frac{0.3\epsilon_{N_\pm}}{g_* K_{N_\pm}^{\text{eff}} (\ln K_{N_\pm}^{\text{eff}})^{0.6}} \quad \text{for} \quad K_{N_\pm}^{\text{eff}} \gg 1.\end{aligned}\quad (15)$$

Here, $g_* \simeq 118$ defined as

$$K_{N_\pm}^{\text{eff}} \simeq \left(\frac{\Gamma_+ + \Gamma_-}{H} \right) \left(\frac{m_{N^+} - m_{N^-}}{\Gamma_\pm} \right)^2 \quad (16)$$

where $H = \sqrt{\frac{4\pi^3 g_*}{45}} \frac{T^2}{M_{Pl}}$ is the Hubble constant.

$$y^\nu = \frac{v_\sigma}{v_2} \left(U_{\text{PMNS}} M_\nu^{\frac{1}{2}} R \mu^{-\frac{1}{2}} y^N \right). \quad (17)$$

$$R = \begin{pmatrix} c_y c_z & -s_x c_z s_y - c_x s_z & s_x s_z - c_x s_y c_z \\ c_y s_z & c_x c_z - s_x s_y s_z & -c_z s_x - c_x s_y s_z \\ s_y & s_x c_y & c_x c_y \end{pmatrix}, \quad (18)$$

$c_x = \cos x$, $s_x = \sin x$ and we set $x = 0$, $y = z = \Re[\theta] + i\Im[\theta]$, $Y^{(N)} = \text{Diag}(0.5, 0.9i, 1.8)$, $v_2 = 24.6 \text{ GeV}$, $v_\sigma \simeq 5 \times 10^3 \text{ GeV}$. Then $\mu \simeq 1 \text{ keV}$.

