FLASY ROME 2025

11TH WORKSHOP
Flavor Symmetries and Consequences in Accelerators and Cosmology

Lepton sector and dark matter phenomenology of a minimal two loop level inverse seesaw model

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Introduction

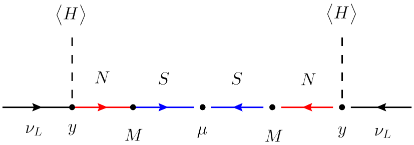
INVERSE SEESAW

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

where $\mu \ll m_D \ll M$ and

$$m_\nu = m_D (M^T)^{-1} \mu M^{-1} m_D^T$$

$$m_\nu \sim \frac{v^2}{M^2}\mu \to 0{,}1\,\mathrm{eV} \sim \frac{(1\,\mathrm{keV})(246\,\mathrm{GeV})^2}{(1\,\mathrm{TeV})^2}$$

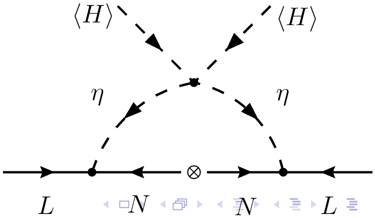


RADIATIVE SEESAW η an scalar and N an inert fermion are odd under a preserved Z_2.

arXiv: hep-ph/0601225v1

Mass matrix for the neutrino sector, where m_D and M are Dirac and Majorana matrices, respectively

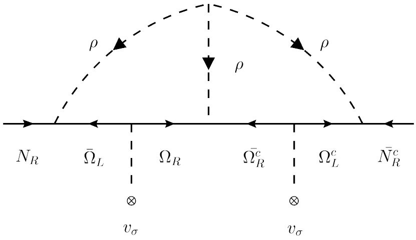
$$M_\nu = \begin{pmatrix} 0_{3\times3} & m_D & 0_{3\times3} \\ m_D & 0_{3\times3} & M \\ 0_{3\times3} & M^T & \mu \end{pmatrix}$$



The model: 2 loops Inverse Seesaw

	l_{iL}	l_{iR}	ν_{kR}	N_{kR}	Ω_{kL}	Ω_{kR}	ϕ	ρ	σ
$SU(3)_C$	1	1	1	1	1	1	1	1	1
$SU(2)_L$	2	1	1	1	1	1	2	1	1
$U(1)_Y$	$-\frac{1}{2}$	-1	0	0	0	0	0	0	0
$U(1)_X$	1	1	1	-1	-1	0	0	0	-1
Z_3	0	0	0	0	-1	-1	0	-1	0

Cuadro: Charge assignments of leptonic and scalar fields of the model under the group $\mathcal{G}$. Here $k = 1, 2$.



Mass matrix for the neutrino sector

$$M_\nu = \begin{pmatrix} 0_{3\times3} & m_D & 0_{3\times3} \\ m_D & 0_{3\times3} & M \\ 0_{3\times3} & M^T & \mu \end{pmatrix}$$

$(\nu_L, \nu_R^C, N_R^C)^T$ interaction basis

This allow us to have O(1) Yukawa couplings with minimal particle content and symmetries.

The model: 2 loops Inverse Seesaw

- We explored two DM candidates scenarios, where ρ is the scalar DM and Ω is the fermionic one
- Some of the physical masses can be derivate directly from the scalar potential and as a consequence of the spontaneous breaking of the global $U(1)_X$ symmetry, we have the masses of the CP even and CP odd part of ρ degenerate

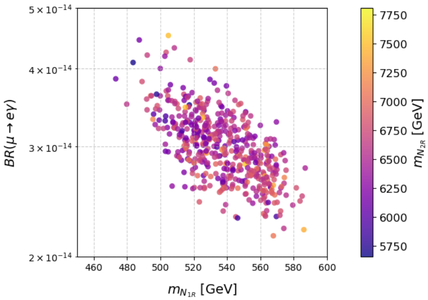
$$\phi = \begin{pmatrix} \phi^+ \\ \frac{v_\phi + h + i\xi}{\sqrt{2}} \end{pmatrix}, \quad \sigma = \frac{v_\sigma + \sigma_R + i\sigma_I}{\sqrt{2}}, \quad \rho = \frac{\rho_R + i\rho_I}{\sqrt{2}}.$$

$$\begin{aligned} m^2_{\rho_R} &= \mu^2_\rho + \frac{1}{2}\lambda_{\rho\sigma} v^2_\sigma + \frac{1}{2}\lambda_{\phi\rho} v^2_\phi \\ m^2_{\rho_I} &= \mu^2_\rho + \frac{1}{2}\lambda_{\rho\sigma} v^2_\sigma + \frac{1}{2}\lambda_{\phi\rho} v^2_\phi \\ m^2_\xi &= 0 \\ m^2_{\sigma_I} &= 0 \end{aligned}$$

(some) RESULTS

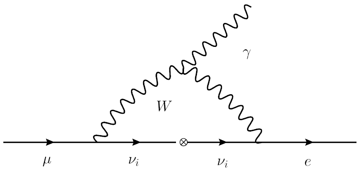
Charged Lepton Flavor Violation

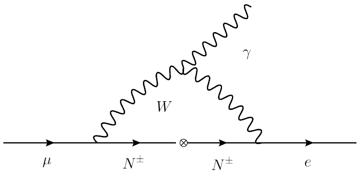
We study the charged lepton flavor violation processes due to the mixing between the light active and heavy sterile neutrino of the model.



Scatter plot between the branching ratio of the process $\mu \to e\gamma$ and the mass of the lightest Majorana neutrino, considering different values of the mass of the heaviest Majorana neutrino.

The branching ratio for the one-loop decay $l_i \to l_j\gamma$ is given by the following diagrams:

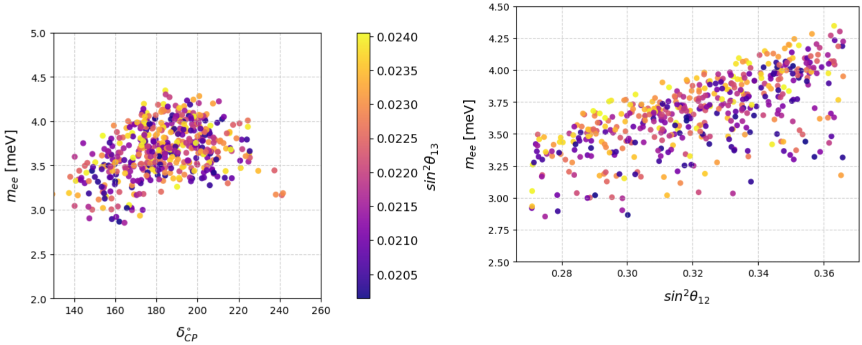




Charged Lepton Flavor Violation

- Our model can indicates the nature of the neutrino: a **Majorana neutrino** due to the effective Majorana neutrino mass parameter of the neutrinoless double beta decay ($0\nu\beta\beta$).

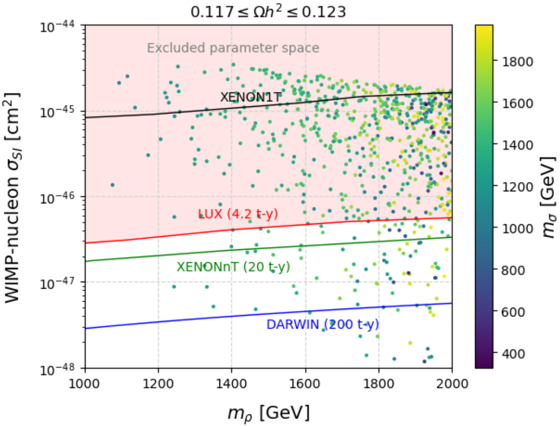
This observable depends on the mixing and mass of the light-active neutrinos.

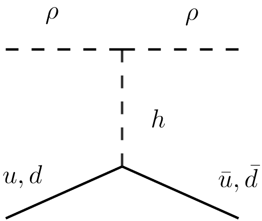


Correlation plot between the effective mass of the neutrinoless double beta decay and a) CP violation phase, for different values of the mixing angle $\sin^2\theta_{13}$ (reactor) and b) for the mixing angle $\sin^2\theta_{12}$ (solar).

Scalar Dark Matter: Direct Detection

For the scalar DM candidate we have contributions from annihilation processes in SM particles and for diagrams of annihilation processes in σ particles.



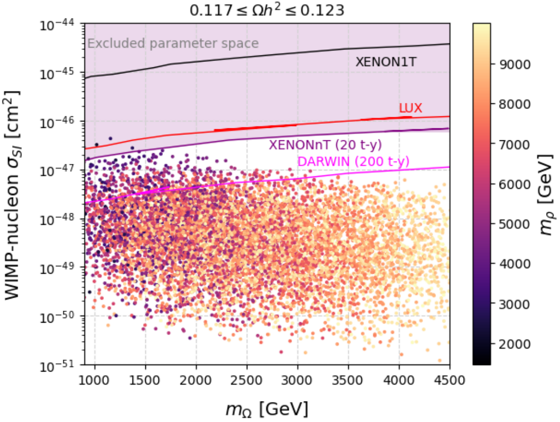


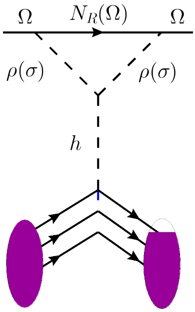
$$\sigma_{SI} = \frac{f_n^2 m_n^4 \lambda_{\rho\phi}^2}{8\pi m_h^4 m_\rho^2}$$

arXiv: 1712.02792v2

All the points satisfy the relic density of DM at 3σ C.L.

Fermionic Dark Matter: Direct Detection





$$\sigma_{SI} = \left(\frac{m_n}{v}\right)^2 \frac{(\mu_{DM-n})^2 g^2_{\bar{f}fh}}{\pi M_h^4} f_n^2 ,$$

arXiv: 2411.13895v2

Correlation plot of WIMP-nucleon σ_{SI} [cm^2] between the mass of the fermionic DM candidate m_Ω and for differeent values of relic density. All the points satisfy the relic density of DM at 3σ C.L.

where μ_{DM-n} is the reduced mass and $g_{\bar{f}fh}$ is the effective coupling between DM and the Higgs.

Conclusions

- Neutrino masses can be generated via two loop level inverse seesaw
- Our work favors the normal neutrino mass hierarchy, due to the relationship between the effective Majorana neutrino mass parameter m_{ee}, the mixing angle and CP violation phase
- The BR of the process $\mu \to e\gamma$ for the lightest Majorana neutrino is below the current experimental limit, which is in line with the sensitivities that MEG II and COMET would obtain
- Dark matter fermionic and scalar, can be accommodated in the 2 loops inverse seesaw model

Acknowledgements

Figura: Universidad Técnica Federico Santa María, Valparaíso, Chile.

We have a good and active research group where Antonio Cárcamo-Hernández is the supervisor

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EXTRA SLIDES

1607.08461 SM diagrams

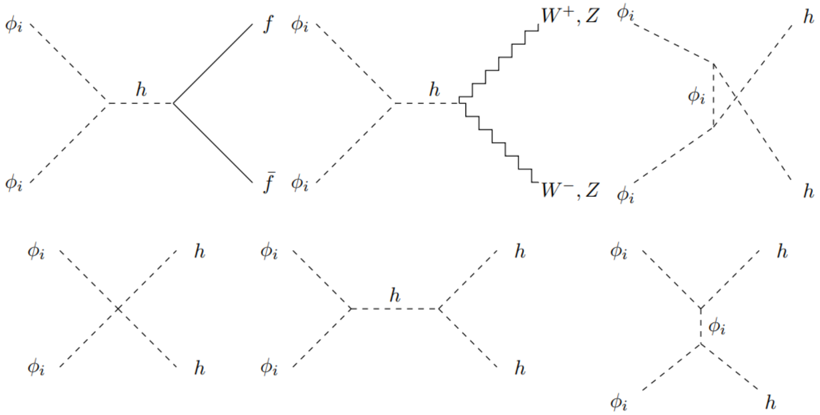


Figure 1. Diagrams contributing to $\phi_i\phi_i$ annihilation to SM particles ($i = \{1, 2\}$ in two component set up).

1607.08461 equations

$$
\begin{aligned}
(\sigma v)_{\phi_1\phi_1\to f\bar{f}} &= \frac{1}{4\pi s\sqrt{s}}\frac{N_c\lambda_1^2 m_f^2}{(s-m_h^2)^2+m_h^2\Gamma_h^2}(s-4m_f^2)^{\frac{3}{2}}\ , \\
(\sigma v)_{\phi_1\phi_1\to W^+W^-} &= \frac{\lambda_1^2}{8\pi}\frac{s}{(s-m_h^2)^2+m_h^2\Gamma_h^2}(1+\frac{12m_W^4}{s^2}-\frac{4m_W^2}{s})(1-\frac{4m_W^2}{s})^{\frac{1}{2}}\ , \\
(\sigma v)_{\phi_1\phi_1\to ZZ} &= \frac{\lambda_1^2}{16\pi}\frac{s}{(s-m_h^2)^2+m_h^2\Gamma_h^2}(1+\frac{12m_Z^4}{s^2}-\frac{4m_Z^2}{s})(1-\frac{4m_Z^2}{s})^{\frac{1}{2}}\ , \\
(\sigma v)_{\phi_1\phi_1\to hh} &= \frac{\lambda_1^2}{16\pi s}\left[1+\frac{3m_h^2}{(s-m_h^2)}-\frac{4\lambda_1 v^2}{(s-2m_h^2)}\right]^2(1-\frac{4m_h^2}{s})^{\frac{1}{2}}\ , \\
(\sigma v)_{\phi_1\phi_1\to SM} &= (\sigma v)_{\phi_1\phi_1\to f\bar{f}}+(\sigma v)_{\phi_1\phi_1\to W^+W^-}+(\sigma v)_{\phi_1\phi_1\to ZZ} \\
&\quad +(\sigma v)_{\phi_1\phi_1\to hh}\ ;
\end{aligned}
$$

1607.08461 other diagrams and equations for $m_\rho > m_\sigma$

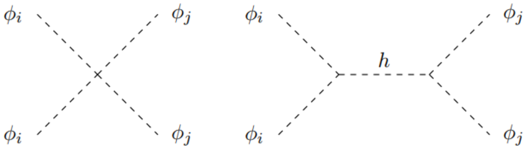
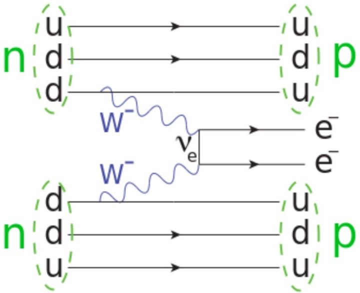


Figure 2. Diagrams contributing to DM conversion in $\mathcal{Z}_2 \times \mathcal{Z}_2'$ model $(i, j = 1, 2;\ i \neq j)$.

$$(\sigma v)_{\phi_1\phi_1 \to \phi_2\phi_2} = \frac{\sqrt{s - 4m_{\phi_2}^2}}{8\pi s\sqrt{s}} \left[\frac{v^4 \lambda_1^2 \lambda_2^2}{(s - m_h^2)^2 + m_h^2 \Gamma_h^2} + \frac{2(s - m_h^2) v^2 \lambda_1 \lambda_2 \lambda_3}{(s - m_h^2)^2 + m_h^2 \Gamma_h^2} + \lambda_3^2 \right] .$$

Neutrinoless double beta decay



The effective Majorana neutrino mass parameter is given by

$$m_{\beta\beta} = \left| \sum_j m_{\nu_j} U_{ej}^2 \right|$$

where U_{ej}^2 and $m_{\nu j}$ j are the PMNS mixing matrix elements and the Majorana neutrino masses, respectively.