Decays of Heavy Scalars in the Grimus–Neufeld Model

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Motivation

- The Grimus-Neufeld model (GNM) is an extension of the Standard Model (SM) and is used to explain neutrino masses
  - Adds a second Higgs doublet and a Majorana neutrino singlet
- It is a general two Higgs doublet model (2HDM);
- We consider the lifetimes of the scalar dark matter candidates of the GNM.

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- The Higgs Lagrangian is:

$$\mathcal{L}_{\mathrm{H}} = \sum_{j=1}^{2} \left(D_\mu H_j\right) \left(D^\mu H_j^\dagger\right) - V\left(H_1, H_2\right), \qquad (1)$$

where H_j are the Higgs doublets and $V\left(H_1, H_2\right)$ is the general Higgs potential;

- The Higgs doublets[1] in Higgs and mass bases are

$$H_1 = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}\left(\sum_S R_{h_1 S} S + v\right) \end{pmatrix}, \; H_2 = \begin{pmatrix} h_2^+ \\ \frac{1}{\sqrt{2}} \sum_S (R_{h_2 S} + i R_{h_3 S}) S \end{pmatrix}, \qquad (2)$$

where $S = \{h_0, H_0, A\}$, v is the vev, and $R_{h_i S}$ are elements of the Higgs rotation matrix R.

[1] In unitary gauge.

The Grimus-Neufeld model (Yukawa sector)

- The Yukawa Lagrangian is

$$-\mathcal{L}_{\mathrm{Y}} = \sum_{i,j,k} \left(Y_L^{(i)}\right)_{jk} \bar{L}_j P_R H_i \ell_{Rk} + \frac{1}{2} \sum_{i,j} \left(Y_N^{(i)}\right)_j \bar{\hat{N}} P_L \tilde{H}_i L_j + h.c., \qquad (3)$$

  - $Y_L^{(i)}$ are the leptonic Yukawas
  - L is the left-handed leptonic doublet
  - ℓ_R is the right-handed leptonic singlet
  - N is the Majorana neutrino singlet;
- Lorentz Covariant Conjugation $\hat{N} = \gamma_0 C N^\star$;

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The Grimus-Neufeld model (Neutrino Yukawas)

- The neutrino Yukawas are

$$\vec{Y}_N^{(1)} = y\vec{\mathrm{v}}_3 \equiv -i\frac{\sqrt{2m_3m_4}}{v}\vec{\mathrm{v}}_3 \ \text{ and } \ \vec{Y}_N^{(2)} = d\vec{\mathrm{v}}_2 + d'\vec{\mathrm{v}}_3 \,, \quad (4)$$

where $\vec{\mathrm{v}}_i$ are columns of the PMNS matrix V, i.e.

$$V = \begin{pmatrix} \vec{\mathrm{v}}_1 & \vec{\mathrm{v}}_2 & \vec{\mathrm{v}}_3 \end{pmatrix} . \quad (5)$$

For normal hierarchy we have m_3 as the seesaw mass and m_4 as the heavy neutrino mass, which are generated at tree-level via the seesaw mechanism;

- The neutrino mass m_2 is generated via radiative corrections at 1-loop level;
- If $y \to 0$, the GNM gets an additional Z_2 symmetry.

The decay rates (1)

- The decay rates are calculated in the tiny seesaw regime, i.e. $y \leq 10^{-6}$ or $m_4 \leq 10$ GeV
  - Z_2 symmetry is approximate;
- The decays into two gauge bosons, charged fermions, a charged boson and a charged Higgs, and a neutral boson into a neutral Higgs matches with literature;

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The decay rates (2)

- The decay rates into neutrinos are:
  - $\Gamma_{S\to n_2 n_3} = \frac{m_S}{16\pi} s^2 d^2 R_S^+ R_S^-$;
  - $\Gamma_{S\to n_2 n_4} = \frac{(m_S^2 - m_4^2)^2}{16\pi m_S^3} c^2 d^2 R_S^+ R_S^-$;
  - $\Gamma_{S\to n_3 n_3} = \frac{m_S}{32\pi} 4 s^2 c^2 |B_S^+|^2$;
  - $\Gamma_{S\to n_3 n_4} = \frac{(m_S^2 - m_4^2)^2}{16\pi m_S^3} (c^2 - s^2)^2 |B_S^+|^2$;
  - $\Gamma_{S\to n_4 n_4} = \frac{\sqrt{m_S^2 - 4m_4^2}}{8\pi m_S^2} s^2 c^2 \left[(m_S^2 - 2m_4^2)|B_S^+|^2 - 2m_4^2 \mathrm{Re}[B_S^{+\,2}] \right]$
    - n_i are the neutrino mass eigenstates $(i = 1, 2, 3, 4)$
    - $B_S^+ = yR_{h_1 S} + id' R_S^+$ and $R_S^\pm = R_{h_2 S} \pm iR_{h_3 S}$
    - $s^2 \equiv \sin^2\theta = \frac{m_3}{m_3 + m_4}$ is the sine of the seesaw angle and $c^2 = 1 - s^2$.

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The Inert Doublet model limit (1)

- The Inert Doublet Model (IDM) is a 2HDM model, where the Higgs mixing matrix $R = 1_{3\times 3}$, and the Z_2 symmetry is conserved
  - No coupling to neutrinos!
- The GNM has a similar coupling structure to the IDM;
- In a CP conserving case and $Y_L^{(2)} = 0$ the GNM pseudoscalar decays only into neutrinos;
- In this case the GNM pseudoscalar A resembles the IDM pseudoscalar;

The Inert Doublet model limit (2)

- The decay $\Gamma_{m_4}^{\mathrm{limit}} = \Gamma_{A \to n_2 n_3}$ in the limit $Y_L^{(2)} = 0$, taking $R = 1_{3\times 3}$:

$$\Gamma_{m_4}^{\mathrm{limit}} = \frac{m_A}{16\pi} s^2 d^2 \tag{6}$$

- The decay rate $\Gamma_{m_4}^{\mathrm{limit}}$ is proportional to $d^2 \sim \frac{1}{\Lambda}$, where [2]

$$\Lambda = \frac{m_4}{32\pi^2} \left[B_0(0, m_4^2, m_A^2) - B_0(0, m_4^2, m_{H_0}^2) \right] . \tag{7}$$

[2] Vytautas Dūdėnas, Thomas Gajdosik, Uladzimir Khasianevich, Wojciech Kotlarski, and Dominik Stöckinger, "Charged Lepton Flavor Violating Processes in the Grimus-Neufeld Model", Journal of High Energy Physics 2022, 9 (2022)

The Inert Doublet model limit (3)

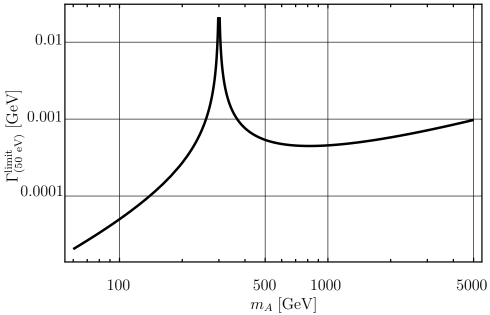

Figure: The lower limit on the decay rate of the pseudoscalar A in the IDM limit, when $m_{H_0} = 300$ GeV and $m_4 = 50$ eV. The lifetimes for $m_A = 60$ GeV are 0.0012 s for $m_4 = 10$ GeV and 3.2×10^{-20} s for $m_4 = 50$ eV.

Conclusions

- The GNM pseudoscalar with the mass 60 GeV can have a lifetime of 0.0012 s, which excludes it as a dark matter candidate!
  - The scalar H_0 is also excluded, since in the limit it couples to even more fields!
- The slight Z_2 symmetry breaking required in the GNM to generate neutrino masses is enough to have a large phenomenological impact, i.e. the stability of the scalars.

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- Expanded versions:

$$\Lambda = \frac{m_4}{32\pi^2}\Big(\frac{\ln x}{1-x} - \frac{\ln y}{1-y}\Big), \tag{8}$$

where $x = m_4^2/m_A^2$ and $y = m_4^2/m_{H_0}^2$.

$$\begin{aligned}\Xi_{SS'S''} = \frac{1}{v^2} R_{h_1S}[(\delta_{S'S''} - R_{h_1S'}R_{h_1S''}) \\ \times (\lambda_3 v^2 - 2m_{h_2^+}^2 + m_{S'}^2) + \delta_{S'S''} m_{S'}^2] \\ + \mathrm{Re}[\lambda_7 R_S^+ R_{S'}^+ R_{S''}^-] + \text{cyclic permutations of } \{S, S', S''\} \ .\end{aligned} \tag{9}$$

Backup

- The neutrino mass matrix M_ν is diagonalised using a unitary matrix U:

$$U^T M_\nu U = \mathrm{diag}\,(m_1, m_2, m_3, m_4)\,; \tag{10}$$

$$M_\nu = \begin{pmatrix} 0_{3\times 3} & \frac{v}{\sqrt{2}}(\vec{Y}_N^{(1)}) \\ \frac{v}{\sqrt{2}}(\vec{Y}_N^{(1)})^T & M \end{pmatrix}\,; \tag{11}$$

  - The matrix U can be decomposed as

$$U = \begin{pmatrix} U_L \\ U_R^* \end{pmatrix} = \begin{pmatrix} \vec{\mathrm{v}}_1^* & \vec{\mathrm{v}}_2^* & c\,\vec{\mathrm{v}}_3^* & is\,\vec{\mathrm{v}}_3^* \\ 0 & 0 & is & c \end{pmatrix}. \tag{12}$$