Generalizing the Scotogenic model

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MultiDark

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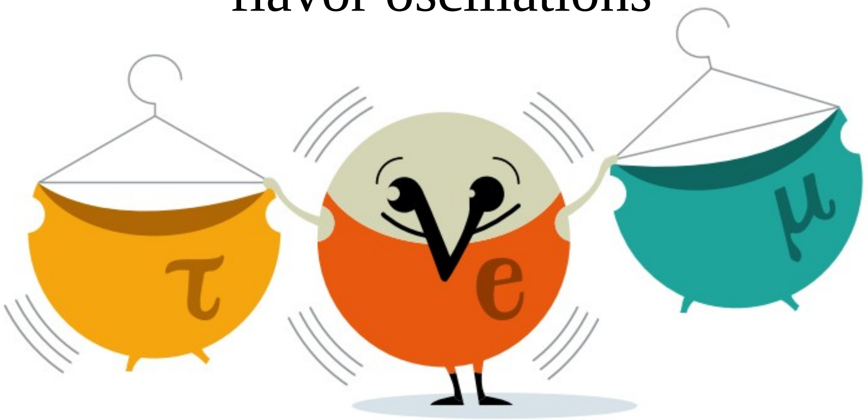
1. Introduction

The Standard Model (SM)
is an incomplete theory and therefore must be extended

- Experimental observation of neutrino flavor oscillations



- Nature of the dark matter of the universe

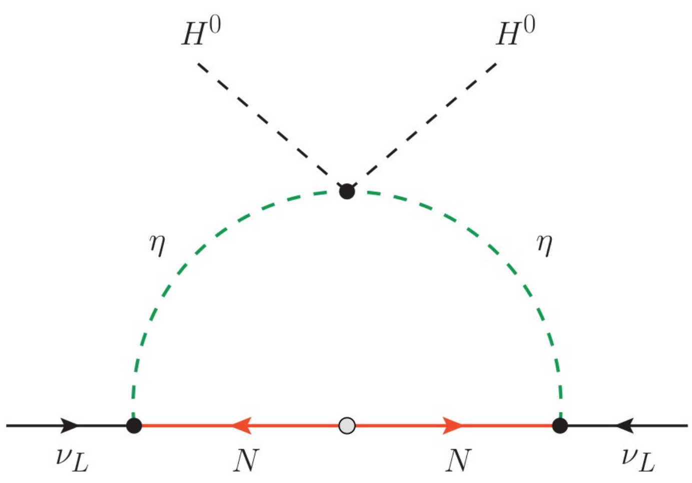
Many models have been proposed but one appealing possibility are radiative models

One of the most popular radiative models proposed to generate neutrino masses is the **Scotogenic model**.

Scotogenic model = SM + 3 singlet fermions + 1 scalar doublet + a dark $\mathbb{Z}_2$ parity

[Ma, hep-ph/0601225]

- It induces neutrino masses at the 1-loop level
- It obtains a weakly-interacting DM candidate



○ Many variations and extensions have emerged since its appearance:
  - colored versions, using additional states and/or symmetries, etc.

⇨ We are going to introduce the *general Scotogenic model*, with arbitrary numbers of generations of the Scotogenic states.

General Scotogenic model (n_N, n_η)

=

SM + n_N singlet fermions (N) + n_η scalar doublet (η) + a dark $\mathbb{Z}_2$ parity

2. The general Scotogenic model

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SM + n_N singlet fermions (N) + n_η scalar doublet (η) + a dark $\mathbb{Z}_2$ parity

We focused on computing the neutrino mass matrix in the general setup.

Yukawa and Majorana mass terms

$$\mathcal{L}_N \supset y_{na\alpha}\,\overline{N}_n\,\eta_a\,\ell_L^\alpha + \frac{1}{2}\,M_{N_n}\,\overline{N^c}_n\,N_n + \text{h.c.}$$

$$n = 1,\ldots,n_N,\; a = 1,\ldots,n_\eta \text{ and } \alpha = 1,2,3$$

Scalar potential

$$\begin{aligned}\mathcal{V} = {} & m_H^2 H^\dagger H + \left(m_\eta^2\right)_{ab}\eta_a^\dagger\eta_b + \frac{1}{2}\lambda_1\left(H^\dagger H\right)^2 + \frac{1}{2}\lambda_2^{abcd}\left(\eta_a^\dagger\eta_b\right)\left(\eta_c^\dagger\eta_d\right) \\ & + \lambda_3^{ab}\left(H^\dagger H\right)\left(\eta_a^\dagger\eta_b\right) + \lambda_4^{ab}\left(H^\dagger\eta_a\right)\left(\eta_b^\dagger H\right) \\ & + \frac{1}{2}\left[\lambda_5^{ab}\left(H^\dagger\eta_a\right)\left(H^\dagger\eta_b\right) + \text{h.c.}\right]\end{aligned}$$

2. The general Scotogenic model

Scalar potential

$$\mathcal{V} = m_H^2 H^\dagger H + \left(m_\eta^2\right)_{ab} \eta_a^\dagger \eta_b + \frac{1}{2} \lambda_1 \left(H^\dagger H\right)^2 + \frac{1}{2} \lambda_2^{abcd} \left(\eta_a^\dagger \eta_b\right) \left(\eta_c^\dagger \eta_d\right)$$
$$+ \lambda_3^{ab} \left(H^\dagger H\right) \left(\eta_a^\dagger \eta_b\right) + \lambda_4^{ab} \left(H^\dagger \eta_a\right) \left(\eta_b^\dagger H\right)$$
$$+ \frac{1}{2} \left[\lambda_5^{ab} \left(H^\dagger \eta_a\right) \left(H^\dagger \eta_b\right) + \text{h.c.}\right]$$

- Vacuum configuration: $\langle H^0 \rangle = \frac{v}{\sqrt{2}} \quad , \quad \langle \eta_a^0 \rangle = 0$

⇨ The electroweak symmetry gets broken in the standard way.

⇨ The $\mathbb{Z}_2$ symmetry remains unbroken and the stability of the lightest $\mathbb{Z}_2$-charged particle is guaranteed.

- If all the scalar potential parameters are real, CP is conserved in the scalar sector.

⇨ The real and imaginary components of the neutral scalar doublets do not mix

$$\eta_a^0 = \frac{1}{\sqrt{2}} \left(\eta_{R_a} + i\, \eta_{I_a}\right)$$

2. The general Scotogenic model

- After EW symmetry breaking,

$$\eta_a^0 = \frac{1}{\sqrt{2}} \left(\eta_{R_a} + i\, \eta_{I_a} \right)$$

$$(\mathcal{M}_R^2)_{ab} = (m_\eta)^2_{aa}\, \delta_{ab} + \left(\lambda_3^{ab} + \lambda_4^{ab} + \lambda_5^{ab} \right) \frac{v^2}{2}$$

$$(\mathcal{M}_I^2)_{ab} = (m_\eta)^2_{aa}\, \delta_{ab} + \left(\lambda_3^{ab} + \lambda_4^{ab} - \lambda_5^{ab} \right) \frac{v^2}{2}$$

If $\lambda_5^{ab} \to 0$
$\left(\mathcal{M}_R^2\right)_{ab} = \left(\mathcal{M}_I^2\right)_{ab}$

- Change of basis matrices from mass to gauge eigenstates : $\eta_A = V_A\, \hat{\eta}_A$

- We can simplify the results using these assumptions:

$$\lambda_{3,4}^{aa} \frac{v^2}{2} \ll \left(m_\eta^2 \right)_{aa} \quad \text{and} \quad \lambda_5^{ab} \ll \lambda_{3,4}^{ab} \ll 1$$

Mass eigenvalues

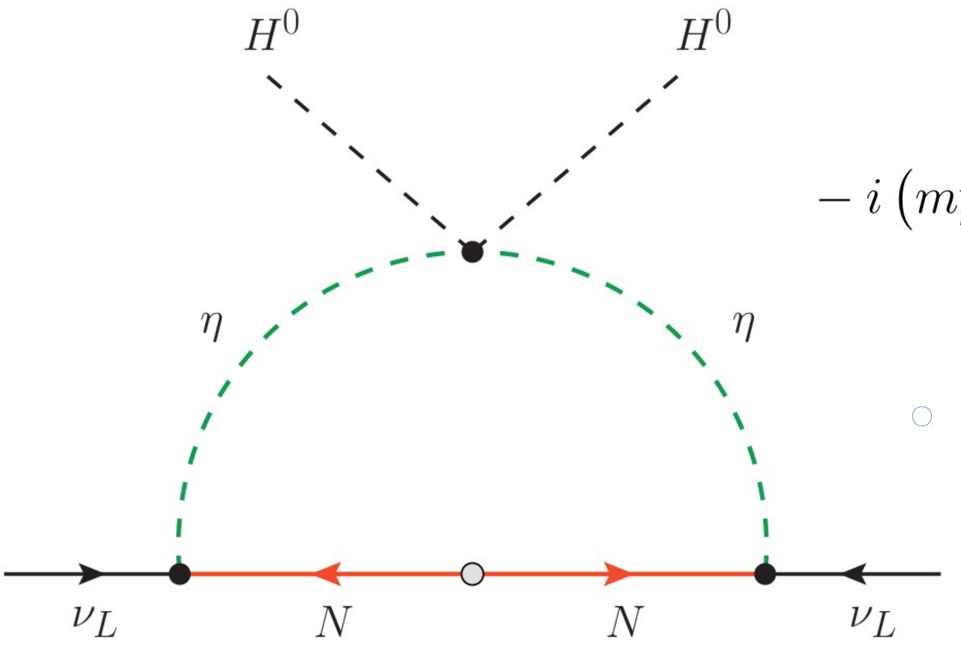
$$m_{R_a}^2 = \left(m_\eta^2 \right)_{aa} + \left(\lambda_3^{aa} + \lambda_4^{aa} + \lambda_5^{aa} \right) \frac{v^2}{2}$$

$$m_{I_a}^2 = \left(m_\eta^2 \right)_{aa} + \left(\lambda_3^{aa} + \lambda_4^{aa} - \lambda_5^{aa} \right) \frac{v^2}{2}$$

Scalar mixing angles

$$\tan 2\,\theta_A^{ab} = \frac{2\,(\mathcal{M}_A^2)_{ab}}{(\mathcal{M}_A^2)_{bb} - (\mathcal{M}_A^2)_{aa}} = \left(\lambda_3^{ab} + \lambda_4^{ab} + \kappa_A^2\, \lambda_5^{ab} \right) \frac{v^2}{m_{A_b}^2 - m_{A_a}^2}$$

$(\kappa_R^2 = +1 \text{ and } \kappa_I^2 = -1)$



$$-i\left(m_\nu^A\right)^{an}_{\alpha\beta} = C^A_{na\alpha}\int \frac{\mathrm{d}^D k}{(2\pi)^D}\,\frac{i}{k^2 - m^2_{A_a}}\,\frac{i\left(\not{k} + M_{N_n}\right)}{k^2 - M^2_{N_n}}\,C^A_{na\beta}$$

- Where $C^A_{na\alpha}$ is the $N_n - \eta_{A_a} - \nu^\alpha_L$ coupling:

$$C^A_{na\alpha} = i\,\frac{\kappa_A}{\sqrt{2}}\sum_b \left(V_A\right)^*_{ba}\,y_{nb\alpha}$$

$$\left(m_\nu\right)_{\alpha\beta} = \sum_{A,a,n}\left(m_\nu^A\right)^{an}_{\alpha\beta}$$

$(\kappa_R^2 = +1 \text{ and } \kappa_I^2 = -1)$

$$\boxed{\left(m_\nu\right)_{\alpha\beta} = -\frac{1}{32\pi^2}\sum_{A,a,b,c,n} M_{N_n}\,\kappa_A^2\left(V_A\right)_{ba}\left(V_A\right)_{ca}\,y_{nb\alpha}\,y_{nc\beta}\,B_0(0, m^2_{A_a}, M_{N_n})}$$

Passarino-Veltman function: $B_0\left(0, m^2_{A_a}, M^2_{N_n}\right) = \Delta_\varepsilon + 1 - \dfrac{m^2_{A_a}\log m^2_{A_a} - M^2_{N_n}\log M^2_{N_n}}{m^2_{A_a} - M^2_{N_n}}$

3. Neutrino masses

Exact neutrino mass matrix formula

$$(m_\nu)_{\alpha\beta} = -\frac{1}{32\pi^2} \sum_{A,a,b,c,n} M_{N_n}\, \kappa_A^2\, (V_A)_{ba}\, (V_A)_{ca}\, y_{nb\alpha}\, y_{nc\beta}\, B_0(0, m_{A_a}^2, M_{N_n})$$

Approximate neutrino mass matrix

$$(m_\nu)_{\alpha\beta} = \frac{v^2}{32\pi^2} \sum_{n,a,b} \frac{y_{na\alpha}\, y_{nb\beta}}{M_{N_n}}\, \Gamma_{abn} + \mathcal{O}\left(\lambda_5^2\right) + \mathcal{O}\left(\lambda_5\, s^2\right)$$

$$s_{ab} = \frac{1}{2}\left(\lambda_3^{ab} + \lambda_4^{ab}\right) \frac{v^2}{m_b^2 - m_a^2} \ll 1$$

$$\Gamma_{abn} = \delta_{ab}\, \lambda_5^{aa}\, f_{an} - (1 - \delta_{ab}) \left[\left(\lambda_5^{aa}\, f_{an} - \lambda_5^{bb}\, f_{bn}\right) s_{ab} - \frac{M_{N_n}^2}{m_b^2 - m_a^2}\, \lambda_5^{ab}\, g_{abn}\right]$$

Loop functions

$$f_{an} = \frac{M_{N_n}^2}{m_a^2 - M_{N_n}^2} + \frac{M_{N_n}^4}{\left(m_a^2 - M_{N_n}^2\right)^2} \log\frac{M_{N_n}^2}{m_a^2} \qquad g_{abn} = \frac{m_a^2}{m_a^2 - M_{N_n}^2} \log\frac{M_{N_n}^2}{m_a^2} - \frac{m_b^2}{m_b^2 - M_{N_n}^2} \log\frac{M_{N_n}^2}{m_b^2}$$

4. High-energy behavior

Possible problem :

- The RGE flow can alter the shape of the potential and lead to the breaking of the $\mathbb{Z}_2$ symmetry.
- In the absence of the $\mathbb{Z}_2$ symmetry at high energies, neutrinos would acquire masses at tree-level and the DM candidate would no longer be stable.

1-loop β function for $(m_\eta^2)_{ab}$

$$\left(\beta_{m_\eta^2}\right)_{ab} = -\frac{9}{10} g_1^2 \left(m_\eta^2\right)_{ab} - \frac{9}{2} g_2^2 \left(m_\eta^2\right)_{ab} + \sum_{c,d=1}^{n_\eta} \left[4\,\lambda_2^{abcd} \left(m_\eta^2\right)_{dc} + 2\,\lambda_2^{acdb} \left(m_\eta^2\right)_{cd}\right]$$

$$+ \left[4\,\lambda_3^{ab} + 2\,\lambda_4^{ab}\right] m_H^2 + \left(m_\eta^2\right)_{ab} \sum_{n=1}^{n_N} \sum_{\alpha=1}^{3} \left(\left|y_{na\alpha}\right|^2 + \left|y_{nb\alpha}\right|^2\right) - 4\,\mathrm{Tr}\left[y_a^\dagger M_N^* M_N y_b\right]$$

$$y_a \equiv \left[y_{na\alpha}\right]$$

With large Yukawas and $M_N \geq m_\eta^2$ the trace term dominates the running.

⇒ The squared mass can eventually become negative and an η scalar acquires a VEV. $\cancel{\langle \eta_a^0 \rangle = 0}$

4. High-energy behavior

- We will concentrate on two versions of the general model:

(3, 1) model: 3 singlet fermions and 1 scalar doublet (the original Scotogenic model)

(1, 3) model: 1 singlet fermion and 3 scalar doublets

- Considerations to do the running:

1- We set all the parameters at the electroweak scale.

2- The potential must be bounded from below.

3- We must accommodate the neutrino squared mass differences and mixing angles. This can be done by means of an adapted Cassas-Ibarra parametrization.

[Casas, Ibarra, hep-ph/0103065]

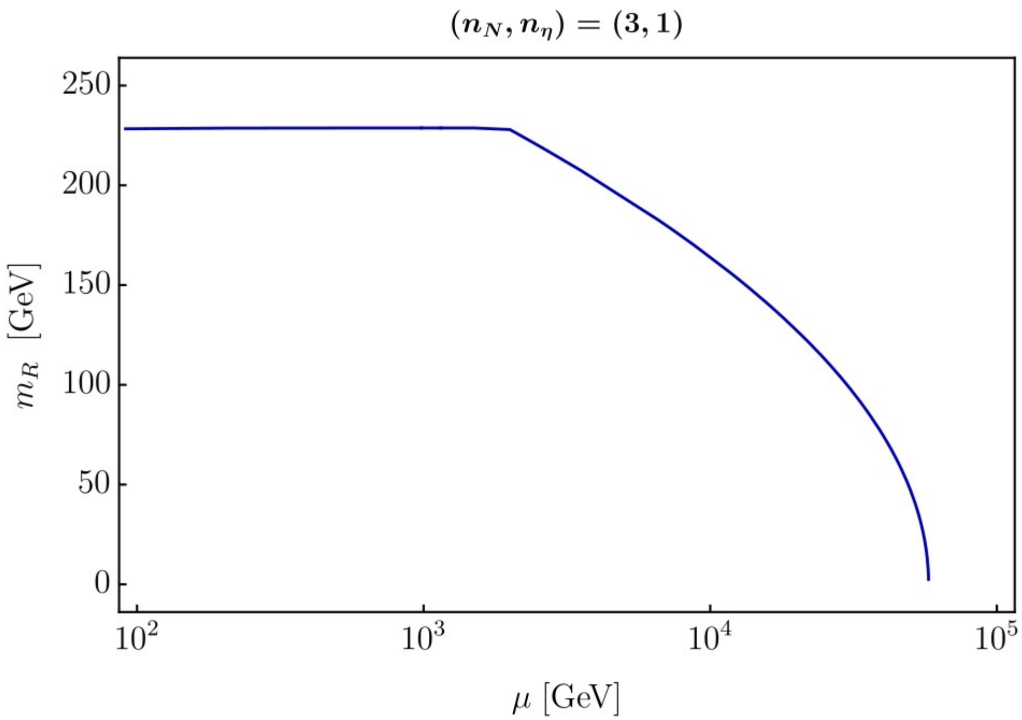
[Cordero-Carrión, Hirsch, Vicente, 1812.03896]

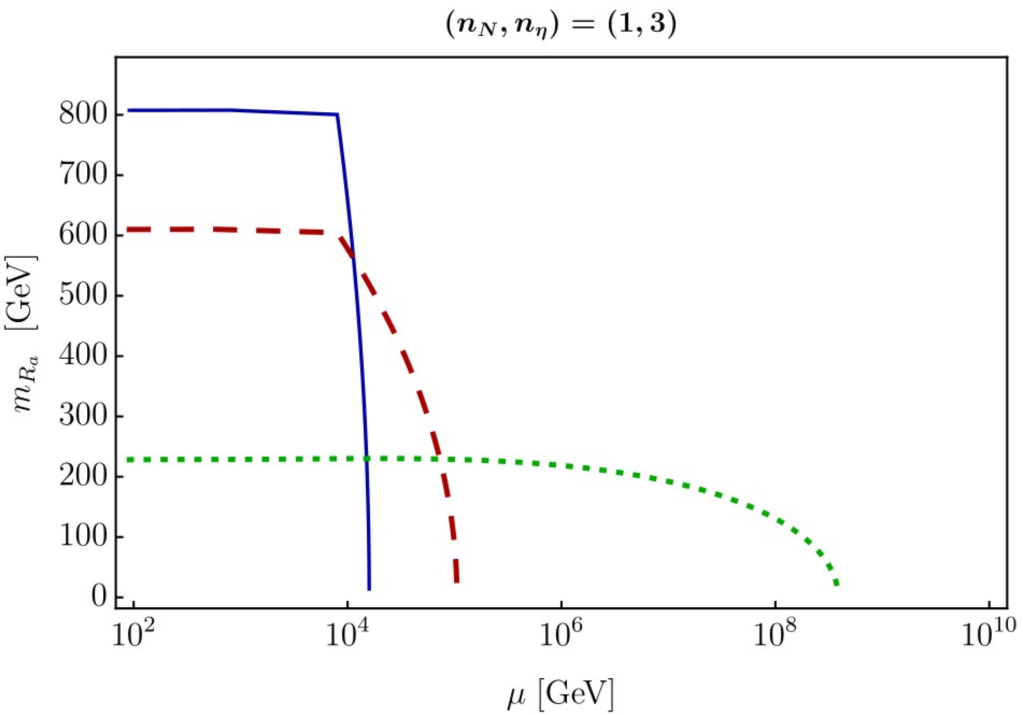
[Cordero-Carrión, Hirsch, Vicente, 1912.08858]

- We will be interested in the effect of the trace term, which seems to be dominant in the majority of the scenarios:

$$\lambda_5 \lll 1 \quad , \quad y_{n a \alpha} \sim 1$$

4. High-energy behavior



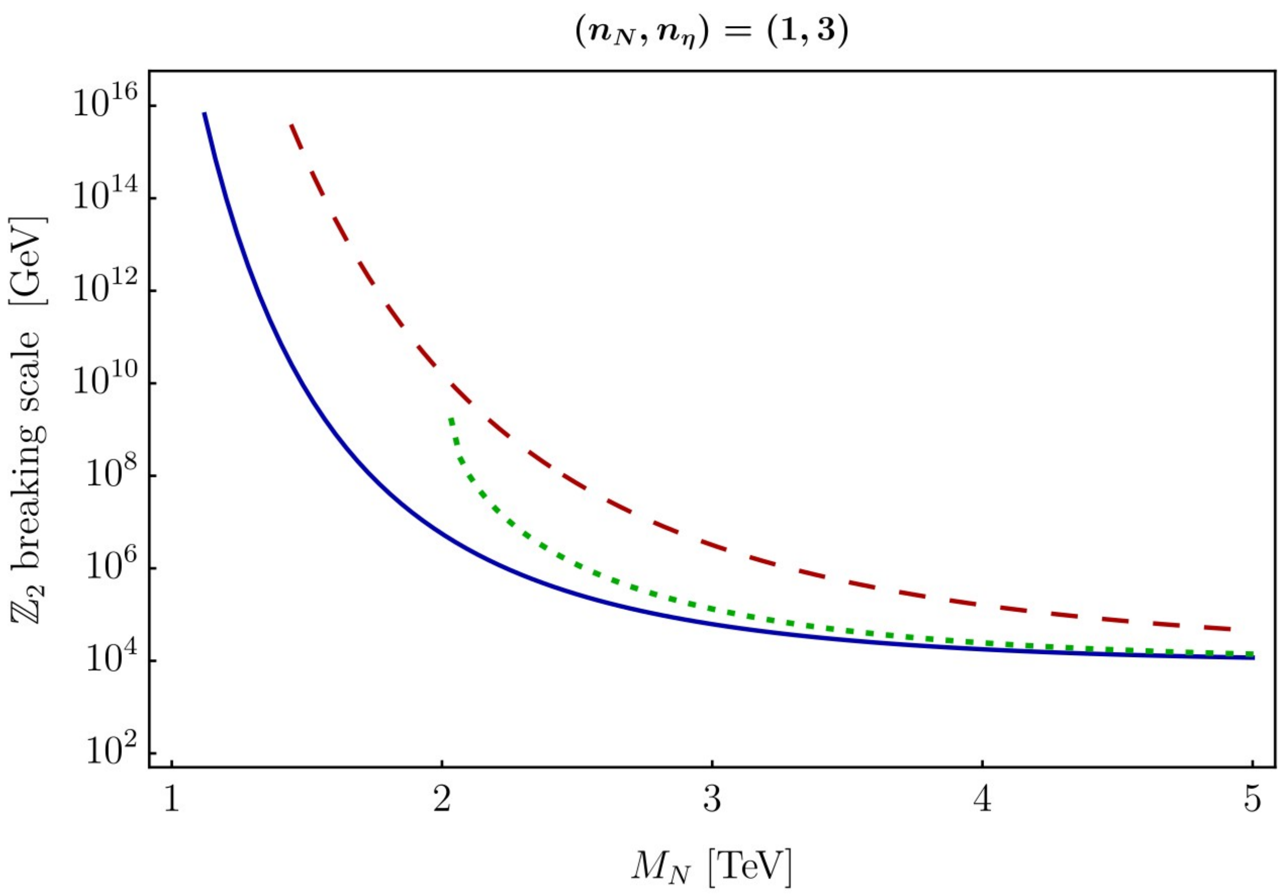


$$M_N = (1, 1.5, 2)\,\text{TeV}$$
$$\lambda_2 = \lambda_3 = \lambda_4 = 0.1$$
$$\lambda_5 = 10^{-9}$$
$$m_\eta^2 = (200\,\text{GeV})^2$$

$$M_N = 8\,\text{TeV}$$
$$\lambda_2^{aaaa} = \lambda_3^{aa} = \lambda_4^{aa} = 0.1$$
$$\lambda_5^{aa} = 10^{-9}$$
$$m_\eta^2 = (200^2, 600^2, 800^2)\text{GeV}^2$$

⇨ The drastic change in the evolution of the masses occurs when the heaviest singlet becomes active.

4. High-energy behavior



Red

$$\lambda_2^{aaaa} = \lambda_3^{aa} = \lambda_4^{aa} = 0.1$$
$$\lambda_5^{aa} = 10^{-9}$$
$$m_\eta^2 = (200^2, 600^2, 800^2)\mathrm{GeV}^2$$

Blue

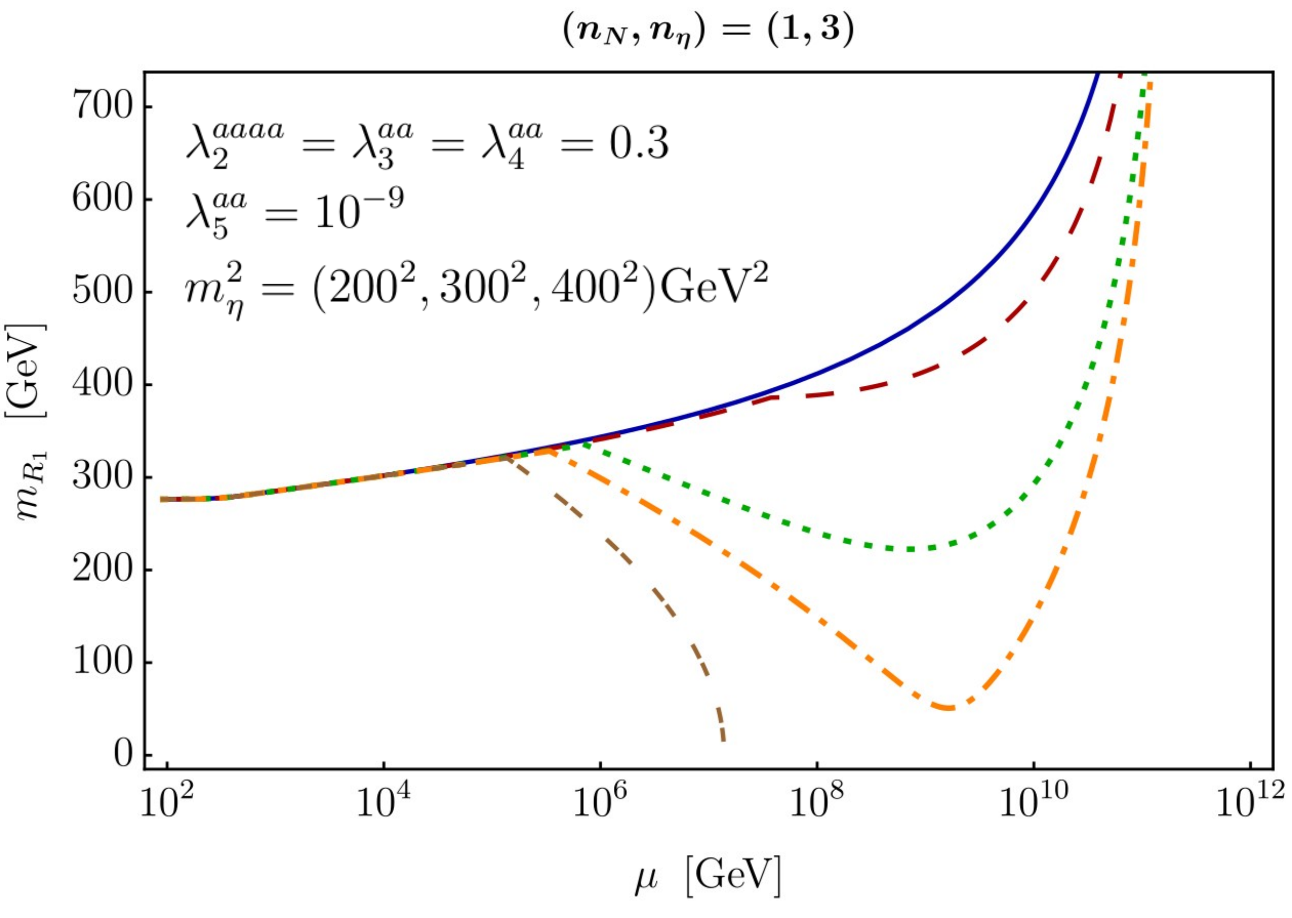
$$\lambda_2^{aaaa} = \lambda_3^{aa} = \lambda_4^{aa} = 0.1$$
$$\lambda_5^{aa} = 10^{-9}$$
$$m_\eta^2 = (200^2, 300^2, 400^2)\mathrm{GeV}^2$$

Green

$$\lambda_2^{aaaa} = \lambda_3^{aa} = \lambda_4^{aa} = 0.3$$
$$\lambda_5^{aa} = 10^{-9}$$
$$m_\eta^2 = (200^2, 300^2, 400^2)\mathrm{GeV}^2$$

- As expected, the symmetry breaking scale decreases for larger singlet masses because the effect of the trace term becomes stronger.
- We will focus now on the green curve, for which the breaking begins at 2 TeV

4. High-energy behavior



Blue

$M_N = 1\,\mathrm{TeV}$

Red

$M_N = 1.5\,\mathrm{TeV}$

Green

$M_N = 1.9\,\mathrm{TeV}$

Orange

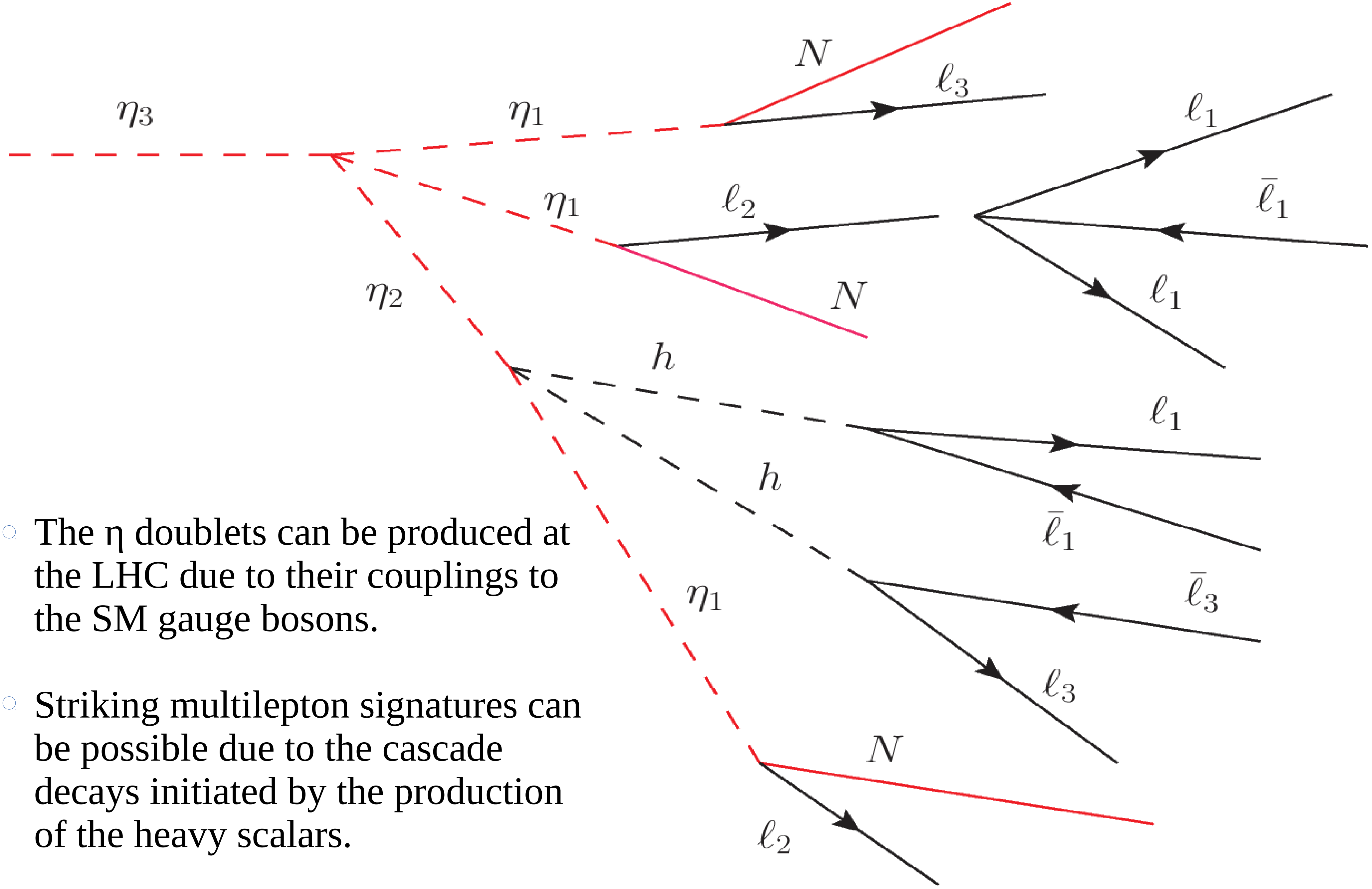
$M_N = 2.025\,\mathrm{TeV}$

Brown

$M_N = 2.2\,\mathrm{TeV}$

- The breaking only happens for $M_N \geq 2.2$ TeV.
- A Landau pole in the λ_2 quartic couplings is preventing the symmetry to break.

5. LHC signatures



- The η doublets can be produced at the LHC due to their couplings to the SM gauge bosons.
- Striking multilepton signatures can be possible due to the cascade decays initiated by the production of the heavy scalars.

6. Summary and discussion

- A generalization of the setup of the Scotogenic model to any number of generations of the BSM particles is provided in this work.

- The 1-loop neutrino mass matrix on the general version of the model has been calculated, exactly and approximately.

- The high-energy behavior of the model has been studied focusing on two specific variants.

  - The features of the original model are present in the multi-scalar version

- Our generalization offers several novel possibilities:

  - The η doublets can be produced at the LHC due to their couplings to the SM gauge bosons.

  - Striking multilepton signatures can be possible due to cascade decays initiated by the production of the heavier η.

  - The dark matter production rates might be affected by the additional scalar degrees of freedom.