Computing tools for the SMEFT: Exercises

Avelino Vicente

1 The Scotogenic model

The Scotogenic model is a popular model for neutrino masses proposed by Ernest Ma in [1]. The Standard Model (SM) particle content is extended by 3 generations of fermion singlets N and the scalar doublet η. The symmetries of the model are also extended with the addition of a *dark* $\mathbb{Z}_2$ parity, under which all the new fields are odd while the SM fields are assumed to be even. The new particles in the model as well as their representations under the gauge and global symmetry groups are shown in Tab. 1.1.

The Lagrangian of the model can be written as

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm NP} \, , \tag{1.1}$$

where $\mathcal{L}_{\rm SM}$ is the SM Lagrangian. The New Physics Lagrangian $\mathcal{L}_{\rm NP}$ contains all the terms involving N and η and can be further split as

$$\mathcal{L}_{\rm NP} = \mathcal{L}_N + \mathcal{L}_\eta + \mathcal{L}_{\eta H} + \mathcal{L}_{\rm Y} \, , \tag{1.2}$$

with

$$\mathcal{L}_N = i \overline{N}^\alpha \, \gamma_\mu D^\mu N^\alpha - \frac{1}{2} M_N^{\alpha\alpha} \, \overline{N^c}^{\,\alpha} \, N^\alpha \, , \tag{1.3}$$

$$\mathcal{L}_\eta = D_\mu \eta^\dagger \, D^\mu \eta - \mu_\eta^2 \, \eta^\dagger \, \eta - \lambda_2 \, \left(\eta^\dagger \eta \right)^2 \, , \tag{1.4}$$

$$\mathcal{L}_{\eta H} = - \lambda_3 \, H^\dagger H \, \eta^\dagger \eta - \lambda_4 \, H^\dagger \eta \, \eta^\dagger H - \frac{1}{2} \left[\lambda_5 \, \left(H^\dagger \eta \right)^2 + \text{h.c.} \right] \, , \tag{1.5}$$

$$\mathcal{L}_{\rm Y} = - Y_N^{\alpha\beta} \, \overline{N}^{\,\alpha} \, \ell_L^\beta \, \eta + \text{h.c.} \, . \tag{1.6}$$

Here $\alpha, \beta = 1, 2, 3$ are flavor indices and μ_η^2 is a parameter with dimensions of mass^2. M_N is a symmetric 3×3 Majorana mass matrix that can be taken diagonal without loss of generality, while Y_N is a general complex 3×3 Yukawa matrix. Finally, $\mathrm{SU}(3)_{\rm c}$ and $\mathrm{SU}(2)_{\rm L}$ contractions have been omitted to simplify the notation.

Some comments about the Scotogenic model:

- The $\mathbb{Z}_2$ symmetry is assumed to be exact, even after the spontaneous breaking of the electroweak symmetry. This implies that the η scalar does not acquire a vacuum expectation value, $\langle \eta \rangle = 0$.
- The conservation of $\mathbb{Z}_2$ forbids several Lagrangian terms. For instance, it forbids a Yukawa of the form $\overline{N} \, \ell_L \, H$. For this reason, neutrinos do not acquire masses at tree-level, but at the 1-loop level, as shown in Fig. 1.1.
- The lightest $\mathbb{Z}_2$-odd state is stable and can potentially be a valid dark matter candidate. This the reason behind the name of the model, which originates from the Greek word *skotos*, which means *darkness*.

	N	η
$\mathrm{SU(3)_c}$	**1**	**1**
$\mathrm{SU(2)_L}$	**1**	**2**
$\mathrm{U(1)_Y}$	0	$\frac{1}{2}$
$\mathbb{Z}_2$	$-$	$-$
GENERATIONS	3	1

Table 1.1: New particles in the Scotogenic model and representations under the gauge and global symmetries.

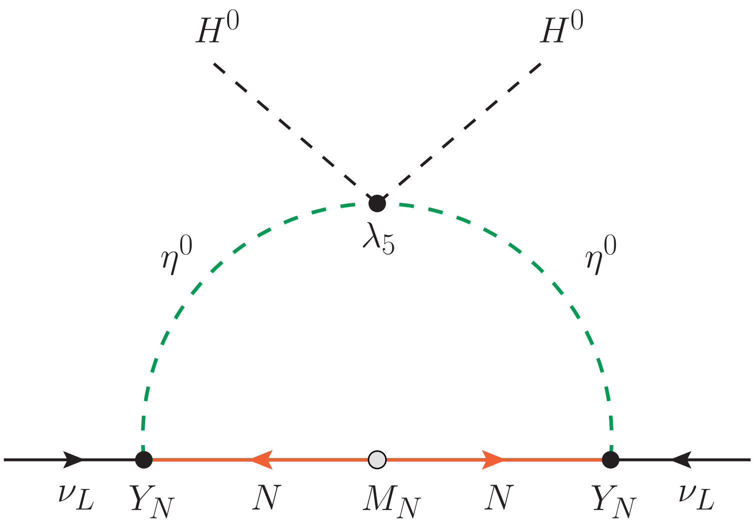

Figure 1.1: Generation of neutrino masses at the 1-loop level.

2 Questions

Q1: Implement the Scotogenic model in `matchmakereft`. Consider N^α and η as heavy fields. Keep in mind that the current version of this code does not allow for heavy fields carrying a generation index. How can you overcome this obstacle?

Q2: Compute the Wilson coefficient of the Weinberg operator by matching the Scotogenic model to the SMEFT. Does it agree with the result for the neutrino mass matrix given in the literature? You may compare your result with Equation (27) of [2].

Q3: Consider the parameter values

$$M_N = (10, 10.1, 10.2)\ \mathrm{TeV}\,, \quad \mu_\eta^2 = (10.5\,\mathrm{TeV})^2\,,$$
$$\lambda_2 = \lambda_3 = \lambda_4 = 0.1\,, \quad \lambda_5 = 10^{-7}\,,$$

$$Y_N = \begin{pmatrix} 0.1 & -0.5 & 0.2 \\ -0.06 & 0.2 & 0.1 \\ -0.6 & 0.8 & 0.02 \end{pmatrix} .$$

Obtain the LEFT Lagrangian at $Q = 5$ GeV with `DsixTools` and compute $\text{BR}(\mu \to e\gamma)$ with `flavio`. Does this parameter point respect the current bound on $\text{BR}(\mu \to e\gamma)$?

References

[1] E. Ma, "Verifiable radiative seesaw mechanism of neutrino mass and dark matter," *Phys. Rev. D* **73** (2006) 077301, `arXiv:hep-ph/0601225`.

[2] P. Escribano, M. Reig, and A. Vicente, "Generalizing the Scotogenic model," *JHEP* **07** (2020) 097, `arXiv:2004.05172 [hep-ph]`.