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A radiative seesaw model with GeV singlet-doublet fermion and TeV triplet scalar dark matter

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By extending the Standard Model with singlet-doublet fermions and triplet scalars, all odd under a new Z_2 symmetry, we introduce a radiative seesaw model that can simultaneously account for dark matter, explain the existence of neutrino masses and allow for gauge coupling unification. We explore the viable parameter space of the model after imposing collider, Higgs mass, dark matter, neutrino mass and lepton flavour violation constraints. We find that dark matter in this model is fermionic for masses below about 1 TeV and scalar above and observe a high degree of complementarity between direct detection and lepton flavour violation experiments, which should soon allow to fully probe the fermionic dark matter sector and at least partially the scalar dark matter sector.

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1. Motivation

Evidence from many different length scales for dark matter (DM) and precision measurements of its relic abundance in the Universe, together with small, but non-zero neutrino masses and an unnaturally light Higgs boson are clear indications that the Standard Model (SM) of particle physics is incomplete. While supersymmetry has long been favoured as a global solution to these and other puzzles, supersymmetric particles have so far not been discovered despite intense searches at the LHC and in direct DM detection experiments [1].

A less encompassing, rather bottom-up approach to these problems consists in extending the SM minimally, e.g. by additional Higgs multiplets ϕ_i, which would, however, not acquire a vacuum expectation value, and/or additional right-handed neutrinos ν_R, that are also employed in different types of seesaw mechanisms to generate the SM neutrino masses. When imposing an additional Z_2 symmetry, under which both ϕ_i and ν_R are odd, it is possible to both render the lightest inert particle into a stable DM candidate, and to avoid tree-level couplings of single Z_2-odd particles to the those of the SM.

2. Radiative seesaw models

Neutrino masses are then generated radiatively, and the corresponding one-loop models have recently been classified [2]. For several among them, we have already performed detailed phenomenological studies in the past, e.g. for doublet scalar DM with singlet fermion coannihilations [3], singlet scalar and singlet-doublet fermion DM [4] and singlet-doublet scalar and singlet-doublet fermion DM [5]. We have also studied inert scalar DM with electroweak one-loop corrections [6], singlet fermion DM interacting with a new singlet scalar [7], fermionic DM in the freeze-in mechanism [8], two-component DM [9] and scalar DM in the $B-L$ model [10].

Here we present a recent study of a model with singlet-doublet fermions and triplet scalars [11], dubbed T1-3-B with $\alpha = 0$ in the classification scheme cited above. The new fields and their quantum numbers in this model are shown in Tab. 1, and the interaction Lagrangian is given by

$$\begin{aligned}\mathscr{L} \;=\; & -\frac{1}{2}(M_\phi^2)^{ij}Tr(\phi_i\phi_j) - \left(\frac{1}{2}M_\Psi\Psi\Psi + \text{h.c.}\right) - \left(M_{\psi\psi'}\psi\psi' + \text{h.c.}\right) \\ & -(\lambda_1)^{ij}(H^\dagger H)Tr(\phi_i\phi_j) - (\lambda_3)^{ijkm}Tr(\phi_i\phi_j\phi_k\phi_m) \\ & - \left(\lambda_4(H^\dagger\psi')\Psi + \text{h.c.}\right) - \left(\lambda_5(H\psi)\Psi + \text{h.c.}\right) - \left((\lambda_6)^{ij}L_i\phi_j\psi' + \text{h.c.}\right). \end{aligned} \tag{2.1}$$

Table 1: New fields and their quantum numbers in model T1-3-B with $\alpha = 0$.

Field	Generations	Spin	Lorentz rep.	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
Ψ	1	$\frac{1}{2}$	$(\frac{1}{2},0)$	**1**	**1**	0	-1
ψ	1	$\frac{1}{2}$	$(\frac{1}{2},0)$	**1**	**2**	-1	-1
ψ'	1	$\frac{1}{2}$	$(\frac{1}{2},0)$	**1**	**2**	1	-1
ϕ_i	2	0	$(0,0)$	**1**	**3**	0	-1

After electroweak symmetry breaking, the neutral fermions acquire the mass terms

$$\mathscr{L}_{\mathrm{f},0} = -\frac{1}{2}M_\Psi \Psi\Psi - M_{\psi\psi'}\psi^0\psi'^0 - \frac{\lambda_4 v}{\sqrt{2}}\psi'^0\Psi - \frac{\lambda_5 v}{\sqrt{2}}\psi^0\Psi + \mathrm{h.c.},$$

which leads to the singlet-doublet fermion mass matrix and corresponding eigenstates

$$M_{\mathrm{f},0} = \begin{pmatrix} M_\Psi & \frac{\lambda_5 v}{\sqrt{2}} & \frac{\lambda_4 v}{\sqrt{2}} \\ \frac{\lambda_5 v}{\sqrt{2}} & 0 & M_{\psi\psi'} \\ \frac{\lambda_4 v}{\sqrt{2}} & M_{\psi\psi'} & 0 \end{pmatrix} \qquad \text{with} \qquad \chi^0 = U_\chi \begin{pmatrix} \Psi^0 \\ \psi^0 \\ \psi'^0 \end{pmatrix}. \tag{2.2}$$

Two generations ($n_s = 2$) of triplet scalars ϕ_i are required for two non-zero SM neutrino masses. They obtain the mass matrices

$$M^2_{\phi^0} = M^2_{\phi^\pm} = M^2_\phi + \lambda_1 v^2. \qquad \text{with} \qquad \eta^{0,\pm} = O_\eta \begin{pmatrix} \phi_1^{0,\pm} \\ \phi_2^{0,\pm} \end{pmatrix}. \tag{2.3}$$

Note that the charged scalars are slightly heavier than their neutral counterparts due to one-loop electroweak diagrams by about [12]

$$\Delta m_{\eta_i} = m_{\eta_i^\pm} - m_{\eta_i^0} = 166 \text{ MeV}. \tag{2.4}$$

When one decouples the scalars by setting

$$(M^2_\phi)^{11} = (M^2_\phi)^{22} = (1000 \text{ TeV})^2,\ (M^2_\phi)^{12} = 0,\ \lambda_1 = \lambda_3 = \lambda_6 = 0 \tag{2.5}$$

while keeping the fermion masses light and couplings non-zero as in

$$M_\Psi = 200 \text{ GeV},\ M_{\psi\psi'} = 300 \text{ GeV},\ \lambda_5 = 0.36, \tag{2.6}$$

we reproduce the relic density and direct detection cross sections predicted in the literature [13, 14]. In our study, we update, however, the Higgs boson mass and the nuclear form factors. As had been noted before, blind spots of spin-independent (SI) and spin-dependent (SD) direct detection can appear depending on the value of λ_4. With the new results of the XENON1T experiment, the mass limits increase to $M_\Psi \simeq M_{\psi\psi'} > 200$ GeV ... 1 TeV.

When one decouples instead the fermions by setting

$$M_\Psi = M_{\psi\psi'} = 1000 \text{ TeV},\ \lambda_4 = \lambda_5 = \lambda_6 = 0 \tag{2.7}$$

and also the unimportant scalar self coupling $\lambda_3 = 0$, we find that for one generation $m_\eta \simeq 2$ TeV except for large Higgs couplings λ_1, where m_η must even be in the multi-TeV region. In this case we found that we had to correct a result in the literature by a normalisation factor of two in the squared neutral mass [15].

3. Radiative neutrino masses

After electroweak symmetry breaking, the SM neutrino masses are generated at one loop through the Feynman diagram shown in Fig. 1. The corresponding neutrino mass matrix is given by

$$(M_\nu)_{ij} = \frac{1}{32\pi^2}\sum_{l=1}^{n_s}\lambda_6^{im}\lambda_6^{jn}(O_\eta)_{ln}(O_\eta)_{lm}\sum_{k=1}^{n_f}(U_\chi)_{k3}^{*\,2}\frac{m^3_{\chi^0_k}}{m^2_{\eta^0_l}-m^2_{\chi^0_k}}\ln\left(\frac{m^2_{\chi^0_k}}{m^2_{\eta^0_l}}\right). \tag{3.1}$$

Since there are no neutrino masses at tree level, the ultraviolet divergences cancel as they must. The mass matrix is diagonalised to D_ν with the PMNS matrix U_ν. When expanded in $\lambda_{4,5} \ll 1$, it simplifies to

$$M_\nu \approx 100\ \text{meV}\ \frac{M_\Psi}{1\ \text{TeV}}\left(\frac{\lambda_6^{ij}\lambda_{4,5}}{10^{-5}}\right)^2, \tag{3.2}$$

showing that the singlet fermion mass is of order 1 TeV for couplings $\lambda_{4,5,6}$ of about 10^{-2} or slightly below. It is useful to diagonalise the neutrino mass matrix without the important coupling λ_6,

$$M_\nu = \lambda_6^T M \lambda_6 = \lambda_6^T U_M^T D_M U_M \lambda_6$$

which allows to express the latter in the so-called Casas-Ibarra parametrisation [16]

$$\lambda_6 = U_M^T D_M^{-\frac{1}{2}} R D_\nu^{\frac{1}{2}} U_\nu^\dagger$$

with an arbitrary rotation matrix

$$R = D_M^{\frac{1}{2}} U_M \lambda_6 U_\nu D_\nu^{-\frac{1}{2}} = \begin{pmatrix} 0 & \cos(\theta) & \sin(\theta) \\ 0 & -\sin(\theta) & \cos(\theta) \end{pmatrix}.$$

We can then directly impose the SM neutrino mass difference and mixing constraints and scan the free parameters of the model over the ranges $\theta \in [0;2\pi]$, $|\lambda_{1,4,5}| \in [10^{-6};1]$, $\lambda_4 > 0$, and M_ϕ, M_Ψ, $M_{\psi\psi'} \in [10\ \text{GeV}; 10000\ \text{GeV}]$. In addition, we impose direct experimental constraints from LEP on $m_{\chi^0,\eta^0} > m_Z/2$, $m_{\psi^-,\psi'^+,\eta_i^\pm} > 102$ GeV, from the LHC on the Higgs boson mass $m_H = 125 \pm 2.5$ GeV, and from Planck on the DM relic density $\Omega_c^{\text{obs}} h^2 = 0.120 \pm 0.001$.

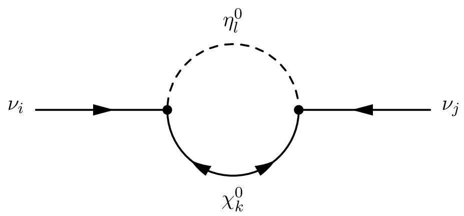

Figure 1: Feynman diagram for the radiative generation of neutrino masses at the one-loop level ($k \in \{1,\ldots,n_f\}$, $l \in \{1,\ldots,n_s\}$).

4. Fermion DM

About one third of all models with the observed neutrino masses and mixings feature singlet–doublet fermion DM, but only a fraction of order 0.02 % yield the correct DM relic density and Higgs mass. These models are shown in Fig. 2 (left) as a function of the DM mass, together with their spin-independent direct detection cross section and the branching ratio for the usually most sensitive LFV process $\mu \to e\gamma$. Other important LFV processes are shown in Fig. 2 (right). The models accumulating at a DM mass of about 1 TeV feature mostly doublet fermions, whereas lighter fermionic DM is generally a superposition of singlet and doublet. A large doublet component below $m_Z/2$ (dark shaded area) is excluded by the fact that the LEP measurement of the invisible Z boson decay width is consistent with three generations of active neutrinos. Furthermore, the accompanying, only slightly heavier charged fermions are excluded below 102 GeV by largely model-independent searches with the OPAL detector at LEP (light shaded area). The LHC limits for heavy long-lived charged particles from ATLAS and CMS reach currently up to 440 GeV and 490 GeV, respectively, but are more model-dependent. The spin-independent direct detection cross section is compared to the current XENON1T exclusion limit (full line) [17] and the expectation for 20 ton-years with the XENONnT experiment (dashed line) [18], which was extrapolated linearly above 1 TeV. XENON1T excludes most of the models with small scalar-fermion couplings λ_6 and therefore also little LFV. These models are therefore similar to those in the pure singlet–doublet fermion DM model. The combination with the scalar sector opens up a considerable parameter space of leptophilic DM, i. e. with nuclear recoil cross sections way below even the expected XENONnT sensitivity. Interestingly, one observes a strong complementarity with LFV experiments, which already probe the models with the smallest spin-independent direct detection cross section [19].

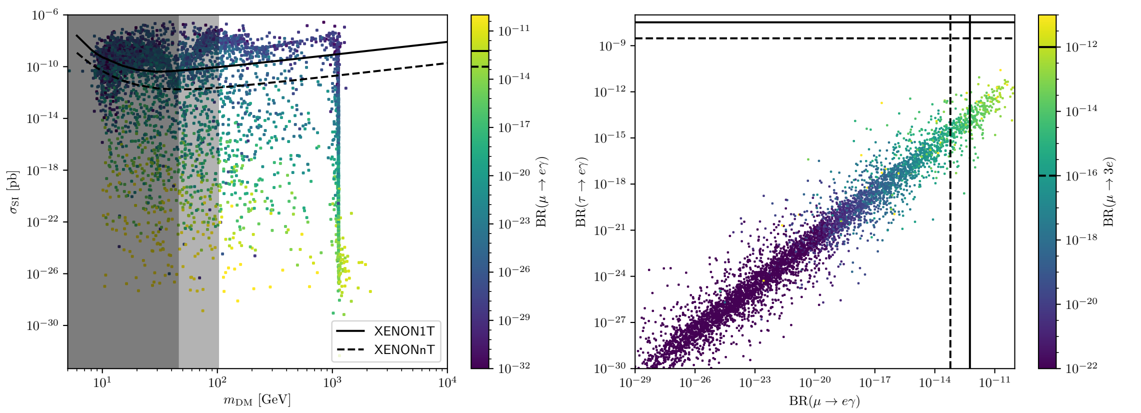

Figure 2: Left: The spin-independent direct detection cross section as a function of the DM mass for singlet–doublet fermion DM. The colours show the branching ratios for the LFV process $\mu \to e\gamma$. Also shown are the LEP limits on light neutral and charged particles (shaded areas), current (full lines) and future (dashed lines) exclusion limits from XENON1T [17] and XENONnT [18]. Right: Correlations of the branching ratios for the LFV processes $\mu \to e\gamma$, $\mu \to 3e$ and $\tau \to e\gamma$ for viable models with singlet–doublet fermion DM. Also shown are current (full lines) and future (dashed lines) exclusion limits [19, 20, 21, 22, 23, 24].

5. Scalar DM

About two thirds of all models with the observed neutrino masses and mixings feature triplet scalar DM, but only a fraction of order 0.02 % yield the correct DM relic density and Higgs mass. These models are shown in Fig. 3 (left) as a function of the DM mass, together with their spin-independent direct detection cross section and the branching ratio for the LFV process $\mu \to e\gamma$. Other important LFV processes are shown in Fig. 3 (right). As for a pure triplet scalar model, we observe an accumulation of points around a mass of 2 TeV. Many of these models have only very small couplings λ_6 to the fermion sector and thus very little LFV. As λ_1 increases, so must the DM mass beyond 2 TeV to compensate for the stronger Higgs annihilation. However, most of these models will soon be probed by XENONnT, and those that will not can soon be excluded by the process $\mu \to e\gamma$. While the mass region from 1 TeV to 2 TeV with leptophilic fermion DM, that was opened up by coupling the fermion and scalar sectors, was already excluded by LFV limits (see above), the corresponding models with scalar DM are still allowed, but will soon be probed by the process $\mu \to e\gamma$. Note that there exists in principle also a region of very light triplet scalar DM of about 6 GeV mass, which is however excluded by the LEP limits on light non-sterile neutral (dark shaded area) and charged (light shaded area) particles.

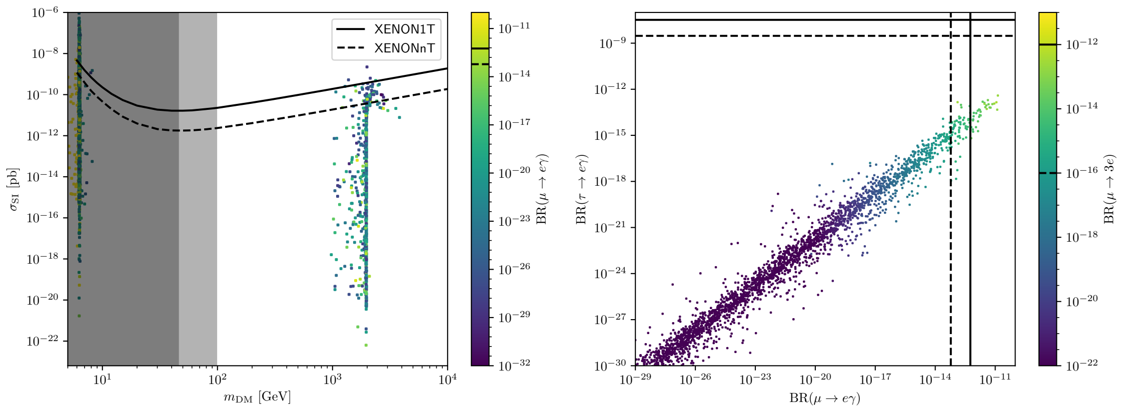

Figure 3: Left: The spin-independent direct detection cross section as a function of the DM mass for triplet scalar DM. The colours show the branching ratios for the LFV process $\mu \to e\gamma$. Also shown are the LEP limits on light neutral and charged particles (shaded areas), current (full lines) and future (dashed lines) exclusion limits from XENON1T [17] and XENONnT [18]. Right: Correlations of the branching ratios for the LFV processes $\mu \to e\gamma$, $\mu \to 3e$ and $\tau \to e\gamma$ for viable models with triplet scalar DM. Also shown are current (full lines) and future (dashed lines) exclusion limits [19, 20, 21, 22, 23, 24].

6. Conclusion

To summarise, we heave presented a phenomenological study of a radiative seesaw model with singlet-doublet fermion and triplet scalar DM. For each individual model, we found that the new XENON1T results doubled the excluded parameter space for singlet-doublet fermion DM, while for triplet scalar DM the viable mass was about 2 TeV for small Higgs couplings, but then increased to compensate for the larger couplings.

The combination of the fermion and scalar sectors required two generations of scalars for the generation of two non-zero neutrino masses. DM was found to be fermionic up to 1 TeV, then scalar, and the combination allowed for smaller masses than the individual models still in agreement with XENON1T data. We observed a strong complementarity of direct detection and lepton flavour violation experiments, while the (model-dependent) LHC limits remained relatively weak at around 440 to 490 GeV.

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