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Singlet–doublet/triplet dark matter and neutrino masses

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In these proceedings, we present a study of a combined singlet–doublet fermion and triplet scalar model for dark matter (DM). Together, these models form a simple extension of the Standard Model (SM) that can account for DM and explain the existence of neutrino masses, which are generated radiatively. However, this also implies the existence of lepton flavour violating (LFV) processes. In addition, this particular model allows for gauge coupling unification. The new fields are odd under a new $\mathbb{Z}_2$ symmetry to stabilise the DM candidate. We analyse the DM, neutrino mass and LFV aspects, exploring the viable parameter space of the model. This is done using a numerical random scan imposing successively the neutrino mass and mixing, relic density, Higgs mass, direct detection, collider and LFV constraints. We find that DM in this model is fermionic for masses below about 1 TeV and scalar above. We observe a high degree of complementarity between direct detection and LFV experiments, which should soon allow to fully probe the fermionic DM sector and at least partially the scalar DM sector.

1 Introduction

Particularly well-motivated DM models do not only provide a DM candidate, but also solve other SM problems such as the smallness of neutrino masses. This is possible when the $d = 5$ Weinberg operator is realised at one loop,[1] such that the particles in the loop have opposite $\mathbb{Z}_2$ parity to the SM particles and include a neutral DM candidate.[2]

In our paper,[3] we study a model of topology T1-3 with one scalar and two fermions, one of which is vector-like. In contrast to the first of these models (T1-3-A with hypercharge parameter $\alpha = 0$), where the scalar DM was a singlet,[4] we investigate here a model (T1-3-B, also with $\alpha = 0$) where the scalar DM is the neutral component of a triplet. Both models, like a previously studied model with both singlet–doublet scalars and fermions (T1-2-A with $\alpha = 0$),[5] have the additional advantage that they allow for gauge coupling unification at a scale $\Lambda = \mathcal{O}(10^{13}\,\mathrm{GeV})$.[6]

2 Description of the model

Following the notation in previous literature,[1,2] the model T1-3-B with hypercharge parameter $\alpha = 0$ is defined by extending the SM with the colour-singlet fields in table 1. The present model therefore combines the $\mathrm{SU(2)_L}$ triplet scalars ϕ_i of zero hypercharge ($\mathrm{U(1)_Y}$) with an $\mathrm{SU(2)_L}$ singlet fermion Ψ and doublet fermions ψ, ψ'. They are all odd under the discrete global

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

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

symmetry $\mathbb{Z}_2$, while the SM fields are even. The components of the new fields are given by

$$\Psi = \Psi^0, \quad \psi = \begin{pmatrix} \psi^0 \\ \psi^- \end{pmatrix}, \quad \psi' = \begin{pmatrix} \psi'^+ \\ \psi'^0 \end{pmatrix}, \quad \phi_i = \begin{pmatrix} \frac{1}{\sqrt{2}}\phi_i^0 & \phi_i^+ \\ \phi_i^- & -\frac{1}{\sqrt{2}}\phi_i^0 \end{pmatrix}, \tag{1}$$

where superscripts indicate electric charges. To obtain two non-zero neutrino mass differences, two generations of scalar triplets are required. Since the scalar triplets have zero hypercharge, they are treated as real, $(\phi_i^0)^\dagger = \phi_i^0, (\phi_i^+)^\dagger = \phi_i^-$. Ψ has the same quantum numbers as a $\mathbb{Z}_2$-odd right-handed neutrino, whereas ψ and ψ' together form a $\mathbb{Z}_2$-odd vector-like lepton doublet, which makes the model automatically anomaly-free. In principle, all neutral field components are possible DM candidates. The $\mathbb{Z}_2$ symmetry not only stabilises the lightest new particle against decay into SM fields, but also forbids neutrino masses from a tree-level type-I seesaw mechanism.

The most general renormalisable Lagrangian for the model is

$$\begin{aligned}\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{kin}} - \frac{1}{2}(M_\phi^2)^{ij}\,\mathrm{Tr}(\phi_i\phi_j) - \left(\frac{1}{2}M_\Psi \Psi\Psi + \mathrm{H.\,c.}\right) - \left(M_{\psi\psi'}\psi\psi' + \mathrm{H.\,c.}\right) \\ - (\lambda_2)^{ij} H^\dagger \phi_i\phi_j H - (\lambda_3)^{ijkm}\,\mathrm{Tr}(\phi_i\phi_j\phi_k\phi_m) \\ - \left(\lambda_4(H^\dagger\psi')\Psi + \mathrm{H.\,c.}\right) - \left(\lambda_5(H\psi)\Psi + \mathrm{H.\,c.}\right) - \left((\lambda_6)^{ij} L_i\phi_j\psi' + \mathrm{H.\,c.}\right),\end{aligned} \tag{2}$$

where H is the SM Higgs field (with vacuum expectation value v and quartic coupling λ). The couplings λ_4 and λ_5 have the function of Yukawa terms, which link the fermion singlet and doublets to the SM Higgs boson. The coupling λ_6 connects the SM lepton doublet L to the new fields, so that it will be involved in the process of radiative neutrino mass generation.

3 Radiative neutrino masses

After electroweak symmetry breaking, neutrino masses in our model arise from a single one-loop diagram. Only the n_f neutral fermion fields χ_k and n_s neutral scalar fields η_l contribute to mass generation, whereas the charged fields enter only into the propagator correction. In our model, the $n_\mathrm{f} = 3$ fermions are superpositions of $\mathrm{SU(2)_L}$ singlets and doublets, while the $n_\mathrm{s} = 2$ scalars are superpositions of the two generations of scalar triplets required for two non-zero neutrino masses. Evaluating the two-point function in dimensional regularisation and summing over all contributions (with the neutral fermionic and scalar mixing matrices U_χ and O_η) leads to

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

As evident from equation (3), the structure of the mass matrix is chiefly determined by the number of scalar generations, which must be at least as large as the desired number of non-zero neutrino masses. The neutrino mass matrix M_ν depends explicitly on the couplings λ_6 and on the masses $m_{\chi^0_k}$ and $m_{\eta^0_l}$ of the neutral fermions and scalars, while the dependence on the other couplings $\lambda_{1,4,5}$ remains implicit in the mixing matrices. The Casas–Ibarra parametrisation [7] then allows to obtain λ_6 from the experimental neutrino data, once the other couplings and masses have been fixed.

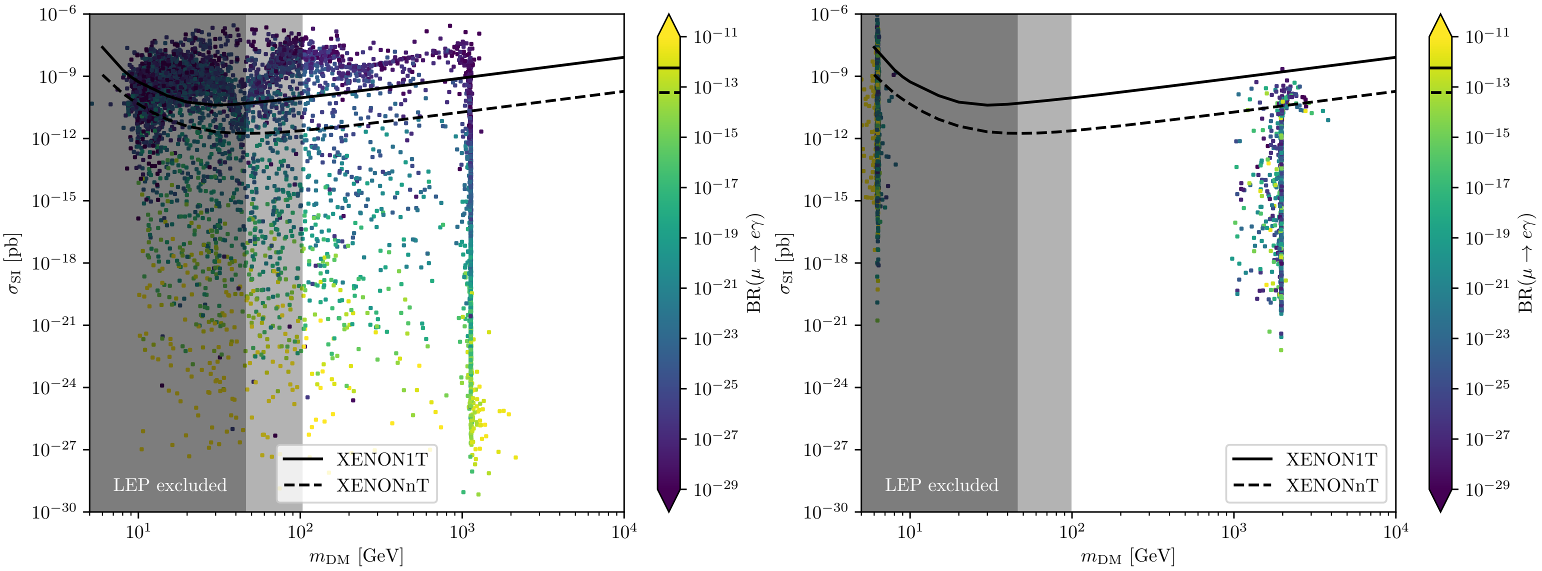

Figure 1 – The spin-independent direct detection cross section as a function of the DM mass for singlet–doublet fermion DM (left) and triplet scalar DM (right). The colours show the branching ratios for the LFV process $\mu \to e\gamma$. Also shown are the LEP limits on light neutral and charged particles (shaded areas) as well as current (full lines) and future (dashed lines) exclusion limits for the DM relic density from XENON1T [8] and XENONnT [9], and for $\mu \to e\gamma$ [10,11].

4 Dark matter direct detection and lepton flavour violation

We now connect singlet–doublet fermions with triplet scalars with the aim to not only explain the observed small neutrino masses as described in the previous section, but also in order to study the effect of the neutrino mass constraints on the nature, allowed parameter space, direct detection prospects and LFV properties of the two DM candidates in this combined model. We explore the model's parameter space with the help of `SARAH` 4.13.0 [12], calculating the physical particle spectrum and relevant precision observables with `SPheno` 4.0.3 [13] as well as the DM relic density and direct detection cross sections with `micrOMEGAs` 4.3.5 [14] using a random parameter scan.

All models resulting from the random scan with the observed neutrino masses and mixings as well as the correct DM relic density $\Omega_c^{\mathrm{obs}} h^2 = 0.120 \pm 0.001$ and Higgs mass are shown in figure 1 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 $\mu \to e\gamma$.

For fermionic DM, 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. 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. Interestingly, one observes a strong complementarity with LFV experiments, which already probe the models with the smallest spin-independent direct detection cross section.[10]

Similarly to the fermionic DM case, LEP constraints already rule out light scalar DM candidates. 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 $\mu \to e\gamma$.

5 Conclusion

We have combined the singlet–doublet fermion model with the triplet scalar model in order to explain not only the observed DM relic density, but also the neutrino masses and mixings, which were generated radiatively. This model allows in addition for the correct Higgs boson mass, couplings of natural size, masses in the TeV range and gauge coupling unification.

We found that DM in our model is fermionic up to the TeV scale and scalar beyond. The scalar–fermion couplings opened the parameter space, so that leptophilic singlet–doublet fermion DM around 1 TeV became again viable below the XENON1T exclusion limit, as did triplet scalar DM between 1 TeV and 2 TeV. In both regions, we observed an interesting complementarity between the expectations for XENONnT and for LFV experiments.

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