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Higgs portal dark matter and neutrino mass and mixing with a doubly charged scalar

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ABSTRACT

We consider an extension of the Standard Model involving two new scalar particles around the TeV scale: a singlet neutral scalar ϕ, to be eventually identified as the Dark Matter candidate, plus a doubly charged $SU(2)_L$ singlet scalar, S^{++}, that can be the source for the non-vanishing neutrino masses and mixings. Assuming an unbroken Z_2 symmetry in the scalar sector, under which only the additional neutral scalar ϕ is odd, we write the most general (renormalizable) scalar potential. The model may be regarded as a possible extension of the conventional Higgs portal Dark Matter scenario which also accounts for neutrino mass and mixing. This framework cannot completely explain the observed positron excess. However a softening of the discrepancy observed in conventional Higgs portal framework can be obtained, especially when the scale of new physics responsible for generating neutrino masses and lepton number violating processes is around 2 TeV.

1. Introduction

The present ensemble of data from accelerators experiment seems to firmly confirm all the Standard Model (SM) ingredients to high level of accuracy, including the presence of a relatively light scalar boson (so-called "Higgs" for short) [1,2].

There are, however, few experimental indications that there should be some type of new physics beyond the SM one. The most clear indication of the need of some new kind of matter, namely the Dark Matter (DM), derives from cosmological and astrophysical observations. Assuming the WIMP ansatz, the amount of measured DM density is consistent with the existence of a weakly interacting particle with a mass around the TeV scale.

On the other side, several theoretical features of the SM still need to be elucidated, like for example the stability of the Higgs mass, the so called "hierarchy problem", or the presence of extremely different parameters describing the masses and mixings of the SM fermions, dubbed often as the "flavour problem".

Following the idea that the fermion mass structures could arise from a symmetry principle, flavour symmetries have been introduced, both in the context of the SM and its extensions. Many different examples have been proposed in the literature based on a large variety of symmetries: either abelian on non-abelian, local or global, continuous or discrete [3]. Despite of all these attempts, however, it seems unlikely that the same mechanism could be responsible to generate at the same time charged and neutral fermion masses. However the unique possibility of having Majorana masses for the neutrinos, associated with the exceedingly small values of the neutrino masses, could be responsible for the differences observed in the neutrino flavour sector.

The see-saw mechanism [4], where heavy right-handed neutrinos with large Majorana masses are responsible for small effective left-handed neutrino masses, is notoriously difficult to directly test. Other mechanisms for generating neutrino masses include R-parity violating supersymmetry [5], Higgs triplet models [6–8], or loop models involving additional Higgs doublets and singlets (e.g. [9–11]). All these models can be tested experimentally (for a review of these different mechanisms see for example [12], and [13] for a very systematic study). In particular, such settings can yield very interesting connections between lepton number violating physics and collider phenomenology [14–16], especially if doubly charged scalars are involved (as in the Higgs triplet case [17,18]).

In this paper we shall focus on a particularly economical loop model of Majorana neutrino mass and mixing [19], in which the low energy effective theory involves just one extra new particle: a doubly charged EW singlet scalar S (denoting both S^{++} and its

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antiparticle S^{--}). It is already known that such a model can lead to an interesting complementarity between low energy charged lepton flavour violation processes, and high energy collider physics, depending on whether the doubly charged scalar S appears as a virtual or real particle [20]. However such a model cannot account for DM, since the doubly charged scalar S decays promptly into either pairs of like-sign charged leptons or W bosons. Here we shall extend the model slightly by introducing an additional neutral scalar ϕ and assume an unbroken Z_2 symmetry in the scalar sector, under which only the additional neutral scalar ϕ is odd, which then becomes a stable DM candidate. The model may be regarded as an extension of the so-called Higgs portal scenario [30], in the presence of a doubly charged scalar which accounts for neutrino mass and mixing. The resulting framework presented here, involving both S and ϕ, then merges two apparently unrelated features: the existence of a new physics sector at the TeV scale, providing naturally small neutrino masses, and the existence of a good DM candidate.

The layout of the remainder of the paper is as follows. In section 2 we review the effective model proposed and studied in [19,20] involving just one extra particle, the doubly charged scalar S. In section 3 we extend this model by introducing an additional neutral scalar ϕ, and discuss the resulting scalar potential of the model involving the Higgs doublet H, the doubly charged scalar S and the neutral scalar ϕ. We then go on to calculate the relic abundance of the DM particles ϕ and their prospects for direct and indirect detection. Section 4 concludes the paper.

2. The effective model with a doubly charged scalar

In this section we review the effective Lagrangian model presented in [19], in which the SM is extended by adding one new scalar particle: a complex $SU(2)_L$ singlet, hypercharge $Y = 2$ (hence electric charge $Q = 2$) state S^{++} and its antiparticle S^{--}, both doubly charged and denoted in the following as S and $S^\dagger$ respectively.

The doubly charged scalar field S has an effective coupling to the SM $W^\pm$ bosons as well as to same-sign right-handed charged SM leptons, giving rise to a rich phenomenology. In addition to contributing to flavour violating leptonic processes, to leptonic dipole moments and to leptonic radiative decays, the scalar S allows a 2-loop diagram which is responsible for providing all mass (and mixings) to neutrinos. It is shown in [19] that the lowest mass dimension at which the vertex SWW can be realised is by effective operators of dimension $d = 7$. The relevant operator, in the unitary gauge, for the generation of neutrino masses is:

$$\mathcal{L}_{SWW} = -\frac{g^2 \xi v^4}{4\Lambda^3}\left(S\, W^\mu W_\mu + h.c.\right) \tag{2.1}$$

being ξ an order $\mathcal{O}(1)$ dimensionless parameter and Λ the new physics scale above which the effective theory breaks. The coupling of S to same-sign RH leptons is given by

$$\mathcal{L}_{Sll} = f_{ab}\, S^\dagger \bar{l}_a P_L l_b^c + h.c. \tag{2.2}$$

with f_{ab} dimensionless parameters. There are strong experimental constraints on the f_{ab} parameter space, basically due to the flavour violating couplings of the charged scalar S with leptons, the strongest bound proceeding from $\mu \to e\gamma$ and $\mu \to 3e$. A detailed analysis of these bounds can be found in [19,20,23].

The simultaneous presence of the SWW and Sll vertices generate a 2-loop contribution to the neutrino masses, that schematically can be written as

$$\mathcal{M}_\nu^{2\text{-loop}} = 2\,\xi\, f_{ab}(1+\delta_{ab})\frac{m_a\, m_b\, m_S^2}{\Lambda^3}\,\tilde{\mathcal{I}}(m_W, m_S, \mu) \tag{2.3}$$

where m_S is the S particle mass, m_i is the mass of the l_i lepton, δ_{ab} is the Kronecker delta and $\tilde{\mathcal{I}}(m_W, m_S, \mu)$ is the two loop integral calculated in [19].

Apart from the usual contribution to $0\nu\beta\beta$ due to massive neutrinos in presence of a lepton number violating interaction, this model also produce an additional non-standard contribution to it, since the doubly charged scalar S can couple both to W^-W^- and e^-e^-. Taking into account the newest GERDA results of $T_{1/2}^{0\nu\beta\beta}(\text{Ge}) > 2.1\cdot 10^{25}$ at 90% C.L., [24], one obtains

$$\frac{\xi\, f_{ee}}{M_S^2\Lambda^3} < \frac{4.0\cdot 10^{-3}}{\text{TeV}^5}\,. \tag{2.4}$$

In general it is not an easy task to fulfil all the flavour/dipole bounds and obtain a realistic description for neutrino masses and mixing compatible with the $0\nu\beta\beta$ decay bounds. In [19] a detailed analysis has been performed that highlighted the presence of three typical regions where this may happen, hereafter denoted as "Benchmark Scenarios":

1. Benchmark Scenario A: $f_{ee} \simeq 0$ and $f_{e\tau} \simeq 0$. In this region the additional contribution to the $0\nu\beta\beta$ essentially vanishes. A normal hierarchy between the neutrino masses with the lightest one around 5 meV is obtained;
2. Benchmark Scenario B: $f_{ee} \simeq 0$ and $f_{e\mu} \simeq -(f^*_{\mu\tau}/f^*_{\mu\mu})f_{e\tau}$. In this region one still has a vanishing additional contribution to the $0\nu\beta\beta$ and a normal ordered neutrino masses with the lightest one around 5 meV. However the constraint relating $f_{e\mu}$ and $f_{e\tau}$ makes this scenario more predictive (falsifiable) in what concerns lepton flavour violation;
3. Benchmark Scenario C: $f_{e\mu} \simeq -(f^*_{\mu\tau}/f^*_{\mu\mu})f_{e\tau}$. In this region one can assume large values for the f_{ee} coupling. However not to enter in conflict with the GERDA limit on $0\nu\beta\beta$ of Eq. (2.4) one has to push the cutoff scale Λ to several TeV, not a desirable thing from the collider phenomenology point of view.

For the analysis presented in the following sections we will use the best fit benchmark point for each of the three scenarios reported by [19]:

1. Benchmark Point A: $m_S = 164.5$ GeV, $\Lambda = 905.9$ GeV, $\xi = 5.02$;
2. Benchmark Point B: $m_S = 364.6$ GeV, $\Lambda = 2505.1$ GeV, $\xi = 6.38$;
3. Benchmark Point C: $m_S = 626.0$ GeV, $\Lambda = 5094.7$ GeV, $\xi = 3.39$.

3. Higgs portal DM with a doubly charged scalar

In order to account for DM, we now introduce a further particle into the scheme of the previous section, namely an electrically neutral real scalar ϕ. An unbroken $\mathbb{Z}_2$ symmetry is assumed, under which the field ϕ is odd, while all the other particles are even. The motivation of such a setup is twofold: firstly, as already discussed, the presence of an extra doubly charged scalar can provide an economical mechanism for triggering light neutrino masses and mixing [19–22]. Secondly, the new neutral scalar can account for DM. Possible UV completions of this model could be pursued along the lines of [21,22]. Here we shall not try to construct an ultraviolet complete model, but continue to consider the effective theory below the cut-off Λ, where the theory has a rather minimal particle content, with the goal of understanding DM in this extended model. In particular, we shall discuss how the presence of an extended scalar sector can potentially modify the limits and the predictions obtained in the standard DM Higgs portal scenario [30]. In