Doublet Singlet Dark Matter

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1 DM simplified frameworks

Dark matter (DM) provides highly compelling experimental evidence for physics beyond the Standard Model. Adding a new particle with non-trivial $SU(2)_L \times U(1)_Y$ quantum numbers provides the most straightforward particle physics solution [1]. While a plethora of well-motivated (in the sense they solve a concrete theoretical problem UV models exist (of which the MSSM is the best studied example), from an experimental perspective the main features of the phenomenology may be captured by simplified models where just a subset of fields and associated parameters are relevant.

Generally speaking, a simplified model is useful as a language that allows us to encode the the full parameter space of a UV model in terms of relatively few parameters, making the analysis tractable. For our particular case, simplified models would only give an appropriate description of the involved phenomena if other degrees of freedom present in the complete UV theory are kinematically or dynamically decoupled from the DM particle at the experimental facilities under study. While reverting back to the UV space ("decoding" the simplified model) allows to propagate these experimental results without a severe loss of information (aka "recasting"), it should be kept in mind that simplified models are "not invertible" because they lack the information content of the UV complete theory: different UV theories could lead to the same simplified model. The value of such an approach lies in its flexibility to agglomerate seemingly different UV models by their experimental signatures and collider signal classes, but its limitations need be kept in mind.

In this proposal we focus on dark matter models consisting of one weak doublet and one weak singlet (plus additional scalars). The choice of one doublet does not work, because the electrically neutral component has non-zero hypercharge, introducing a Z-current in flagrant conflict with direct detection results [2] [1]. Models with higher SU(2) representations (n-plets with $n > 2$) have been extensively studied in the literature. The common lore: these are well covered by the current and future facilities, with the $n = 3$ case having been studied for fermions (see e.g [3, 4]) and for scalars(see e.g [5]) [2].

We consider three scenarios. First, we will consider the case where both new multiplets are fermions [6], which also serves as the limit of several supersymmetric scenarios, e.g: the pure-Higgsino and the well tempered Higgsino-Bino of the MSSM, the Higgsino-Singlino NMSSM, etc. In second place, we will augment the first scenario with the inclusion of a pseudoscalar mediator, which serves as a proxy for extended scalar sectors, such as the NMSSM (for recent work see e.g [7]). Finally we will also consider the possibility of an augmented Higgs sector with light scalars. [3] We would like to note that this framework encompasses both prompt and long-lived searches for dark matter . This study will attempt to collect current results in the literature, e.g [8–15] and cast the predicted HL-LHC and other future collider exclusions (including other Snowmass studies), together with the current and expected bounds from direct an indirect detection. Together with the relic density constraints, we aim to obtain a "no-lose" theorem for the singlet doublet scenario, the last standing bulwark of the minimal dark matter paradigm, and also to be able to compare the coverage of different future collider proposals, while informing on the target parameters (energies, luminosities, detector layout, detection

[1]In the pseudo-Dirac case, when the singlet is decoupled, the low-energy spectrum only has one doublet, reproducing the correct relic density for a mass of 1.1 TeV. If the neutral state of the doublet does not saturate the relic abundance the pure state for lower masses may not be ruled out by direct detection. Both these important cases are indeed a particular limit of our proposed framework

[2]In particular $n > 3$ models with fermions require the addition of non-renormalizable interactions.

[3]Given the ambitious breadth of this proposal, we leave the scenario with scalars as an open option, depending on the human resources available to engage in its study. We then refrain from providing more details in this LoI. Furthermore, while is also tempting to extend the study for vectors, these require an important amount of model-building, and lead to complex models with non-trivial constraints, except for those featuring Kaluza-Klein modes.

efficiencies, etc).

1.1 Singlet-doublet fermion model (SDFM)

We introduce a Majorana fermion singlet χ_S[4] and a fermion doublet χ_D. The Lagrangian we have in mind is the following:

$$\mathcal{L}_{DM} \supset \frac{M_S}{2}\overline{\chi}_S\chi_S + M_D\overline{\chi}_D\chi_D + (y_1 H\chi_S\chi_D + y_2 H^\dagger\chi_S\overline{\chi}_D + \text{h.c.}) \tag{1}$$

where H is the SM Higgs. This can describe a particular limit of the MSSM in the decoupling limit but $y_{1,2}$ need not be related to gauge couplings in the spirit of a simplified model.

1.2 Adding a pseudo scalar (SDFMa)

We will also consider the case when there is an extra degree of freedom, a pseudoscalar a and we add the following new terms to the interactions introduced in Eq. 1:

$$\begin{aligned}\mathcal{L}_a \;&\supset\; \frac{1}{2}m_a^2 a^2 + \lambda_H a^2|H|^2 + (i\lambda_S a\overline{\chi}_S\gamma_5\chi_S + i\lambda_D a\overline{\chi}_D\gamma_5\chi_D + \text{h.c.}) + \\ &+\; \frac{1}{\Lambda}(iy_U aHQU + iy_D aH^\dagger QD + iy_L aH^\dagger LE + \text{h.c.})\end{aligned} \tag{2}$$

where Q, U, D, L and E denote the SM fields and generation indices are omitted. The first line of Eq. 2 corresponds to the renormalizable couplings of the pseudoscalar a to the DM fermionic sector and the Higgs whereas the second line lists the couplings to SM fermions. We are writing the lowest order operators in every sector, renormalizable for the Higgs and DM and dim-5 for the couplings with SM fermions, which will provide the leading phenomenology of our scenario. We are assuming MFV to avoid flavour constrains. Λ could correspond to the mass a second Higgs that has been integrated out, but we are agnostic about the possible UV completions of this setup.

1.3 Including a singlet scalar (SDFMs)

Reference [7] analysed the possibility that a light (nearly) singlet Majorana fermion with a mass between a few GeV and 62.5 GeV (so that the 125 GeV Higgs boson could decay invisibly) could be thermal cold DM due to resonant annihilation via a singlet spin-zero scalar or pseudoscalar . Planck constraints are satisfied because these resonances are extremely narrow. Surprisingly, it was found that for the NMSSM points consistent with all experimental constraints including the *thermal* relic density constraint, the scalar and pseudoscalar have masses of similar magnitude. Since such a light scalar can significantly alter the phenomenology of direct detection experiments, we extend the simplified models to include a very weakly coupled light scalar as well. The relevant Lagrangian is analogous to equation 2 and we will not write it down explicitly.

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