

Two dark matter candidates in three-Higgs-doublet models with S_3 symmetry

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Models with an extended scalar electroweak sector can have vanishing vacuum expectation values in a basis where an underlying symmetry is imposed. Such extensions are very well motivated. If a symmetry prevents couplings between fermions and additional scalars, such scalars could become viable dark matter candidates if some additional criteria are satisfied. We catalogue S_3 -symmetric three-Higgs-doublet models, also allowing for softly broken S_3 -symmetric scalar potential terms, based on whether a specific model could possibly accommodate a dark matter candidate. The variety of the S_3 -symmetric family models arises due to different possibilities to arrange vacuum expectation values. Such models can have vacua with one or two vanishing vacuum expectation values. In our study we assume that the dark matter candidate is stabilised by the \mathbb{Z}_2 symmetry. The \mathbb{Z}_2 symmetry is a remnant of S_3 symmetry which survived spontaneous symmetry breaking, and not superimposed over S_3 . We explore two models; with and without CP violation. These models have a single dark and two active scalar sectors. The active sectors behave in many aspects like a Type-I two-Higgs-doublet model. The dark matter candidate masses, in two cases, are different from the known (previously studied) models with three scalar doublets. After investigating the models in detail, identifying parameters compatible with both theoretical and experimental constraints, we found that the dark matter candidate mass could be within the range of [52.5, 89] GeV or [6.5, 44.5] GeV for a model with CP violation.

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1. Introduction

Cosmological observations expose our limited knowledge of the Universe, namely that the standard cosmological model proposes that around 85% of the matter of the Universe is made up of hypothetical Dark Matter (DM), of which we have little to no knowledge. There are many models attempting to account for the DM of the Universe. This paper summarises two studies [1, 2] based on the assumption that the scalar electroweak sector of the Standard Model (SM) could be enlarged by two SU(2) Higgs doublets and constrained by an S_3 symmetry [3], while accounting for DM. In the defining representation, S_3 is the symmetry under permutations of three objects.

One of the simplest extensions of the SM which addresses the issue of DM is the Inert Doublet Model (IDM) [4]. In the IDM, the lightest neutral member of a \mathbb{Z}_2 -odd doublet could become a DM candidate. Models with three Higgs doublets (3HDM) have also been proposed and studied:

1. Models with two non-inert doublets along with one inert doublet [5, 6];
2. Models with one non-inert doublet along with two inert doublets [7, 8].

This contribution is based on two models with an underlying S_3 symmetry, classified in [9]. The models are denoted by R-II-1a [1] and C-III-a [2]. The C-III-a model allows for spontaneous CP violation. The DM candidate mass ranges of several models are presented in figure 1.

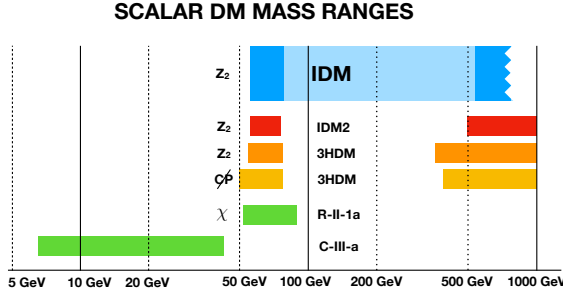


Figure 1: Sketch of allowed DM mass ranges up to 1 TeV in various models. Blue: IDM according to Refs. [10], the pale region indicates a non-saturated relic density. Red: IDM2 [6]. Ochre: 3HDM without [7] and with CP violation [8]. Green: S_3 -symmetric 3HDM without CP violation (R-II-1a) [1] and with CP violation (C-III-a) [2].

2. The S_3 -symmetric models

In terms of the S_3 singlet (h_S) and doublet (h_1, h_2) fields, the S_3 -symmetric scalar potential in the irreducible representation can be written as [11]:

$$V_2 = \mu_0^2 h_S^\dagger h_S + \mu_1^2 (h_1^\dagger h_1 + h_2^\dagger h_2), \quad (1a)$$

$$\begin{aligned} V_4 = & \lambda_1 (h_1^\dagger h_1 + h_2^\dagger h_2)^2 + \lambda_2 (h_1^\dagger h_2 - h_2^\dagger h_1)^2 + \lambda_3 [(h_1^\dagger h_1 - h_2^\dagger h_2)^2 + (h_1^\dagger h_2 + h_2^\dagger h_1)^2] \\ & + \lambda_4 [(h_S^\dagger h_1)(h_1^\dagger h_2 + h_2^\dagger h_1) + (h_S^\dagger h_2)(h_1^\dagger h_1 - h_2^\dagger h_2) + \text{h.c.}] + \lambda_5 (h_S^\dagger h_S)(h_1^\dagger h_1 + h_2^\dagger h_2) \\ & + \lambda_6 [(h_S^\dagger h_1)(h_1^\dagger h_S) + (h_S^\dagger h_2)(h_2^\dagger h_S)] + \lambda_7 [(h_S^\dagger h_1)(h_S^\dagger h_1) + (h_S^\dagger h_2)(h_S^\dagger h_2) + \text{h.c.}] \\ & + \lambda_8 (h_S^\dagger h_S)^2. \end{aligned} \quad (1b)$$

We have chosen to work with real coefficients. However, there remains the possibility of breaking CP spontaneously. The scalar S_3 -symmetric potential has an additional \mathbb{Z}_2 symmetry under which $h_1 \leftrightarrow -h_1$. In the irreducible representation, the S_3 fields can be decomposed as

$$h_i = \begin{pmatrix} h_i^+ \\ (w_i + \eta_i + i\chi_i)/\sqrt{2} \end{pmatrix}, \quad i = 1, 2, \quad h_S = \begin{pmatrix} h_S^+ \\ (w_S + \eta_S + i\chi_S)/\sqrt{2} \end{pmatrix}, \quad (2)$$

where the w_i and w_S are vacuum expectation values (vev) that can be complex [9].

3. Scalar dark matter candidates

In Ref. [1] we identified all possible S_3 -symmetric 3HDMs which could accommodate a DM candidate. Some models have minimisation conditions requiring $\lambda_4 = 0$, giving rise to an additional $O(2)$ symmetry [9]. Apart from this, additional continuous symmetries [12] could arise, which can be spontaneously broken. These models are associated with Goldstone bosons and would require soft breaking of the S_3 symmetry in the potential to eliminate massless states.

There are two approaches when constructing the Yukawa Lagrangian, depending on how the fermions transform under the S_3 symmetry. If they transform trivially, they can only couple to h_S and there are no constraints on the couplings. Realistic masses and mixing can be generated. This is no longer possible when a DM candidate resides in the S_3 singlet and therefore $w_S = 0$. Another possibility is when fermions transform non-trivially under S_3 . In this case fermions are grouped into S_3 doublets and singlets, and it may not be possible to obtain realistic masses and mixing.

Most S_3 -symmetric models with a vanishing vev, which is required to stabilise DM, yield massless scalars or an unrealistic fermionic sector. Despite the variety of models presented in Ref. [1] (eleven in total), barring soft symmetry breaking, only three models survive the requirements of having a good DM candidate: no additional massless scalars present and realistic fermion masses and mixing. In these three models the fermions transform trivially under S_3 .

We explored two models: R-II-1a [1] and C-III-a [2] with vevs $(0, w_2, w_S)$ and $(0, \hat{w}_2 e^{i\sigma}, \hat{w}_S)$, respectively. Both models share a common vacuum pattern, apart from the σ phase in the C-III-a model. However, as discussed in Ref. [2], these models do not coincide in the limit of a vanishing phase for C-III-a. The R-II-1a and C-III-a correspond to different regions of the parameter space of the S_3 -symmetric 3HDM potential, which yields different acceptable DM candidate mass ranges. The full particle content, including interactions, is presented in Refs. [1, 2].

4. Models analysis

The two models are described in terms of eight input parameters. In R-II-1a two angles and six masses are used. In C-III-a, due to CP violation, we trade three masses for three angles to simplify computation; five angles and three masses are used as input. We scan over these parameters in order to identify regions that are compatible with a possible DM candidate. Several constraints are imposed, with each subsequent constraint being superimposed over the previous ones:

- Cut 1: perturbativity, stability, unitarity checks, a selection of relevant LEP constraints;
- Cut 2: SM-like gauge and Yukawa sector, S and T variables, $\bar{B} \rightarrow X(s)\gamma$ decays;
- Cut 3: SM-like Higgs particle decays, DM relic density, direct searches;

The applied numerical bounds are taken from PDG [13]. We impose $3\text{-}\sigma$ tolerance along with an additional ten per cent computational uncertainty in relevant checks. Only Cut 3 checks rely on public codes. We used micrOMEGAs 5.2.7 [14] to evaluate these constraints.

5. Discussion

In the R-II-1a model due to no mixing between the inert neutral states there are potentially two possible DM candidates. However, only one of these states is a possible DM candidate, namely χ_1 , see eq. (2). The state η_1 with $m_{\eta_1}^2 \sim \lambda_4 v^2$ does not satisfy Cut 3. In contrast to R-II-1a, there is a single DM candidate in C-III-a due to mixing of the inert neutral fields. Moreover, there is mixing among all neutral active scalars in C-III-a, and hence the SM-like Higgs boson is CP indefinite.

In figure 2 we present mass scatter plots after applying the previously discussed constraints. We allowed for scalars to be as heavy as 1 TeV. However, after applying Cut 1 an upper bound of around 600-800 GeV develops. The allowed regions shrink after applying Cut 2 and Cut 3. Both models favour light states of 200-400 GeV as indicated by the surviving grey regions. Such light states are not completely ruled out by the LHC searches due to the suppressed couplings and imposed constraints on the SM-like Higgs boson. While the active scalars of R-II-1a can in principle decay into other active scalars, if kinematically allowed, in C-III-a the dominant decay channel for all of the active scalars, except the SM-like Higgs, is into states with at least one DM candidate with the second scalar also coming from the inert doublet. Such processes would be accompanied by large missing transverse momentum in the detector.

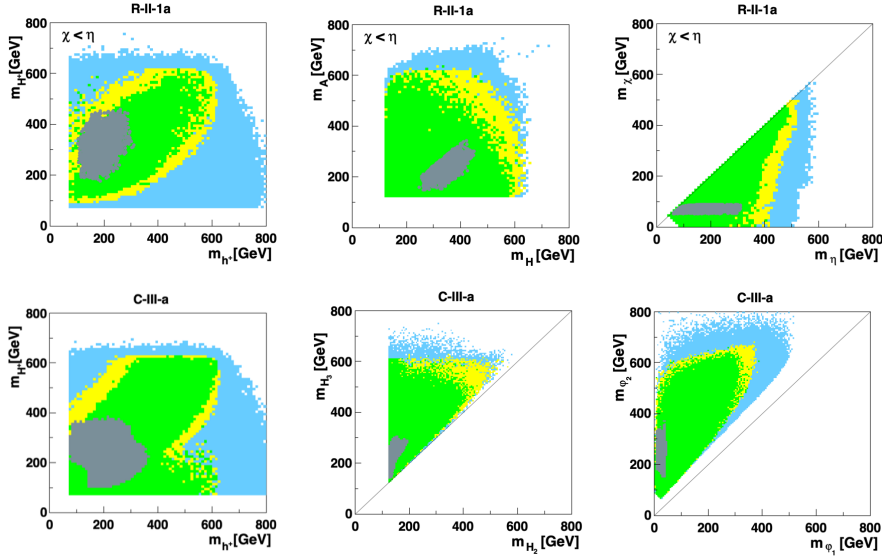


Figure 2: Scatter plots of masses that satisfy different sets of successive Cuts. Left column: the charged sector. Middle column: the active heavy neutral sector. Right column: the inert neutral sector. The blue region satisfies Cut 1. The yellow region accommodates a $3\text{-}\sigma$ tolerance with respect to Cut 2, whereas the green region accommodates the $2\text{-}\sigma$ bound. The grey region is compatible with Cut 1, Cut 2 and Cut 3.

After applying all three cuts over the parameter space we found that the viable DM mass regions differ drastically from the multi-doublet DM models proposed earlier, see figure 1. There is no high mass DM region in our models. In those the portal couplings grow fast with the DM candidate mass. High portal couplings would lead to a DM candidate annihilating too fast in the Early Universe. Heavy DM candidates in IDM-like models require the tuning of portal couplings as well as near mass degeneracy between the inert scalars. In the C-III-a model near degeneracy is impossible and we obtain a mass gap of around 70 GeV for the parameter region of interest for DM.

Another interesting property, particular to C-III-a, is that there are only DM candidates with masses $m_{\text{DM}} < 50$ GeV, a region that is ruled out for the other models, whereas masses above this limit are excluded due to the strength of the portal couplings. Furthermore, in the C-III-a model the direct DM detection criteria are satisfied for light DM states, presented in figure 3. There are points for both models with spin-independent DM-nucleon cross section several orders of magnitudes lower than what would be probed by future DM experiments.

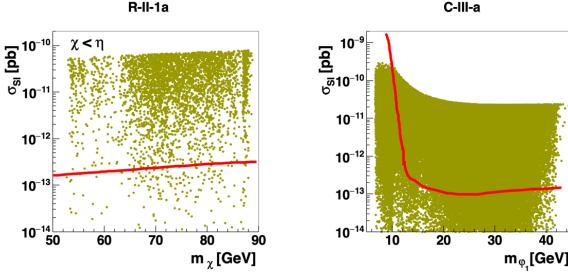


Figure 3: The spin-independent DM-nucleon cross section compatible with XENON1T [15] data at 90% C.L. The points represent cases that satisfy Cut 3. The red line corresponds to an approximate neutrino floor.

Deciphering the nature of DM remains one of the most important challenges in both particle physics and cosmology. After applying a selected set of constraints we determined possible DM mass ranges. Those are [52.5, 89] GeV for R-II-1a and [6.5, 44.5] GeV for C-III-a. These models look very promising, showing that the S_3 -symmetric 3HDM has a very rich structure.

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