

An Inert Scalar In The S_3 Symmetric Model.

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Abstract. We consider the S_3 symmetric extension of the Standard Model in which all the irreducible representations of the permutation group are occupied by $SU(2)$ scalar doublets, one of which is taken as inert. We study the parameter space of the model probing points against physical constraints ranging from unitarity tests to experimental Higgs searches limits. We find that the latter constraints severely restrict the parameter space of the model, and that the relic density of the dark matter candidates lies below the Planck bound for a large portion of the probed regions.

1. Introduction.

The search for extensions of the Standard Model (SM) capable of tackling one or more of the well known issues present in this paradigm of particle physics continues to be one of the most active fields of contemporary research. One strategy is to approach the subject from the scalar sector of the SM, enlarging its field content with extra scalars while keeping the rest of the sectors untouched. As demonstrated by the vast literature on the Two Higgs Doublet Model (THDM) (see e.g. [1] and references therein), the simplest of such extensions, the possibility of stumbling into rich and interesting phenomenology is just around the corner. Moreover, by taking the extra scalar doublet as inert (the Inert Doublet Model [2, 3, 4, 5, 6, 7, 8, 9, 10, 11]) we end up with a very simple and at the same time highly illustrative model containing a candidate for dark matter.

Multihiggs models are natural generalizations of this scheme, including those with additional symmetries imposed, for example the S_3 symmetric model where a total of three Higgs doublets are present and it is assumed that these scalars belong to irreducible representations of the permutation group S_3 reflecting a hypothesized discrete symmetry of the model (see e.g. [12, 13, 14, 15, 16, 17, 18, 19], and references therein).

In this letter we briefly report on the findings of [20] wherein the totality of the irreducible representations of S_3 accommodate four scalar doublets one of which is taken as inert, thereby keeping the nice characteristics of the S_3 model and at the same time equipping the model with a dark matter candidate, exploring in detail its phenomenology. While higher order corrections can be of sizable importance for non-supersymmetric models (see e.g. [21, 22]), we keep the analysis at the tree level only.

2. The model.

The model is an extension of the scalar sector of the SM with a potential defined as:

$$V = V_{S3} + V_{2a} + V_{4a} + V_{4sa} \quad (1)$$

where V_{S3} is the scalar potential of the $S3$ model with three Higgs doublets (see for instance [23, 24, 17, 18, 19]), two of them Φ_1 and Φ_2 transforming as an $S3$ doublet and one more Φ_s as a symmetric singlet. The rest of the terms in the potential include an extra scalar doublet Φ_a transforming as an anti-symmetric singlet and are given explicitly by:

$$V_{2a} = \mu_2^2 \Phi_a^\dagger \Phi_a \quad (2)$$

$$\begin{aligned} V_{4a} = & \lambda_9 [(\Phi_a^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1 + \Phi_1^\dagger \Phi_2) + (\Phi_a^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2 - \Phi_1^\dagger \Phi_1) + \text{h.c.}] \\ & + \lambda_{10} (\Phi_a^\dagger \Phi_a)(\Phi_1^\dagger \Phi_1 + \Phi_2^\dagger \Phi_2) \\ & + \lambda_{11} [(\Phi_a^\dagger \Phi_1)(\Phi_1^\dagger \Phi_a) + (\Phi_a^\dagger \Phi_2)(\Phi_2^\dagger \Phi_a)] \\ & + \lambda_{12} [(\Phi_a^\dagger \Phi_1)(\Phi_a^\dagger \Phi_1) + (\Phi_a^\dagger \Phi_2)(\Phi_a^\dagger \Phi_2) + \text{h.c.}] \\ & + \lambda_{13} (\Phi_a^\dagger \Phi_a)^2 \end{aligned} \quad (3)$$

$$V_{4sa} = \lambda_{14} (\Phi_s^\dagger \Phi_a \Phi_a^\dagger \Phi_s) + \lambda_{15} (\Phi_1^\dagger \Phi_s \Phi_2^\dagger \Phi_a + \text{h.c.}) \quad (4)$$

a total of 18 free parameters are present in the potential but two of them (λ_9 and λ_{15}) need to be removed when we impose the additional requirement that the theory remains invariant under $\Phi_a \rightarrow -\Phi_a$ so as to be able to consider this field as a dark matter candidate. Two more parameters, the coefficients of the quadratic terms in V_{S3} , can be expressed in terms of the rest via the minimization conditions (tadpole equations) of the scalar potential leaving a total of 14 free parameters: the quartic couplings of V_{S3} , $\lambda_1, \dots, \lambda_8$, the quartic couplings in the previous terms, $\lambda_{10}, \dots, \lambda_{14}$ and the coefficient μ_2^2 . In addition we assumed the quartic couplings to be real so as to not introduced additional CP violating sources.

After electroweak symmetry breaking all of the scalar doublets except Φ_a acquire vacuum expectation values (vev) v_1, v_2 and v_s but consistency of the tadpole equations requires two of them to be aligned $v_1 = \sqrt{3}v_2$. We define $\tan \theta = 2v_2/v_s$ with the usual SM vev given by $v = \sqrt{v_s^2 + 4v_2^2} = 246$ GeV which results in just one additional free parameter.

The scalar fields mix into physical mass eigenstates except for the dark fields which remained unmixed; the complete field content of the scalar sector becomes in our notation: H, H_3 and h for the neutral scalars, A and h_2^p for the neutral pseudo-scalars, H^\pm and h_2^\pm for the charged scalars, and finally h_a^n, h_a^p and h_a^\pm the corresponding fields on the dark sector. After diagonalization, expressions for the masses of the physical fields are obtained in terms of the free parameters, but it is convenient for the numerical calculations to invert this equations so as to have the physical masses as input parameters. In this way we end up working with all the scalar masses as input parameters as well as the set $\mu_2^2, \lambda_{13}, \lambda_{14}, \tan \theta$ and α , where the last parameter defines the mixing angle between H and h . In addition we are able to identify $\cos(\theta - \alpha) \approx 0$ as the decoupling limit wherein h has SM-like couplings and can be identified with the SM Higgs, hence we fix the mass of h to lie within the experimental Higgs mass interval [25, 26] for the numerical calculations.

3. Numerical analysis and results.

For the numerical calculations we imposed several physical restrictions, including stability constraints [19, 27] for the scalar potential, unitarity conditions both for the large energy limit [28] as well as for finite energies [29, 30], and experimental limits from Higgs searches (e.g. [31, 32, 33, 34, 35] and references therein). We take advantage of the capabilities of several computational tools including SARAH [36, 37, 38, 39, 40, 41], SPheno [42, 43], HiggsBounds [31, 32, 33, 34, 35], MicrOMEGAS [44], FeynArts [45] and FormCalc [46], most of which facilitate their intercommunication by supporting the SLHA [47, 48] protocol, for full details see [20].

We scan the parameter space randomly and we show results for the case where the dark scalar h_a^n is taken as the dark matter candidate in the following plots. In figure (1) we show (left panels) the DM mass as a function of $\tan\theta$ and (right panels) the calculated relic density as a function of the DM mass and how it compares with the measured Planck value [49]. Different set of points are separated for visual clarity, showing all the sets together in the lower panels. We notice that already the first constraints on stability and unitarity force the great majority of points to lie below a value of $\tan\theta < 10$, with just a handful of points reaching a value of ~ 19 . With respect to the relic density calculations, we find a region of small masses below 100 GeV wherein there is overproduction of dark matter, but also many points lie below the Planck value and some of them satisfy it. Also we observe a marked dip around 62 – 63 GeV where the annihilation amplitude has a pole in the s channel when the exchanged particle corresponds to the Higgs-like h whose mass was fixed at around 125 GeV. Above 100 GeV and all the way to 5 TeV the relic density values lie well below the Planck bound, increasing steadily at around 1 TeV, but with very few points satisfying all the lines of constraints.

Finally in figure (3) we show for small DM masses (< 100 GeV) the annihilation cross section relevant for indirect DM searches as a function of the DM mass, where points are calibrated with respect to their predicted relic density value and how it compares to the Planck value, by means of a Gaussian likelihood function centered at the latter measured value. Hence, the darkest points in the plot lie above or below the experimental Planck interval while bright points predict relic density values in accordance with the experimental interval. We compare this points with the current FermiLAT combined limits from dwarf spheroidal galaxies [50] for the $b\bar{b}$ channel. We find the existence of points in parameter space that lie safely below this exclusion curve.

4. Conclusions.

We presented an analysis of a multihiggs doublet model with a discrete S_3 permutation symmetry, the total number of scalar doublet fields chosen so as to fill up the entire number of irreducible representations of S_3 . By choosing one of the doublets as inert, the rest of the field content resembles the S_3 model with three scalar doublets, thereby recovering the nice phenomenological aspects of this model and at the same time empowering it with an interesting dark matter candidate. We probed regions of parameter space within a range of masses between 10 GeV and 5 TeV for the dark matter candidate; we found a sub-region of low masses (< 100 GeV) with points of the parameter space satisfying experimental scalar searches bounds, the relic density abundance Planck bound, and also the present FermiLAT combined limits for annihilation cross section for the $b\bar{b}$ channel, thus demonstrating the viability of the model.

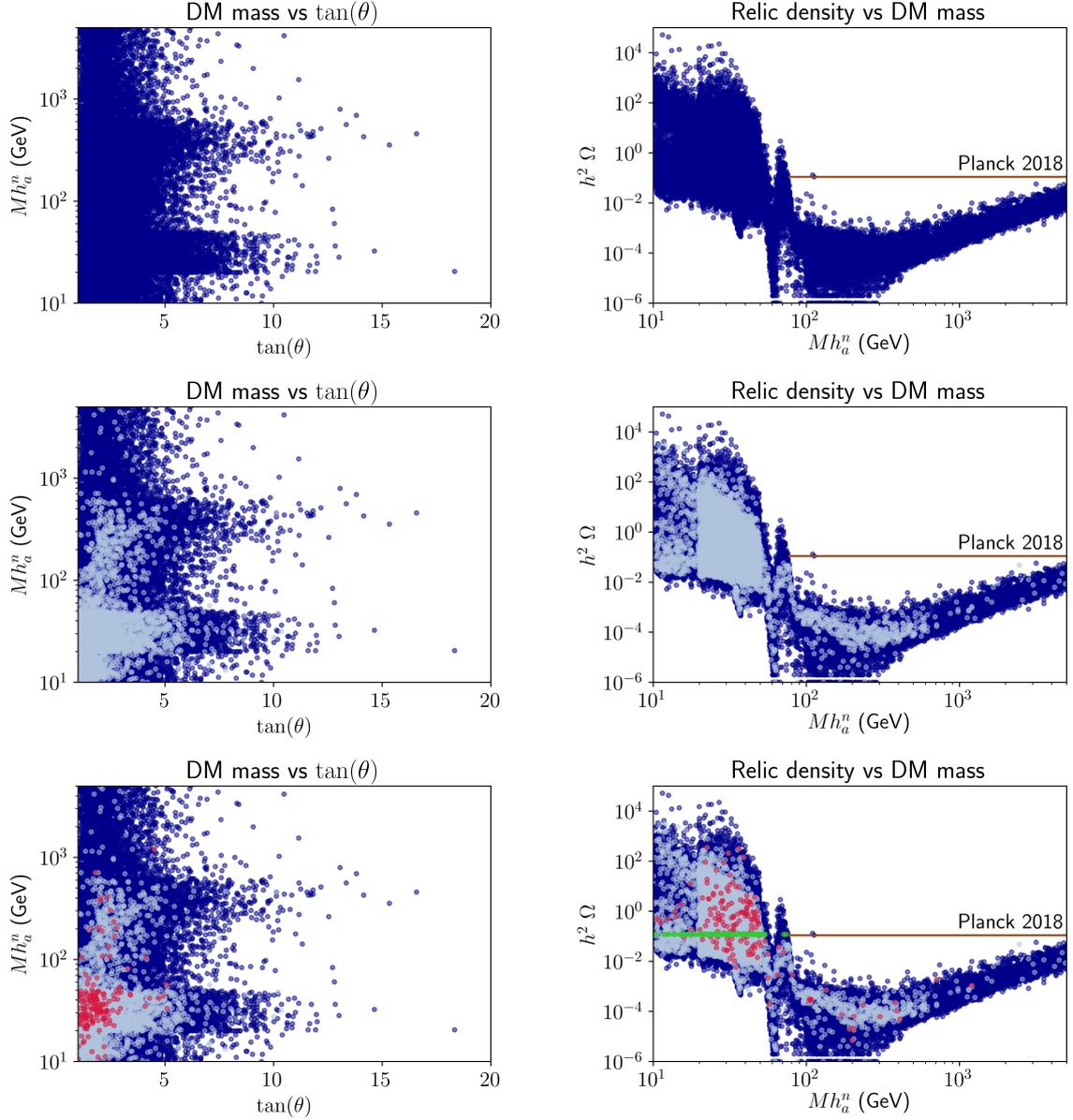


Figure 1. Mass of the DM candidate as a function of $\tan\theta$ (left panels), and value of the DM relic density as a function of the DM mass (right panels). The dark blue points (top panels) are the ones that comply with stability and unitarity constraints, the light blue points (middle panels) are also compatible with the experimental bounds for extra scalar searches, the red points (lower panels) also satisfy the decoupling limit and the green points (lower right panel) lie within the experimental Planck bound.

Acknowledgements

C.E. acknowledges the support of CONACYT (México) Cátedra 341. This work is supported in part by grant PAPIIT IN111518.

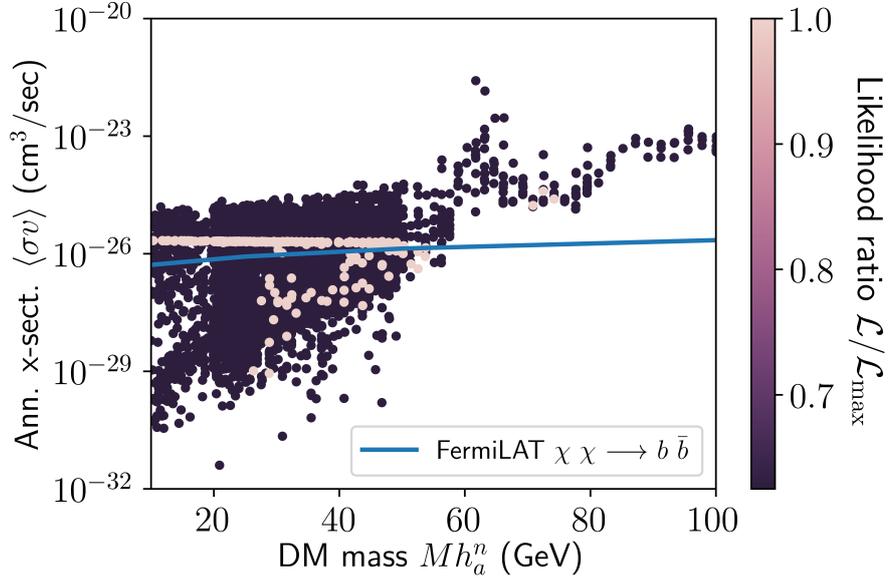


Figure 2. Annihilation cross section as a function of the DM mass for small DM masses, the points are colored according to their (normalized) likelihood (with respect to the relic density) value. Also shown is the FermiLAT dwarf spheroidal combined DM exclusion curve.

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