STATUS OF DARK MATTER IN S_3-SYMMETRIC THREE-HIGGS-DOUBLET MODEL

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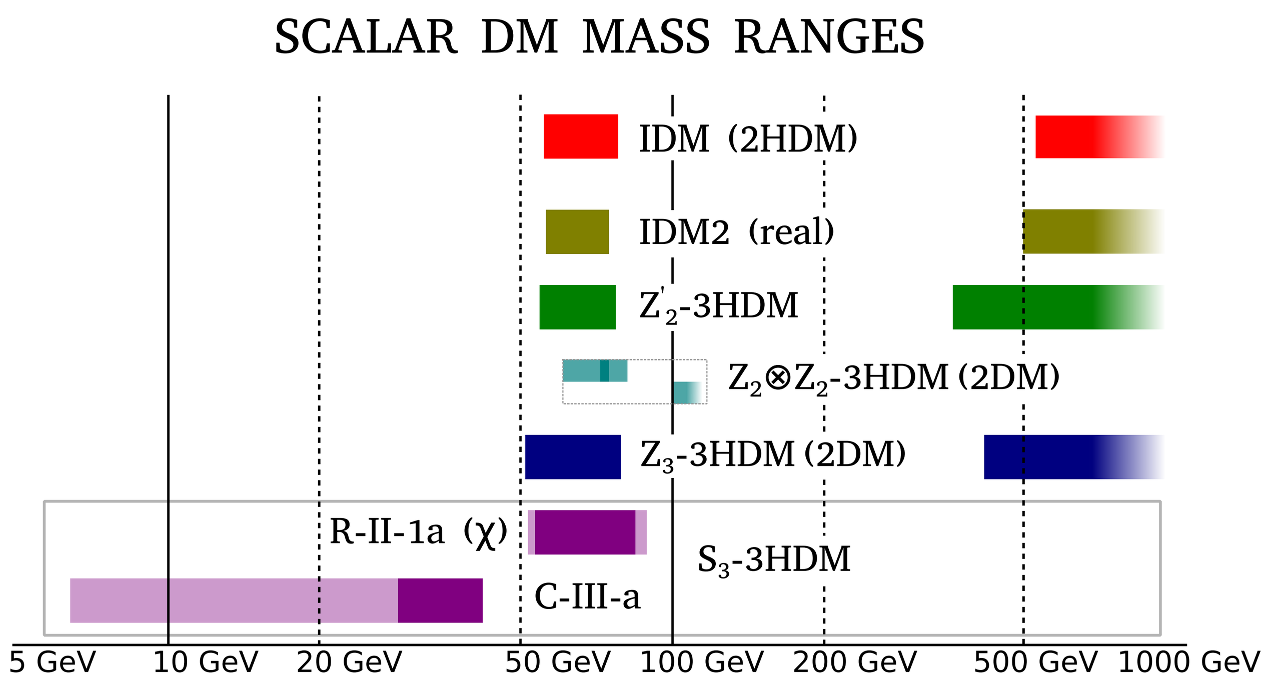
Introduction

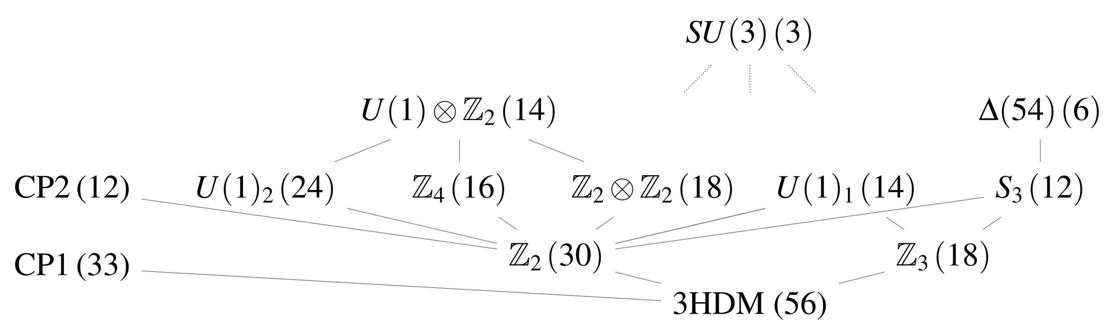
In scenarios beyond the Standard Model (SM) it is common to invoke models with an extended scalar sector. Such extensions are appealing due to their simplicity from the mathematical point of view and the ability to deal with several shortcomings of the SM. Models with a non-minimal Higgs sector are well motivated, despite the fact that the properties of the observed Higgs boson are in good agreement with the SM predictions. The simplest extension, the two-Higgs-doublet model, suffers from the fact that it cannot simultaneously accommodate a Dark Matter (DM) candidate, in the the Inert Doublet Model (IDM), and provide new sources for CP violation. Governed by this, we consider an S_3-symmetric three-Higgs-doublet model (3HDM). Within this framework there are different cases which could possibly accommodate a DM candidate and provide new sources for CP. The family of S_3-3HDM implementations arises due to different vacuum expectation values (vevs). In this framework the DM candidate falls into the class of weakly interacting massive particles. The DM candidate is associated with a $\mathbb{Z}_2$ symmetry which survives spontaneous symmetry breaking and is a remnant of the S_3 symmetry. After classifying all possible DM candidates within the framework we further explore two cases numerically.



Sketch of allowed DM mass ranges in IDM and 3HDMs up to 1 TeV. Olive: IDM2 with real coefficients [1]. Red: IDM2 [2]. Green: truncated $\mathbb{Z}_2$-3HDM [3] with an without CP violation (merged). Teal: $\mathbb{Z}_2\otimes\mathbb{Z}_2$ with two DM candidates [4]. The darker region (only for the lighter DM candidate) indicates the surviving region in light of the updated DM searches. Navy: $\mathbb{Z}_3$ with two mass-degenerate DM candidates [5]. Purple: S_3-3HDM without CP violation R-II-1a [6] and with CP violation C-III-a [7]. The darker purple region is consistent with refined constraints of Ref. [8].

S_3-Symmetric 3HDM

The 3HDM may be constrained by an underlying symmetry, $\mathscr{G}$, leading to characteristic phenomenology and controlling degrees of freedom in a natural way. There are several realisable symmetries within 3HDMs [9]:



Choice of $\mathscr{G}$:
- too large—might result in unrealistic physics;
- too small—too many free parameters;

In terms of the S_3 singlet (h_S) and doublet ($(h_1\, h_2)^{\mathrm{T}}$) fields, the S_3-symmetric potential can be written as:

$$\begin{aligned}
V_2 &= \mu_0^2 h_S^\dagger h_S + \mu_1^2 (h_1^\dagger h_1 + h_2^\dagger h_2),\\
V_4 &= \lambda_1 (h_1^\dagger h_1 + h_2^\dagger h_2)^2 + \lambda_2 (h_1^\dagger h_2 - h_2^\dagger h_1)^2 + \lambda_3[(h_1^\dagger h_1 - h_2^\dagger h_2)^2 + (h_1^\dagger h_2 + h_2^\dagger h_1)^2]\\
&\quad + \lambda_4[(h_S^\dagger h_1)(h_1^\dagger h_2 + h_2^\dagger h_1) + (h_S^\dagger h_2)(h_1^\dagger h_1 - h_2^\dagger h_2) + \text{h.c.}] + \lambda_5 (h_S^\dagger h_S)(h_1^\dagger h_1 + h_2^\dagger h_2)\\
&\quad + \lambda_6[(h_S^\dagger h_1)(h_1^\dagger h_S) + (h_S^\dagger h_2)(h_2^\dagger h_S)] + \lambda_7[(h_S^\dagger h_1)(h_S^\dagger h_1) + (h_S^\dagger h_2)(h_S^\dagger h_2) + \text{h.c.}] + \lambda_8 (h_S^\dagger h_S)^2.
\end{aligned}$$

The S_3 symmetry is expanded into the Yukawa Lagrangian:
- For $\langle h_S \rangle \neq 0$ it is possible to construct a trivial representation, $\mathscr{L}_Y \sim 1_f \otimes 1_h$, identical to the SM case;
- For a non-trivial representation we need an S_3 doublet (seven different possibilities to assign S_3 $(\mathbf{1}, \mathbf{1}')$):

$$\text{For example, } \begin{pmatrix} \mathbf{2}: (Q_1\, Q_2)^{\mathrm{T}}, (u_{1R}\, u_{2R})^{\mathrm{T}}, (d_{1R}\, d_{2R})^{\mathrm{T}}, \\ \mathbf{1}: Q_3, u_{3R}, d_{3R}, \end{pmatrix} \text{ yields } \mathscr{M}_u = \frac{1}{\sqrt{2}} \begin{pmatrix} y_1^u w_S^* + y_2^u w_2^* & y_2^u w_1^* & y_4^u w_1^* \\ y_2^u w_1^* & y_1^u w_S^* - y_2^u w_2^* & y_4^u w_2^* \\ y_5^u w_1^* & y_5^u w_2^* & y_3^u w_S^* \end{pmatrix}.$$

The S_3 symmetry can be spontaneously broken by vevs, giving rise to additional Goldstone bosons:

Constraints	Continuous symmetries	# of massless states
$[\lambda_4 = 0]$	O(2)	1
$\cdots + [\lambda_7 = 0]$	$\mathrm{O(2)}\otimes\mathrm{U(1)}_{\Phi_S}$	2
$\cdots + [\lambda_2 + \lambda_3 = 0]$	SU(2) [$\mathrm{O(2)}\otimes\mathrm{U(1)}_{\Phi_1}\otimes\mathrm{U(1)}_{\Phi_2}\otimes\mathrm{U(1)}_{\Phi_S}$]	3

Our philosophy is to identify vacua [11] with at least one vanishing vev as possible frameworks for a DM model:

Vacuum	vevs	λ_4	Remnant symmetries	# of massless states	Fermions under S_3
R-I-1	$(0,0,w_S)$	$\surd$	S_3, $h_1 \to -h_1$	none	trivial
R-I-2a	$(w,0,0)$	$\surd$	S_2	none	unrealistic
R-I-2b,2c	$(w,\pm\sqrt{3}w,0)$	$\surd$	S_2	none	unrealistic
R-II-1a	$(0,w_2,w_S)$	$\surd$	S_2, $h_1 \to -h_1$	none	trivial
R-II-2	$(0,w,0)$	0	S_2, $h_1 \to -h_1, h_S \to -h_S$	1	unrealistic
R-II-3	$(w_1,w_2,0)$	0	$h_S \to -h_S$	1	unrealistic
R-III-s	$(w_1,0,w_S)$	0	$h_2 \to -h_2$	1	trivial
C-I-a	$(\hat{w}_1,\pm i\hat{w}_1,0)$	$\surd$	cyclic $\mathbb{Z}_3$	none	unrealistic
C-III-a	$(0,\hat{w}_2 e^{i\sigma_2},\hat{w}_S)$	$\surd$	S_2, $h_1 \to -h_1$	none	trivial
C-III-b	$(\pm i\hat{w}_1,0,\hat{w}_S)$	0	$h_2 \to -h_2$	1	trivial
C-III-c	$(\hat{w}_1 e^{i\sigma_1},\hat{w}_2 e^{i\sigma_2},0)$	0	$h_S \to -h_S$	2	non-trivial
C-IV-a	$(\hat{w}_1 e^{i\sigma_1},0,\hat{w}_S)$	0	$h_2 \to -h_2$	2	trivial

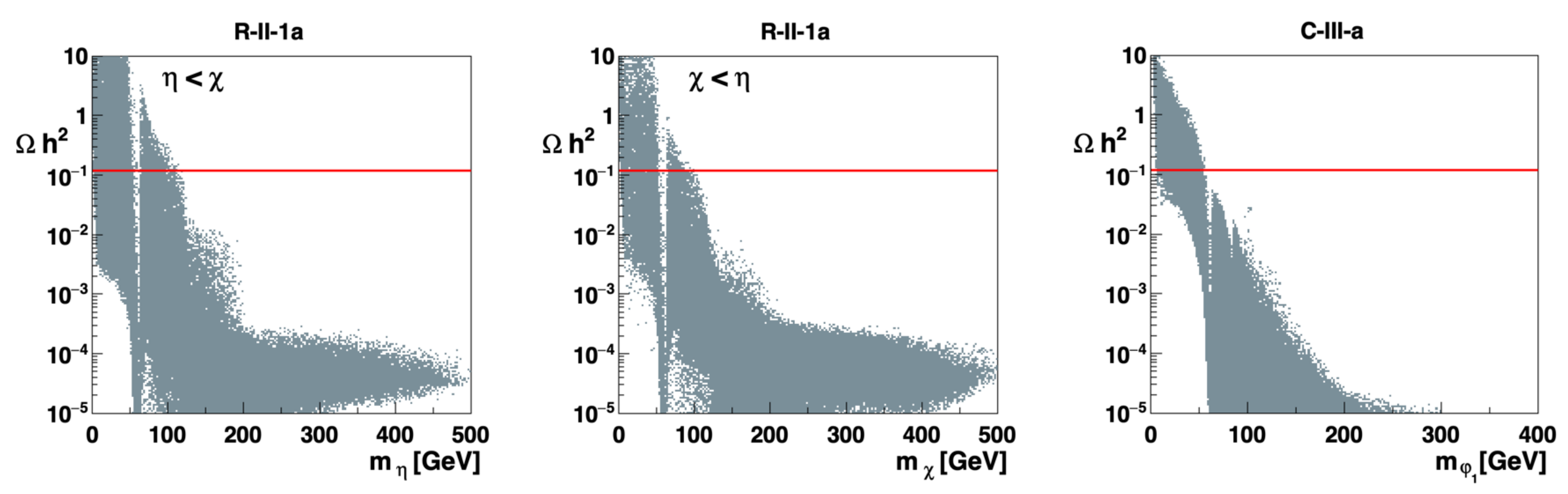
The "hat", $\hat{w}_i$, denotes an absolute value and all w_i are real. In the second column vevs are listed in the irreducible representation. In the fourth column remnant symmetries explicit in the defining representation are presented.

Model Analysis

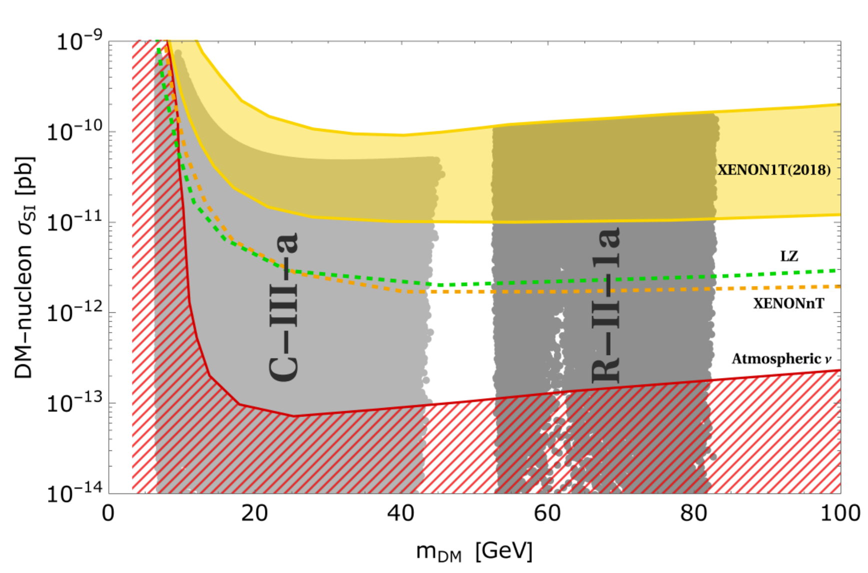
Both implementations are described in terms of eight input parameters: R-II-1a (6 masses and 2 angles), C-III-a (3 masses and 5 angles). In order to identify the viable DM mass region several constraints are imposed:

- Cut 1: perturbativity, stability, unitarity checks, LEP constraints;
- Cut 2: SM-like $h \to \{VV,\ FF\}$ decays, S and T variables, $\overline{B} \to X(s)\gamma$ decays;
- Cut 3: SM-like $h \to \{\text{invisible},\ \gamma\gamma\}$ decays, DM relic density (micrOMEGAs), direct DM detection constraints;
- Cut 4: LHC searches implemented in HiggsTools, indirect DM detection constraints;

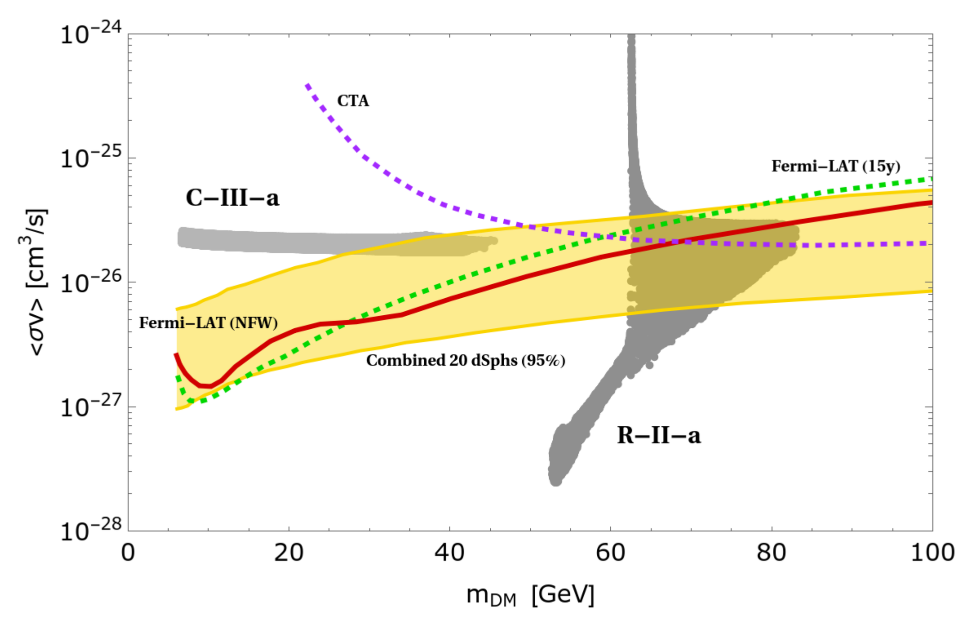
We allow for a 3-σ tolerance in relevant checks. Cuts 1-3 were considered in Refs. [6, 7] and Cut 4 in Ref. [8].



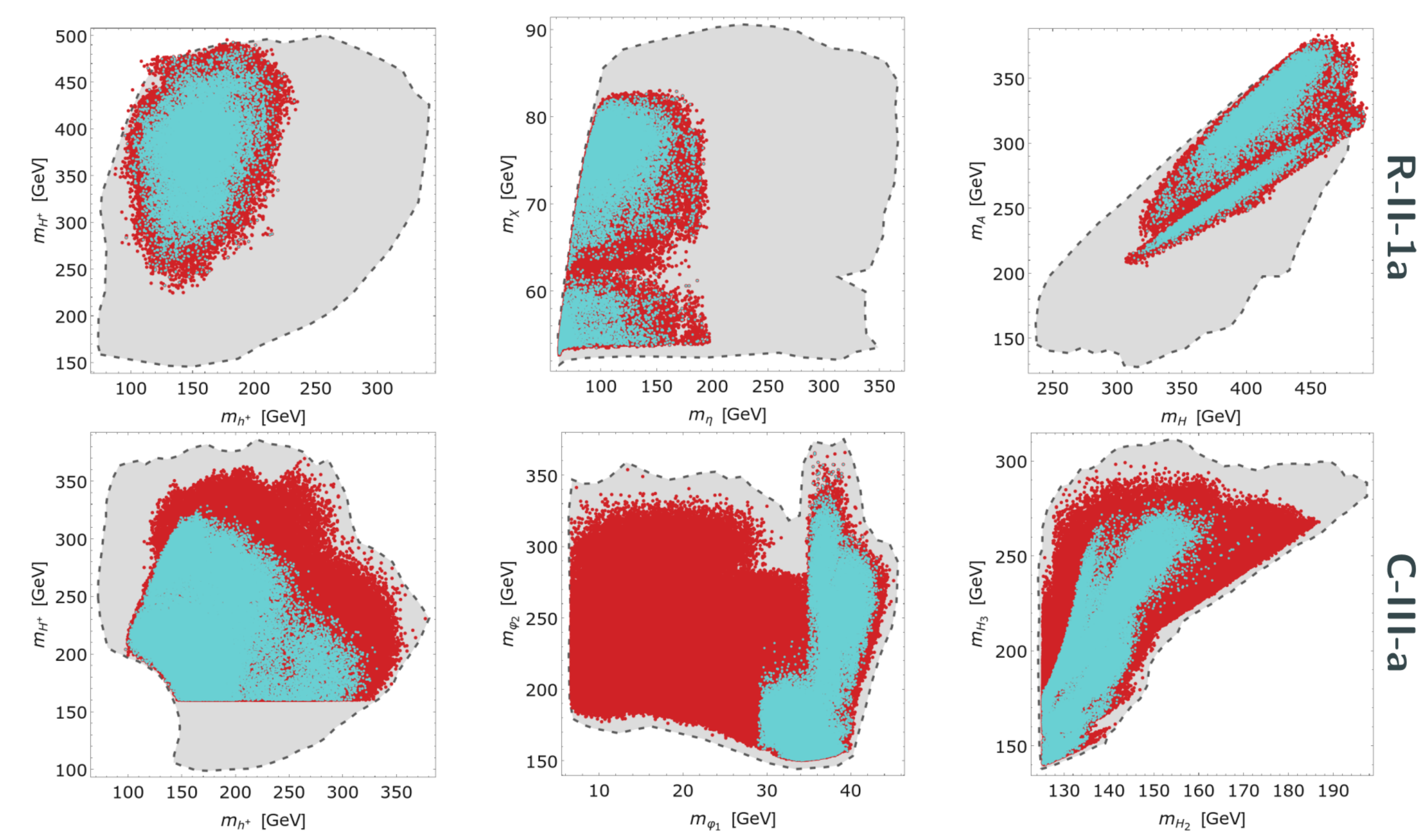
DM relic density for R-II-1a (η and χ) and C-III-a implementations. In the high-mass region, $m_{\mathrm{DM}} \gtrsim 500$ GeV, the DM relic density is shown to be too low. In this region the portal couplings scale like $g \sim m_{\mathrm{DM}}^2/v^2$.



The spin-independent DM-nucleon cross-section compatible with XENON1T data at 90% C.L. (yellow band). The dashed lines represent future sensitivities of XENONnT (orange) and LUX-ZEPLIN (green). Coloured regions (light grey: C-III-a, grey: R-II-1a) represent cases that satisfy Cut 3. The red line corresponds to an approximate neutrino floor.



DM self-annihilation cross-section as a function of the DM mass. The yellow band represents bounds at 90% C.L. compatible with observation of 20 dwarf spheroidal galaxies (dSphs). The red line represents Fermi-LAT assuming the NFW profile with $\rho = 0.3$ GeV/cm^3. The dashed lines represent future expectations from future sensitivities of Fermi-LAT (green) and probes by the Cherenkov Telescope Array (CTA) (purple). The light grey points represent C-III-a and the grey points R-II-1a cases that survive HiggsTools.



Scatter plots of masses that satisfy different constraints. Left column: the charged sector. Middle column: the inert neutral sector. Right column: the active heavy neutral sector. The grey region satisfies Cut 3. The red region relies on HiggsTools. The cyan region accommodates indirect DM detection and assumes portal $\mathrm{Br}(h \to \text{inv.}) \leq 0.1$.

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