Dark matter in three-Higgs-doublet models with S_3 symmetry

Anton Kunčinas

Centro de Física Teórica de Partículas – CFTP and Dept de Física Instituto Superior Técnico – IST,

Universidade de Lisboa, Portugal

In collaboration with: **W. Khater**, **O. M. Øgreid**, **P. Osland**, **M. N. Rebelo**
Based on **[2108.07026]**

DISCRETE 2020-2021

November 30, 2021

CFTP
CENTRO DE FÍSICA
TEÓRICA DAS PARTÍCULAS
TÉCNICO LISBOA

Introduction

Particle physics is best described by the Standard Model.

Introduction

Particle physics is best described by the Standard Model.

However, it fails to describe ______________________________________.

Possible solution: ____.

Particle physics is best described by the Standard Model.

However, it fails to describe *dark matter*.

Possible solution: *extend the scalar sector with interplay of symmetries*.

Motivation: check S_3-3HDM for dark matter candidates.

Introduction

Particle physics is best described by the Standard Model.

However, it fails to describe *dark matter*.
Possible solution: *extend the scalar sector with interplay of symmetries*.

Motivation: check S_3-3HDM for dark matter candidates.

Outline:

- Inert Doublet Model;
- General S_3-3HDM;
- Dark matter within S_3-3HDM;

Inert Doublet Model: Generalities

Main building block: SU(2) scalar doublet, $h = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$.

Inert Doublet Model: Generalities

Main building block: SU(2) scalar doublet, $h = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$.

Bilinear $h_{ij} = h_i^\dagger h_j$ is a singlet under SU(2).

Main building block: SU(2) scalar doublet, $h = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$.

Bilinear $h_{ij} = h_i^\dagger h_j$ is a singlet under SU(2).

$$\begin{aligned} \mathcal{V}_{\mathsf{2HDM}} = {} & m_{11}^2 h_{11} + m_{22}^2 h_{22} - \left(m_{12}^2 h_{12} + \mathrm{h.c.} \right) \\ & + \frac{1}{2}\lambda_1 h_{11}^2 + \frac{1}{2}\lambda_2 h_{22}^2 + \lambda_3 h_{11} h_{22} + \lambda_4 h_{12} h_{21} \\ & + \left\{ \frac{1}{2}\lambda_5 h_{12}^2 + \lambda_6 h_{11} h_{12} + \lambda_7 h_{22} h_{12} + \mathrm{h.c.} \right\} . \end{aligned}$$

Inert Doublet Model: Generalities

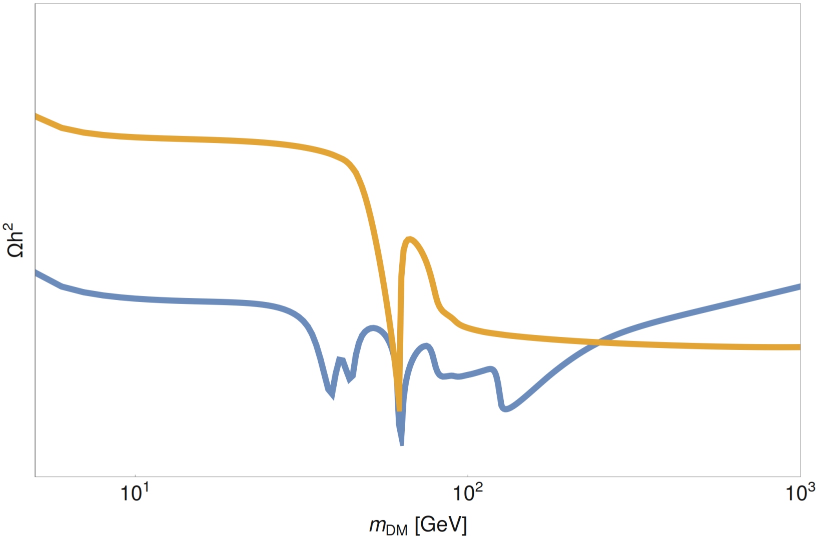
Main building block: SU(2) scalar doublet, $h = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$.

Bilinear $h_{ij} = h_i^\dagger h_j$ is a singlet under SU(2).

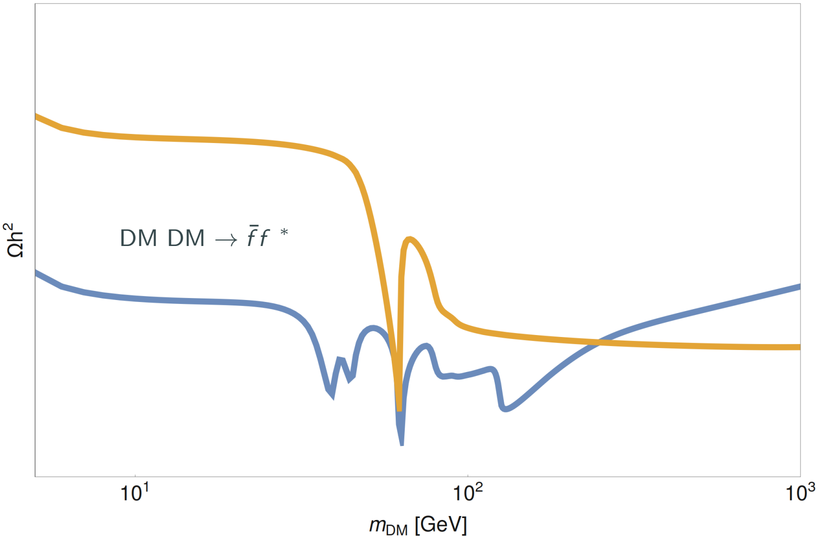
$$\begin{aligned} \mathcal{V}_{\rm IDM} &= m_{11}^2 h_{11} + m_{22}^2 h_{22} - \left(m_{12}^2 h_{12} + \text{h.c.} \right) \\ &\quad + \frac{1}{2}\lambda_1 h_{11}^2 + \frac{1}{2}\lambda_2 h_{22}^2 + \lambda_3 h_{11} h_{22} + \lambda_4 h_{12} h_{21} \\ &\quad + \left\{ \frac{1}{2}\lambda_5 h_{12}^2 + \lambda_6 h_{11} h_{12} + \lambda_7 h_{22} h_{12} + \text{h.c.} \right\}. \end{aligned}$$

$$\mathbb{Z}_2 : \begin{cases} h_1 \to h_1, \\ h_2 \to -h_2, \end{cases} \qquad \text{vacuum:} \begin{cases} \langle 0|h_1|0\rangle \neq 0, \\ \langle 0|h_2|0\rangle = 0. \end{cases}$$

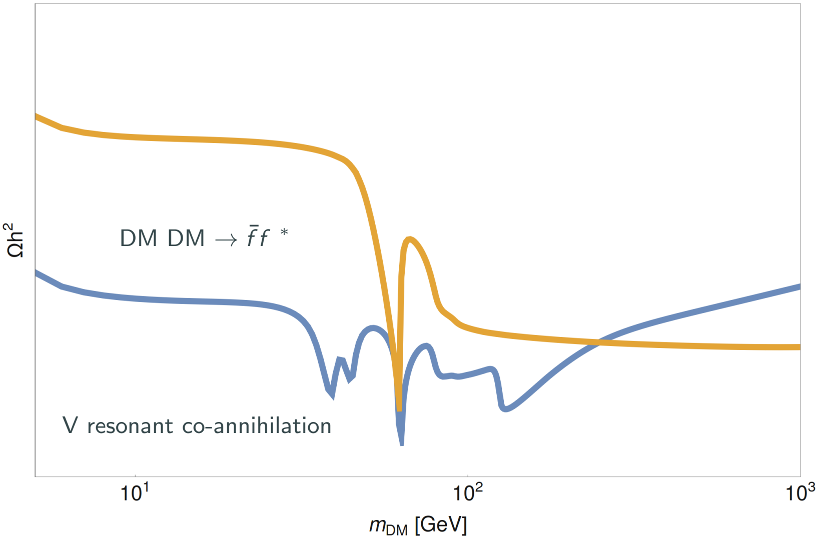
Inert Doublet Model: Profile



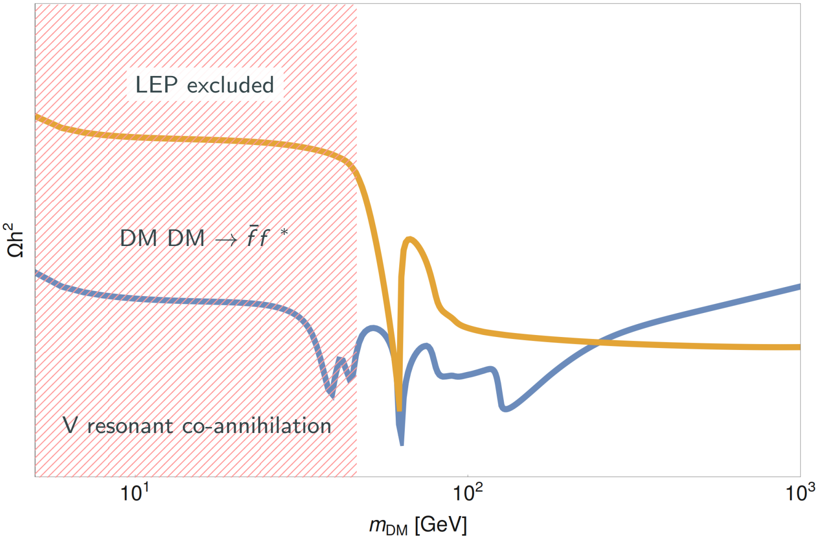
Inert Doublet Model: Profile



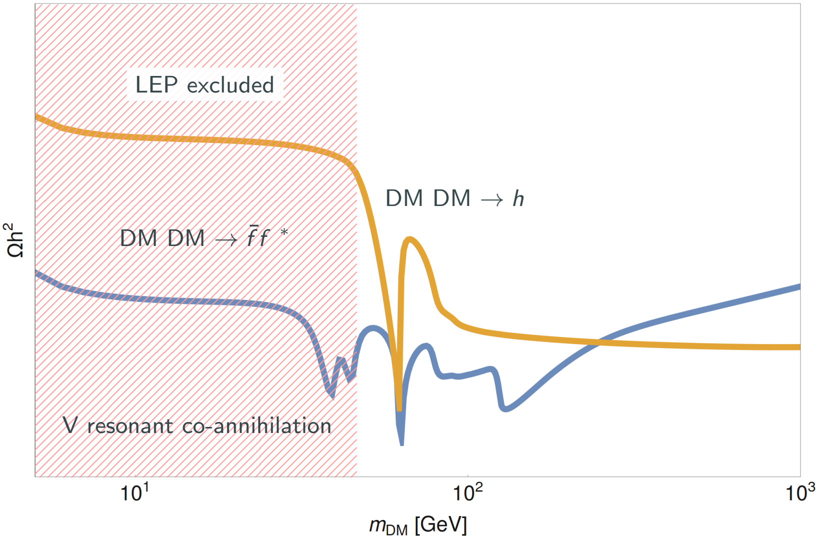
Inert Doublet Model: Profile



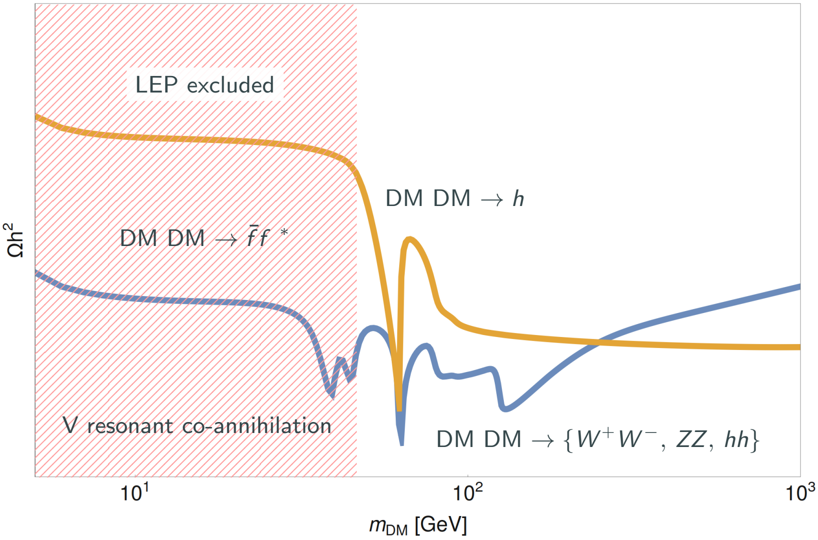
Inert Doublet Model: Profile

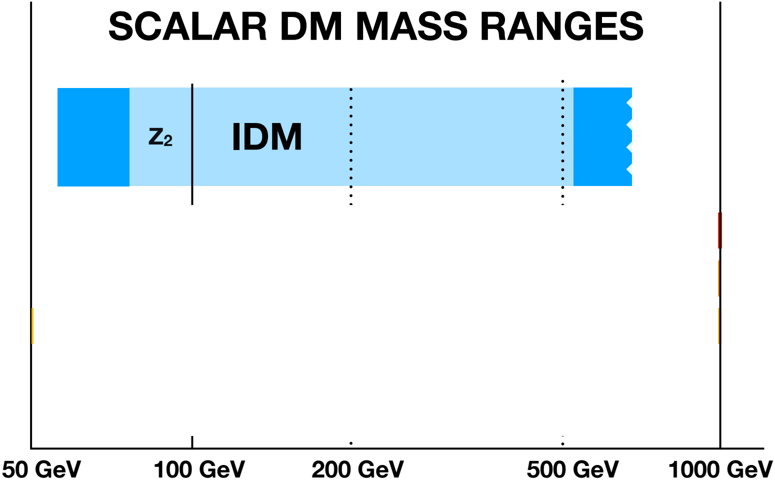


Inert Doublet Model: Profile



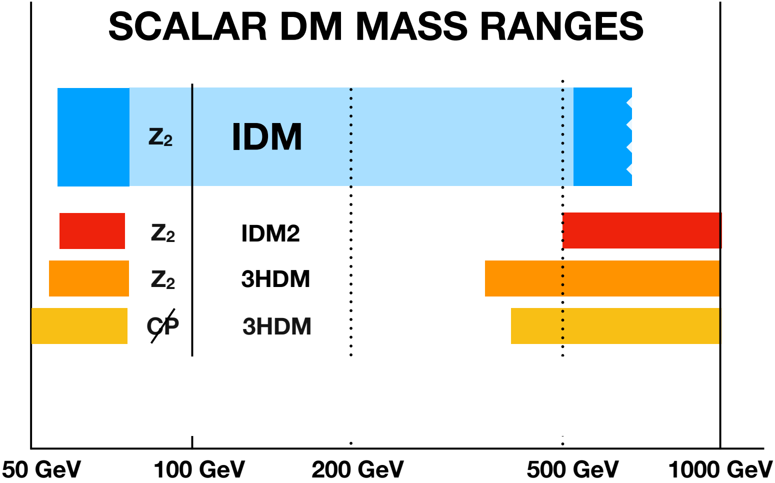
Inert Doublet Model: Profile





IDM: **[1612.00511]**, **[1809.07712]**;
IDM2 (one inert doublet): **[1911.06477]**;

(Two inert doublets)
3HDM: **[1407.7859]**, **[1507.08433]**, **[1712.09598]**;
~~CP~~-3HDM: **[1608.01673]**;



IDM: **[1612.00511]**, **[1809.07712]**;
IDM2 (one inert doublet): **[1911.06477]**;

(Two inert doublets)
3HDM: **[1407.7859]**, **[1507.08433]**, **[1712.09598]**;
~~CP~~-3HDM: **[1608.01673]**;

Multi-Higgs-Doublet Models

$$\mathcal{L}_{\mathrm{NHDM}} = \overbrace{\sum_{i=1}^{N} \left(D^{\mu} h_i\right)^{\dagger} \left(D_{\mu} h_i\right)}^{\mathcal{L}_{\text{Kinetic}}} - \overbrace{\mathcal{V}\left(h_1,\, \ldots,\, h_N\right)}^{\mathcal{V}_{\text{Scalar}}} - \mathcal{L}_{\text{Yukawa}}\,.$$

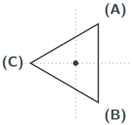
Multi-Higgs-Doublet Models

$$\mathcal{L}_{\mathrm{NHDM}} = \overbrace{\sum_{i=1}^{N} \left(D^{\mu} h_i\right)^{\dagger} \left(D_{\mu} h_i\right)}^{\mathcal{L}_{\mathsf{Kinetic}}} - \overbrace{\mathcal{V}\left(h_1,\, \ldots,\, h_N\right)}^{\mathcal{V}_{\mathsf{Scalar}}} - \mathcal{L}_{\mathsf{Yukawa}}\,.$$

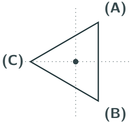
$\mathbb{R}\mathrm{e}$ parameters (dependent) of NHDM **[1007.1424]**:

$$N_{\mathrm{tot}} = \frac{1}{2} N^2 \left(N^2 + 3\right) \quad \rightarrow \quad \begin{cases} N = 1: & N_{\mathrm{tot}} = 2, \\ N = 2: & N_{\mathrm{tot}} = 14, \\ N = 3: & N_{\mathrm{tot}} = 54, \\ \ldots \end{cases}$$

S_3-Symmetric Three-Higgs-Doublet Models: Generalities

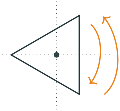
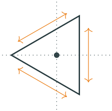
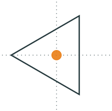
Consider an equilateral triangle:  .

S_3-Symmetric Three-Higgs-Doublet Models: Generalities

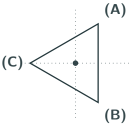
Consider an equilateral triangle:  .

Possible transformations:

- 2 rotations
- 3 reflections
- Identity

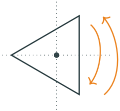




S_3-Symmetric Three-Higgs-Doublet Models: Generalities

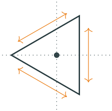
Consider an equilateral triangle:  .

Possible transformations:

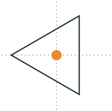
- 2 rotations



- 3 reflections



- Identity



S_3 irreducible representation: $\chi_{\mathbf{1}} \oplus \chi_{\mathbf{1'}} \oplus \chi_{\mathbf{2}}$.

Assume an S_3 structure $(h_S)_{\mathbf{1}} \oplus \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}_{\mathbf{2}}$.

S_3-Symmetric Three-Higgs-Doublet Models: Scalar Potential

Assume an S_3 structure $(h_S)_{\mathbf{1}} \oplus \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}_{\mathbf{2}}$.

$$\begin{aligned}
\mathcal{V}_{\mathrm{3HDM}} = {} & \mu_1^2 [2 \otimes 2]_1 + \mu_0^2 [1 \otimes 1]_1 \\
& + \lambda_1 \Big([2 \otimes 2]_1 \otimes [2 \otimes 2]_1 \Big) + \lambda_2 \Big([2 \otimes 2]_{1'} \otimes [2 \otimes 2]_{1'} \Big) \\
& + \lambda_3 \Big([2 \otimes 2]_2 \otimes [2 \otimes 2]_2 \Big) + \Big\{ \lambda_4 \Big([2 \otimes 2]_2 \otimes [1 \otimes 2]_2 \Big) + \xleftrightarrow{\mathrm{sym}} \Big\} \\
& + \lambda_5 \Big([2 \otimes 2]_1 \otimes [1 \otimes 1]_1 \Big) + \lambda_6 \Big([1 \otimes 2]_2 \otimes [2 \otimes 1]_2 \Big) \\
& + \Big\{ \lambda_7 \Big([1 \otimes 2]_2 \otimes [1 \otimes 2]_2 \Big) + \xleftrightarrow{\mathrm{sym}} \Big\} + \lambda_8 \Big([1 \otimes 1]_1 \otimes [1 \otimes 1]_1 \Big).
\end{aligned}$$

S_3-Symmetric Three-Higgs-Doublet Models: Scalar Potential

Assume an S_3 structure $(h_S)_{\mathbf{1}} \oplus \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}_{\mathbf{2}}$.

$$\begin{aligned}
\mathcal{V}_{\mathrm{3HDM}} = & \mu_1^2 (h_{11} + h_{22}) + \mu_0^2 h_{SS} \\
& + \lambda_1 (h_{11} + h_{22})^2 + \lambda_2 (h_{12} - h_{21})^2 + \lambda_3 \left[(h_{11} - h_{22})^2 + (h_{12} + h_{21})^2\right] \\
& + \{\lambda_4 [h_{S1} (h_{12} + h_{21}) + h_{S2} (h_{11} - h_{22})] + \mathrm{h.c.}\} + \lambda_5 [h_{SS} (h_{11} + h_{22})] \\
& + \lambda_6 [h_{1S} h_{S1} + h_{2S} h_{S2}] + \left\{\lambda_7 \left[h_{S1}^2 + h_{S2}^2\right] + \mathrm{h.c.}\right\} + \lambda_8 h_{SS}^2.
\end{aligned}$$

S_3-Symmetric Three-Higgs-Doublet Models: Scalar Potential

Assume an S_3 structure $(h_S)_{\mathbf{1}} \oplus \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}_{\mathbf{2}}$.

$$\begin{aligned}
\mathcal{V}_{\mathrm{3HDM}} =& \mu_1^2 \left(h_{11} + h_{22}\right) + \mu_0^2 h_{SS} \\
&+ \lambda_1 \left(h_{11} + h_{22}\right)^2 + \lambda_2 \left(h_{12} - h_{21}\right)^2 + \lambda_3 \left[\left(h_{11} - h_{22}\right)^2 + \left(h_{12} + h_{21}\right)^2\right] \\
&+ \left\{\lambda_4 \left[h_{S1} \left(h_{12} + h_{21}\right) + h_{S2} \left(h_{11} - h_{22}\right)\right] + \mathrm{h.c.}\right\} + \lambda_5 \left[h_{SS} \left(h_{11} + h_{22}\right)\right] \\
&+ \lambda_6 \left[h_{1S} h_{S1} + h_{2S} h_{S2}\right] + \left\{\lambda_7 \left[h_{S1}^2 + h_{S2}^2\right] + \mathrm{h.c.}\right\} + \lambda_8 h_{SS}^2 .
\end{aligned}$$

Symmetries reduce free parameters:

$$\mathrm{NHDM} \xrightarrow{\text{3HDM}} (54) \xrightarrow{S_3} 12 \xrightarrow{\mathbb{R}\mathrm{e}} 10.$$

S_3-Symmetric Three-Higgs-Doublet Models: Scalar Potential

Assume an S_3 structure $(h_S)_{\mathbf{1}} \oplus \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}_{\mathbf{2}}$.

$$
\begin{aligned}
\mathcal{V}_{\mathrm{3HDM}} = & \mu_1^2 (h_{11} + h_{22}) + \mu_0^2 h_{SS} \\
& + \lambda_1 (h_{11} + h_{22})^2 + \lambda_2 (h_{12} - h_{21})^2 + \lambda_3 \left[(h_{11} - h_{22})^2 + (h_{12} + h_{21})^2 \right] \\
& + \{ \lambda_4 [h_{S1} (h_{12} + h_{21}) + h_{S2} (h_{11} - h_{22})] + \mathrm{h.c.} \} + \lambda_5 [h_{SS} (h_{11} + h_{22})] \\
& + \lambda_6 [h_{1S} h_{S1} + h_{2S} h_{S2}] + \left\{ \lambda_7 \left[h_{S1}^2 + h_{S2}^2 \right] + \mathrm{h.c.} \right\} + \lambda_8 h_{SS}^2 .
\end{aligned}
$$

Symmetries reduce free parameters:

$$
\mathrm{NHDM} \xrightarrow{\text{3HDM}} (54) \xrightarrow{S_3} 12 \xrightarrow{\mathbb{R}\mathrm{e}} 10.
$$

S_3-3HDM models were classified in **[1601.04654]**:

$$
\text{vacuum:} \quad \begin{cases} \text{11 real } \ (w_1,\, w_2,\, w_S)\,, \\ \text{17 complex } \ \left(\hat{w}_1 e^{i\sigma_1},\, \hat{w}_2 e^{i\sigma_2},\, \hat{w}_S\right). \end{cases}
$$

S_3-Symmetric Three-Higgs-Doublet Models: Yukawa Interactions

Whenever $w_S \neq 0$ we can construct a trivial Yukawa sector, $\mathcal{L}_Y \sim 1_f \otimes 1_h$:

$$\mathcal{M}_u = \frac{1}{\sqrt{2}} \mathrm{diag}\left(y_1^u,\, y_2^u,\, y_3^u\right) w_S^*, \qquad \mathcal{M}_d = \ldots$$

Whenever $w_S \neq 0$ we can construct a trivial Yukawa sector, $\mathcal{L}_Y \sim 1_f \otimes 1_h$:

$$\mathcal{M}_u = \frac{1}{\sqrt{2}}\mathrm{diag}\left(y_1^u,\, y_2^u,\, y_3^u\right) w_S^*, \qquad \mathcal{M}_d = \ldots$$

Fermions can transform non-trivially under S_3, $\mathcal{L}_Y \sim (2 \oplus 1)_f \otimes (2 \oplus 1)_h$:

$$\mathbf{2} : \left(Q_1\, Q_2\right)^{\mathrm{T}},\, \left(u_{1R}\, u_{2R}\right)^{\mathrm{T}},\, \left(d_{1R}\, d_{2R}\right)^{\mathrm{T}} \quad \text{and} \quad \mathbf{1} : Q_3,\, u_{3R},\, d_{3R},$$

$$\mathcal{M}_u = \frac{1}{\sqrt{2}} \begin{pmatrix} y_1^u w_S^* + y_2^u w_2^* & y_2^u w_1^* & y_4^u w_1^* \\ y_2^u w_1^* & y_1^u w_S^* - y_2^u w_2^* & y_4^u w_2^* \\ y_5^u w_1^* & y_5^u w_2^* & y_3^u w_S^* \end{pmatrix}, \qquad \mathcal{M}_d = \ldots$$

S_3-Symmetric Three-Higgs-Doublet Models: Massless States

Massless state:

$$\mathcal{V}\left(Uh\right) = \mathcal{V}\left(h\right),$$
$$\langle 0|\left(Uh\right)|0\rangle \neq \langle 0|h|0\rangle .$$

S_3-Symmetric Three-Higgs-Doublet Models: Massless States

Massless state:

$$\mathcal{V}\left(Uh\right) = \mathcal{V}\left(h\right),$$
$$\langle 0|\left(Uh\right)|0\rangle \neq \langle 0|h|0\rangle .$$

Results of **[2001.01994]**:

Constraints	Continuous symmetries	# of massless states
$[\lambda_4 = 0]$	O(2)	1
$\cdots + [\lambda_7 = 0]$	O(2)$\otimes$U(1)$_{h_S}$	2
$\cdots + [\lambda_2 + \lambda_3 = 0]$	SU(2) [O(2)$\otimes$U(1)$_{h_1}\otimes$U(1)$_{h_2}\otimes$U(1)$_{h_S}$]	3

S_3-Symmetric Three-Higgs-Doublet Models: Dark Matter Models

Vacuum	vevs	λ_4	symmetry	# 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	non-trivial
R-I-2b,2c	$(w, \pm\sqrt{3}w, 0)$	$\surd$	S_2	none	non-trivial
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	$h_1 \to -h_1, h_S \to -h_S$	1	non-trivial
R-II-3	$(w_1, w_2, 0)$	0	$h_S \to -h_S$	1	non-trivial
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	non-trivial
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

Possible DM candidates: 3 (exact S_3) and 8 (softly broken S_3) solutions.

S_3-Symmetric Three-Higgs-Doublet Models: Dark Matter Models

Vacuum	vevs	λ_4	symmetry	# 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	non-trivial
R-I-2b,2c	$(w, \pm\sqrt{3}w, 0)$	$\surd$	S_2	none	non-trivial
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	$h_1 \to -h_1, h_S \to -h_S$	1	non-trivial
R-II-3	$(w_1, w_2, 0)$	0	$h_S \to -h_S$	1	non-trivial
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	non-trivial
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

Possible DM candidates: 3 (exact S_3) and 8 (softly broken S_3) solutions.

S_3-Symmetric Three-Higgs-Doublet Models: Dark Matter Models

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

Possible DM candidates: 3 (exact S_3) and 8 (softly broken S_3) solutions.

S_3-Symmetric Three-Higgs-Doublet Models: Dark Matter Models

Vacuum	vevs	λ_4	symmetry	# 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	non-trivial
R-I-2b,2c	$(w, \pm\sqrt{3}w, 0)$	$\surd$	S_2	none	non-trivial
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	$h_1 \to -h_1, h_S \to -h_S$	1	non-trivial
R-II-3	$(w_1, w_2, 0)$	0	$h_S \to -h_S$	1	non-trivial
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	non-trivial
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

Possible DM candidates: 3 (exact S_3) and 8 (softly broken S_3) solutions.

R-II-1a: Physical Spectrum

Vacuum: $\{0,\, w_2,\, w_S\}$.

R-II-1a: Physical Spectrum

Vacuum: $\{0,\, w_2,\, w_S\}$.

The $\mathbb{Z}_2$ symmetry is preserved for: $h_1 \to -h_1, \quad \{h_2,\, h_S\} \to \pm\{h_2,\, h_S\}$.

R-II-1a: Physical Spectrum

Vacuum: $\{0, w_2, w_S\}$.

The $\mathbb{Z}_2$ symmetry is preserved for: $h_1 \to -h_1, \quad \{h_2, h_S\} \to \pm\{h_2, h_S\}$.

The inert doublet is associated with h_1.

R-II-1a: Physical Spectrum

Vacuum: $\{0, w_2, w_S\}$.

The $\mathbb{Z}_2$ symmetry is preserved for: $h_1 \to -h_1, \quad \{h_2, h_S\} \to \pm\{h_2, h_S\}$.

The inert doublet is associated with h_1.

Trivial Yukawa sector $\mathcal{L}_Y \sim 1_f \otimes 1_h$.

R-II-1a: Physical Spectrum

Vacuum: $\{0,\, w_2,\, w_S\}$.

The $\mathbb{Z}_2$ symmetry is preserved for: $h_1 \to -h_1, \quad \{h_2,\, h_S\} \to \pm\{h_2,\, h_S\}$.

The inert doublet is associated with h_1.

Trivial Yukawa sector $\mathcal{L}_Y \sim 1_f \otimes 1_h$.

Mass eigenstates:

$$h_1 = \begin{pmatrix} h^+ \\ \frac{1}{\sqrt{2}}\left(\eta + i\chi\right) \end{pmatrix},$$

$$h_2 = \begin{pmatrix} \sin\beta\, G^+ - \cos\beta\, H^+ \\ \frac{1}{\sqrt{2}}\left(\sin\beta\, v + \cos\alpha\, h - \sin\alpha\, H + i\left(\sin\beta\, G^0 - \cos\beta\, A\right)\right) \end{pmatrix},$$

$$h_S = \begin{pmatrix} \cos\beta\, G^+ + \sin\beta\, H^+ \\ \frac{1}{\sqrt{2}}\left(\cos\beta\, v + \sin\alpha\, h + \cos\alpha\, H + i\left(\cos\beta\, G^0 + \sin\beta\, A\right)\right) \end{pmatrix}.$$

R-II-1a: Physical Spectrum

Vacuum: $\{0,\, w_2,\, w_S\}$.

The $\mathbb{Z}_2$ symmetry is preserved for: $h_1 \to -h_1, \quad \{h_2,\, h_S\} \to \pm\{h_2,\, h_S\}$.

The inert doublet is associated with h_1.

Trivial Yukawa sector $\mathcal{L}_Y \sim 1_f \otimes 1_h$.

Mass eigenstates:

$$
\begin{aligned}
h_1 &= \begin{pmatrix} h^+ \\ \frac{1}{\sqrt{2}}\left(\eta + i\chi\right) \end{pmatrix}, \\
h_2 &= \begin{pmatrix} \sin\beta\, G^+ - \cos\beta\, H^+ \\ \frac{1}{\sqrt{2}}\left(\sin\beta\, v + \cos\alpha\, h - \sin\alpha\, H + i\left(\sin\beta\, G^0 - \cos\beta\, A\right)\right) \end{pmatrix}, \\
h_S &= \begin{pmatrix} \cos\beta\, G^+ + \sin\beta\, H^+ \\ \frac{1}{\sqrt{2}}\left(\cos\beta\, v + \sin\alpha\, h + \cos\alpha\, H + i\left(\cos\beta\, G^0 + \sin\beta\, A\right)\right) \end{pmatrix}.
\end{aligned}
$$

Inert, physical states: $\{h^\pm,\, \eta,\, \chi\}$.

R-II-1a: Physical Spectrum

Vacuum: $\{0,\, w_2,\, w_S\}$.

The $\mathbb{Z}_2$ symmetry is preserved for: $h_1 \to -h_1, \quad \{h_2,\, h_S\} \to \pm\{h_2,\, h_S\}$.

The inert doublet is associated with h_1.

Trivial Yukawa sector $\mathcal{L}_Y \sim 1_f \otimes 1_h$.

Mass eigenstates:

$$h_1 = \begin{pmatrix} h^+ \\ \frac{1}{\sqrt{2}}\left(\eta + i\chi\right) \end{pmatrix},$$

$$h_2 = \begin{pmatrix} \sin\beta\, G^+ - \cos\beta\, H^+ \\ \frac{1}{\sqrt{2}}\left(\sin\beta\, v + \cos\alpha\, h - \sin\alpha\, H + i\left(\sin\beta\, G^0 - \cos\beta\, A\right)\right) \end{pmatrix},$$

$$h_S = \begin{pmatrix} \cos\beta\, G^+ + \sin\beta\, H^+ \\ \frac{1}{\sqrt{2}}\left(\cos\beta\, v + \sin\alpha\, h + \cos\alpha\, H + i\left(\cos\beta\, G^0 + \sin\beta\, A\right)\right) \end{pmatrix}.$$

Inert, physical states: $\{h^\pm,\, \eta,\, \chi\}$. Two possible DM candidates: $\{\eta,\, \chi\}$.

Vacuum: $\{0,\, w_2,\, w_S\}$.

The $\mathbb{Z}_2$ symmetry is preserved for: $h_1 \to -h_1, \quad \{h_2,\, h_S\} \to \pm\{h_2,\, h_S\}$.

The inert doublet is associated with h_1.

Trivial Yukawa sector $\mathcal{L}_Y \sim 1_f \otimes 1_h$.

Mass eigenstates:

$$h_1 = \begin{pmatrix} h^+ \\ \frac{1}{\sqrt{2}}\left(\eta + i\chi\right) \end{pmatrix},$$
$$h_2 = \begin{pmatrix} \sin\beta\, G^+ - \cos\beta\, H^+ \\ \frac{1}{\sqrt{2}}\left(\sin\beta\, v + \cos\alpha\, h - \sin\alpha\, H + i\left(\sin\beta\, G^0 - \cos\beta\, A\right)\right) \end{pmatrix},$$
$$h_S = \begin{pmatrix} \cos\beta\, G^+ + \sin\beta\, H^+ \\ \frac{1}{\sqrt{2}}\left(\cos\beta\, v + \sin\alpha\, h + \cos\alpha\, H + i\left(\cos\beta\, G^0 + \sin\beta\, A\right)\right) \end{pmatrix}.$$

Inert, physical states: $\{h^\pm,\, \eta,\, \chi\}$. Two possible DM candidates: $\{\eta,\, \chi\}$.

Active, physical states: $\{H^\pm,\, h - H,\, A\}$.

R-II-1a: Model Analysis

The model is analysed using the following input (6 masses + 2 angles):

- Mass of the SM-like Higgs is fixed at $m_h = 125.25$ GeV;
- The Higgs basis rotation angle $\beta \in [-\frac{\pi}{2},\ \frac{\pi}{2}]$
  and the h-H diagonalisation angle $\alpha \in [0,\ \pi]$;
- The charged scalar masses $m_{\varphi_i^\pm} \in [0.07,\ 1]$ TeV;
- The inert sector masses $m_{\varphi_i} \in [0,\ 1]$ TeV.
  Either η or χ could be a DM candidate, whichever is lighter;
- The active sector masses $\{m_H,\ m_A\} \in [m_h,\ 1\ \mathrm{TeV}]$;

R-II-1a: Model Analysis

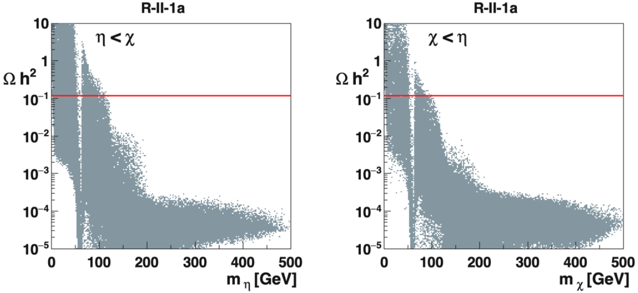
The model is analysed using the following input (6 masses + 2 angles):

- Mass of the SM-like Higgs is fixed at $m_h = 125.25$ GeV;
- The Higgs basis rotation angle $\beta \in [-\frac{\pi}{2},\ \frac{\pi}{2}]$ and the h-H diagonalisation angle $\alpha \in [0,\ \pi]$;
- The charged scalar masses $m_{\varphi_i^\pm} \in [0.07,\ 1]$ TeV;
- The inert sector masses $m_{\varphi_i} \in [0,\ 1]$ TeV. Either η or χ could be a DM candidate, whichever is lighter;
- The active sector masses $\{m_H,\ m_A\} \in [m_h,\ 1\ \mathrm{TeV}]$;

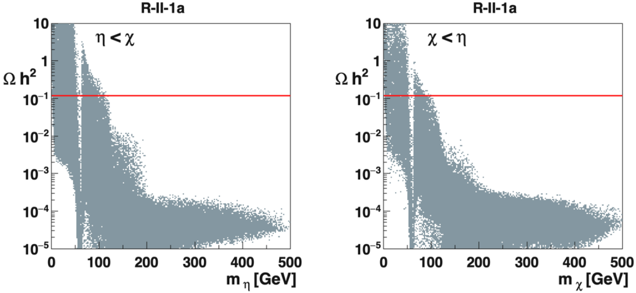
Both theoretical and experimental constraints, at 3-σ, are evaluated:

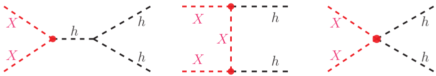
- Cut 1: perturbativity, stability, unitarity checks, LEP constraints;
- Cut 2: SM-like gauge and Yukawa sector, electroweak precision observables and B physics;
- Cut 3: $h \to \{\mathrm{invisible},\ \gamma\gamma\}$ decays, $\Omega_{\mathrm{CDM}} h^2$, direct searches;

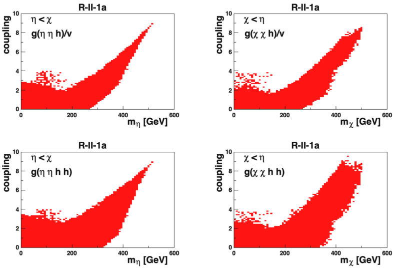
R-II-1a: Relic Density



R-II-1a: Relic Density







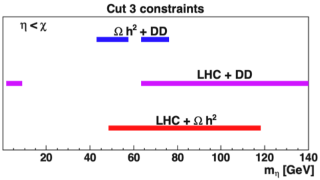
Trilinear and quartic couplings are not tuneable!

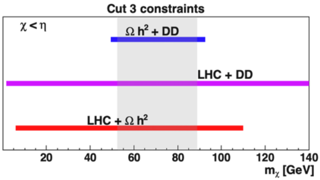
$$\left.\frac{g(XXh)}{v}\right|_{\rm SM} = g(XXhh)\big|_{\rm SM} = \frac{1}{v^2}\left[m_h^2 + 2m_X^2\right].$$

R-II-1a: Cut 3

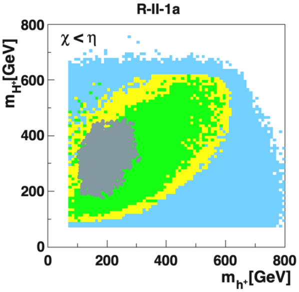
All constraints satisfied:

- $m_\eta < m_\chi$: no overlap in **all** parameters;
- $m_\eta > m_\chi$: overlap in **all** parameters for $m_\chi \in [52.5, 89]$ GeV;





R-II-1a: Cut 3

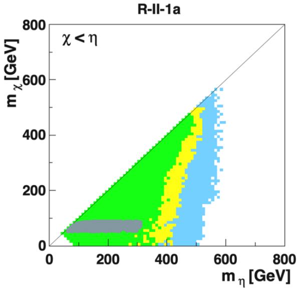


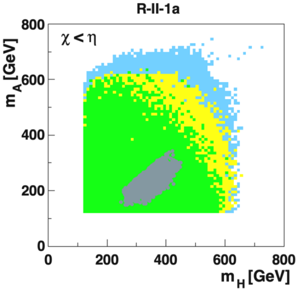
Cut 1: Unitarity $< 16\pi$

Cut 2: $3\text{-}\sigma$

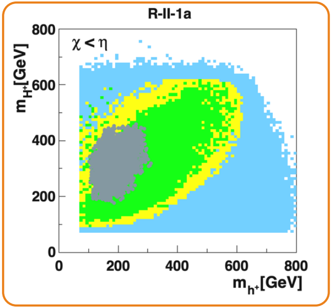
Cut 2: $2\text{-}\sigma$

Cut 3





R-II-1a: Cut 3

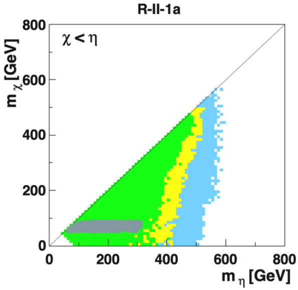


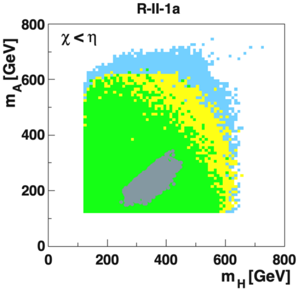
Cut 1: Unitarity $< 16\pi$

Cut 2: $3 \text{-} \sigma$

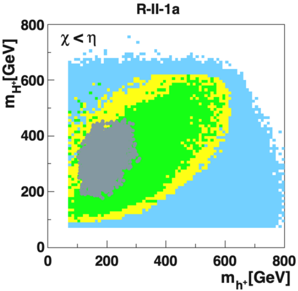
Cut 2: $2 \text{-} \sigma$

Cut 3





R-II-1a: Cut 3

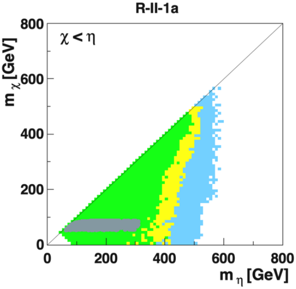


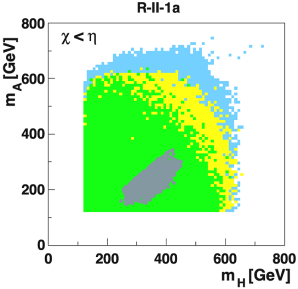
Cut 1: Unitarity $< 16\pi$

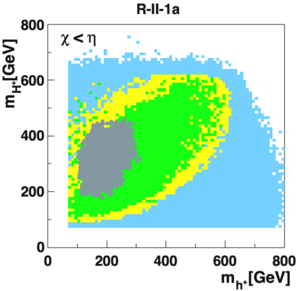
Cut 2: $3\text{-}\sigma$

Cut 2: $2\text{-}\sigma$

Cut 3





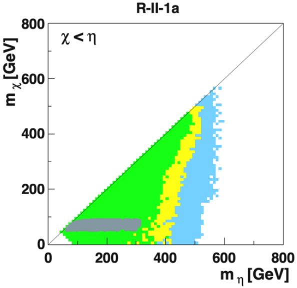


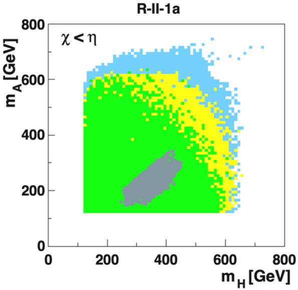
Cut 1: Unitarity $< 16\pi$

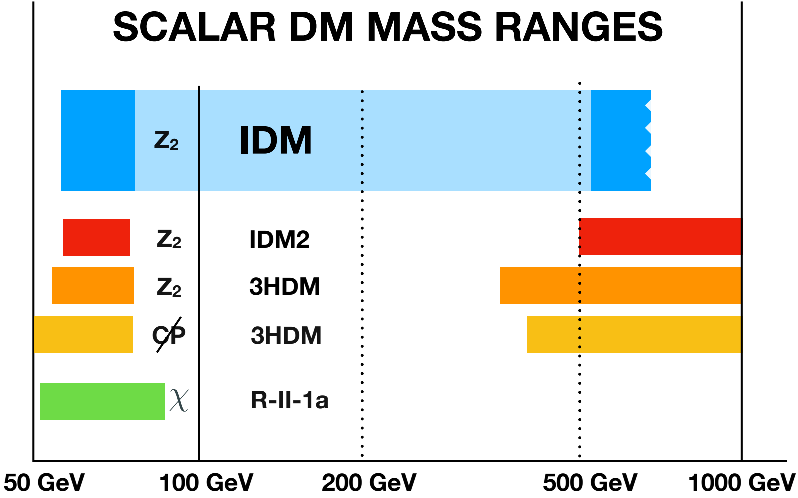
Cut 2: $3\text{-}\sigma$

Cut 2: $2\text{-}\sigma$

Cut 3






SCALAR DM MASS RANGES
Z2
IDM
Z2
IDM2
Z2
3HDM
CP
3HDM
χ
R-II-1a
50 GeV
100 GeV
200 GeV
500 GeV
1000 GeV

Conclusions

- Multi-Higgs-doublet models are phenomenology rich and can accommodate a dark matter candidate;
- Possible DM candidates were identified within S_3-3HDM;
- Analysed the R-II-1a model, and found a viable dark matter region $[52.5, 89]$ GeV;

Work supported by the Fundação para a Ciência e a Tecnologia (FCT, Portugal) PhD fellowship with reference UI/BD/150735/2020 as well as through the FCT projects CERN/FIS-PAR/0002/2021, UIDB/00777/2020, UIDP/00777/2020, PTDC/FIS-PAR/29436/2017.

Appendix

We can generate the following S_3 structures:

$$\begin{aligned} \mathbf{1}:&\ [2\otimes 2]_1,\ [1\otimes 1]_1,\ [1'\otimes 1']_1;\\ \mathbf{1}':&\ [2\otimes 2]_{1'},\ [1\otimes 1']_{1'},\ [1'\otimes 1]_{1'};\\ \mathbf{2}:&\ [2\otimes 2]_2,\ [1\otimes 2]_2,\ [2\otimes 1]_2,\ [1'\otimes 2]_2,\ [2\otimes 1']_2; \end{aligned}$$

Products:

$$\begin{aligned} &\begin{pmatrix} x_1 \\ x_2 \end{pmatrix}_{\mathbf{2}} \otimes \begin{pmatrix} y_1 \\ y_2 \end{pmatrix}_{\mathbf{2}} = (x_1y_1 + x_2y_2)_{\mathbf{1}} + (x_1y_2 - x_2y_1)_{\mathbf{1}'} + \begin{pmatrix} x_1y_2 + x_2y_1 \\ x_1y_1 - x_2y_2 \end{pmatrix}_{\mathbf{2}},\\ &\begin{pmatrix} x_1 \\ x_2 \end{pmatrix}_{\mathbf{2}} \otimes (y')_{\mathbf{1}'} = \begin{pmatrix} -x_2y' \\ x_1y' \end{pmatrix}_{\mathbf{2}},\\ &(x')_{\mathbf{1}'} \otimes (y')_{\mathbf{1}'} = (x'y')_{\mathbf{1}}. \end{aligned}$$

$$\begin{aligned} \mathcal{V}_{\rm 3HDM} =& \mu_1^2[2\otimes 2]_1 + \mu_0^2[1\otimes 1]_1\\ &+ \lambda_1\Big([2\otimes 2]_1 \otimes [2\otimes 2]_1\Big) + \lambda_2\Big([2\otimes 2]_{1'} \otimes [2\otimes 2]_{1'}\Big) + \lambda_3\Big([2\otimes 2]_2 \otimes [2\otimes 2]_2\Big)\\ &+ \lambda_4\left\{\Big([2\otimes 2]_2 \otimes [1\otimes 2]_2\Big) + \xleftrightarrow{\rm sym}\right\} + \lambda_5\Big([2\otimes 2]_1 \otimes [1\otimes 1]_1\Big) + \lambda_6\Big([1\otimes 2]_2 \otimes [2\otimes 1]_2\Big)\\ &+ \lambda_7\left\{\Big([1\otimes 2]_2 \otimes [1\otimes 2]_2\Big) + \xleftrightarrow{\rm sym}\right\} + \lambda_8\Big([1\otimes 1]_1 \otimes [1\otimes 1]_1\Big). \end{aligned}$$

Appendix

R-II-1a masses:

$$m_{h^+}^2 = -2\lambda_3 w_2^2 + \frac{5}{2}\lambda_4 w_2 w_S - \frac{1}{2}(\lambda_6 + 2\lambda_7) w_S^2,$$

$$m_{H^+}^2 = \frac{v^2}{2w_S}\left[\lambda_4 w_2 - (\lambda_6 + 2\lambda_7)\, w_S\right],$$

$$m_\eta^2 = \frac{9}{2}\lambda_4 w_2 w_S,$$

$$m_\chi^2 = -2(\lambda_2 + \lambda_3) w_2^2 + \frac{5}{2}\lambda_4 w_2 w_S - 2\lambda_7 w_S^2,$$

$$m_A^2 = \frac{v^2}{2w_S}\left(\lambda_4 w_2 - 4\lambda_7 w_S\right),$$

$$m_h^2 = \frac{1}{4w_S^2}\left[4\left(\lambda_1 + \lambda_3\right) w_2^2 w_S^2 + \lambda_4 w_2 w_S \left(w_2^2 - 3w_S^2\right) + 4\lambda_8 w_S^4 - w_S \Delta\right],$$

$$m_H^2 = \frac{1}{4w_S^2}\left[4\left(\lambda_1 + \lambda_3\right) w_2^2 w_S^2 + \lambda_4 w_2 w_S \left(w_2^2 - 3w_S^2\right) + 4\lambda_8 w_S^4 + w_S \Delta\right],$$

where

$$\begin{aligned}\Delta^2 = {} & 16\left(\lambda_1 + \lambda_3\right)^2 w_2^4 w_S^2 - 8\left(\lambda_1 + \lambda_3\right) w_2^2 w_S \left[\lambda_4 \left(w_2^3 + 3w_2 w_S^2\right) + 4\lambda_8 w_S^3\right] \\ & + 16\lambda_a^2 w_2^2 w_S^4 - 48\lambda_4 \lambda_a w_2^3 w_S^3 + \lambda_4^2 \left(w_2^6 + 42 w_2^4 w_S^2 + 9 w_2^2 w_S^4\right) \\ & + 8\lambda_4 \lambda_8 w_2 w_S^3 \left(w_2^2 + 3w_S^2\right) + 16\lambda_8^2 w_S^6.\end{aligned}$$

R-II-1a gauge couplings:

$$\mathcal{L}_{VVH} = \left[\frac{g}{2\cos\theta_W} m_Z Z_\mu Z^\mu + g m_W W_\mu^+ W^{\mu-}\right] \left[\sin(\alpha+\beta)h + \cos(\alpha+\beta)H\right],$$

$$\begin{aligned}
\mathcal{L}_{VHH} = & -\frac{g}{2\cos\theta_W} Z^\mu \left[\eta \overleftrightarrow{\partial}_\mu \chi - \cos(\alpha+\beta) h \overleftrightarrow{\partial}_\mu A + \sin(\alpha+\beta) H \overleftrightarrow{\partial}_\mu A\right] \\
& - \frac{g}{2}\left\{ i W_\mu^+ \left[i h^- \overleftrightarrow{\partial^\mu} \chi + h^- \overleftrightarrow{\partial^\mu} \eta - \cos(\alpha+\beta) H^- \overleftrightarrow{\partial^\mu} h \right.\right. \\
& \qquad \left.\left. + \sin(\alpha+\beta) H^- \overleftrightarrow{\partial^\mu} H + i H^- \overleftrightarrow{\partial^\mu} A \right] + \mathrm{h.c.} \right\} \\
& + \left[i e A^\mu + \frac{ig}{2}\frac{\cos(2\theta_W)}{\cos\theta_W} Z^\mu \right] \left(h^+ \overleftrightarrow{\partial}_\mu h^- + H^+ \overleftrightarrow{\partial}_\mu H^- \right),
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{VVHH} = & \left[\frac{g^2}{8\cos^2\theta_W} Z_\mu Z^\mu + \frac{g^2}{4} W_\mu^+ W^{\mu-}\right] \left(\eta^2 + \chi^2 + h^2 + H^2 + A^2\right) \\
& + \left\{ \left[\frac{eg}{2} A^\mu W_\mu^+ - \frac{g^2}{2}\frac{\sin^2\theta_W}{\cos\theta_W} Z^\mu W_\mu^+ \right] \left[\eta h^- + i\chi h^- - \cos(\alpha+\beta) h H^- \right.\right. \\
& \qquad \left.\left. + \sin(\alpha+\beta) H H^- + i A H^- \right] + \mathrm{h.c.} \right\} \\
& + \left[e^2 A_\mu A^\mu + eg \frac{\cos(2\theta_W)}{\cos\theta_W} A_\mu Z^\mu + \frac{g^2}{4}\frac{\cos^2(2\theta_W)}{\cos^2\theta_W} Z_\mu Z^\mu + \frac{g^2}{2} W_\mu^- W^{\mu+} \right] \\
& \times \left(h^- h^+ + H^- H^+ \right).
\end{aligned}$$

R-II-1a fermionic couplings:

$$g\left(h\bar{f}f\right) = -i\frac{m_f}{v}\frac{\sin\alpha}{\cos\beta}, \quad g\left(H\bar{f}f\right) = -i\frac{m_f}{v}\frac{\cos\alpha}{\cos\beta},$$
$$g\left(A\bar{u}u\right) = -\gamma_5\frac{m_u}{v}\tan\beta, \quad g\left(A\bar{d}d\right) = \gamma_5\frac{m_d}{v}\tan\beta,$$

and for the leptonic sector, the Dirac mass terms would lead to similar relations.

$$g\left(H^+\bar{u}_i d_j\right) = i\frac{\sqrt{2}}{v}\tan\beta\left[P_L m_u - P_R m_d\right]\left(V_{\mathrm{CKM}}\right)_{ij},$$
$$g\left(H^-\bar{d}_i u_j\right) = i\frac{\sqrt{2}}{v}\tan\beta\left[P_R m_u - P_L m_d\right]\left(V^\dagger_{\mathrm{CKM}}\right)_{ji},$$
$$g\left(H^+\bar{\nu}l\right) = -i\frac{\sqrt{2}m_l}{v}\tan\beta P_R,$$
$$g\left(H^-\bar{l}\nu\right) = -i\frac{\sqrt{2}m_l}{v}\tan\beta P_L.$$

We adopt 3-σ bounds from **PDG [2021]**:

$$\kappa_{VV}^2 \equiv |\sin(\alpha+\beta)|^2 \in \{1.19 \pm 3\,\sigma\}, \text{ which comes from } h_{\rm SM} W^+ W^-,$$

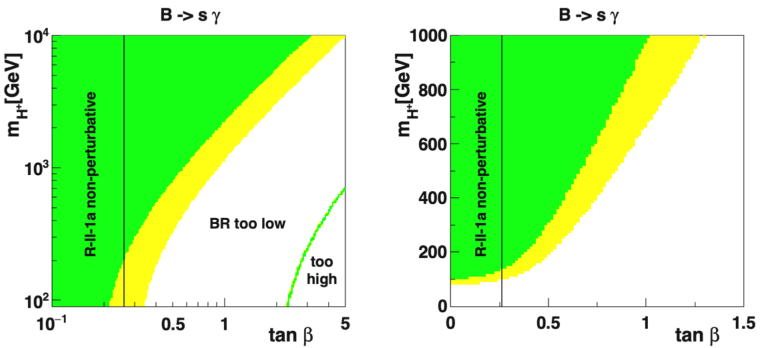
$$\kappa_{ff}^2 \equiv \left|\frac{\sin\alpha}{\cos\beta}\right|^2 \in \{1.04 \pm 3\,\sigma\}, \text{ which comes from } h_{\rm SM} \bar{b} b.$$

We impose the same sign for these two couplings not to spoil the interference required for $h_{\rm SM} \to \gamma\gamma$.

We adopt the experimental value, $\mathrm{Br}\left(\bar{B} \to X(s)\gamma\right) \times 10^4 = 3.32 \pm 0.15$ **PDG [2021]** and impose an $(n = 3)$-σ tolerance, together with an additional 10 per cent computational uncertainty,

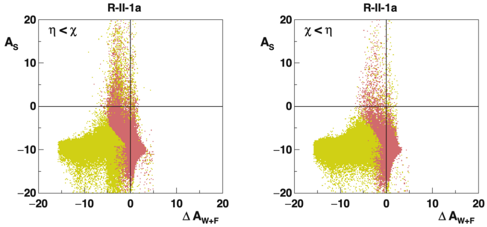
$$\mathrm{Br}\left(\bar{B} \to X(s)\gamma\right) \times 10^4 = 3.32 \pm \sqrt{(3.32 \times 0.1)^2 + (0.15\, n)^2}\,.$$

The acceptable region, corresponding to the 3-σ bound, is [2.76; 3.88].

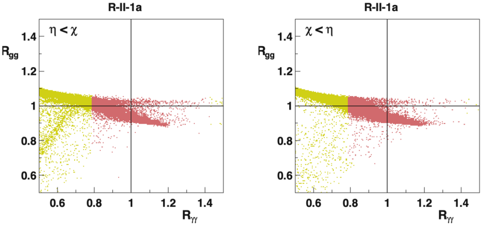


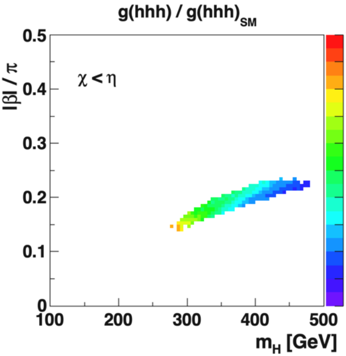
Appendix

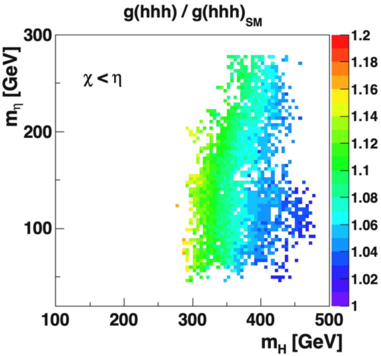
Scatter plots of additional contributions to the di-photon decay amplitudes, normalised to the SM value, expressed in per cent:

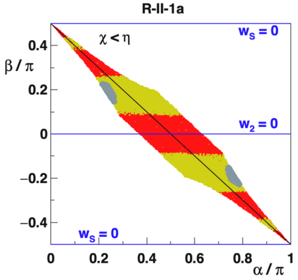


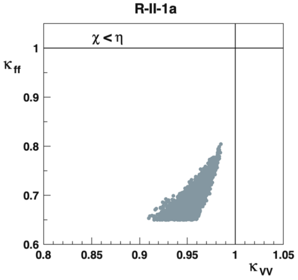
Two-gluon versus di-photon Higgs-like particle branching ratios, normalised to the SM value:

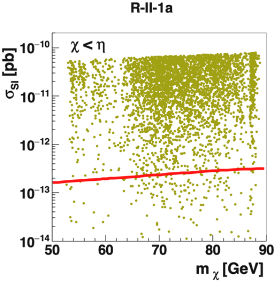



g(hhh) / g(hhh)SM
|β| / π
χ < η
0.5
0.4
0.3
0.2
0.1
0
100
200
300
400
500
mH [GeV]
1.2
1.18
1.16
1.14
1.12
1.1
1.08
1.06
1.04
1.02
1


g(hhh) / g(hhh)SM
mη [GeV]
χ < η
300
200
100
100
200
300
400
500
mH [GeV]
1.2
1.18
1.16
1.14
1.12
1.1
1.08
1.06
1.04
1.02
1


R-II-1a
χ < η
$w_S = 0$
$w_2 = 0$
$w_S = 0$
β / π
α / π
0.4
0.2
0
−0.2
−0.4
0
0.2
0.4
0.6
0.8
1


R-II-1a
χ < η
κ_{ff}
κ_{VV}
1
0.9
0.8
0.7
0.6
0.8
0.85
0.9
0.95
1
1.05


R-II-1a
χ < η
σ_{SI} [pb]
m_χ [GeV]
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
50
60
70
80
90

Appendix

Parameter	BP 1	BP 2	BP 3	BP 4	BP 5	BP6	BP7	BP8	BP9
DM (χ) mass [GeV]	52.6	56.1	59.6	63.02	65.7	70.3	75.0	82.2	88.6
η mass [GeV]	62.7	203.8	270.4	169.38	150.5	157.7	202.8	127.8	210.7
h^+ mass [GeV]	115.4	167.4	273.6	188.6	214.1	170.5	232.0	151.8	243.0
H^+ mass [GeV]	192.6	369.5	367.4	246.6	265.5	405.8	319.8	410.6	311.9
H mass [GeV]	263.9	349.3	352.9	276.3	298.2	402.0	368.5	405.2	317.6
A mass [GeV]	179.2	208.0	190.7	173.9	205.2	255.3	251.3	330.0	247.0
β/π	0.162	-0.204	-0.201	-0.165	0.163	0.220	0.203	-0.218	0.183
α/π	0.252	0.763	0.765	0.752	0.254	0.225	0.239	0.769	0.238
$\sigma_{\rm SI}$ [10^{-11} pb]	0.029	1.456	4.928	0.176	5.326	1.341	2.711	8.553	4.491
$\eta \to \chi q\bar{q}$ [%]	63.27				54.38	54.35		53.95	
$\eta \to \chi b\bar{b}$ [%]	0.48				14.80	14.85		13.90	
$\eta \to \chi \nu\bar{\nu}$ [%]	24.62				20.48	20.46		20.72	
$\eta \to \chi l\bar{l}$ [%]	11.61				10.33	10.33		11.42	
$\eta \to \chi Z$ [%]		99.98	53.09	100			100		100
$\eta \to \chi A$ [%]			46.91						
$h^+ \to \chi W^+$ [%]		100	100	99.98	99.89	99.99	99.99		99.99
$h^+ \to \eta q\bar{q}$ [%]	20.18							0.30	
$h^+ \to \eta \nu\bar{l}$ [%]	9.88							0.16	
$h^+ \to \chi q\bar{q}$ [%]	46.94							66.82	
$h^+ \to \chi \nu\bar{l}$ [%]	22.99							32.71	
$H^+ \to t\bar{b}$ [%]	9.07	43.69	58.23	95.09	95.78	30.95	96.25	31.54	93.59
$H^+ \to AW^+$ [%]		20.56	35.74	0.29	0.06	8.66	0.05	0.05	0.05
$H^+ \to hW^+$ [%]		1.94	2.67	4.46	4.00	1.23	2.86	1.15	6.20
$H^+ \to h^+\eta$ [%]	85.9					43.74		61.68	
$H^+ \to h^+\chi$ [%]	5.0	33.74	3.26			15.36	0.68	5.53	
$H \to \chi\chi$ [%]	0.15	0.03	0.07	0.87	15.03		11.34	7.63	63.75
$H \to \eta\eta$ [%]	89.9					24.89		25.31	
$H \to hh$ [%]	3.07	2.64	9.40	34.59	33.53	1.33	13.43	0.88	14.72
$H \to AZ$ [%]	0.09	13.55	70.93	13.91	2.87	7.61	22.78		0.07
$H \to W^+W^-$ [%]	4.06	3.13	10.40	34.98	33.35	1.89	16.32	1.26	14.70
$H \to ZZ$ [%]	1.75	1.43	4.77	15.29	14.82	0.88	7.53	0.59	6.62
$H \to h^+h^-$ [%]	0.8	78.59				52.94		56.33	
$H \to q\bar{q}$ [%]		0.62	4.40	0.32	0.34	10.43	28.52	8.00	0.12
$A \to \eta\chi$ [%]	99.97					99.32		99.01	
$A \to b\bar{b}$ [%]	0.02	79.78	84.15	84.63	75.28	0.07	8.84	0.02	4.76
$A \to q\bar{q}$ [%]		3.56	3.75	3.77	3.36		0.39		0.21
$A \to \tau^+\tau^-$ [%]		9.85	10.19	10.00	9.24		1.13		0.61
$A \to hZ$ [%]		6.81	1.87	1.55	12.08	0.6	89.63	0.96	94.42

Appendix