Examples of 3HDM with DM Candidates

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Motivation for three Higgs doublets

Three generations may suggest three doublets

Possibility of having a discrete symmetry and still having spontaneous CP violation

Interesting scenario for dark matter

Rich phenomenology

Motivation for imposing discrete symmetries

Symmetries reduce the number of free parameters leading to (testable) predictions

Symmetries help to control HFCNC

Example: NFC, no HFCNC due to Z_2 Symmetry (ies)

Example: MFV suppression of HFCNC, BGL models

Symmetries are needed to stabilise dark matter

DM in extended Scalar Sectors

Simplest extensions: (examples)

i) **One Higgs doublet and one Higgs singlet**

V. Silveira and A. Zee (1985)

J. McDonald, hep-ph/0702143

ii) **Inert Doublet Model (IDM) (2 Higgs doublets)**

N. G. Deshpande and E. Ma (1978)

R. Barbieri, L. J. Hall and V. S. Rychkov (2006)

Examples with three Higgs doublets:

i) **Inert-plus-two-doublet model (IDM2)**

Grzadkowski, Ogreid, Osland, Pukhov, Purmohammadi, Pruna, 0904.2173; 1012.4680; 1302.3713;

Merchant and Sher , 1911.06477

ii) **Two Inert Doublets plus One Higgs Doublet**

A. C. B. Machado and V. Pleitez, (2012), V. Keus, S. King, S. Moretti (2013), E. C. S. Fortes, J. Montaño, D. Sokolowska, A.Aranda, J. Hernández-Sánchez, P. Noriega-Papaqui, C. A. Vaquera-Araujo, A, Cordero-Cid, D. Rojas-Ciofalo

iii) **S_3 Symmetric Three Higgs Doublet Model**

Multi-Higgs Models

Possibility of having vacua with vanishing vevs in basis where symmetry is imposed (different from choice of Higgs/scalar basis)

If a sym stabilises such a vacuum it may lead to interesting DM candidates

Symmetry must prevent couplings among DM candidates and fermions

The cases with two active Higgs doublets lead to similarities with the 2HDM

Both in the Inert-plus-two-doublet model (IDM2) and in the S_3 Symmetric Model there is the possibility of having spontaneous CP violation

Some Specific Features of the Inert Doublet Model

2HDM with a Z_2 symmetry under which ϕ_2 is odd and all the other fields are even.

$$\begin{aligned} V &= -m_1^2(\phi_1^\dagger\phi_1) - m_2^2(\phi_2^\dagger\phi_2) + \lambda_1(\phi_1^\dagger\phi_1)^2 + \lambda_2(\phi_2^\dagger\phi_2)^2 \\ &+ \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_2^\dagger\phi_1)(\phi_1^\dagger\phi_2) + \frac{\lambda_5}{2}\left[(\phi_1^\dagger\phi_2)^2 + (\phi_2^\dagger\phi_1)^2\right] \end{aligned}$$

CP is conserved by the potential. Large region of parameter space where:

$$\phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+H \end{pmatrix} \qquad \phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}h^+ \\ h_1 + ih_2 \end{pmatrix}$$

This vacuum does not break the Z_2 symmetry. Furthermore, it forbids direct couplings of any single inert field to SM particles and stabilises the lightest inert boson against decay

Pairwise interactions of the inert scalars with the gauge bosons and with the SM like Higgs H are allowed. This has implications for collider signatures and detection experiments

Some Specific Features of the Inert-plus-two doublet model (IDM2)

Weinberg Model with real couplings — S. Weinberg *Phys. Rev. Lett.* **37** (1976) 657

Certain vacua allow for spontaneous CP violation — G. C. Branco *Phys. Rev. D* **22** (1980) 2901

The potential of the IDM2: B. Grzadkowski, O. M. Ogreid and P. Osland, *Phys. Rev.* **D80** (2009) 055013.

two doublets, $\Phi_{1,2}$ plus, the inert-doublet η $\quad Z_2 \times Z_2'$ symmetry: $\eta \to -\eta \quad \Phi_1 \to -\Phi_1$

Choice of vacuum, inert doublet acquires zero vev: $\eta = \begin{pmatrix} \eta^+ \\ (S + iA)/\sqrt{2} \end{pmatrix}$

With this vacuum spontaneous CP violation is not possible

Soft Symmetry breaking introduced in order to have spontaneous CP violation:

$$\left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}\right]$$

It was assumed that S is the lightest neutral scalar. S can be a good DM candidate

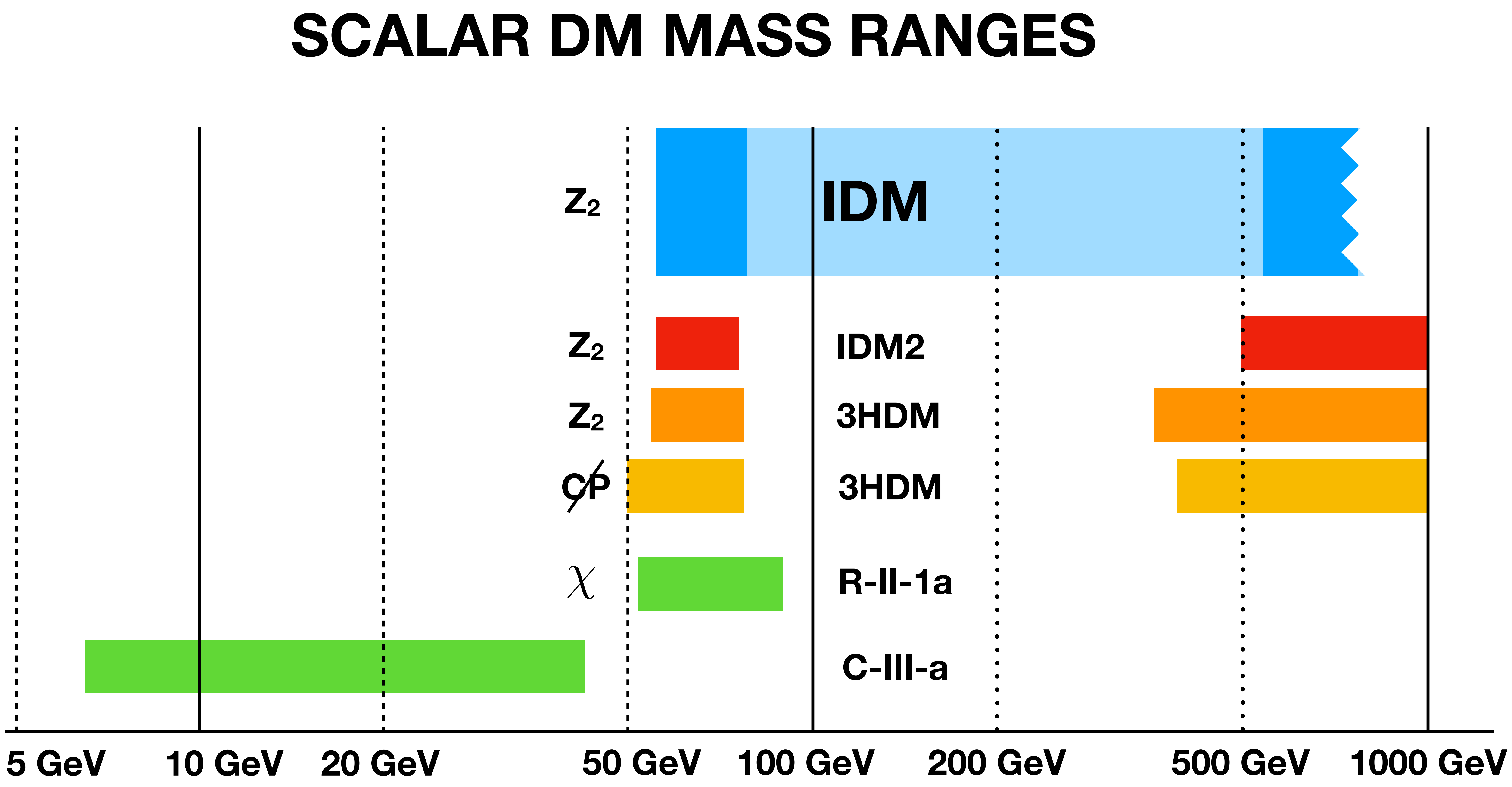

Figure 1: Sketch of allowed DM mass ranges up to 1 TeV in various models. Blue: IDM according to Refs. [22, 23], the pale region indicates a non-saturated relic density. Red: IDM2 [9]. Ochre: three-Higgs-doublet model (3HDM) without [14, 16, 18] and with CP violation [17]. Green: S_3-symmetric 3HDM with a non-CP violating scalar sector (R-II-1a) [10] and with a CP violating scalar sector (C-III-a)[More].

References in the figure caption of previous slide

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[17] A. Cordero-Cid, J. Hernández-Sánchez, V. Keus, S. F. King, S. Moretti, D. Rojas et al., *CP violating scalar Dark Matter*, *JHEP* **12** (2016) 014, [1608.01673].

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[More] A. Kunčinas, O. M. Ogreid, P. Osland and M. N. Rebelo, *Dark matter in a CP-violating three-Higgs-doublet model with S_3 symmetry*, *Phys. Rev.* **D106** (2022) 075002, [2204.05684].

Dark matter in theee-Higgs-doublet models with S_3 Symmetry

S_3 is the permutation group involving three objects, ϕ_1, ϕ_2, ϕ_3

Derman 1978, Derman and Tsao 1979

Two irreducible representations doublet and singlet:

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix}, \quad h_S \qquad \begin{pmatrix} h_1 \\ h_2 \\ h_S \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{6}} & -\frac{2}{\sqrt{6}} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{pmatrix} \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \end{pmatrix}$$

Notice similarity with tribimaximal mixing: **Harrison, Perkins and Scott, 1999**

$$(F =) \begin{pmatrix} -\frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \end{pmatrix}$$

The scalar potential in terms of fields from irreducible representations

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

D. Das and U. K. Dey, 2014

no symmetry under the interchange of h_1 and h_2

however there is symmetry for $h_1 \to -h_1$

In the special case $\lambda_4 = 0$ **the potential has SO(2) symmetry:**

$$\begin{pmatrix} h_1' \\ h_2' \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

Danger: massless scalar!

no spontaneous CP violation whenever $\lambda_4 = 0$

Constraining the potential by the vevs, real vacua

Vacuum	ρ_1, ρ_2, ρ_3	w_1, w_2, w_S	Comment
R-0	$0, 0, 0$	$0, 0, 0$	Not interesting
R-I-1	x, x, x	$0, 0, w_S$	$\mu_0^2 = -\lambda_8 w_S^2$
R-I-2a	$x, -x, 0$	$w, 0, 0$	$\mu_1^2 = -\left(\lambda_1 + \lambda_3\right) w_1^2$
R-I-2b	$x, 0, -x$	$w, \sqrt{3}w, 0$	$\mu_1^2 = -\frac{4}{3}\left(\lambda_1 + \lambda_3\right) w_2^2$
R-I-2c	$0, x, -x$	$w, -\sqrt{3}w, 0$	$\mu_1^2 = -\frac{4}{3}\left(\lambda_1 + \lambda_3\right) w_2^2$
R-II-1a	x, x, y	$0, w, w_S$	$\mu_0^2 = \frac{1}{2}\lambda_4 \frac{w_2^3}{w_S} - \frac{1}{2}\lambda_a w_2^2 - \lambda_8 w_S^2,$ $\mu_1^2 = -\left(\lambda_1 + \lambda_3\right) w_2^2 + \frac{3}{2}\lambda_4 w_2 w_S - \frac{1}{2}\lambda_a w_S^2$
R-II-1b	x, y, x	$w, -w/\sqrt{3}, w_S$	$\mu_0^2 = -4\lambda_4 \frac{w_2^3}{w_S} - 2\lambda_a w_2^2 - \lambda_8 w_S^2,$ $\mu_1^2 = -4\left(\lambda_1 + \lambda_3\right) w_2^2 - 3\lambda_4 w_2 w_S - \frac{1}{2}\lambda_a w_S^2$
R-II-1c	y, x, x	$w, w/\sqrt{3}, w_S$	$\mu_0^2 = -4\lambda_4 \frac{w_2^3}{w_S} - 2\lambda_a w_2^2 - \lambda_8 w_S^2,$ $\mu_1^2 = -4\left(\lambda_1 + \lambda_3\right) w_2^2 - 3\lambda_4 w_2 w_S - \frac{1}{2}\lambda_a w_S^2$
R-II-2	$x, x, -2x$	$0, w, 0$	$\mu_1^2 = -\left(\lambda_1 + \lambda_3\right) w_2^2,\ \lambda_4 = 0$
R-II-3	$x, y, -x-y$	$w_1, w_2, 0$	$\mu_1^2 = -\left(\lambda_1 + \lambda_3\right)(w_1^2 + w_2^2), \lambda_4 = 0$
R-III	ρ_1, ρ_2, ρ_3	w_1, w_2, w_S	$\mu_0^2 = -\frac{1}{2}\lambda_a(w_1^2 + w_2^2) - \lambda_8 w_S^2,$ $\mu_1^2 = -\left(\lambda_1 + \lambda_3\right)(w_1^2 + w_2^2) - \frac{1}{2}\lambda_a w_S^2,$ $\lambda_4 = 0$

$$\lambda_a = \lambda_5 + \lambda_6 + 2\lambda_7,$$
$$\lambda_b = \lambda_5 + \lambda_6 - 2\lambda_7.$$

Constraining the potential by the vevs, complex vacua

Table 2: Complex vacua. Notation: $\epsilon = 1$ and -1 for C-III-d and C-III-e, respectively; $\xi = \sqrt{-3\sin 2\rho_1/\sin 2\rho_2}$, $\psi = \sqrt{[3+3\cos(\rho_2-2\rho_1)]/(2\cos\rho_2)}$. With the constraints of Table 4 the vacua labelled with an asterisk (*) are in fact real.

	IRF (Irreducible Rep.)	RRF (Reducible Rep.)
	w_1, w_2, w_S	ρ_1, ρ_2, ρ_3
C-I-a	$\hat{w}_1, \pm i\hat{w}_1, 0$	$x, xe^{\pm\frac{2\pi i}{3}}, xe^{\mp\frac{2\pi i}{3}}$
C-III-a	$0, \hat{w}_2 e^{i\sigma_2}, \hat{w}_S$	$y, y, xe^{i\tau}$
C-III-b	$\pm i\hat{w}_1, 0, \hat{w}_S$	$x+iy, x-iy, x$
C-III-c	$\hat{w}_1 e^{i\sigma_1}, \hat{w}_2 e^{i\sigma_2}, 0$	$xe^{i\rho} - \frac{y}{2}, -xe^{i\rho} - \frac{y}{2}, y$
C-III-d,e	$\pm i\hat{w}_1, \epsilon\hat{w}_2, \hat{w}_S$	$xe^{i\tau}, xe^{-i\tau}, y$
C-III-f	$\pm i\hat{w}_1, i\hat{w}_2, \hat{w}_S$	$re^{i\rho} \pm ix, re^{i\rho} \mp ix, \frac{3}{2}re^{-i\rho} - \frac{1}{2}re^{i\rho}$
C-III-g	$\pm i\hat{w}_1, -i\hat{w}_2, \hat{w}_S$	$re^{-i\rho} \pm ix, re^{-i\rho} \mp ix, \frac{3}{2}re^{i\rho} - \frac{1}{2}re^{-i\rho}$
C-III-h	$\sqrt{3}\hat{w}_2 e^{i\sigma_2}, \pm\hat{w}_2 e^{i\sigma_2}, \hat{w}_S$	$xe^{i\tau}, y, y$ $y, xe^{i\tau}, y$
C-III-i	$\sqrt{\frac{3(1+\tan^2\sigma_1)}{1+9\tan^2\sigma_1}}\hat{w}_2 e^{i\sigma_1}$, $\pm\hat{w}_2 e^{-i\arctan(3\tan\sigma_1)}, \hat{w}_S$	$x, ye^{i\tau}, ye^{-i\tau}$ $ye^{i\tau}, x, ye^{-i\tau}$
C-IV-a*	$\hat{w}_1 e^{i\sigma_1}, 0, \hat{w}_S$	$re^{i\rho} + x, -re^{i\rho} + x, x$
C-IV-b	$\hat{w}_1, \pm i\hat{w}_2, \hat{w}_S$	$re^{i\rho} + x, -re^{-i\rho} + x, -re^{i\rho} + re^{-i\rho} + x$
C-IV-c	$\sqrt{1+2\cos^2\sigma_2}\hat{w}_2$, $\hat{w}_2 e^{i\sigma_2}, \hat{w}_S$	$re^{i\rho} + r\sqrt{3(1+2\cos^2\rho)} + x$, $re^{i\rho} - r\sqrt{3(1+2\cos^2\rho)} + x, -2re^{i\rho} + x$
C-IV-d*	$\hat{w}_1 e^{i\sigma_1}, \pm\hat{w}_2 e^{i\sigma_1}, \hat{w}_S$	$r_1 e^{i\rho} + x, (r_2 - r_1)e^{i\rho} + x, -r_2 e^{i\rho} + x$
C-IV-e	$\sqrt{-\frac{\sin 2\sigma_2}{\sin 2\sigma_1}}\hat{w}_2 e^{i\sigma_1}$, $\hat{w}_2 e^{i\sigma_2}, \hat{w}_S$	$re^{i\rho_2} + re^{i\rho_1}\xi + x, re^{i\rho_2} - re^{i\rho_1}\xi + x$, $-2re^{i\rho_2} + x$
C-IV-f	$\sqrt{2 + \frac{\cos(\sigma_1 - 2\sigma_2)}{\cos\sigma_1}}\hat{w}_2 e^{i\sigma_1}$, $\hat{w}_2 e^{i\sigma_2}, \hat{w}_S$	$re^{i\rho_1} + re^{i\rho_2}\psi + x$, $re^{i\rho_1} - re^{i\rho_2}\psi + x, -2re^{i\rho_1} + x$
C-V*	$\hat{w}_1 e^{i\sigma_1}, \hat{w}_2 e^{i\sigma_2}, \hat{w}_S$	$xe^{i\tau_1}, ye^{i\tau_2}, z$

Constraints

Vacuum	Constraints
C-I-a	$\mu_1^2 = -2\left(\lambda_1 - \lambda_2\right)\hat{w}_1^2$
C-III-a	$\mu_0^2 = -\frac{1}{2}\lambda_b\hat{w}_2^2 - \lambda_8\hat{w}_S^2,$ $\mu_1^2 = -\left(\lambda_1 + \lambda_3\right)\hat{w}_2^2 - \frac{1}{2}\left(\lambda_b - 8\cos^2\sigma_2\lambda_7\right)\hat{w}_S^2,$ $\lambda_4 = \frac{4\cos\sigma_2\hat{w}_S}{\hat{w}_2}\lambda_7$
C-III-b	$\mu_0^2 = -\frac{1}{2}\lambda_b\hat{w}_1^2 - \lambda_8\hat{w}_S^2,$ $\mu_1^2 = -\left(\lambda_1 + \lambda_3\right)\hat{w}_1^2 - \frac{1}{2}\lambda_b\hat{w}_S^2,$ $\lambda_4 = 0$
C-III-c	$\mu_1^2 = -(\lambda_1 + \lambda_3)(\hat{w}_1^2 + \hat{w}_2^2),$ $\lambda_2 + \lambda_3 = 0, \lambda_4 = 0$
C-III-d,e	$\mu_0^2 = \left(\lambda_2 + \lambda_3\right)\frac{(\hat{w}_1^2 - \hat{w}_2^2)^2}{\hat{w}_S^2} - \epsilon\lambda_4\frac{(\hat{w}_1^2 - \hat{w}_2^2)(\hat{w}_1^2 - 3\hat{w}_2^2)}{4\hat{w}_2\hat{w}_S}$ $-\frac{1}{2}\left(\lambda_5 + \lambda_6\right)\left(\hat{w}_1^2 + \hat{w}_2^2\right) - \lambda_8\hat{w}_S^2,$ $\mu_1^2 = -\left(\lambda_1 - \lambda_2\right)\left(\hat{w}_1^2 + \hat{w}_2^2\right) - \epsilon\lambda_4\frac{\hat{w}_S(\hat{w}_1^2 - \hat{w}_2^2)}{4\hat{w}_2} - \frac{1}{2}\left(\lambda_5 + \lambda_6\right)\hat{w}_S^2,$ $\lambda_7 = \frac{\hat{w}_1^2 - \hat{w}_2^2}{\hat{w}_S^2}(\lambda_2 + \lambda_3) - \epsilon\frac{(\hat{w}_1^2 - 5\hat{w}_2^2)}{4\hat{w}_2\hat{w}_S}\lambda_4$
C-III-f,g	$\mu_0^2 = -\frac{1}{2}\lambda_b\left(\hat{w}_1^2 + \hat{w}_2^2\right) - \lambda_8\hat{w}_S^2,$ $\mu_1^2 = -\left(\lambda_1 + \lambda_3\right)\left(\hat{w}_1^2 + \hat{w}_2^2\right) - \frac{1}{2}\lambda_b\hat{w}_S^2, \lambda_4 = 0$
C-III-h	$\mu_0^2 = -2\lambda_b\hat{w}_2^2 - \lambda_8\hat{w}_S^2,$ $\mu_1^2 = -4\left(\lambda_1 + \lambda_3\right)\hat{w}_2^2 - \frac{1}{2}\left(\lambda_b - 8\cos^2\sigma_2\lambda_7\right)\hat{w}_S^2,$ $\lambda_4 = \mp\frac{2\cos\sigma_2\hat{w}_S}{\hat{w}_2}\lambda_7$
C-III-i	$\mu_0^2 = \frac{16\left(1-3\tan^2\sigma_1\right)^2}{(1+9\tan^2\sigma_1)^2}(\lambda_2 + \lambda_3)\frac{\hat{w}_2^4}{\hat{w}_S^2} \pm \frac{6\left(1-\tan^2\sigma_1\right)\left(1-3\tan^2\sigma_1\right)}{(1+9\tan^2\sigma_1)^{\frac{3}{2}}}\lambda_4\frac{\hat{w}_2^3}{\hat{w}_S}$ $-\frac{2(1+3\tan^2\sigma_1)}{1+9\tan^2\sigma_1}(\lambda_5 + \lambda_6)\hat{w}_2^2 - \lambda_8\hat{w}_S^2,$ $\mu_1^2 = -\frac{4(1+3\tan^2\sigma_1)}{1+9\tan^2\sigma_1}(\lambda_1 - \lambda_2)\hat{w}_2^2 \mp \frac{\left(1-3\tan^2\sigma_1\right)}{2\sqrt{1+9\tan^2\sigma_1}}\lambda_4\hat{w}_2\hat{w}_S$ $-\frac{1}{2}(\lambda_5 + \lambda_6)\hat{w}_S^2,$ $\lambda_7 = -\frac{4\left(1-3\tan^2\sigma_1\right)\hat{w}_2^2}{(1+9\tan^2\sigma_1)\hat{w}_S^2}(\lambda_2 + \lambda_3) \mp \frac{\left(5-3\tan^2\sigma_1\right)\hat{w}_2}{2\sqrt{1+9\tan^2\sigma_1}\hat{w}_S}\lambda_4$

Vacuum	Constraints
C-IV-a*	$\mu_0^2 = -\frac{1}{2}\left(\lambda_5 + \lambda_6\right)\hat{w}_1^2 - \lambda_8\hat{w}_S^2,$ $\mu_1^2 = -\left(\lambda_1 + \lambda_3\right)\hat{w}_1^2 - \frac{1}{2}\left(\lambda_5 + \lambda_6\right)\hat{w}_S^2,$ $\lambda_4 = 0, \lambda_7 = 0$
C-IV-b	$\mu_0^2 = \left(\lambda_2 + \lambda_3\right)\frac{\left(\hat{w}_1^2 - \hat{w}_2^2\right)^2}{\hat{w}_S^2} - \frac{1}{2}\left(\lambda_5 + \lambda_6\right)\left(\hat{w}_1^2 + \hat{w}_2^2\right) - \lambda_8\hat{w}_S^2,$ $\mu_1^2 = -\left(\lambda_1 - \lambda_2\right)\left(\hat{w}_1^2 + \hat{w}_2^2\right) - \frac{1}{2}\left(\lambda_5 + \lambda_6\right)\hat{w}_S^2,$ $\lambda_4 = 0, \lambda_7 = -\frac{\left(\hat{w}_1^2 - \hat{w}_2^2\right)}{\hat{w}_S^2}\left(\lambda_2 + \lambda_3\right)$
C-IV-c	$\mu_0^2 = 2\cos^2\sigma_2\left(1 + \cos^2\sigma_2\right)\left(\lambda_2 + \lambda_3\right)\frac{\hat{w}_2^4}{\hat{w}_S^2}$ $-\left(1 + \cos^2\sigma_2\right)\left(\lambda_5 + \lambda_6\right)\hat{w}_2^2 - \lambda_8\hat{w}_S^2,$ $\mu_1^2 = -\left[2\left(1 + \cos^2\sigma_2\right)\lambda_1 - \left(2 + 3\cos^2\sigma_2\right)\lambda_2 - \cos^2\sigma_2\lambda_3\right]\hat{w}_2^2$ $-\frac{1}{2}\left(\lambda_5 + \lambda_6\right)\hat{w}_S^2,$ $\lambda_4 = -\frac{2\cos\sigma_2\hat{w}_2}{\hat{w}_S}\left(\lambda_2 + \lambda_3\right), \lambda_7 = \frac{\cos^2\sigma_2\hat{w}_2^2}{\hat{w}_S^2}\left(\lambda_2 + \lambda_3\right)$
C-IV-d*	$\mu_0^2 = -\frac{1}{2}\left(\lambda_5 + \lambda_6\right)\left(\hat{w}_1^2 + \hat{w}_2^2\right) - \lambda_8\hat{w}_S^2,$ $\mu_1^2 = -\left(\lambda_1 + \lambda_3\right)\left(\hat{w}_1^2 + \hat{w}_2^2\right) - \frac{1}{2}\left(\lambda_5 + \lambda_6\right)\hat{w}_S^2,$ $\lambda_4 = 0, \lambda_7 = 0$
C-IV-e	$\mu_0^2 = \frac{\sin^2(2(\sigma_1 - \sigma_2))}{\sin^2(2\sigma_1)}\left(\lambda_2 + \lambda_3\right)\frac{\hat{w}_2^4}{\hat{w}_S^2}$ $-\frac{1}{2}\left(1 - \frac{\sin 2\sigma_2}{\sin 2\sigma_1}\right)\left(\lambda_5 + \lambda_6\right)\hat{w}_2^2 - \lambda_8\hat{w}_S^2,$ $\mu_1^2 = -\left(1 - \frac{\sin 2\sigma_2}{\sin 2\sigma_1}\right)\left(\lambda_1 - \lambda_2\right)\hat{w}_2^2 - \frac{1}{2}\left(\lambda_5 + \lambda_6\right)\hat{w}_S^2,$ $\lambda_4 = 0, \lambda_7 = -\frac{\sin(2(\sigma_1 - \sigma_2))\hat{w}_2^2}{\sin 2\sigma_1\hat{w}_S^2}\left(\lambda_2 + \lambda_3\right)$
C-IV-f	$\mu_0^2 = -\frac{(\cos(\sigma_1 - 2\sigma_2) + 3\cos\sigma_1)\cos(\sigma_2 - \sigma_1)}{2\cos^2\sigma_1}\lambda_4\frac{\hat{w}_2^3}{\hat{w}_S}$ $-\frac{\cos(\sigma_1 - 2\sigma_2) + 3\cos\sigma_1}{2\cos\sigma_1}\left(\lambda_5 + \lambda_6\right)\hat{w}_2^2 - \lambda_8\hat{w}_S^2,$ $\mu_1^2 = -\frac{\cos(\sigma_1 - 2\sigma_2) + 3\cos\sigma_1}{\cos\sigma_1}\left(\lambda_1 + \lambda_3\right)\hat{w}_2^2$ $-\frac{3\cos 2\sigma_1 + 2\cos(2(\sigma_1 - \sigma_2)) + \cos 2\sigma_2 + 4}{4\cos(\sigma_1 - \sigma_2)\cos\sigma_1}\lambda_4\hat{w}_2\hat{w}_S - \frac{1}{2}\left(\lambda_5 + \lambda_6\right)\hat{w}_S^2,$ $\lambda_2 + \lambda_3 = -\frac{\cos\sigma_1\hat{w}_S}{2\cos(\sigma_2 - \sigma_1)\hat{w}_2}\lambda_4, \lambda_7 = -\frac{\cos(\sigma_2 - \sigma_1)\hat{w}_2}{2\cos\sigma_1\hat{w}_S}\lambda_4$
C-V*	$\mu_0^2 = -\frac{1}{2}\left(\lambda_5 + \lambda_6\right)\left(\hat{w}_1^2 + \hat{w}_2^2\right) - \lambda_8\hat{w}_S^2,$ $\mu_1^2 = -\left(\lambda_1 + \lambda_3\right)\left(\hat{w}_1^2 + \hat{w}_2^2\right) - \frac{1}{2}\left(\lambda_5 + \lambda_6\right)\hat{w}_S^2,$ $\lambda_2 + \lambda_3 = 0, \lambda_4 = 0, \lambda_7 = 0$

Potentially interesting cases for DM

Vacua with $w_1 = 0$ $w_S \neq 0$ $\lambda_4 \neq 0$

R-I-1, R-II-1a, C-III-a

$(0, 0, w_S)$ $\boldsymbol{(0,\ w_2,\ w_S)}$ $\boldsymbol{(0,\ \hat{w}_2 e^{i\sigma_2},\ \hat{w}_S)}$

R-I-1 was studied imposing $\lambda_4 = 0$ A. C. B. Machado and V. Pleitez (2012)

E. C. F. S. Fortes, A. C. B. Machado, J. Montaño and V. Pleitez (2014)

In our cases, R-II-1a and C-III-a only one of the three Higgs doublets is inert

Symmetry that stabilises DM is a remnant which survives SSB

In all these cases w_s is different from zero, fermions only couple to one Higgs doublet as a result of the S_3 symmetry thus avoiding FCNC

List of different constraints applied in our analysis

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

In order to evaluate Cut 3 micrOMEGAS was used

G. Belanger, F. Boudjema, A. Pukhov and A. Semenov, *Comput. Phys. Commun.* **185** (2014) 960–985.

Full numerical analysis done by Anton Kunčinas

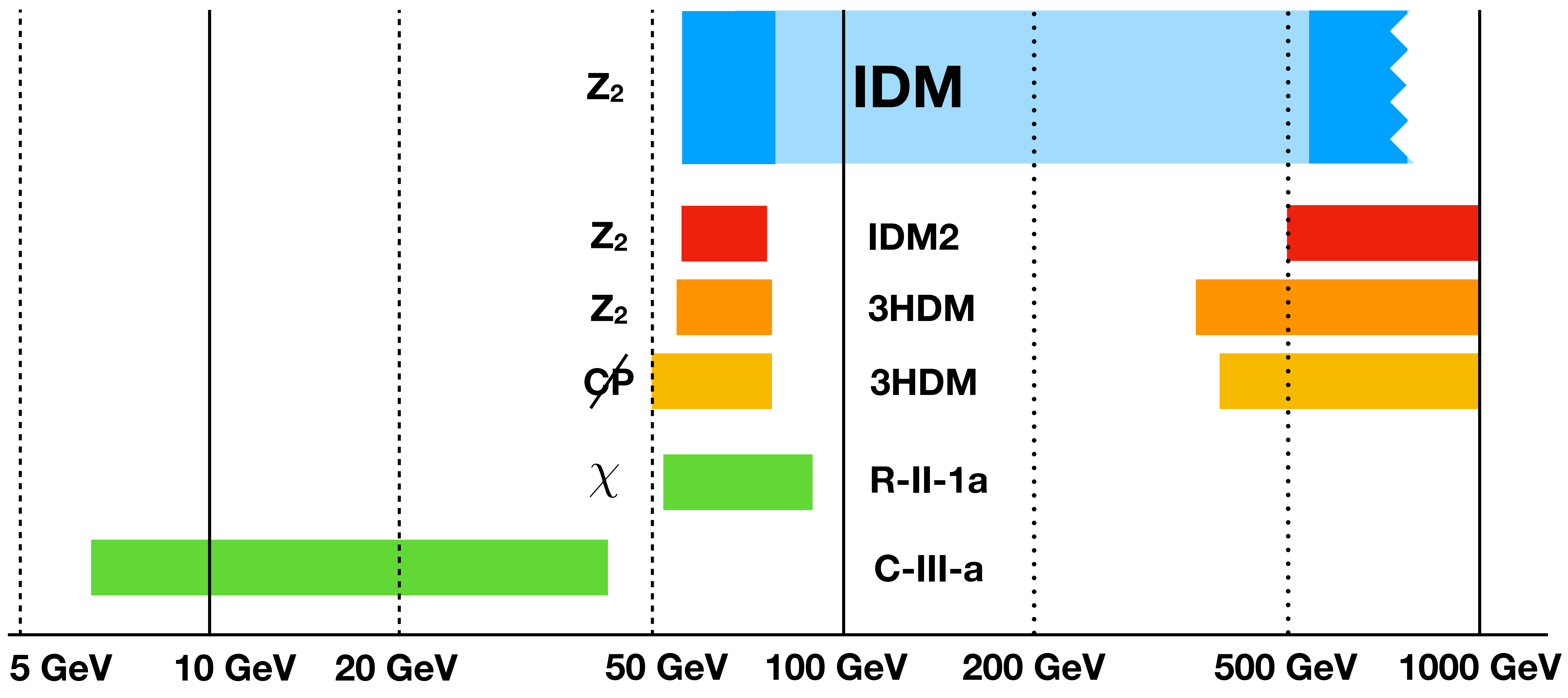
R-II-1a allows DM masses in range 52.5 to 89 GeV

CP is conserved

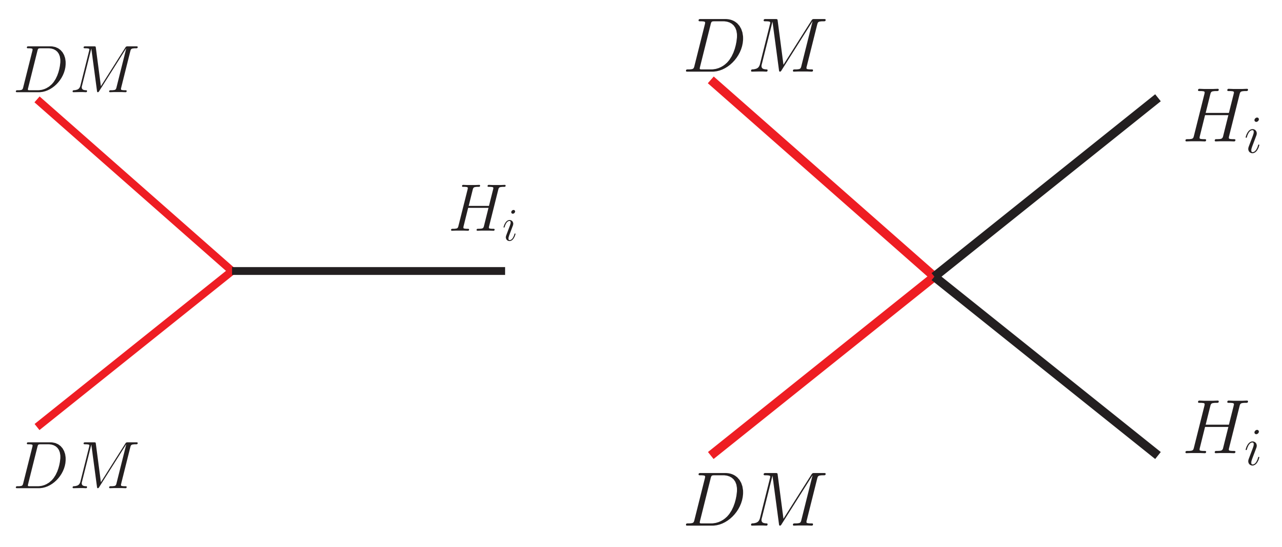
No high-mass region. Reason:

Portal coupling grows with DM mass

SCALAR DM MASS RANGES



Triliniar and quartic portal couplings:



Tuneable in the IDM

C-III-a allows DM mass in range 6.5 to 44.5 GeV

CP is violated

It is possible to suppress DM-DM-active scalar couplings at low mass

No high-mass region, same as above

Conclusions

Symmetries play a crucial rôle in multi-Higgs models

Multi-Higgs models provide interesting scenarios for Dark Matter

Multi-Higgs Models have a rich phenomenology

There is presently a lot of interest for this kind of models

Discoveries at the LHC are eagerly awaited