S_3-based 3HDMs with Dark Matter

Per Osland

University of Bergen

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Wafaa Khater, Anton Kuncinas,
Odd Magne Ogreid, Gui Rebelo, P.O.

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Introduction

2HDM's may provide additional CP violation
or a DM candidate, not both

3HDM's have 46 linearly independent parameters
(Olaussen et al, 2011), limited predictivity

Imposing some symmetry, get predictivity

This talk: S_3 symmetry
Robin Plantay: Weinberg's 3HDM

Introduction

Initial basis, S_3 symmetry (under interchange of 3 objects)

$$\phi_1, \quad \phi_2, \quad \phi_3.$$

Irreducible representation:

$$h_S = \frac{1}{\sqrt{3}}(\phi_1 + \phi_2 + \phi_3) \qquad \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{2}}(\phi_1 - \phi_2) \\ \frac{1}{\sqrt{6}}(\phi_1 + \phi_2 - 2\phi_3) \end{pmatrix}$$

decomposed as

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

Introduction

Express S_3-symmetric 3HDM potential as [Das & Dey, 2014]

$$V = V_2 + V_4$$

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

2 quadratic terms, 8 quartic ones (fewer than general 2HDM)

All parameters real, no explicit CP violation

Symmetry under $h_1 \to -h_1$, but *not* under $h_2 \to -h_2$

Introduction

2016, David Emmanuel-Costa, Odd Magne Ogreid, Gui Rebelo and P. O.:
11 real vacua, 16 complex vacua identified

Phase convention: w_S real, w_1 and/or w_2 may be complex

Potential can have vacua with one or more vanishing vevs, interesting for DM modeling

DM can be stabilized by Z_2 remnant of the S_3 symmetry $(h_1 \to -h_1)$

Introduction

Vacuum terminology (examples):

R-II-1a: “R” - real

“II” - two constraints

C-III-a: “C” - complex

“III” - three constraints

12 vacua have at least one vanishing vev, but some have massless states. Others have no stabilising symmetry or non-suitable Yukawa sectors. Left with two (or three).

DM studies

We have studied in some detail two cases, having a vanishing vev:

$$\text{R-II-1a}: \quad \{v_1, v_2, v_3\} = \{0, w_2, w_S\}$$

$$\text{C-III-a}: \quad \{v_1, v_2, v_3\} = \{0, w_2 e^{i\sigma}, w_S\}$$

both can accommodate Dark Matter

the inert doublet is associated with h_1, here $\langle h_1 \rangle = 0$

We choose the fermions to transform trivially under S_3
fermions couple to h_S, c.f. SM

Gauge couplings R-II-1a

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

$$\mathcal{L}_{VHH} = -\frac{g}{2\cos\theta_W} Z^\mu \left[\eta \overleftrightarrow{\partial}_\mu \chi - \cos(\alpha+\beta) h \overleftrightarrow{\partial}_\mu A + \sin(\alpha+\beta) H \overleftrightarrow{\partial}_\mu A\right]$$ opposite CP

$$- \frac{g}{2}\Big\{ i W_\mu^+ \Big[i h^- \overleftrightarrow{\partial}^\mu \chi + h^- \overleftrightarrow{\partial}^\mu \eta - \cos(\alpha+\beta) H^- \overleftrightarrow{\partial}^\mu h$$

$$+ \sin(\alpha+\beta) H^- \overleftrightarrow{\partial}^\mu H + i H^- \overleftrightarrow{\partial}^\mu A \Big] + \text{h.c.} \Big\}$$

$$+ \left[i e A^\mu + \frac{ig}{2} \frac{\cos(2\theta_W)}{\cos\theta_W} Z^\mu \right] \left(h^+ \overleftrightarrow{\partial}_\mu h^- + H^+ \overleftrightarrow{\partial}_\mu H^- \right)$$

$$\mathcal{L}_{VVHH} = \ldots$$

diagonalization of CP-even sector: α

$$\tan\beta = \frac{w_2}{w_S}$$

Alignment: $\sin(\alpha+\beta) = 1$

Gauge couplings C-III-a

$$\mathcal{L}_{VVH} = \left[\frac{g}{2c_w} m_Z Z_\mu Z^\mu + g m_W W_\mu^+ W^{\mu -}\right] \sum_{i=1}^{3} \mathcal{R}^0_{i1} H_i$$

$$\mathcal{L}_{VHH} = -\frac{g}{2c_w} Z^\mu \left(\sum_{i<j=2}^{3} \left(\mathcal{R}^0_{i2}\mathcal{R}^0_{j3} - \mathcal{R}^0_{i3}\mathcal{R}^0_{j2}\right) H_i \overset{\leftrightarrow}{\partial}_\mu H_j + \varphi_1 \overset{\leftrightarrow}{\partial}_\mu \varphi_2 \right)$$

$$- \frac{g}{2}\left\{ i W_\mu^+ \left(\sum_{i=1}^{3} \left(\mathcal{R}^0_{i2} + i\mathcal{R}^0_{i3}\right) H^- \overset{\leftrightarrow}{\partial^\mu} H_i + h^- \overset{\leftrightarrow}{\partial^\mu} (\varphi_1 + i\varphi_2) \right) + \text{h.c.} \right\}$$

$$+ \left[ieA^\mu + \frac{ig}{2}\frac{c_{2w}}{c_w} Z^\mu \right] \left(H^+ \overset{\leftrightarrow}{\partial}_\mu H^- + h^+ \overset{\leftrightarrow}{\partial}_\mu h^- \right)$$

$$\mathcal{L}_{VVHH} = \ldots$$

three neutral H_i states (η's and χ's mix)

DM studies

R-II-1a

- h_1: inert, physical states h^+, η and χ (opposite parity)
- h_2: "active" member of S_3 doublet, vev w_2
- h_S: S_3 singlet, "active", couples to fermions, vev w_S

Model preserves CP

States: h^+, H^+, χ, η, h, H, A

DM studies

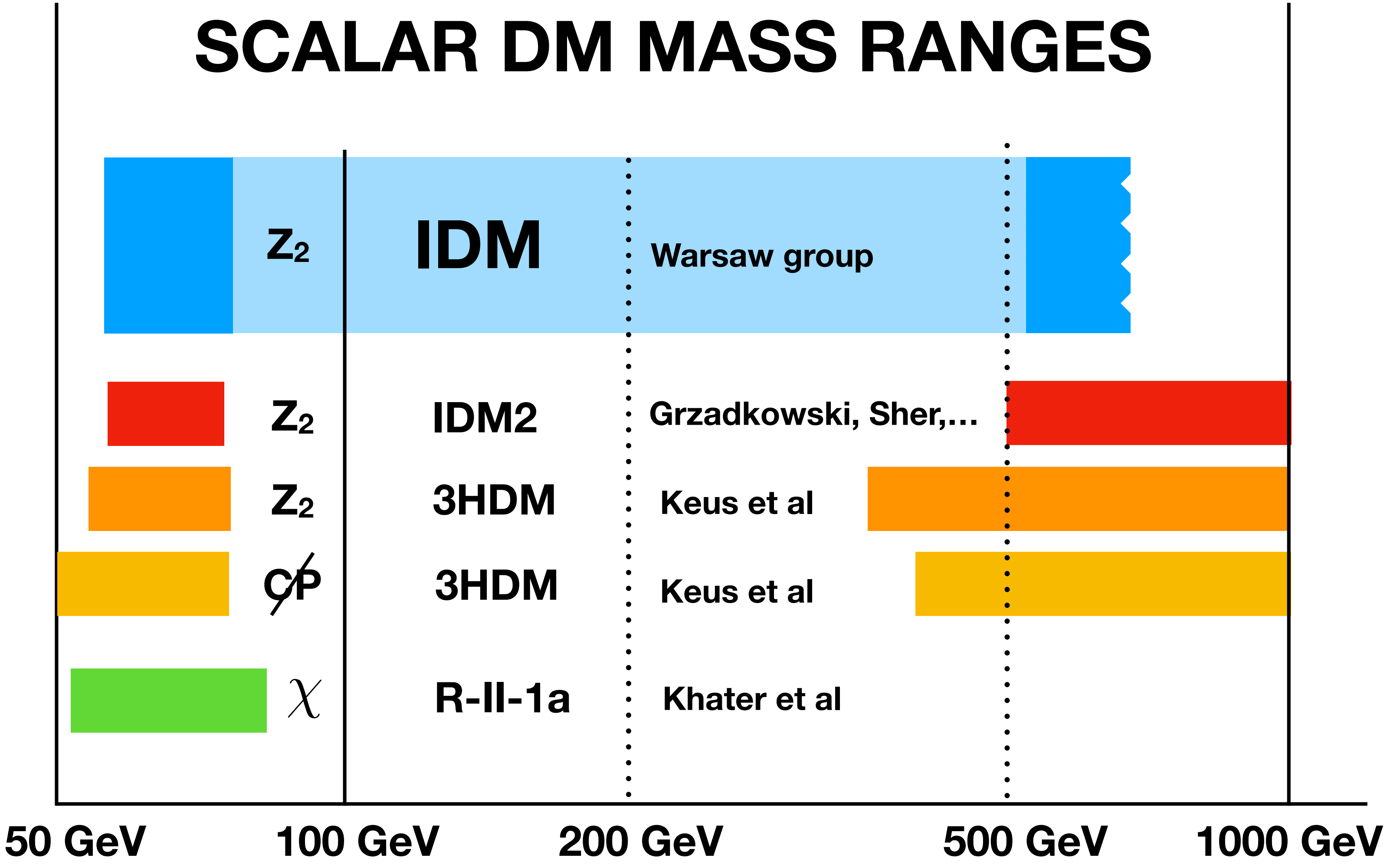
C-III-a

- h_1: inert, physical states h^+, φ_1 (DM) and φ_2
- h_2, h_S: "active" members of S_3 doublet and singlet, mix, physical states H^+, H_1, H_2, H_3. CP violated
- h_S: S_3 singlet, "active", couples to fermions, vev w_S

Model violates CP

States: h^+, H^+, φ_1, φ_2, H_1, H_2, H_3

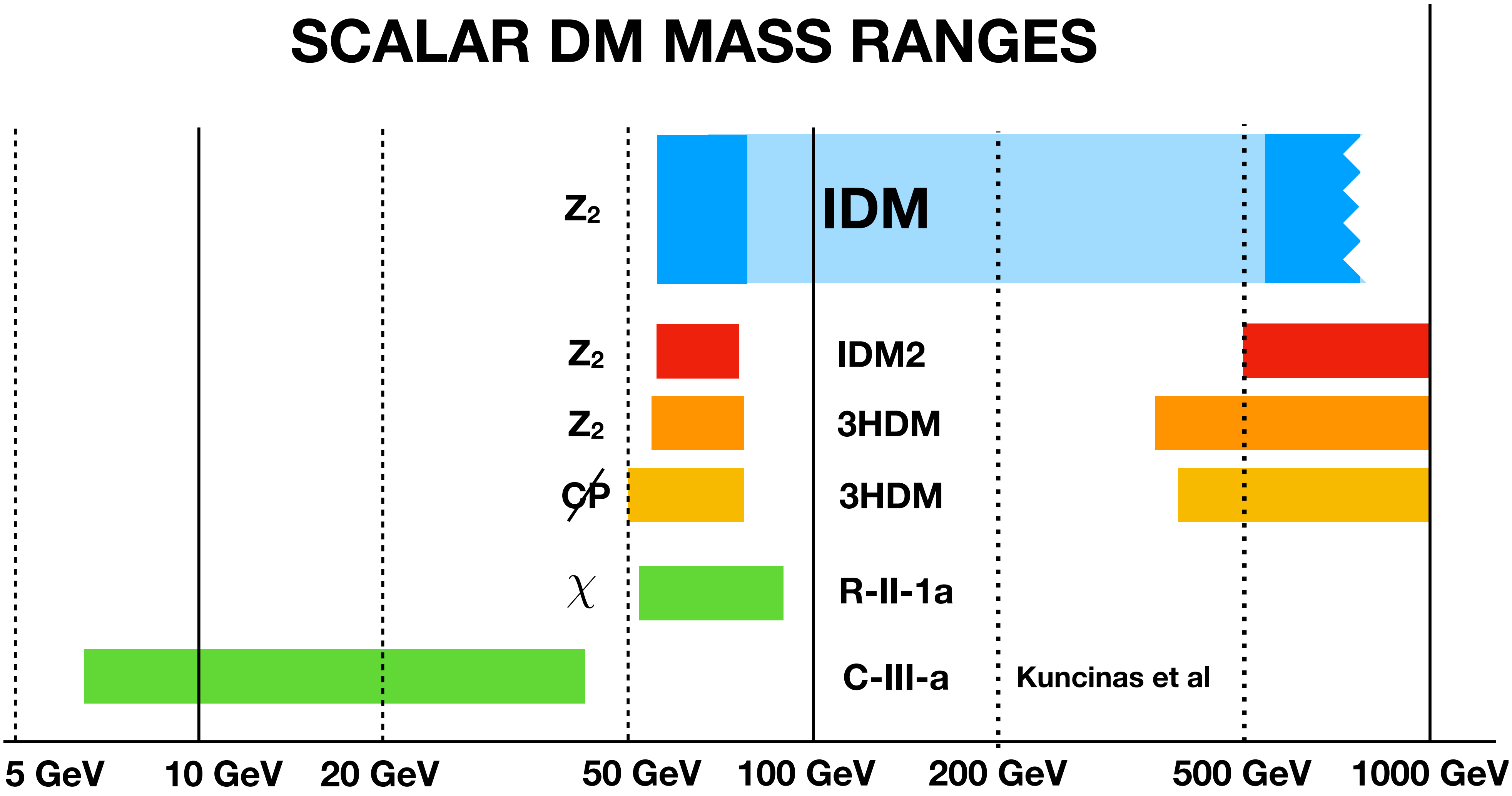
DM studies



SCALAR DM MASS RANGES
Z2
IDM
Warsaw group
Z2
IDM2
Grzadkowski, Sher,…
Z2
3HDM
Keus et al
CP
3HDM
Keus et al
χ
R-II-1a
Khater et al
50 GeV
100 GeV
200 GeV
500 GeV
1000 GeV

DM studies

SCALAR DM MASS RANGES



DM studies

Note that the S_3-symmetry-based models do not accommodate a high-mass (> 500 GeV) region

At high DM masses, the relic density becomes too low, due to efficient early-universe annihilation $\mathrm{DM} + \mathrm{DM} \to H_i$ or $H_i H_j$

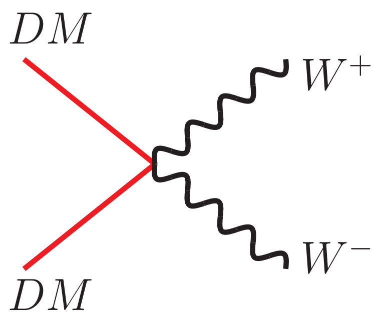
End up with

R-II-1a: $m_\chi \in [52.5,\ 89]$ GeV

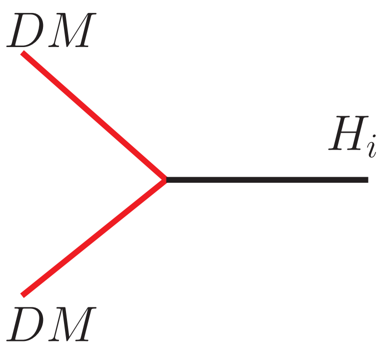
C-III-a: $m_{\varphi_1} \in [6.5,\ 44.5]$ GeV

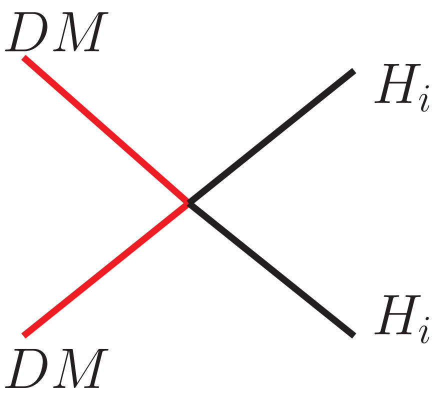
DM studies

Important Early Universe annihilation mechanism:



Trilinear and quartic portal couplings

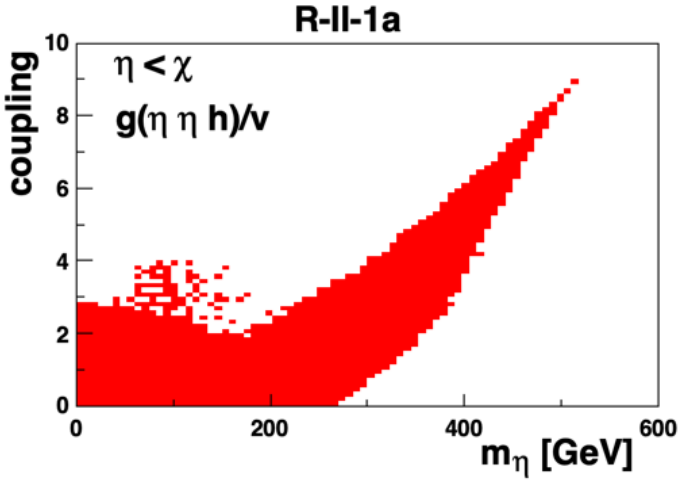


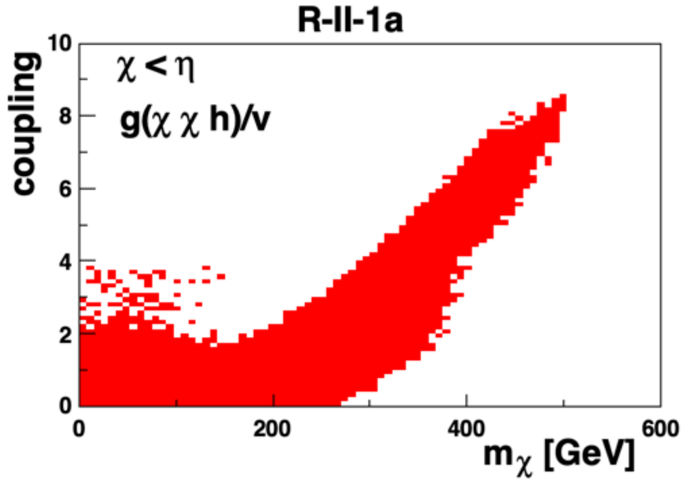


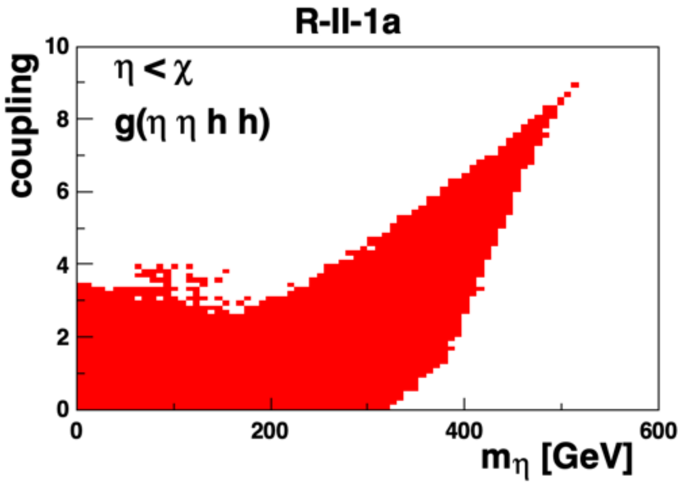
In the IDM this is a tuneable coupling
Here, not an independent parameter

The couplings grow with DM mass

DM studies


R-II-1a
η < χ
g(η η h)/v
coupling
m_η [GeV]
0
200
400
600
0
2
4
6
8
10


R-II-1a
χ < η
g(χ χ h)/v
coupling
m_χ [GeV]
0
200
400
600
0
2
4
6
8
10


R-II-1a
η < χ
g(η η h h)
coupling
m_η [GeV]
0
200
400
600
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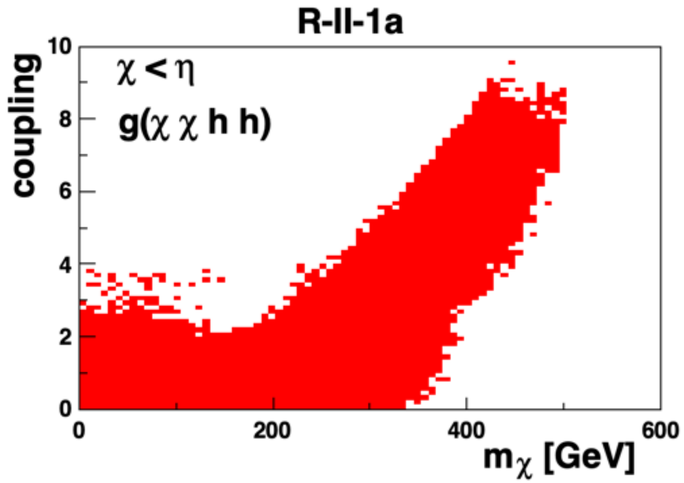
2
4
6
8
10


R-II-1a
χ < η
g(χ χ h h)
coupling
m_χ [GeV]
0
200
400
600
0
2
4
6
8
10

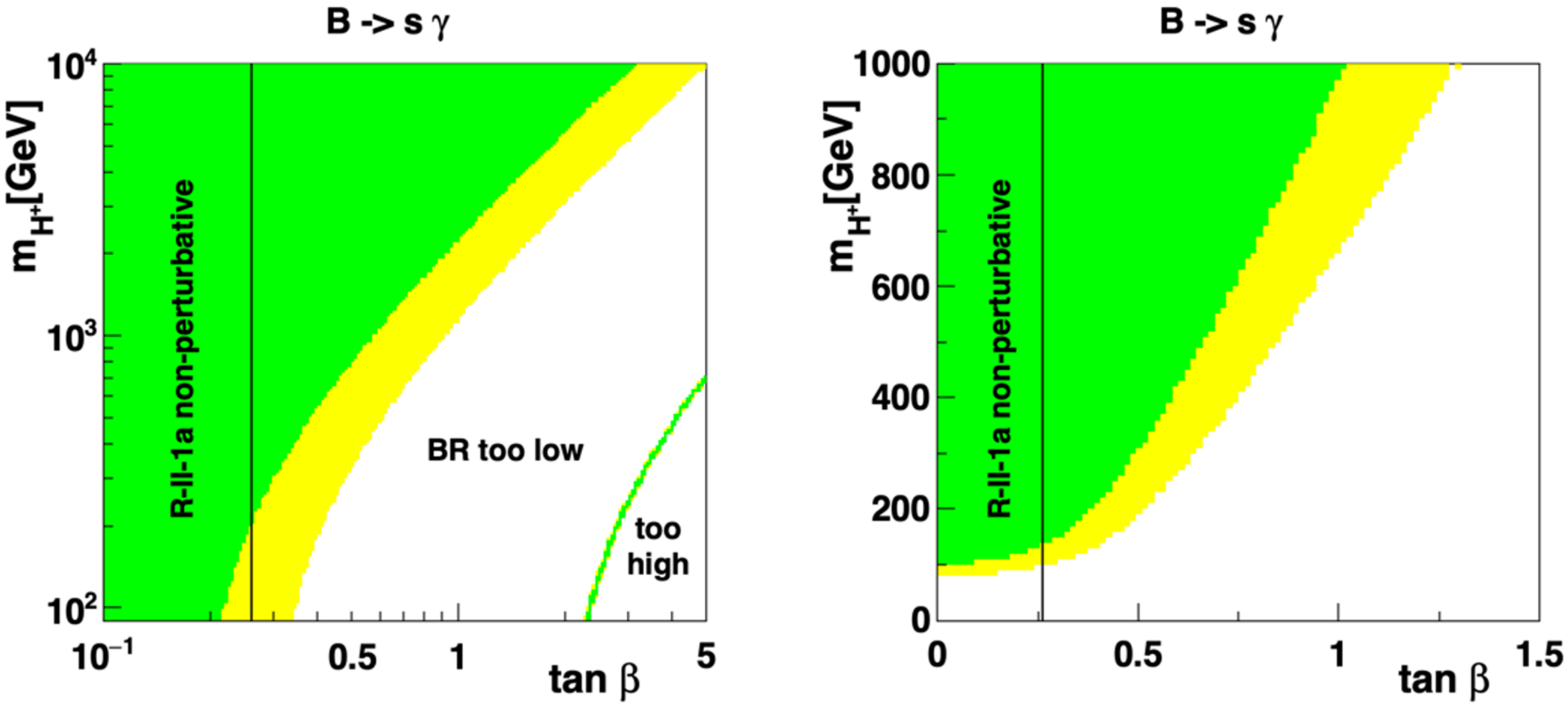
Scan

Scan over model parameters:

- Cut 1: perturbativity, stability, unitarity checks, a selection of relevant 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;

B—>sγ

The $\bar{B} \to s\gamma$ constraint is similar to that of the 2HDM (only one charged state couples to fermions), but note our definition of $\tan\beta = w_2/w_S$.



green (yellow) within 2 (3) σ

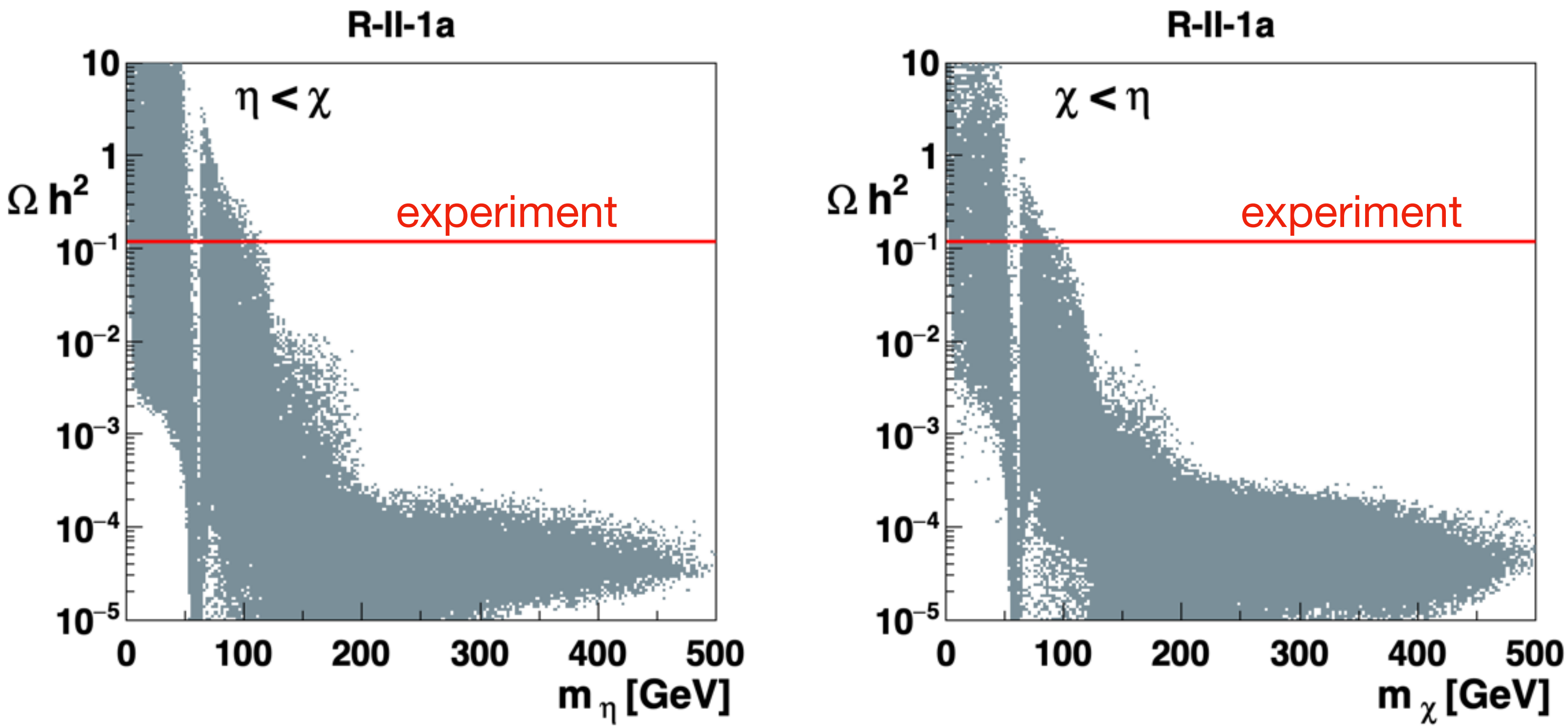
Scan

DM density vs DM mass

Scan over model parameters:

micrOMEGAs 5.2.7

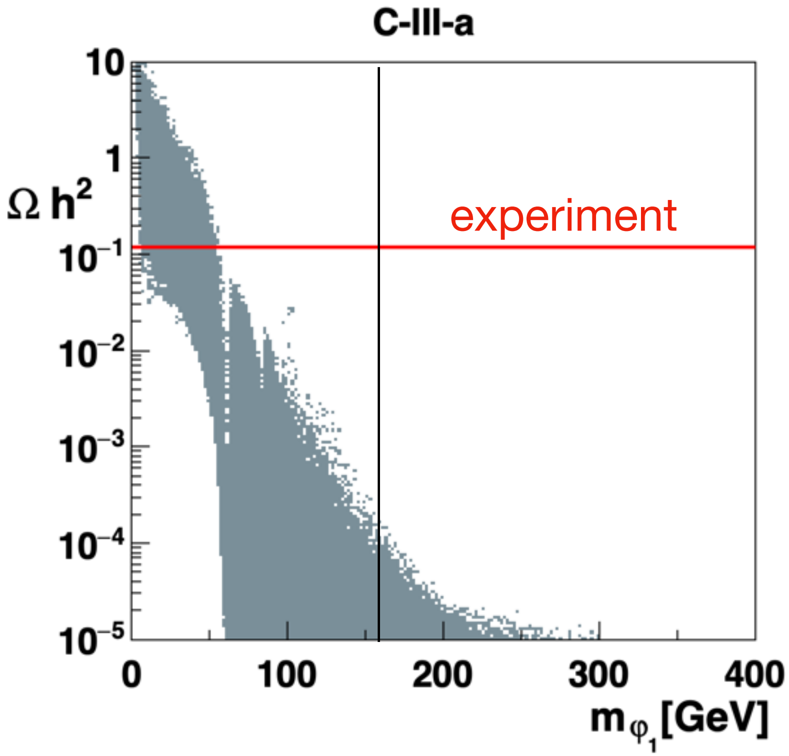
No solution above 120 GeV



Scan

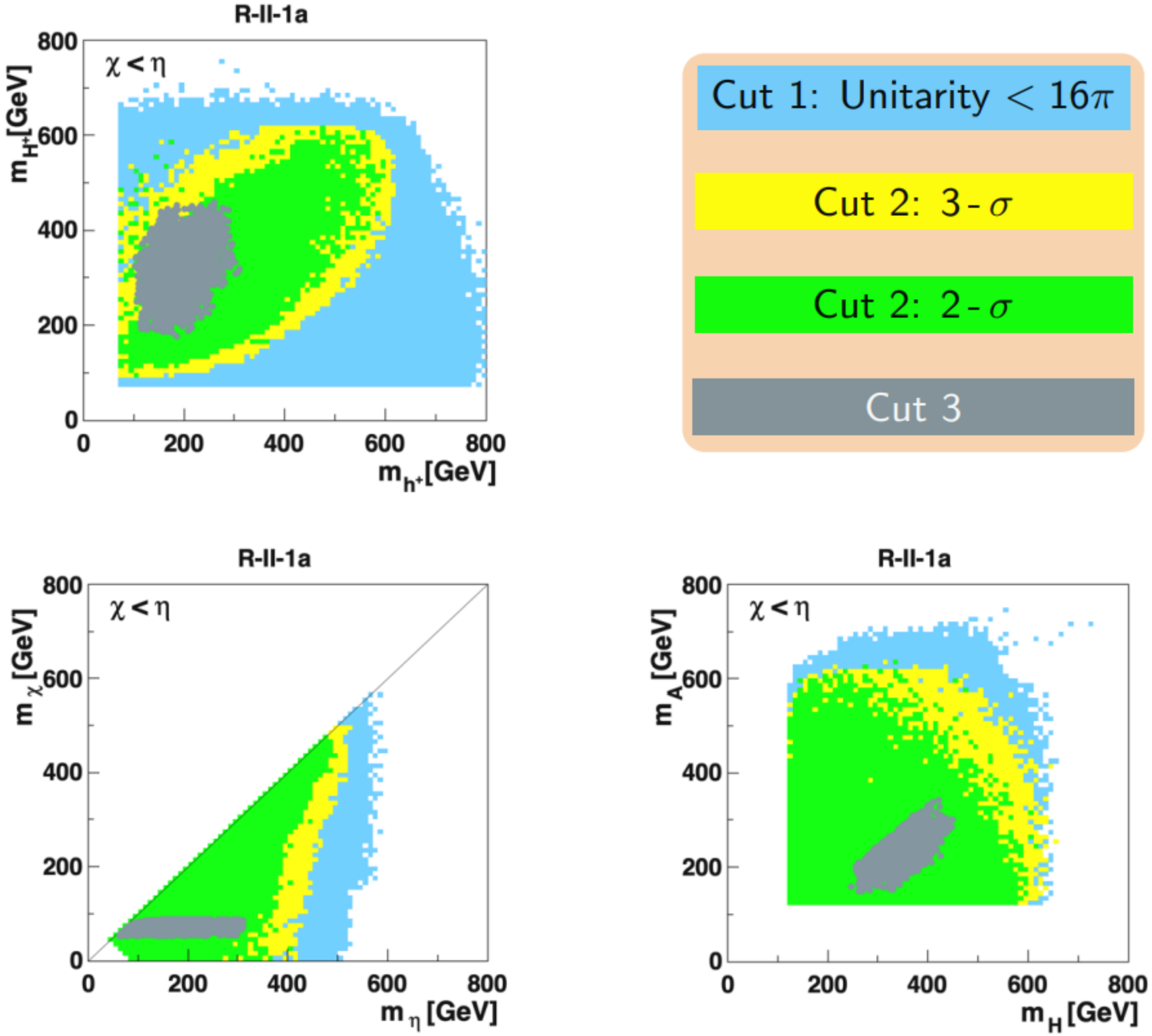
DM density vs DM mass

No solution above 70 GeV



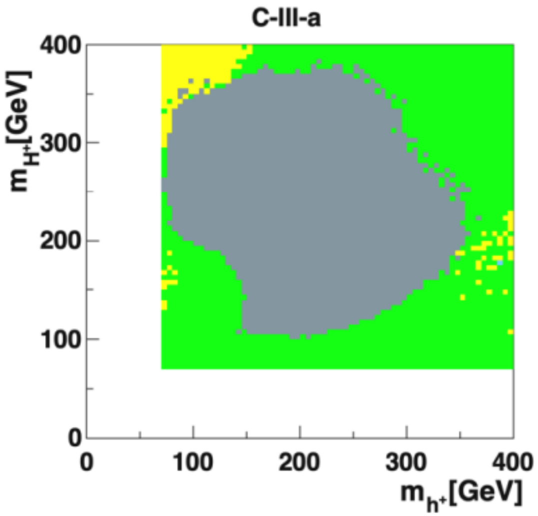
Scan

Allowed mass ranges



Scan

Allowed mass ranges



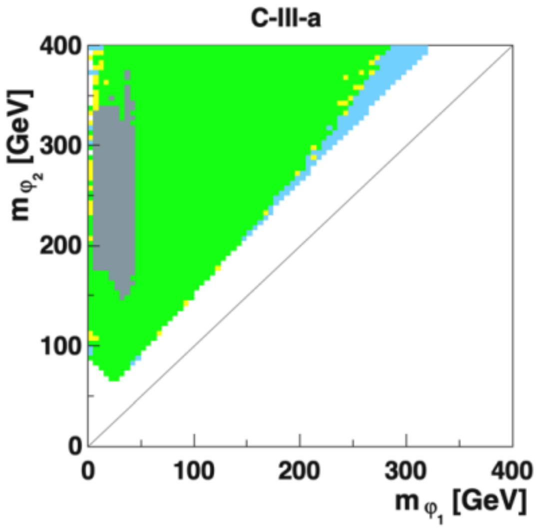
Cut 1: Unitarity $< 16\pi$

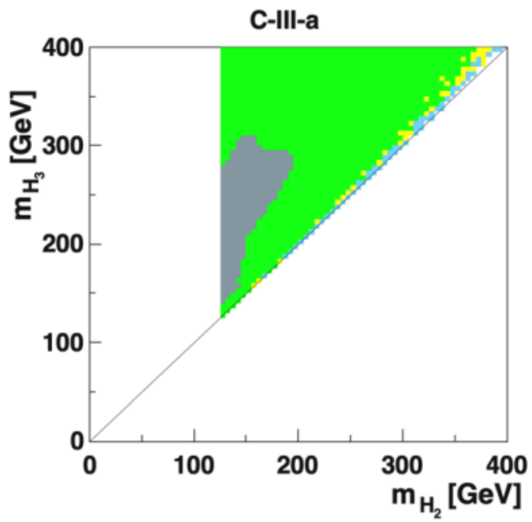
Cut 2: 3-σ

Cut 2: 2-σ

Cut 3

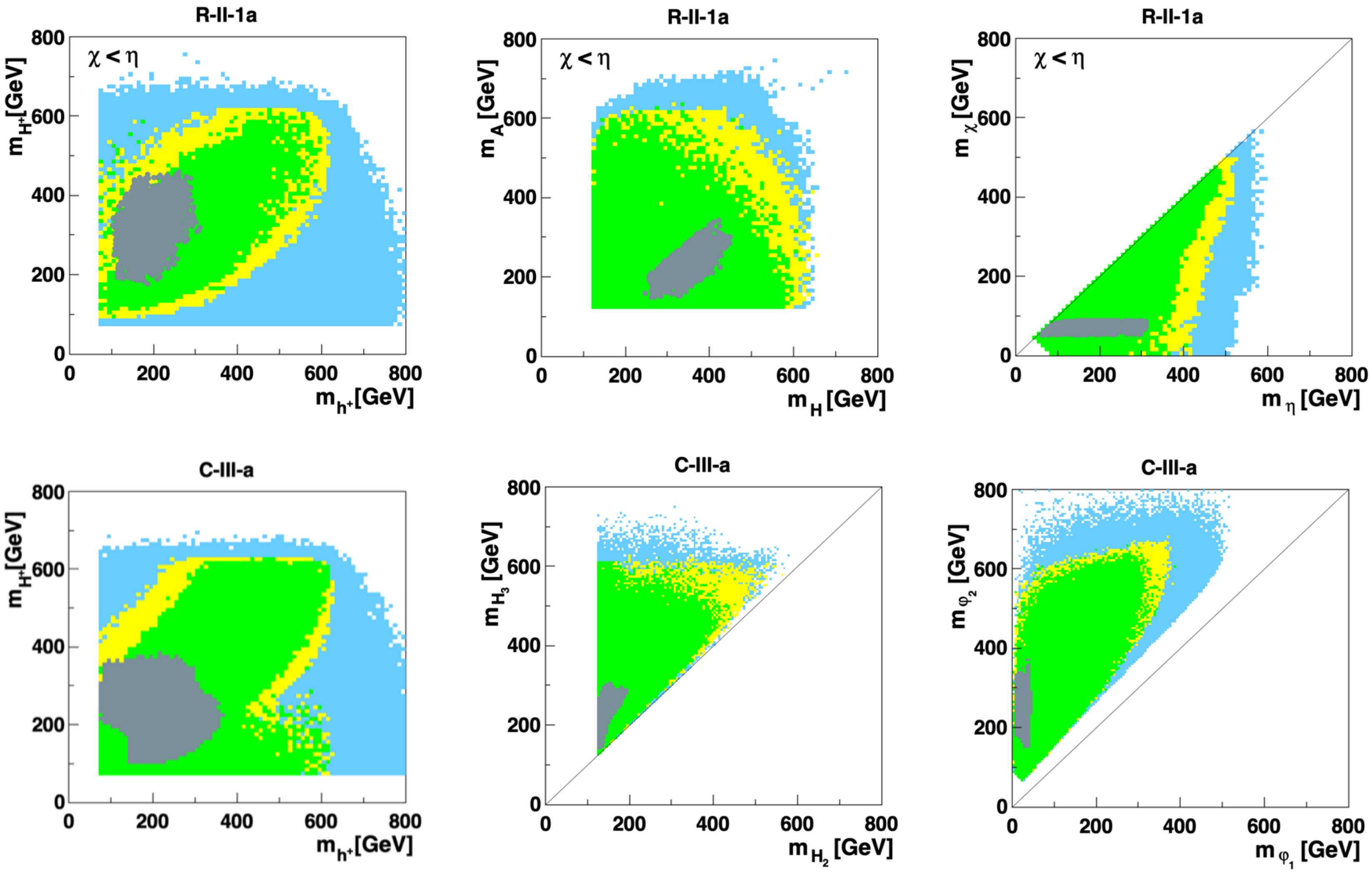
Different scale!





Scan

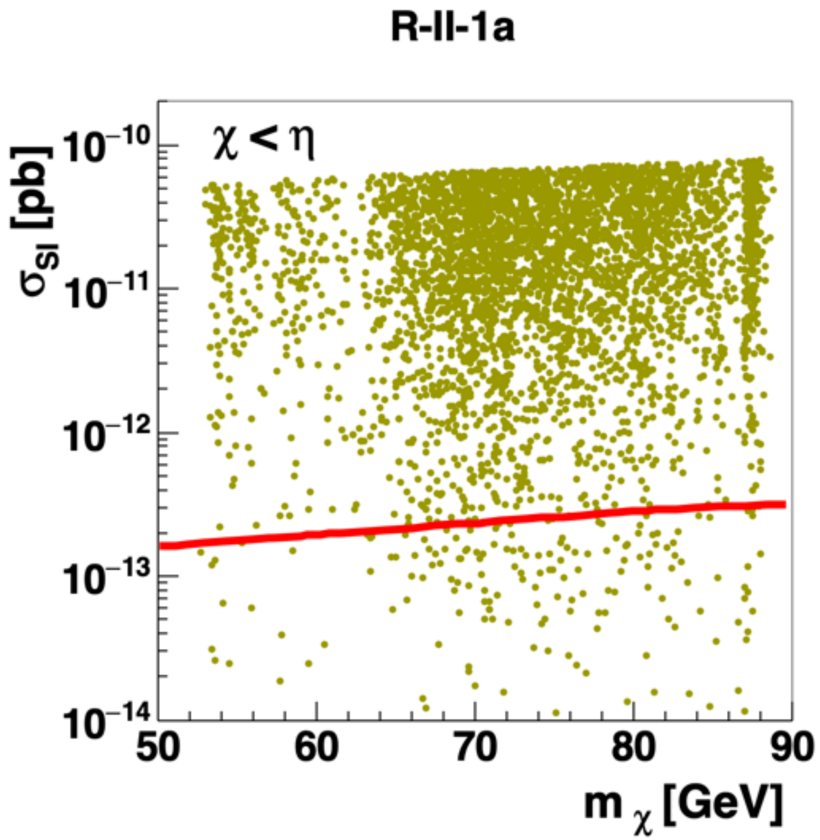
On same scale

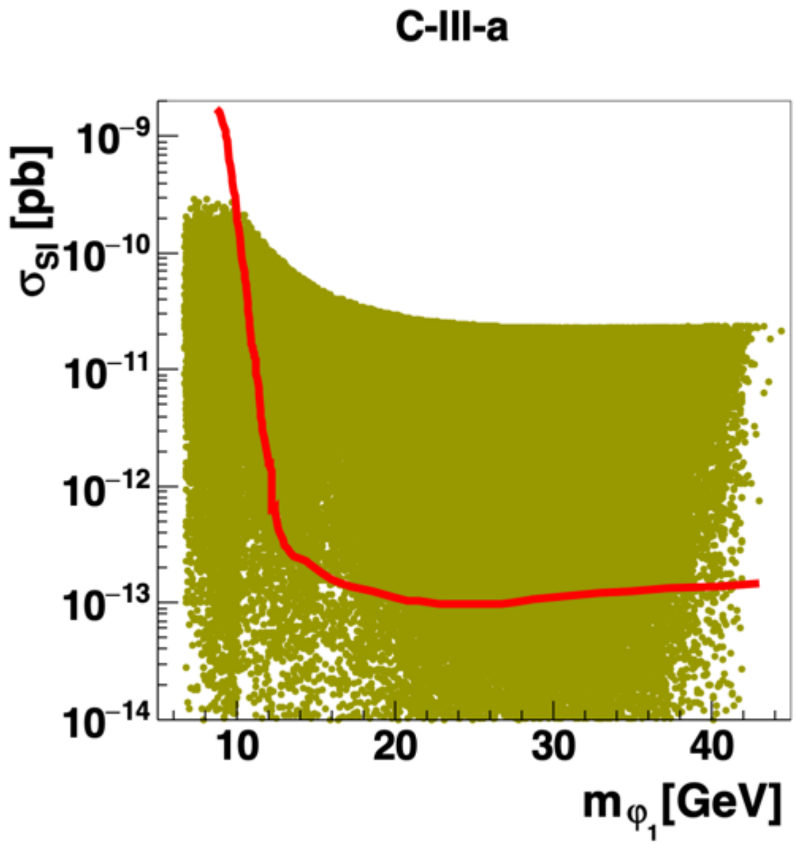


Scan

Spin-independent cross section

brown points survive Xenon1T, red curve: neutrino floor





Other choice of doublet basis:

$$\begin{pmatrix} \hat{h}_1 \\ \hat{h}_2 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} i & 1 \\ -i & 1 \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

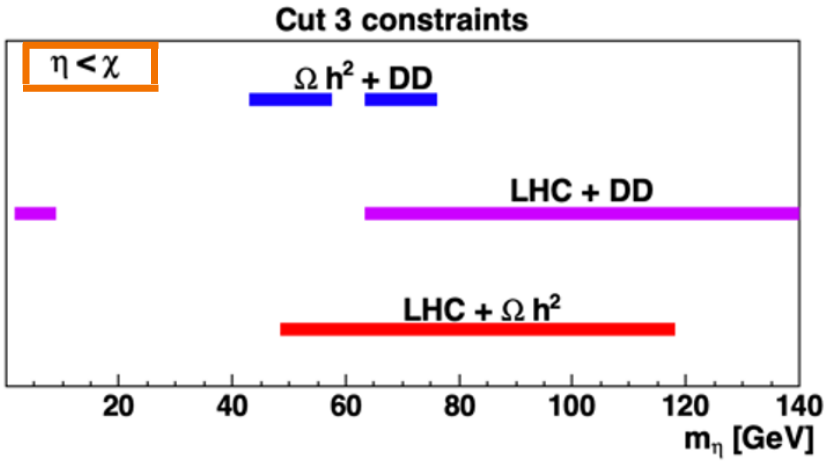
$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} -i & i \\ 1 & 1 \end{pmatrix} \begin{pmatrix} \hat{h}_1 \\ \hat{h}_2 \end{pmatrix}$$

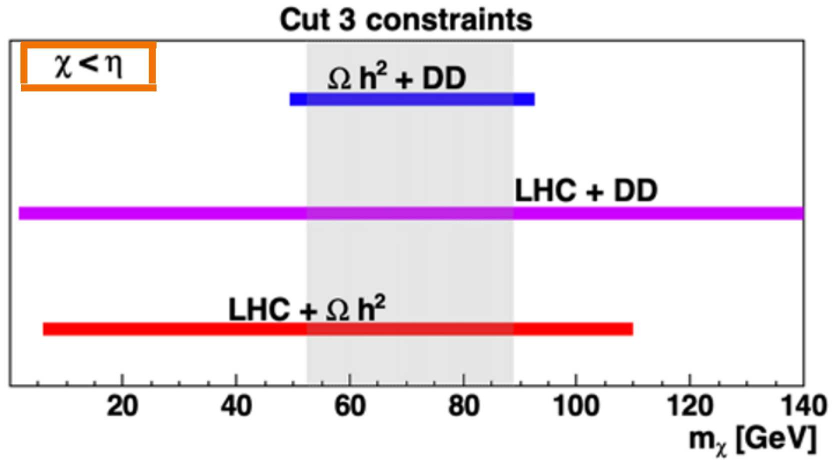
$$\langle h_1 \rangle = 0 \Longleftrightarrow \langle \hat{h}_1 \rangle = \langle \hat{h}_2 \rangle$$

Same physics, book-keeping different

R-II-1a “curiosity” #1: colored bars: mass range allowed by pair of constraints

Either η or χ could be the lighter one (DM).

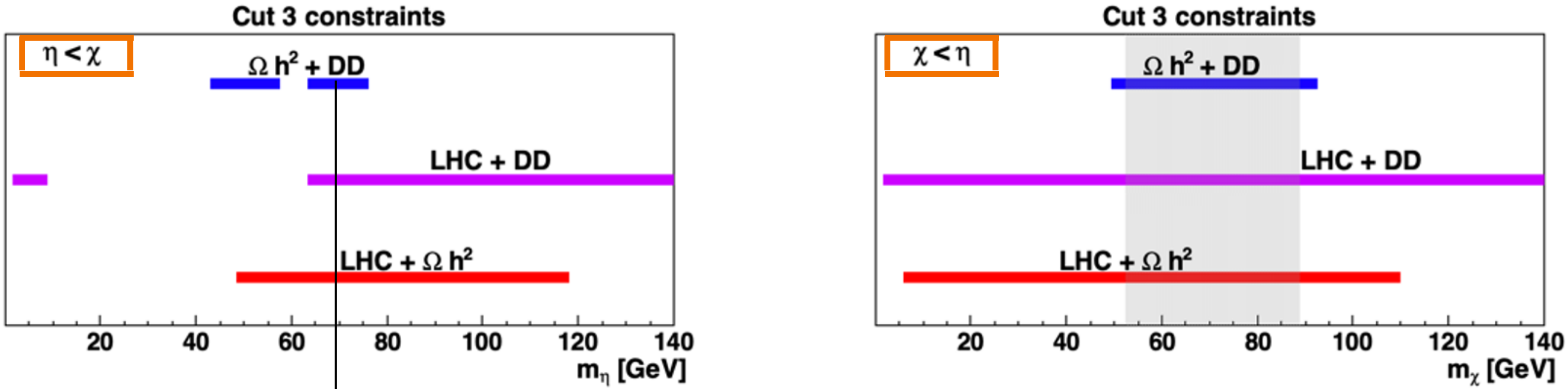




Grey region: overlap

R-II-1a “curiosity” #1:

Either η or χ could be the lighter one (DM).



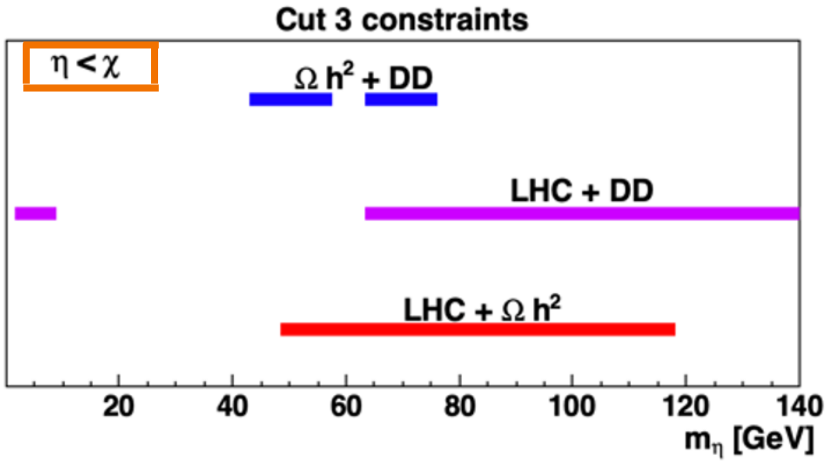
Grey region: overlap

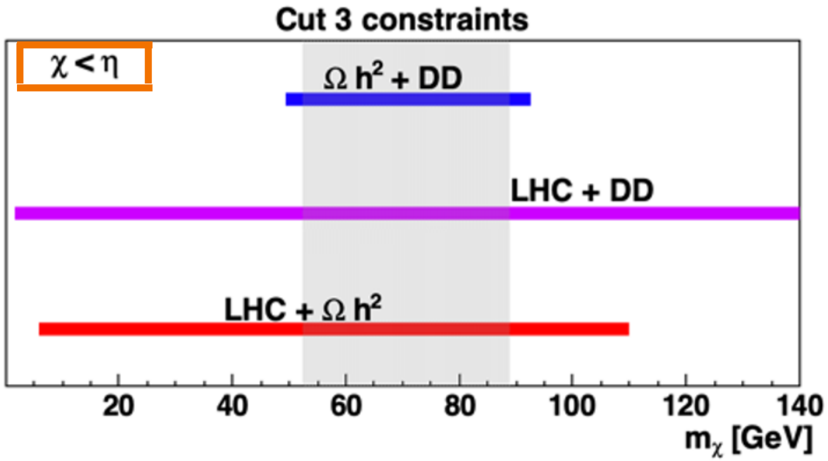
Even if all constraints are satisfied for a certain mass, the allowed regions need not overlap in other parameters.

Example: perhaps charged scalar mass does not overlap

R-II-1a "curiosity" #1:

Either η or χ could be the lighter one (DM).





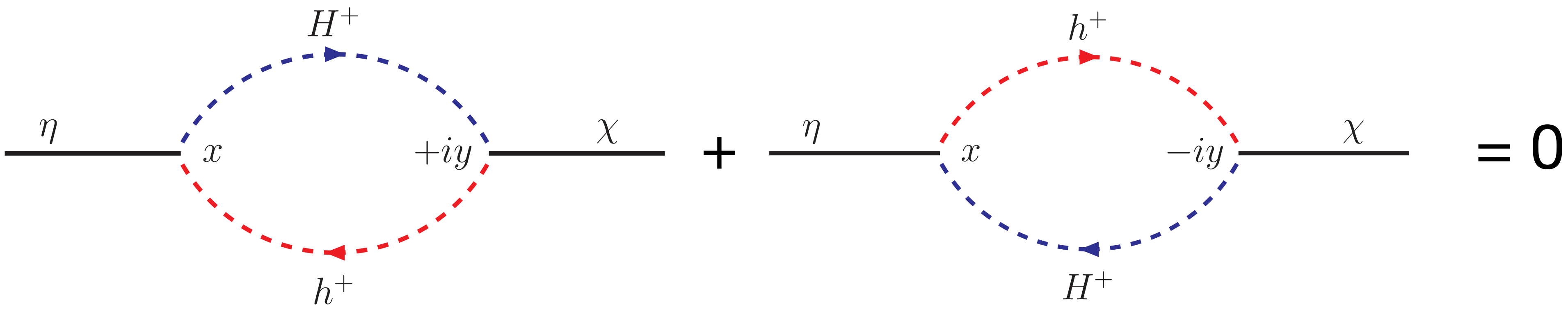
Grey region: overlap

If experimental constraints (numbers) had been a little different, both η and χ could have been DM candidates, whichever is lighter.

R-II-1a “curiosity” #2:

The R-II-1a preserves CP both at the Lagrangian level and by the vacuum.

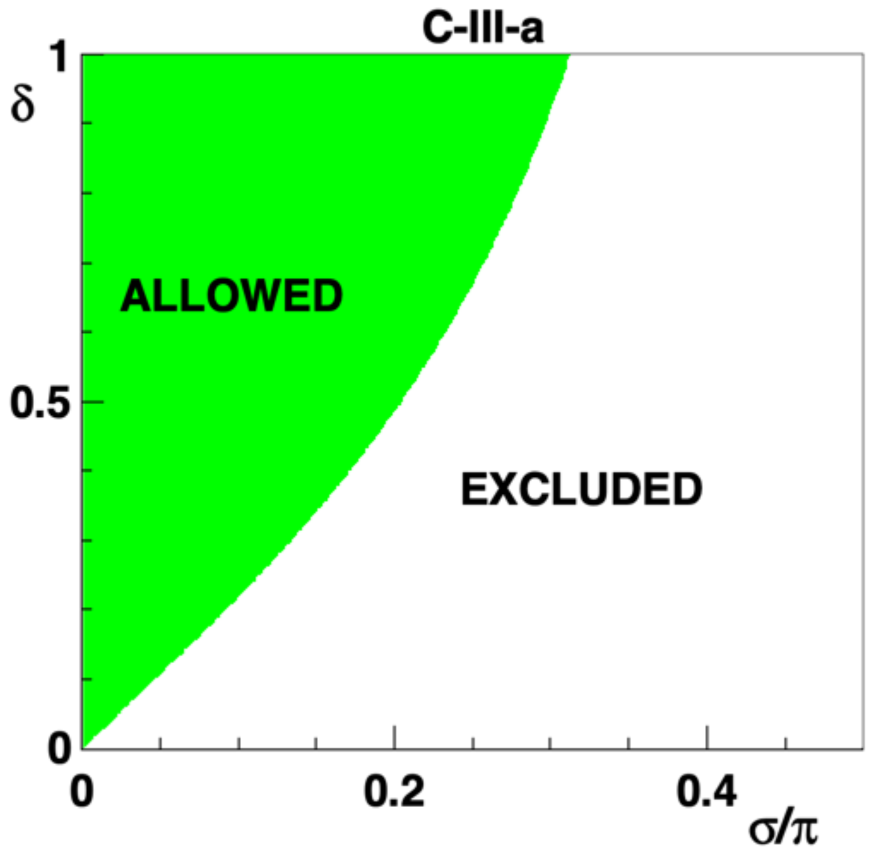
The presence of both $g\,(\eta h^{\pm} H^{\mp})$ and $g\,(\chi h^{\pm} H^{\mp})$ couplings suggests there might be mixing at the one-loop level, but the two diagrams associated with the different charge assignments cancel.



C-III-a “curiosity”:

There is a mass gap between the two neutral states φ_1 and φ_2 of the inert doublet, given by σ:

$$\delta = \frac{m^2_{\varphi_2} - m^2_{\varphi_1}}{\sqrt{m^2_{\varphi_1} m^2_{\varphi_2}}} > \frac{2}{3}|\tan\sigma|$$



Apology

We did not study any electric dipole moment

CONCLUSIONS

Symmetries play a crucial rôle in multi-Higgs models

Multi-Higgs models provide interesting scenarios for Dark Matter

Symmetries are needed to stabilise Dark Matter

The R-II-1a model provides Dark Matter without imposing
ad hoc symmetry for stability

The C-III-a offers also CP violation and light DM

Multi-Higgs Models have a rich phenomenology

Considered models have other particles which are relatively light

Discoveries at the LHC are eagerly awaited

ACKNOWLEDGEMENTS