Dark Matter in S_3-Symmetric Three-Higgs Doublet Model With Spontaneous CP Violation

Anton Kunčinas

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

Universidade de Lisboa, Portugal

In collaboration with: **O. M. Øgreid**, **P. Osland**, **M. N. Rebelo**
Based on **[2108.07026]** and **[2204.05684]**

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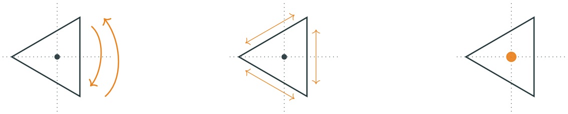
S_3-Symmetric Three-Higgs-Doublet Models



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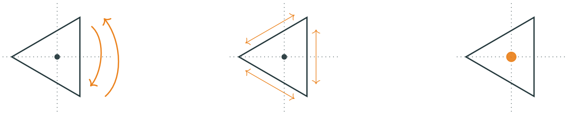

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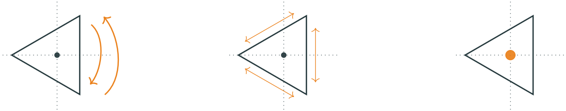

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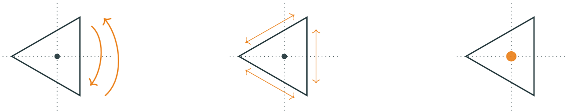

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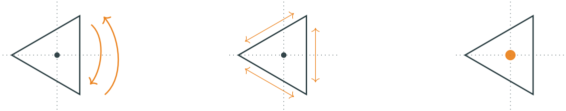

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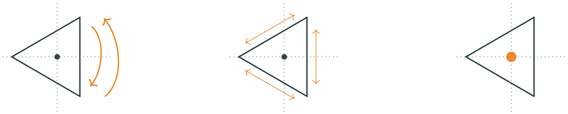
Different S_3-3HDM models (**D. Emmanuel-Costa, O. M. Ogreid, P. Osland, M. N. Rebelo**):

$$\text{vacuum:} \begin{cases} 11 \text{ real } (w_1,\, w_2,\, w_S)\,, \\ 18 \text{ complex } (\hat{w}_1 e^{i\sigma_1},\, \hat{w}_2 e^{i\sigma_2},\, \hat{w}_S)\,. \end{cases}$$



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Possible DM candidates: 3 exact $V(S_3)$ and 8 softly broken $V(S_3)$ **[App]**.

Comparing Two Models

	R-II-1a	C-III-a
Vacuum	$\{0,\ w_2,\ w_S\}$	$\{0,\ \hat{w}_2 e^{i\sigma},\ \hat{w}_S\}$ spontaneous $\not{C}\not{P}$

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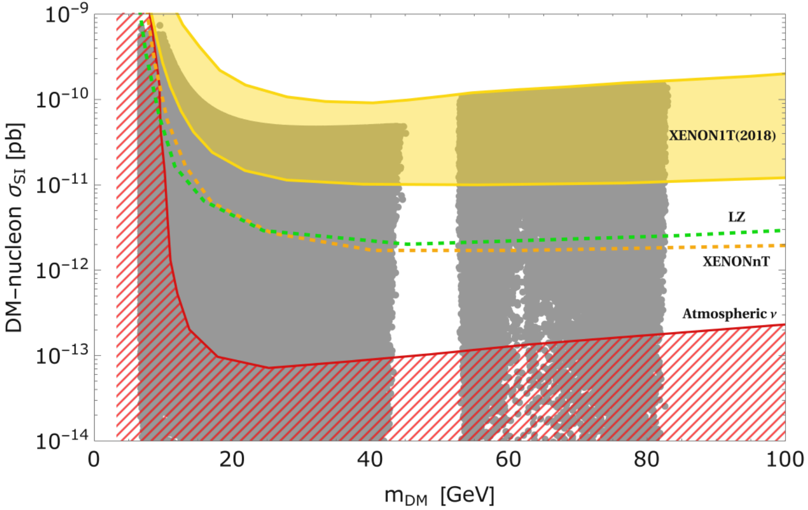
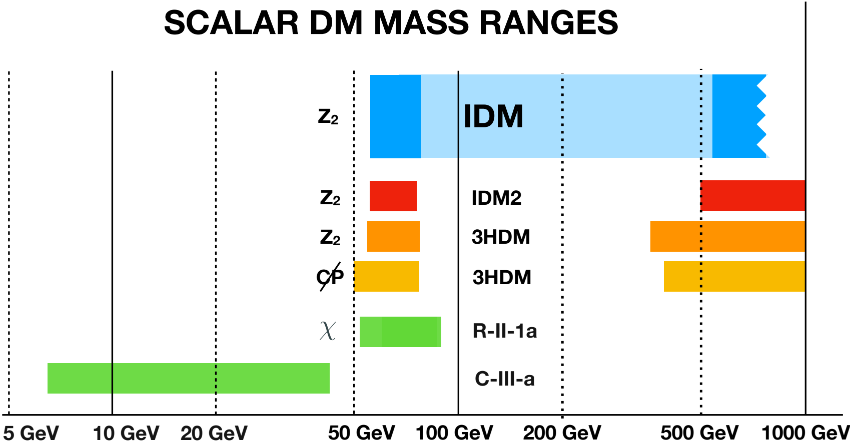
Theoretical and experimental constraints evaluated:

- Cut 1: perturbativity, stability, unitarity checks, LEP constraints;
- Cut 2: $h \to \{VV,\ FF\}$, S and T, $\bar{B} \to X(s)\gamma$;
- Cut 3: $h \to \{\text{invisible},\ \gamma\gamma\}$, $\Omega_{\text{CDM}} h^2$, direct searches;

Results: Direct Detection of Dark Matter



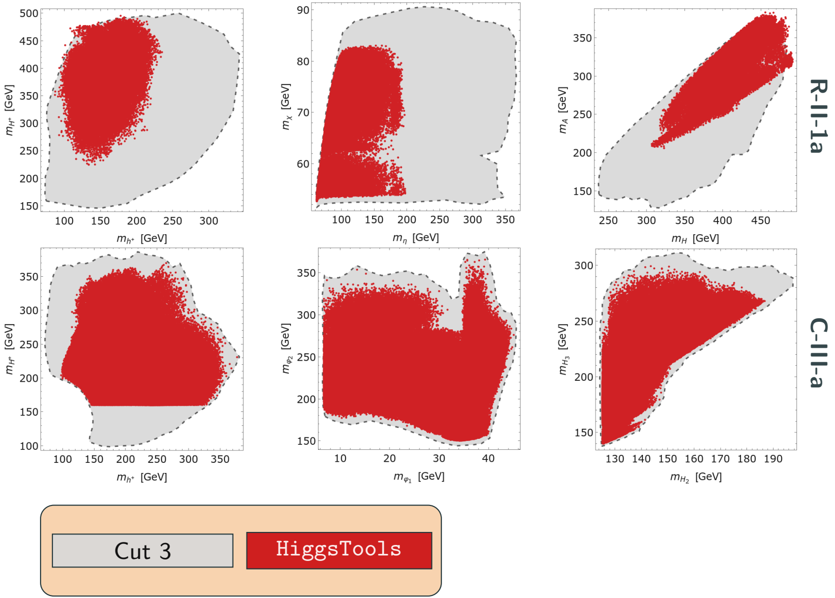


IDM: **(A. Belyaev, G. Cacciapaglia, I. P. Ivanov, F. Rojas-Abatte, M. Thomas)**, **(J. Kalinowski, W. Kotlarski, T. Robens, D. Sokolowska, A. F. Zarnecki)**;

IDM2 (one inert doublet): **(M. Merchand, M. Sher)**;

3HDM and ~~CP~~-3HDM (two inert doublets): **(A. Cordero-Cid, J. Hernández-Sánchez, V. Keus, S. F. King, S. Moretti, D. Rojas, D. Sokołowska)**

HiggsTools (HiggsBounds and HiggsSignals)



Generalised NFW profile with $\rho = 0.3\,\text{GeV}/\text{cm}^3$.

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C-III-a:
$$\text{Br}\left(\varphi_1\varphi_1 \to b\bar{b}\right) \in \{0.8;\ 0.92\}\,,$$
$$\text{Br}\left(\varphi_1\varphi_1 \to \tau^-\tau^+\right) \in \{0.04;\ 0.18\}\,.$$

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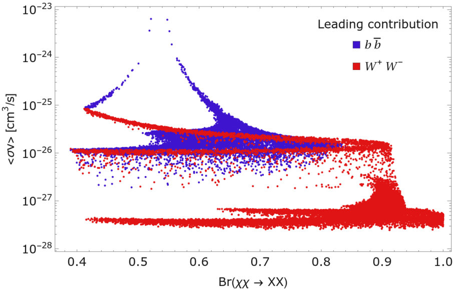
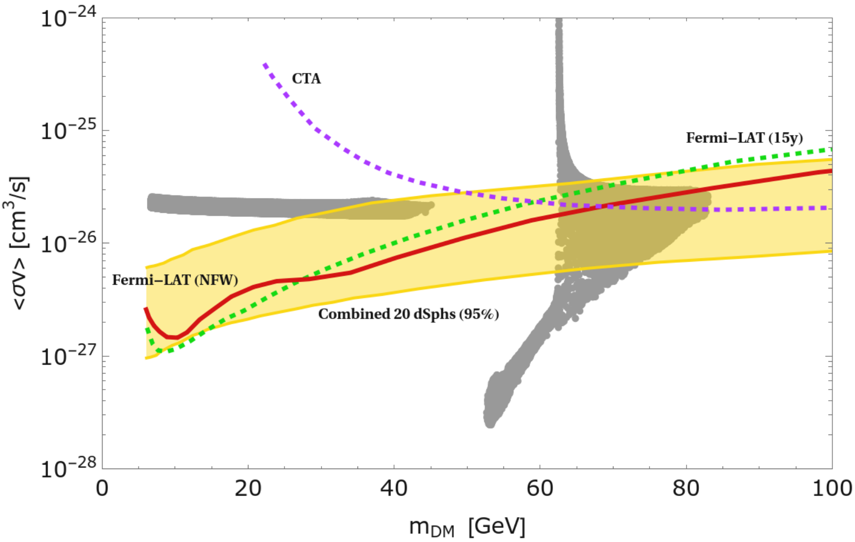
R-II-1a:

$$\mathrm{Br}\left(\chi\chi \to b\bar{b}\right) \in \{0.38;\ 0.84\}\,,$$
$$\mathrm{Br}\left(\chi\chi \to \{gg,\ \tau^-\tau^+,\ W^-W^+\}\right) \in \{0.08;\ 0.45\}\,,$$

or

$$\mathrm{Br}\left(\chi\chi \to W^-W^+\right) \in \{0.38;\ 0.99\}\,,$$
$$\mathrm{Br}\left(\chi\chi \to \{gg,\ ZZ,\ b\bar{b}\}\right) \in \{\sim 0;\ 0.45\}\,.$$




CTA
Fermi–LAT (15y)
Fermi–LAT (NFW)
Combined 20 dSphs (95%)
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
<σv> [cm³/s]
0
20
40
60
80
100
m_{DM} [GeV]

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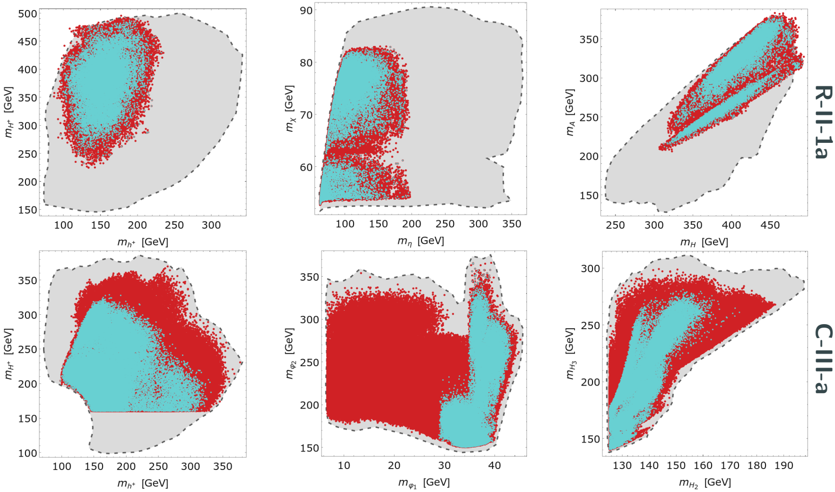

Cut 3

HiggsTools

Indirect DM detection,
XENONnT + LZ,
Br($h \to$ inv.) ≤ 0.10.

Probing $Hf\bar{f}$ Coupling CP Properties

$$\mathcal{L} \supset -\frac{m_f}{v}\overline{\psi_f}\left(\kappa_f + i\gamma_5\tilde{\kappa}_f\right)\psi_f .$$

ATLAS: $\alpha = \arctan\left(\tilde{\kappa}_f/\kappa_f\right)$, with $|\alpha| \in \{0;\ 43^\circ\}$,

CMS: $f_{CP} = \frac{\left|\tilde{\kappa}_f\right|^2}{\left|\kappa_f\right|^2 + \left|\tilde{\kappa}_f\right|^2} \times \text{sign}\left(\tilde{\kappa}_f/\kappa_f\right)$, with $f_{CP} = 0.00 \pm 0.33$.

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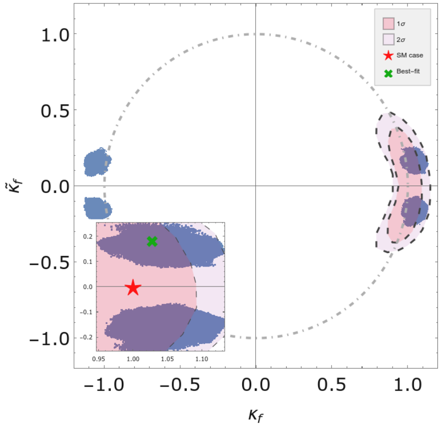

C-III-a: $|\alpha| \in \{3.34^\circ;\ 14.91^\circ\}$,
$f_{CP} \in \{-0.07;\ 0.06\}$.

What Else?

$$\Gamma^{\text{tot}} = \begin{cases} \text{C-III-a: } \mathcal{O}(\text{GeV}), \\ \text{R-II-1a: } \in \left\{10^{-12}; 100\right\} \text{GeV}. \end{cases}$$

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$$\text{Production at } \sqrt{s} = 14 \text{ TeV: } \begin{cases} \text{C-III-a: } \sigma \in \left\{10^{-2};\, 1\right\} \text{pb}, \\ \text{R-II-1a: } \sigma \in \left\{10^{-7};\, 10^{-1}\right\} \text{pb}. \end{cases}$$

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In both models there are solutions for $\text{Br}(h \to \text{inv.}) \approx 0$.

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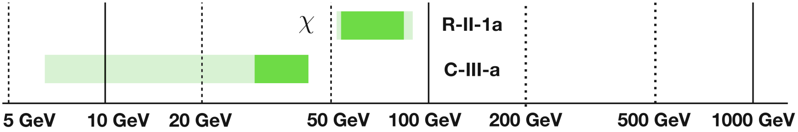
Plans: measure $\not{CP}$ via EDMs for C-III-a.

Conclusions

- Multi-Higgs-doublet models are phenomenologically rich and can accommodate a dark matter candidate;
- Viable dark matter regions: R-II-1a {52; 83} GeV, C-III-a {29; 44} GeV;



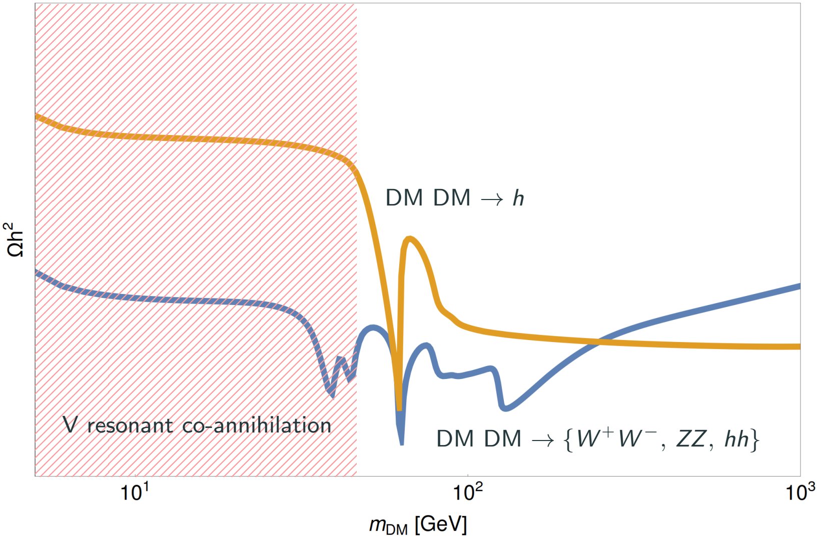
Work supported by the Fundação para a Ciência e a Tecnologia (FCT, Portugal) PhD fellowship with reference UI/BD/150735/2020 as well as through the FCT projects CERN/FIS-PAR/0002/2021, UIDB/00777/2020, UIDP/00777/2020, CERN/FIS-PAR/0008/2019, PTDC/FIS-PAR/29436/2017.

FCT Fundação para a Ciência e a Tecnologia

COMPETE PROGRAMA OPERACIONAL FACTORES DE COMPETITIVIDADE

QUADRO DE REFERÊNCIA ESTRATÉGICO NACIONAL

Appendix: Inert Doublet Model Relic Density



Appendix: Yukawa Interactions

Whenever $w_S \neq 0$ we can construct a trivial Yukawa sector:

$$\mathcal{M}_u = \frac{1}{\sqrt{2}} \left(y^u_{ij}\right) w^*_S, \qquad \mathcal{M}_d = \ldots$$

Fermions can transform non-trivially under S_3:

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

$$\mathcal{M}_u = \frac{1}{\sqrt{2}} \begin{pmatrix} y^u_1 w^*_S + y^u_2 w^*_2 & y^u_2 w^*_1 & y^u_4 w^*_1 \\ y^u_2 w^*_1 & y^u_1 w^*_S - y^u_2 w^*_2 & y^u_4 w^*_2 \\ y^u_5 w^*_1 & y^u_5 w^*_2 & y^u_3 w^*_S \end{pmatrix}, \qquad \mathcal{M}_d = \ldots$$

$$\mathbf{2} : Q_3,\ \mathbf{1}'\ u_{3R} : \qquad \mathcal{M}_u = \frac{1}{\sqrt{2}} \begin{pmatrix} y^u_1 w^*_S + y^u_2 w^*_2 & y^u_2 w^*_1 & y^u_4 w^*_2 \\ y^u_2 w^*_1 & y^u_1 w^*_S - y^u_2 w^*_2 & -y^u_4 w^*_1 \\ y^u_5 w^*_2 & -y^u_5 w^*_1 & y^u_3 w^*_S \end{pmatrix},$$

$$\mathbf{1} : Q_3,\ \mathbf{1}' : u_{3R} : \qquad \mathcal{M}_u = \frac{1}{\sqrt{2}} \begin{pmatrix} y^u_1 w^*_S + y^u_2 w^*_2 & y^u_2 w^*_1 & y^u_4 w^*_2 \\ y^u_2 w^*_1 & y^u_1 w^*_S - y^u_2 w^*_2 & -y^u_4 w^*_1 \\ y^u_5 w^*_1 & y^u_5 w^*_2 & 0 \end{pmatrix}.$$

Appendix: Continuous Symmetries

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

Appendix: Dark Matter in S_3-Symmetric Three-Higgs-Doublet 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.

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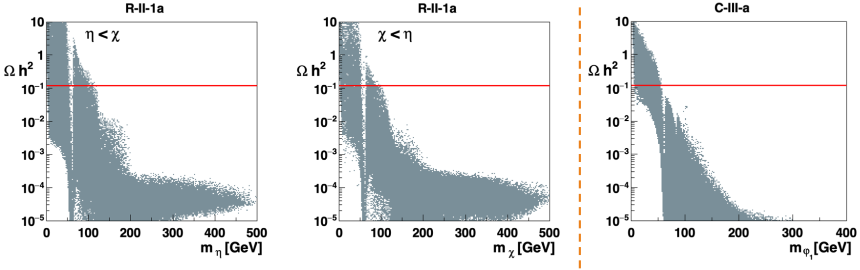
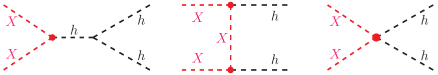
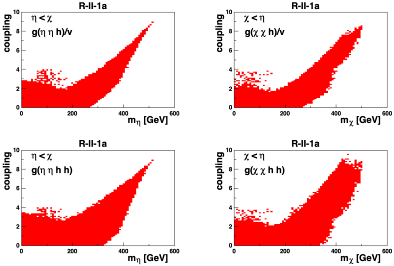


Scans performed using `micrOMEGAs` 5.3.35.





Trilinear and quartic couplings are not tuneable!

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

Appendix: SU(2) Doublets in Terms of the Mass Eigenstates

R-II-1a:

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

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

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

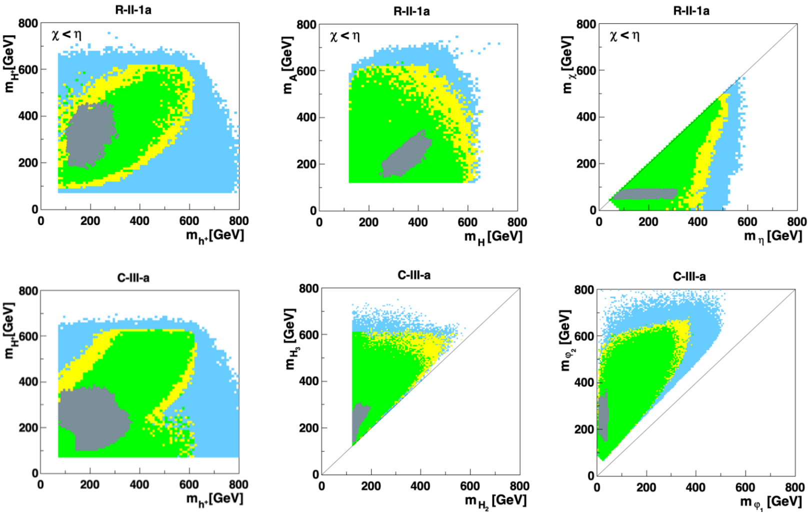
C-III-a:

$$h_1 = e^{i\gamma}\begin{pmatrix} h^+ \\ \frac{1}{\sqrt{2}}\left(\varphi_1 + i\varphi_2\right) \end{pmatrix},$$

$$h_2 = e^{i\sigma}\begin{pmatrix} \sin\beta\, G^+ - \cos\beta\, H^+ \\ \frac{1}{\sqrt{2}}\left(\sin\beta\, v + i\sin\beta\, G^0 + \sum_{i=1}^{3}\left[\sin\beta\,\mathcal{R}^0_{i1} - \cos\beta\,\left(\mathcal{R}^0_{i2} + i\mathcal{R}^0_{i3}\right)\right] H_i\right) \end{pmatrix},$$

$$h_S = \begin{pmatrix} \cos\beta\, G^+ + \sin\beta\, H^+ \\ \frac{1}{\sqrt{2}}\left(\cos\beta\, v + i\cos\beta\, G^0 + \sum_{i=1}^{3}\left[\cos\beta\,\mathcal{R}^0_{i1} + \sin\beta\,\left(\mathcal{R}^0_{i2} + i\mathcal{R}^0_{i3}\right)\right] H_i\right) \end{pmatrix}.$$

Appendix: Scalar Masses



Cut 1

Cut 2: 3 - σ

Cut 2: 2 - σ

Cut 3