

A 3HDM with possible two dark matter candidates

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arXiv:1907.12470 [hep-ph]
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First Mediterranean Conference on Higgs Physics



Shortcomings of SM and the need of BSM

No sign of New Physics at the LHC

- No viable DM candidate
- Insufficient amount of CP violation
- An unstable vacuum
- No explanation for the fermion mass hierarchy
- ...

Scalar extensions aiming to provide a solution:

- Higgs portal models: ϕ , S
- 2HDM: ϕ_1, ϕ_2
- IDM - I(1+1)HDM: ϕ_1, ϕ_2
- 3HDM - I(1+2)HDM: ϕ_1, ϕ_2, ϕ_3 , I(2+1)HDM: ϕ_1, ϕ_2, ϕ_3

Motivations to include more than one doublet

- The Higgs discovered in 2012 is compatible with the one predicted by SM
- Many theoretical reasons to have a non-minimal Higgs structure
- Both supersymmetric theories and axion models require two higgs doublets
- Additional sources of CPV
- Existence of FCNC (flavour-changing neutral currents), which can explain neutrino oscillation
- Can explain some *flavour problems*¹
- The IDMs offer proper dark matter candidates

¹ J.L. Diaz, J. Hernandez-Sanchez, S. Moretti, R. Noeriega-Papaqui, A. Rosado, Yukawa textures and charged Higgs boson phenomenology in the 2HDM-III, Phys. Rev. D79:095025. (2009)

3HDM · Motivations

- Richer symmetry groups than the 2HDMs
- Richer particle spectrum
- Possible update to 6HDM
- It resembles the 3 generation of fermions
- Different DM pheno: CPV-DM, multi-components, ...
- Two inert possibilities:
 - Two inert plus One Higgs doublet, $I(2+1)$ HDM
 - One inert plus Two Higgs doublets, $I(1+2)$ HDM
 - CPC and CPV versions

- * Amongst 2HDMs, the IDM has the advantage of including DM candidates
- * Characteristic: An unbroken Z_n symmetry is imposed²
 - Z_2 is the most studied, here we analyse Z_3
- * Is an example of the Higgs-portal DM models³

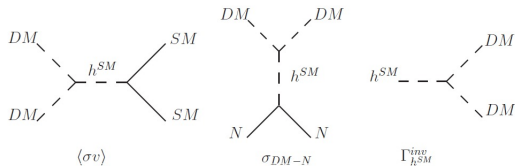


Figure: Higgs-portal Feynman diagrams. LEFT: DM annihilation produce SM particles (astrophysical observation). MIDDLE: nucleon-DM scattering (direct detection). RIGHT: Higgs decaying to DM pair (collider signature).

² I. P. Ivanov and V. Keus, Phys. Rev. D **86**, 016004 (2012) doi:10.1103/PhysRevD.86.016004 [arXiv:1203.3426 [hep-ph]].
³ B. Patt and F. Wilczek, hep-ph/0605188.

Scalar potential

The most general phase invariant part of a 3HDM potential is⁴

$$V_0 = -\mu_i^2(\Phi_i^\dagger\Phi_i) + \lambda_{ij}(\Phi_i^\dagger\Phi_i)(\Phi_j^\dagger\Phi_j) + \lambda'_{ij}(\Phi_i^\dagger\Phi_j)(\Phi_j^\dagger\Phi_i)$$

and, considering a Z_3 symmetry we add the terms:

$$V_{Z_3} = -\mu_{12}^2(\phi_1^\dagger\phi_2) + \lambda_1(\phi_2^\dagger\phi_1)(\phi_3^\dagger\phi_1) \\ + \lambda_2(\phi_1^\dagger\phi_2)(\phi_3^\dagger\phi_2) + \lambda_3(\phi_1^\dagger\phi_3)(\phi_2^\dagger\phi_3) + h.c.$$

where

$$g_{Z_3} = (1, 2, 0)$$

and

$$\Phi_\alpha = \begin{pmatrix} H_\alpha^\pm \\ \frac{1}{\sqrt{2}}(H_\alpha + iA_\alpha) \end{pmatrix}, \quad \alpha = 1, 2, 3$$

~~1, 2 are the *inerts* and 3 is the *active*~~

⁴V. Keus, S. F. King and S. Moretti, Phys. Rev. D **90**, no. 7, 075015 (2014) doi:10.1103/PhysRevD.90.075015 [arXiv:1408.0796 [hep-ph]].

Higgs physical states

- From active doublet: h_{SM} and $G^0(G^\pm)$ goldstones which gives massive $Z(W^\pm)$
- Two inert generations: (H_1, A_1, H_1^\pm) and (H_2, A_2, H_2^\pm) , the lightest of each doublet are the DM candidates
- ① The fields are rotated by

$$R_{\theta_i} = \begin{pmatrix} \cos \theta_i & \sin \theta_i \\ -\sin \theta_i & \cos \theta_i \end{pmatrix}, \quad \theta_i = \theta_h, \theta_c, \theta_a$$

$\theta_{h(c)(a)}$ rotation angle for the neutral (charged) (pseudo-scalar)

Mass spectrum

- $m_{H_1}^2 = (-\mu_1^2 + \Lambda_1) \cos^2 \theta_h + (-\mu_2^2 + \Lambda_2) \sin^2 \theta_h - 2\Lambda_h \sin \theta_h \cos \theta_h$
- $m_{H_2}^2 = (-\mu_1^2 + \Lambda_1) \sin^2 \theta_h + (-\mu_2^2 + \Lambda_2) \cos^2 \theta_h + 2\Lambda_h \sin \theta_h \cos \theta_h$
- $m_{A_1}^2 = (-\mu_1^2 + \Lambda_1) \cos^2 \theta_a + (-\mu_2^2 + \Lambda_2) \sin^2 \theta_a - 2\Lambda_a \sin \theta_a \cos \theta_a$
- $m_{A_2}^2 = (-\mu_1^2 + \Lambda_1) \sin^2 \theta_a + (-\mu_2^2 + \Lambda_2) \cos^2 \theta_a + 2\Lambda_a \sin \theta_a \cos \theta_a$
- $m_{H_1^\pm}^2 = (-\mu_1^2 + \Lambda'_1) \cos^2 \theta_c + (-\mu_2^2 + \Lambda'_2) \sin^2 \theta_c - 2\mu_{12}^2 \sin \theta_c \cos \theta_c$
- $m_{H_2^\pm}^2 = (-\mu_1^2 + \Lambda'_1) \sin^2 \theta_c + (-\mu_2^2 + \Lambda'_2) \cos^2 \theta_c + 2\mu_{12}^2 \sin \theta_c \cos \theta_c$

Dark democracy limit

We simplify the model⁵

$$\mu_1^2 = n\mu_2^2, \quad \lambda_3 = n\lambda_2, \quad \lambda_{31} = n\lambda_{23}, \quad \lambda'_{31} = n\lambda'_{23}$$

Note: if $\mu_{12}^2 = 0 \rightarrow$ mass degeneracy

Mass spectrum:

$$m_{H_1}^2 = (-\mu_2^2 + \Lambda_2)(n \cos^2 \theta_h + \sin^2 \theta_h) - 2\Lambda_h \sin \theta_h \cos \theta_h,$$
$$m_{H_2}^2 = (-\mu_2^2 + \Lambda_2)(n \sin^2 \theta_h + \cos^2 \theta_h) + 2\Lambda_h \sin \theta_h \cos \theta_h,$$

and the mixing angle for the CP-even inert scalars is given by

$$\tan 2\theta = \frac{-2\Lambda_h}{(n-1)(-\mu_2^2 + \Lambda_2)}.$$

For the CP-odd scalars and the charged scalars replace:

$$(\Lambda_h, \Lambda_2, \theta_h) \rightarrow (\Lambda_a, \Lambda'_2, \theta_a) \text{ and } (\Lambda_h, \Lambda_2, \theta_h) \rightarrow (\mu_{12}^2, \Lambda'_2, \theta_c).$$

⁵B. Grzadkowski, O. M. Ogreid, P. Osland, A. Pukhov and M. Purmohammadi, JHEP **1106**, 003 (2011)

Interaction	Coupling
$h H_1 H_1$	$-v((\lambda_{23} + \lambda'_{23})(s_{\theta_h}^2 + nc_{\theta_h}^2) - 2\lambda_3 c_{\theta_h} s_{\theta_h})$
$h H_1 H_2$	$v((\lambda_{23} + \lambda'_{23})(1 - n)c_{\theta_h} s_{\theta_h} - \lambda_3 c_{2\theta_h})$
$h H_2 H_2$	$-v((\lambda_{23} + \lambda'_{23})(ns_{\theta_h}^2 + c_{\theta_h}^2) + 2\lambda_3 c_{\theta_h} s_{\theta_h})$
$h H_1^\pm H_1^\mp$	$-v\lambda_{23}(s_{\theta_c}^2 + nc_{\theta_c}^2)$
$h H_1^\pm H_2^\mp$	$v\lambda_{23}(1 - n)c_{\theta_c} s_{\theta_c}$
$h H_2^\pm H_2^\mp$	$-v\lambda_{23}(c_{\theta_c}^2 + ns_{\theta_c}^2)$
$A_1 A_1 H_1$	$-v\lambda_2(nc_{\theta_a}(c_{\theta_a} s_{\theta_h} - 2c_{\theta_h} s_{\theta_a}) - s_{\theta_a}(s_{\theta_a} c_{\theta_h} - 2c_{\theta_a} s_{\theta_c}))$
$A_1 A_1 H_2$	$v\lambda_2(nc_{\theta_a}(c_{\theta_a} c_{\theta_h} + 2s_{\theta_a} s_{\theta_h}) + s_{\theta_a}(s_{\theta_a} s_{\theta_h} + 2c_{\theta_a} c_{\theta_h}))$
$A_1 A_2 H_1$	$-v\lambda_2(n(c_{\theta_a} s_{\theta_a} s_{\theta_h} + c_{2\theta_a} c_{\theta_h}) + (c_{\theta_a} s_{\theta_a} c_{\theta_h} - c_{2\theta_a} s_{\theta_h}))$
$A_1 A_2 H_2$	$v\lambda_2(n(c_{\theta_a} c_{\theta_h} s_{\theta_a} - c_{2\theta_a} s_{\theta_h}) - (c_{\theta_a} s_{\theta_a} s_{\theta_h} + c_{2\theta_a} c_{\theta_h}))$
$A_2 A_2 H_1$	$-v\lambda_2(ns_{\theta_a}(s_{\theta_a} s_{\theta_h} + 2c_{\theta_a} c_{\theta_h}) - c_{\theta_a}(c_{\theta_a} c_{\theta_h} + 2s_{\theta_a} s_{\theta_h}))$
$A_2 A_2 H_2$	$v\lambda_2(ns_{\theta_a}(s_{\theta_a} c_{\theta_h} - 2c_{\theta_a} s_{\theta_h}) + c_{\theta_a}(c_{\theta_a} s_{\theta_h} - 2s_{\theta_a} c_{\theta_h}))$
$H_1 H_1 H_1$	$3v\lambda_2(nc_{\theta_h} - s_{\theta_h})s_{\theta_h} c_{\theta_h}$
$H_1 H_1 H_2$	$-v\lambda_2(nc_{\theta_h}(1 - 3s_{\theta_h}^2) - s_{\theta_h}(2 - 3s_{\theta_h}^2))$
$H_1 H_2 H_2$	$-v\lambda_2(ns_{\theta_h}(2 - 3s_{\theta_h}^2) + c_{\theta_h}(1 - 3s_{\theta_h}^2))$
$H_2 H_2 H_2$	$-3v\lambda_2(ns_{\theta_h} + c_{\theta_h})s_{\theta_h} c_{\theta_h}$

The $n = 1$ case

Interaction	Coupling	Interaction	Coupling
$h H_1 H_1$	$-v(\lambda_{23} + \lambda'_{23} - \lambda_3)$	$H_1 H_1 H_1$	0
$h H_1 H_2$	0	$H_1 H_1 H_2$	$\frac{1}{\sqrt{2}}v\lambda_2$
$h H_2 H_2$	$-v(\lambda_{23} + \lambda'_{23} + \lambda_3)$	$H_1 H_2 H_2$	0
$h H_{1,2}^\pm H_{1,2}^\pm$	$-v\lambda_{23}$	$H_2 H_2 H_2$	$-\frac{3}{\sqrt{2}}v\lambda_2$
$A_1 A_1 H_1$	0	$H_1 H_{1,2}^\pm H_{1,2}^\mp$	0
$A_1 A_1 H_2$	$\frac{3}{\sqrt{2}}v\lambda_2$	$H_2 H_1^\pm H_1^\mp$	$\pm \frac{v}{\sqrt{2}}\lambda_2$
$A_1 A_2 H_1$	$-\frac{1}{\sqrt{2}}v\lambda_2$	$A_1 H_{1,2}^\pm H_{2,1}^\mp$	$\mp i \frac{v}{\sqrt{2}}\lambda_2$
$A_1 A_2 H_2$	0	$A_2 H_1^\pm H_2^\mp$	0
$A_2 A_2 H_1$	0		
$A_2 A_2 H_2$	$-\frac{1}{\sqrt{2}}v\lambda_2$		

Note that in in this case the model is $Z_3 \times Z'_3$ symmetric.

Simplified mass spectrum

If $\theta_h = \theta_a = \theta_c = \frac{\pi}{4}$,

$$m_{H_1}^2 = \frac{1}{2}v^2(\lambda_{23} + \lambda'_{23} + \lambda_3) - \mu_{12}^2 - \mu_2^2,$$

$$m_{A_1}^2 = \frac{1}{2}v^2(\lambda_{23} + \lambda'_{23} - \lambda_3) - \mu_{12}^2 - \mu_2^2,$$

$$m_{H_2}^2 = \frac{1}{2}v^2(\lambda_{23} + \lambda'_{23} - \lambda_3) + \mu_{12}^2 - \mu_2^2,$$

$$m_{A_2}^2 = \frac{1}{2}v^2(\lambda_{23} + \lambda'_{23} + \lambda_3) + \mu_{12}^2 - \mu_2^2,$$

$$m_{H_1^\pm}^2 = \frac{1}{2}v^2\lambda_{23} - \mu_{12}^2 - \mu_2^2,$$

$$m_{H_2^\pm}^2 = \frac{1}{2}v^2\lambda_{23} + \mu_{12}^2 - \mu_2^2.$$

If $\theta_i \rightarrow -\pi/4 \Rightarrow m_{i_1} \rightarrow m_{i_2}$.

Note that in the dark democracy limit **the two DM candidates always have opposite CP charge**. This can be seen explicitly from using mass formulae to get the mass relations as

$$\begin{aligned}m_{A_1}^2 &= m_{H_2}^2 - m_{H_2^\pm}^2 + m_{H_1^\pm}^2, \\m_{A_2}^2 &= m_{H_1}^2 + m_{H_2^\pm}^2 - m_{H_1^\pm}^2.\end{aligned}$$

Then, if $H_{1(2)}$ is the lightest inert scalar, the second lightest is $A_{1(2)}$ and, if $A_{1(2)}$ is the lightest, the second lightest is $H_{1(2)}$.

Input parameters

We can rewrite the Lagrangian parameters by using the mass eigenvalues and a dimensionless parameter $g_{\text{DM}} = \lambda_{23} + \lambda'_{23} - \lambda_3$

$$\mu_2^2 = -m_{H_2}^2 + \frac{\Delta_+}{2} + \frac{v^2}{2} g_{\text{DM}}, \quad \mu_{12}^2 = \frac{\Delta_+}{2},$$
$$\lambda_{23} = \frac{2\Delta_2}{v^2} + g_{\text{DM}}, \quad \lambda'_{23} = -\frac{\Delta_1 + \Delta_2}{v^2}, \quad \lambda_3 = \frac{\Delta_2 - \Delta_1}{v^2},$$

where

$$\Delta_1 = m_{H_1^\pm}^2 - m_{H_1}^2, \quad \Delta_2 = m_{H_2^\pm}^2 - m_{H_2}^2, \quad \Delta_+ = m_{H_2^\pm}^2 - m_{H_1^\pm}^2.$$

- Base input parameters

$$m_{H_1}, m_{H_2}, m_{H_1^\pm}, m_{H_2^\pm}, \text{DM}.$$

- DM input parameters

$$\lambda_{11}, \lambda_{22}, \lambda_{12}, \lambda'_{12}, \lambda_2.$$

Constraints on parameters

- If the 3rd doublet is SM-like:

$$m_h^2 = 2\mu_3^2 = 2\lambda_{33}v^2.$$

- Boundedness of the potential⁶:

- $\lambda_{11}, \lambda_{22}, \lambda_{33} > 0$

- $\lambda_{12} + \lambda'_{12} > -2\sqrt{\lambda_{11}\lambda_{22}}$

- $\lambda_{23} + \lambda'_{23} > -2\sqrt{\lambda_{22}\lambda_{33}}$

- $\lambda_{31} + \lambda'_{31} > -2\sqrt{\lambda_{33}\lambda_{11}}$

- $|\lambda_2|, |\lambda_3| < |\lambda_{ii}|, |\lambda_{ij}|, |\lambda'_{ij}|, \quad i \neq j = 1, 2, 3$

- Positive-definiteness of Hessian:

- $\left(-\mu_2^2 + (\lambda_{23} + \lambda'_{23})\frac{v^2}{2}\right)^2 > |\mu_{12}^2|^2$

⁶V. Keus, S. F. King and S. Moretti, Phys. Rev. D **90**, no. 7, 075015 (2014) doi:10.1103/PhysRevD.90.075015 [arXiv:1408.0796 [hep-ph]].

Constraints on parameters

- LEP limits

- $m_{H_i^\pm} + m_{H_i, A_i} > m_{W^\pm}$
- $m_{H_i} + m_{A_i} > m_Z$
- $2m_{H_i^\pm} > m_Z$
- $m_{H_i^\pm} > 70 - 90 \text{ GeV}$
- $m_A - m_H > 8 \text{ GeV}$ if $(m_H < 80\text{GeV}, m_A < 100\text{GeV})$

- Invisible decays

$$\text{BR}(h \rightarrow \text{inv}) = \frac{\sum_{i,j} \Gamma(h \rightarrow S_i S_j)}{\Gamma_h^{\text{SM}} + \sum_{i,j} \Gamma(h \rightarrow S_i S_j)},$$

where $S_i S_j = A_1 H_2$ or $H_2 A_1$.

ATLAS & CMS: $\text{BR}(h \rightarrow \text{inv}) < 0.23 - 0.36$

then $\lambda \lesssim 0.02$ for masses $m_{H_1} \lesssim m_h/2$.

Relic abundance: semi-annihilation

- **DM semi-annihilation:** $S_2 S_2 \rightarrow h S_1$ where $S = H, A$.
Affected by λ_2 .
- **Partial DM conversion:**
 $S_2 S_2 \rightarrow S_2 S_1$ where $S = H, A$. Affected by $\lambda_{11} - \lambda_{22}$.
- **Total DM conversion:**
 $S_2 S_2 \rightarrow S_1 S_1$ where $S = H, A$. Affected by $(\lambda_{11} + \lambda_{22})$ and $(\lambda_{12} + \lambda'_{12})$.

DM conversion

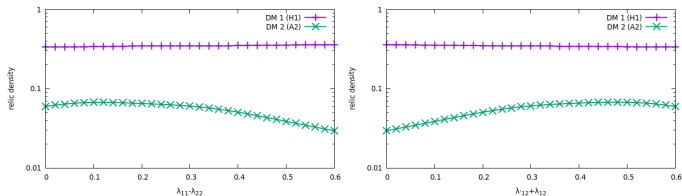


Figure: The first plot shows the effect of $\lambda_{11} - \lambda_{22}$ (via partial DM conversion) and the second that of $\lambda_{12} + \lambda'_{12}$ (via total DM conversion) on the relic density. Here, $m_{H_1} = 74$ GeV, $m_{H_2} = 96$ GeV, $m_{H_1^\pm} = 108$ GeV, $m_{H_2^\pm} = 110$ GeV, $\lambda_2 = -0.25$ and $g_{\text{DM}} = -0.001$. Neither of these scenarios is actually viable.

Semi-annihilation

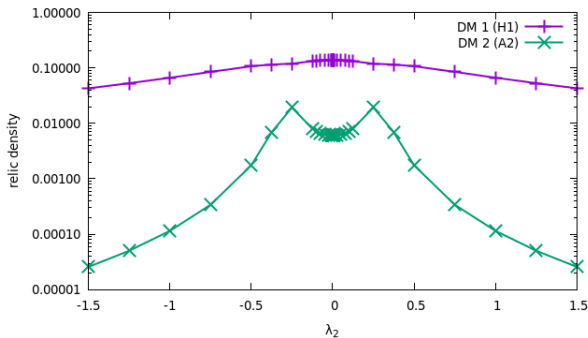
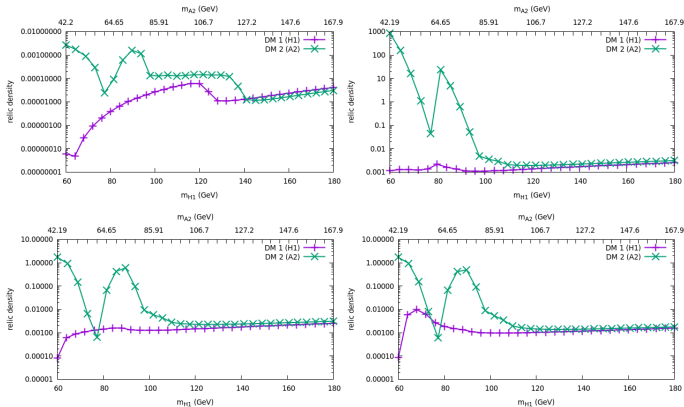


Figure: This plot shows the effect of λ_2 (via DM semi-annihilation) on the relic density. Here, $m_{H_1} = 76$ GeV, $m_{H_2} = 98$ GeV, $m_{H_1^\pm} = 110$ GeV, $m_{H_2^\pm} = 112$ GeV, $\lambda_{11} = \lambda_{22} = \lambda_{12} = \lambda'_{12} = 0.3$ and $g_{\text{DM}} = -0.001$. Note that the contribution of the two DM candidates is comparable within the region $-0.25 \leq \lambda_2 \leq 0.25$.

Non-degenerate scenario

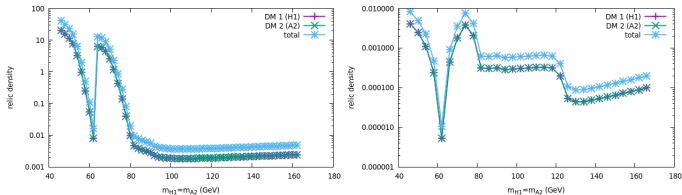
$$m_{H_2} - m_{H_1} = 17 \text{ GeV}, m_{H_2^\pm} - m_{H_2} = 9 \text{ GeV}, m_{H_1^\pm} - m_{H_1} = 36 \text{ GeV}$$



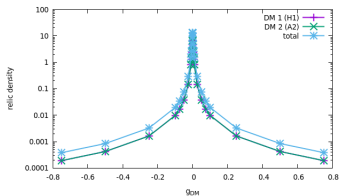
$\lambda_2 = 0.0001$ on the top with $g_{DM} = -1.5$ (right) and -0.001 (left).
 $g_{DM} = -0.05$ at the bottom with $\lambda_2 = 0.0001$ (left) and $\lambda_2 = -0.25$ (right).

Charged degeneracy scenario

$$m_{H_2} - m_{H_1} = 22 \text{ GeV}, m_{H_2^\pm} - m_{H_2} = 12 \text{ GeV}, m_{H_1^\pm} - m_{H_1} = 34 \text{ GeV}.$$



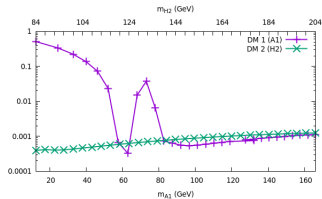
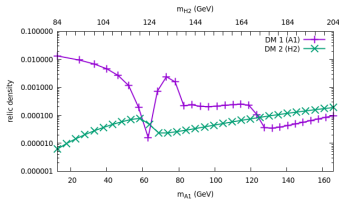
$g_{DM} = -0.001$ (left) and -1.0 (right), with $\lambda_2 = -0.25$.



Dependence of the relic density on the parameter g_{DM} for $m_{DM} = 64 \text{ GeV}$.

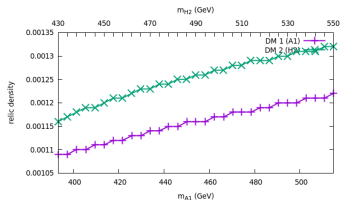
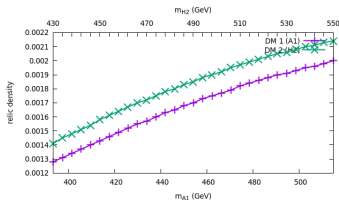
- CP-even degeneracy scenario

$$m_{H_1} - m_{H_2} = 0, m_{H_2^\pm} - m_{H_2} = 46 \text{ GeV}, m_{H_1^\pm} - m_{H_1} = 16 \text{ GeV}.$$



- Heavy dark matter

$$m_{H_2} - m_{H_1} = 30 \text{ GeV}, m_{H_2^\pm} - m_{H_2} = 90 \text{ GeV}, m_{H_1^\pm} - m_{H_1} = 90 \text{ GeV}.$$



Lifting slightly the degeneracy

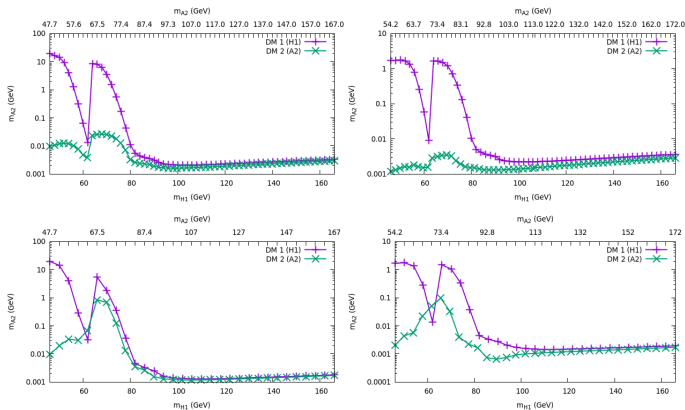


Figure: In these plots we show the relic density for a scenario where the mass difference between the two charged inerts is 1 GeV (left) and 5 GeV (right). In the upper plots $\lambda_2 = 0.0001$ and in the lower plots $\lambda_2 = -0.25$.

Lifting slightly the degeneracy

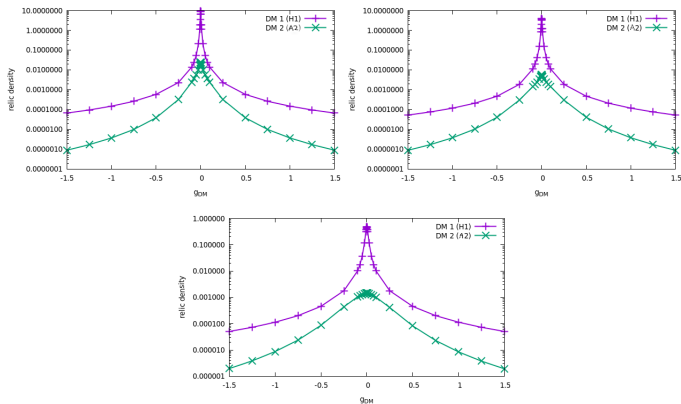


Figure: In these plots we show the relic density dependence when we change the mass difference of the charged masses. The mass difference is 1 GeV in the first, 3 GeV in the second and 8 GeV in the third (clock-wise).

DM constraints · Indirect detection

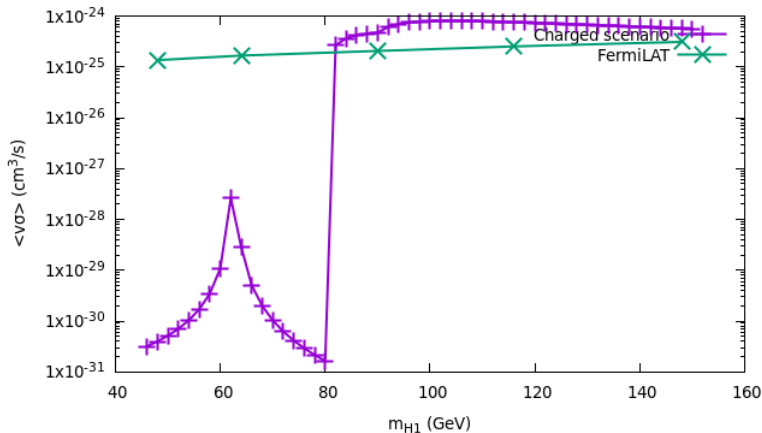


Figure: The charged degeneracy scenario against the indirect detection cross section limits from FermiLAT. Only the mass region below 80 GeV is in accordance with the results from FermiLAT.

DM constraints · Direct detection

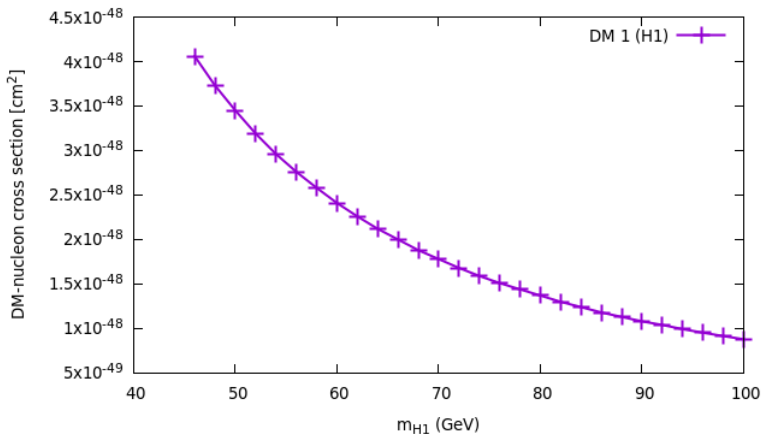


Figure: In this plot we show the DM-nucleon cross section for the scenario where the charged mass difference is 5 GeV and $g_{\text{DM}} = -0.001$. As this plot shows, this scenario is in accordance with the results from LUX and

Summary

- We studied a 3HDM with two generations of inert doublets, the $I(2+1)$ HDM
- The possible symmetries of the 3HDM have been identified and it is interesting to explore different DM pheno
- In inert models the Z_2 symmetry has been the most studied, here we analysed the Z_3 symmetric case
- In the case of highly symmetric potential and assigning different charges the lightest particle from each doublet becomes stable
- The two DM candidates have opposite CP charge
- Both candidates contribute to the total relic density if a(n approximate) mass degeneracy exists
- All such a dynamics has been obtained in presence of known (in)direct constraints on DM, EWPOs and collider data
- Is there any peculiar signature to study at the LHC?

Thanks for
your attention!