A 3HDM with possible two dark matter candidates

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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

IDM

* Amongst 2HDMs, the IDM has the advantage of including DM candidates
* Characteristic: An unbroken Z_n symmetry is imposed[2]
    - Z_2 is the most studied, here we analyse Z_3
* Is an example of the Higgs-portal DM models[3]

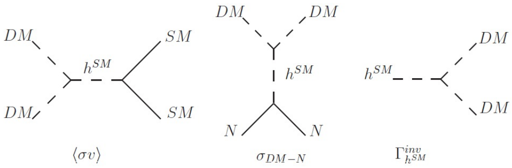


Figure: Higgs-portal Feynman diagrams. LEFT: DM annihilation produce SM particles (astrophysical observation). MIDDLE: nucleon-DM scattering (direct detection). RIGHT: Higgs decaying to DM pair (collider signature).

[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 is[4]

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

and, considering a Z_3 symmetry we add the terms:

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

where

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

and

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

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

[4] V. 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]].

I(2+1)HDM (CPC) Higgs sector

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

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

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

Mass spectrum

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

Dark democracy limit

We simplify the model[5]

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

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

Mass spectrum:

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

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:

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

[5] B. Grzadkowski, O. M. Ogreid, P. Osland, A. Pukhov and M. Purmohammadi, JHEP **1106**, 003 (2011) doi:10.1007/JHEP06(2011)003 [arXiv:1012.4680 [hep-ph]].

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

The $n = 1$ case

Interaction	Coupling	Interaction	Coupling
$h\ H_1\ H_1$	$-v\left(\lambda_{23} + \lambda'_{23} - \lambda_3\right)$	$H_1\ H_1\ H_1$	0
$h\ H_1\ H_2$	0	$H_1\ H_1\ H_2$	$\frac{1}{\sqrt{2}} v \lambda_2$
$h\ H_2\ H_2$	$-v\left(\lambda_{23} + \lambda'_{23} + \lambda_3\right)$	$H_1\ H_2\ H_2$	0
$h\ H^{\pm}_{1,2}\ H^{\pm}_{1,2}$	$-v\lambda_{23}$	$H_2\ H_2\ H_2$	$-\frac{3}{\sqrt{2}} v \lambda_2$
$A_1\ A_1\ H_1$	0	$H_1\ H^{\pm}_{1,2}\ H^{\mp}_{1,2}$	0
$A_1\ A_1\ H_2$	$\frac{3}{\sqrt{2}} v \lambda_2$	$H_2\ H^{\pm}_1\ H^{\mp}_1$	$\pm\frac{v}{\sqrt{2}}\lambda_2$
$A_1\ A_2\ H_1$	$-\frac{1}{\sqrt{2}} v \lambda_2$	$A_1\ H^{\pm}_{1,2}\ H^{\mp}_{2,1}$	$\mp i \frac{v}{\sqrt{2}}\lambda_2$
$A_1\ A_2\ H_2$	0	$A_2\ H^{\pm}_1\ H^{\mp}_2$	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 $\theta_i \to -\pi/4 \Rightarrow m_{i_1} \to m_{i_2}$.

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

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

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 $g_{\rm DM} = \lambda_{23} + \lambda'_{23} - \lambda_3$

$$\mu_2^2 = -m_{H_2}^2 + \frac{\Delta_+}{2} + \frac{v^2}{2} g_{\rm DM}\,, \quad \mu_{12}^2 = \frac{\Delta_+}{2}\,,$$

$$\lambda_{23} = \frac{2\Delta_2}{v^2} + g_{\rm DM}\,, \quad \lambda'_{23} = -\frac{\Delta_1 + \Delta_2}{v^2}\,, \quad \lambda_3 = \frac{\Delta_2 - \Delta_1}{v^2}\,,$$

where

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

- Base input parameters

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

- DM input parameters

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

Contraints on parameters

- If the 3rd doublet is SM-like:

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

- Boundedness of the potential[6]:

$$\bullet \quad \lambda_{11}, \lambda_{22}, \lambda_{33} > 0$$
$$\bullet \quad \lambda_{12} + \lambda'_{12} > -2\sqrt{\lambda_{11}\lambda_{22}}$$
$$\bullet \quad \lambda_{23} + \lambda'_{23} > -2\sqrt{\lambda_{22}\lambda_{33}}$$
$$\bullet \quad \lambda_{31} + \lambda'_{31} > -2\sqrt{\lambda_{33}\lambda_{11}}$$
$$\bullet \quad |\lambda_2|, |\lambda_3| < |\lambda_{ii}|, |\lambda_{ij}|, |\lambda'_{ij}|, \quad i \neq j = 1, 2, 3$$

- Positive-definiteness of Hessian:

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

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

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

where $S_i S_j = A_1 H_2$ or $H_2 A_1$.
ATLAS & CMS: $\text{BR}(h \to \text{inv}) < 0.23 - 0.36$
then $\lambda \lesssim 0.02$ for masses $m_{H_1} \lesssim m_h/2$.

Relic abundance: semi-annihilation

- DM semi-annihilation: $S_2 S_2 \to h S_1$ where $S = H, A$. Affected by λ_2.

- Partial DM conversion: $S_2 S_2 \to S_2 S_1$ where $S = H, A$. Affected by $\lambda_{11} - \lambda_{22}$.

- Total DM conversion: $S_2 S_2 \to S_1 S_1$ where $S = H, A$. Affected by $(\lambda_{11} + \lambda_{22})$ and $(\lambda_{12} + \lambda'_{12})$.

DM conversion

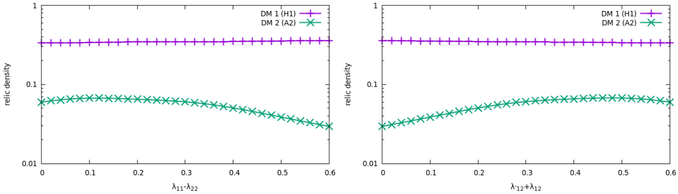


Figure: The first plot shows the effect of $\lambda_{11} - \lambda_{22}$ (via partial DM conversion) and the second that of $\lambda_{12} + \lambda'_{12}$ (via total DM conversion) on the relic density. Here, $m_{H_1} = 74$ GeV, $m_{H_2} = 96$ GeV, $m_{H_1^\pm} = 108$ GeV, $m_{H_2^\pm} = 110$ GeV, $\lambda_2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

Semi-annihilation

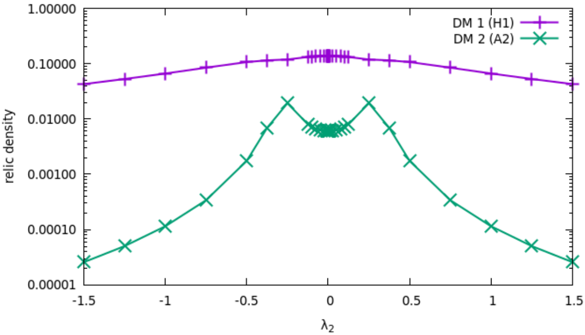
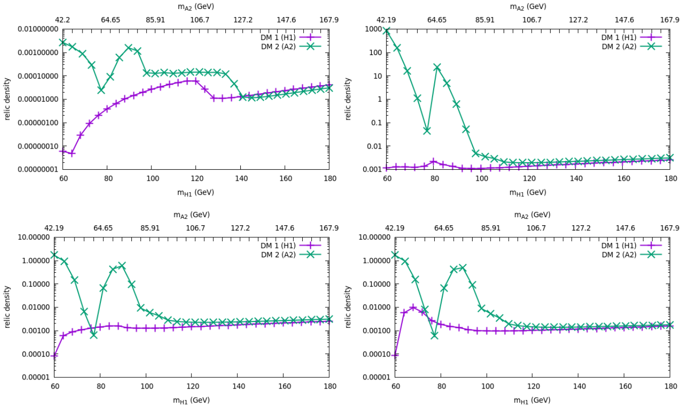


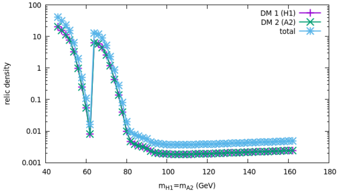
Figure: This plot shows the effect of λ_2 (via DM semi-annihilation) on the relic density. Here, $m_{H_1} = 76$ GeV, $m_{H_2} = 98$ GeV, $m_{H_1^\pm} = 110$ GeV, $m_{H_2^\pm} = 112$ GeV, $\lambda_{11} = \lambda_{22} = \lambda_{12} = \lambda'_{12} = 0.3$ and $g_{\mathrm{DM}} = -0.001$. Note that the contribution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

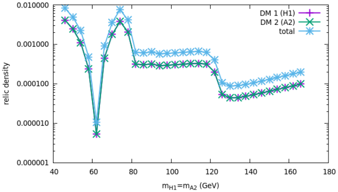
Non-degenerate scenario
$m_{H_2} - m_{H_1} = 17$ GeV, $m_{H_2^\pm} - m_{H_2} = 9$ GeV, $m_{H_1^\pm} - m_{H_1} = 36$ GeV



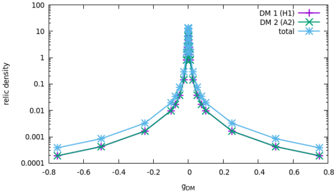
$\lambda_2 = 0.0001$ on the top with $g_{\rm DM} = -1.5$ (right) and -0.001 (left). $g_{\rm DM} = -0.05$ at the bottom with $\lambda_2 = 0.0001$ (left) and $\lambda_2 = -0.25$ (right).

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





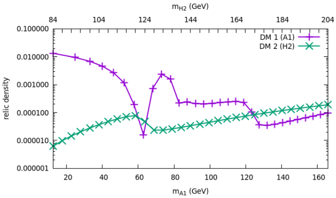
$g_{\rm DM} = -0.001$ (left) and -1.0 (right), with $\lambda_2 = -0.25$.

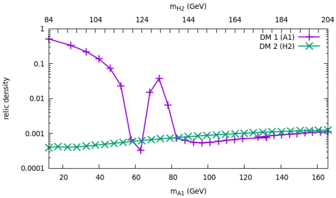


Dependence of the relic density on the parameter $g_{\rm DM}$ for $m_{\rm DM} = 64$ GeV.

- ## CP-even degeneracy scenario

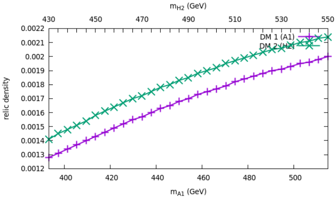
$$m_{H_1} - m_{H_2} = 0,\ m_{H_2^\pm} - m_{H_2} = 46 \text{ GeV},\ m_{H_1^\pm} - m_{H_1} = 16 \text{ GeV}.$$

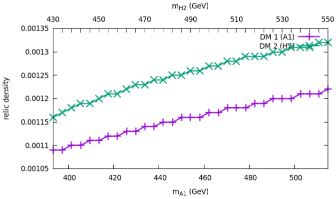




- ## Heavy dark matter

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





Lifting slightly the degeneracy

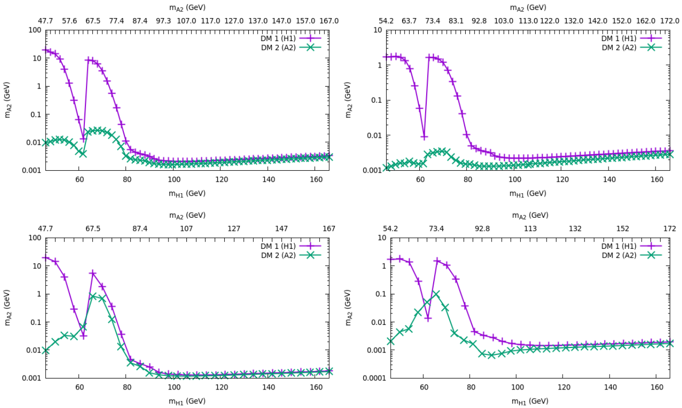


Figure: In these plots we show the relic density for a scenario where the mass difference between the two charged inerts is 1 GeV (left) and 5 GeV (right). In the upper plots $\lambda_2 = 0.0001$ and in the lower plots $\lambda_2 = -0.25$.

Lifting slightly the degeneracy

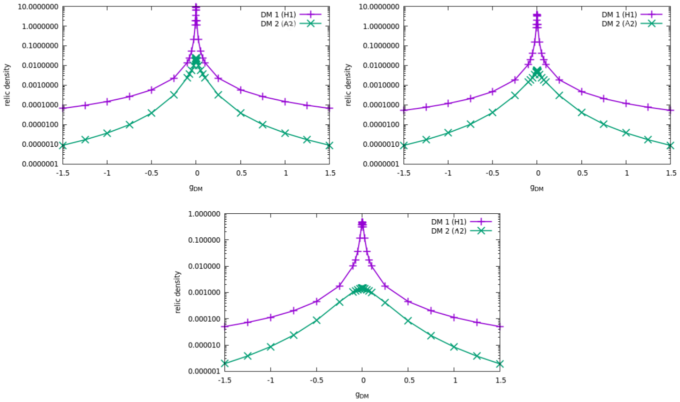


Figure: In these plots we show the relic density dependence when we change the mass difference of the charged masses. The mass difference is 1 GeV in the first, 3 GeV in the second and 8 GeV in the third (clock-wise).

DM constraints · Indirect detection

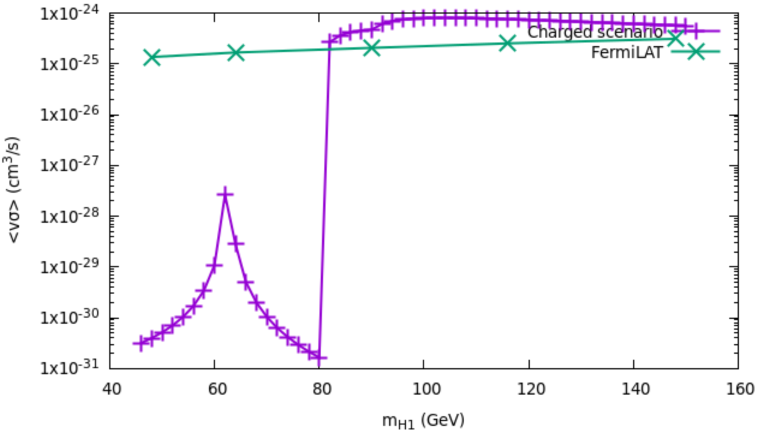


Figure: The charged degeneracy scenario against the indirect detection cross section limits from FermiLAT. Only the mass region below 80 GeV is in accordance with the results from FermiLAT.

DM constraints · Direct detection

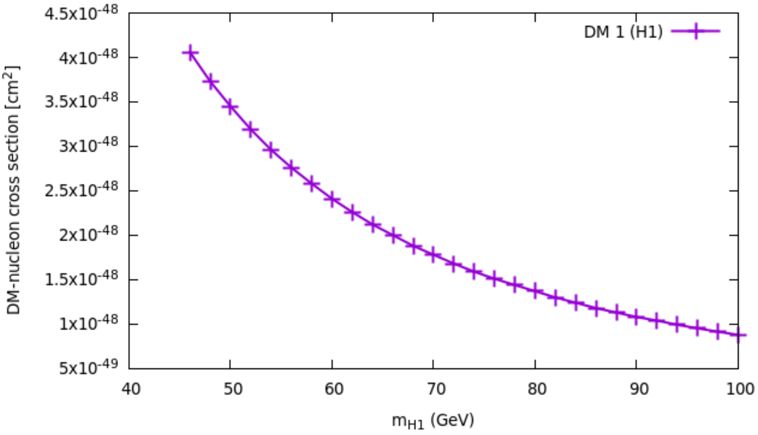


Figure: In this plot we show the DM-nucleon cross section for the scenario where the charged mass difference is 5 GeV and $g_{\rm DM} = -0.001$. As this plot shows, this scenario is in accordance with the results from LUX and

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!