Dark matter in the Z_3 I(2+1)HDM

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The I(2+1)HDM history:

V. Keus, S.F. King, S. Moretti, D. Sokolowska

- * Constraints and DM phenomenology [JHEP 1401 (2014) 051],[Phys.Rev.D 90,075015 (2014)]
- * Heavy DM [JHEP 1511 (2015) 003]

A. Cordero, J. Hernández-Sánchez, V. Keus, S.F. King, S. Moretti, D. Rojas-Ciofalo, D. Sokolowska

- * CP Violation [JHEP 1612 (2016) 014]
- * LHC signatures [JHEP 1805 (2018) 030]
- * Work in progress (lepton collider signatures, CP invariants)

Z_3 Dark Matter

- The stability of DM is guaranteed by residual Z_N symmetry
- Z_2 has been widely studied but $N > 2$ is also interesting
- Z_3 models in the literature:
  - supersymmetric models
  - extra dimensions
  - vector DM models
  - many other
- New DM processes appear:
  - semiannihilation
  - DM conversion

Some remarks

- Just starting the project
- Not any result yet
- We are testing the parameter space to obtain a good relic density

The Z_3 I(2+1)HDM

The most general phase invariant part of a 3HDM potential is[1]

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

and, considering an unbroken Z_3 symmetry we add the terms:

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

where

$$g_{Z_2} = (1, 2, 0)$$

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 *inert* doublets and 3 is the *active*

[1] 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]].

Mass eigenstates: neutral sector

$$
\begin{aligned}
m_{H_1}^2 &= (-\mu_1^2+\Lambda_1)\cos^2\theta_h + (-\mu_2^2+\Lambda_2)\sin^2\theta_h - \Lambda_h \sin\theta_h\cos\theta_h \\
m_{H_2}^2 &= (-\mu_1^2+\Lambda_1)\sin^2\theta_h + (-\mu_2^2+\Lambda_2)\cos^2\theta_h + \Lambda_h \sin\theta_h\cos\theta_h \\
m_{A_1}^2 &= (-\mu_1^2+\Lambda_1)\cos^2\theta_a + (-\mu_2^2+\Lambda_2)\sin^2\theta_a - \Lambda_a \sin\theta_a\cos\theta_a \\
m_{A_2}^2 &= (-\mu_1^2+\Lambda_1)\sin^2\theta_a + (-\mu_2^2+\Lambda_2)\cos^2\theta_a + \Lambda_a \sin\theta_a\cos\theta_a
\end{aligned}
$$

where:

$$
\Lambda_1 = \frac{1}{2}(\lambda_{31}+\lambda'_{31})v^2, \qquad \Lambda_2 = \frac{1}{2}(\lambda_{23}+\lambda'_{23})v^2,
$$

$$
\Lambda_h = \mu_{12}^2 - \frac{1}{2}\lambda_3 v^2, \qquad \Lambda_a = \mu_{12}^2 + \frac{1}{2}\lambda_3 v^2
$$

$$
\tan 2\theta_{h,a} = \frac{2\Lambda_{h,a}}{\mu_1^2 - \Lambda_1 - \mu_2^2 + \Lambda_2} \tag{1}
$$

Mass eigenstates: charged sector

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

where:

$$\Lambda_1' = \frac{1}{2}\lambda_{31} v^2, \qquad \Lambda_2' = \frac{1}{2}\lambda_{23} v^2 \tag{2}$$

$$\tan 2\theta_c = \frac{2\mu_{12}^2}{\mu_1^2 - \Lambda_1' - \mu_2^2 + \Lambda_2'} \tag{3}$$

Inert couplings

	Variational derivative of Lagrangian by fields
$h\ H_1\ H_1$	$-v\big((\lambda_{23}+\lambda'_{23})s_{\theta_c}{}^2+(\lambda_{31}+\lambda'_{31})c_{\theta_h}{}^2-2\lambda_3 c_{\theta_h}s_{\theta_c}\big)$
$h\ H_1\ H_2$	$v\big((\lambda_{23}+\lambda'_{23}+\lambda_{31}+\lambda'_{31})c_{\theta_c}s_{\theta_c}-\lambda_3 c_{2\theta_c}\big)$
$h\ H_2\ H_2$	$-v\big((\lambda_{23}+\lambda'_{23})c_{\theta_c}{}^2+(\lambda_{31}+\lambda'_{31})s_{\theta_h}{}^2+2\lambda_3 c_{\theta_h}s_{\theta_c}\big)$
$A_1\ A_1\ H_1$	$-v\big(\lambda_1 c_{\theta_a}(c_{\theta_a}s_{\theta_c}-2c_{\theta_h}s_{\theta_a})-\lambda_2 s_{\theta_a}(s_{\theta_a}c_{\theta_h}-2c_{\theta_a}s_{\theta_c})\big)$
$A_1\ A_1\ H_2$	$v\big(\lambda_1 c_{\theta_a}(c_{\theta_a}c_{\theta_h}+2s_{\theta_a}s_{\theta_c})+\lambda_2 s_{\theta_a}(s_{\theta_a}s_{\theta_c}+2c_{\theta_a}c_{\theta_h})\big)$
$A_1\ A_2\ H_1$	$-v\big(\lambda_1(c_{\theta_a}s_{\theta_a}s_{\theta_c}+c_{2\theta_a}c_{\theta_h})+\lambda_2(c_{\theta_a}s_{\theta_a}c_{\theta_h}-c_{2\theta_a}s_{\theta_c})\big)$
$A_1\ A_2\ H_2$	$v\big(\lambda_1(c_{\theta_a}c_{\theta_h}s_{\theta_a}-c_{2\theta_a}s_{\theta_c})-\lambda_2(c_{\theta_a}s_{\theta_a}s_{\theta_c}+c_{2\theta_a}c_{\theta_h})\big)$
$A_2\ A_2\ H_1$	$-v\big(\lambda_1 s_{\theta_a}(s_{\theta_a}s_{\theta_c}+2c_{\theta_a}c_{\theta_h})-\lambda_2 c_{\theta_a}(c_{\theta_a}c_{\theta_h}+2s_{\theta_a}s_{\theta_c})\big)$
$A_2\ A_2\ H_2$	$v\big(\lambda_1 s_{\theta_a}(s_{\theta_a}c_{\theta_h}-2c_{\theta_a}s_{\theta_c})+\lambda_2 c_{\theta_a}(c_{\theta_a}s_{\theta_c}-2s_{\theta_a}c_{\theta_h})\big)$
$H_1\ H_1\ H_1$	$3v\big(\lambda_1 c_{\theta_h}-\lambda_2 s_{\theta_c}\big)s_{\theta_c}c_{\theta_h}$
$H_1\ H_1\ H_2$	$-v\big(\lambda_1 c_{\theta_h}(1-3s^2_{\theta_c})-\lambda_2 s_{\theta_c}(2-3s^2_{\theta_c})\big)$
$H_1\ H_2\ H_2$	$-v\big(\lambda_1 s_{\theta_c}(2-3s^2_{\theta_c})+\lambda_2 c_{\theta_h}(1-3s^2_{\theta_c})\big)$
$H_2\ H_2\ H_2$	$-3v\big(\lambda_1 s_{\theta_c}+\lambda_2 c_{\theta_h}\big)s_{\theta_c}c_{\theta_h}$

Dark democracy limit

We assume

$$\mu_1^2 = n\mu_2^2, \qquad \lambda_{31} = n\lambda_{23}, \qquad \lambda'_{31} = n\lambda'_{23}, \qquad \lambda_1 = n\lambda_2, \quad (4)$$

resulting in

$$\Lambda_1 = n\Lambda_2, \qquad \Lambda'_1 = n\Lambda'_2. \quad (5)$$

The masses are then simplified to

$$\begin{aligned} m_{H_1}^2 &= (-\mu_2^2 + \Lambda_2)(n\cos^2\theta_h + \sin^2\theta_h) - \Lambda_h \sin\theta_h \cos\theta_h \\ m_{H_2}^2 &= (-\mu_2^2 + \Lambda_2)(n\sin^2\theta_h + \cos^2\theta_h) - \Lambda_h \sin\theta_h \cos\theta_h \end{aligned} \quad (6)$$

with the CP-even mixing angle given by

$$\tan 2\theta = \frac{-2\Lambda_h}{(n-1)(\Lambda_2 - \mu_2^2)}, \quad (7)$$

$m_{A_1}^2, m_{A_2}^2$ and $m_{H_1^\pm}^2, m_{H_2^\pm}^2$, have similar values with Λ_h, Λ_2 replaced by $\Lambda_a, \mu_{12}^2, \Lambda'_2$ and θ_a, θ_c respectively.

	Variational derivative of Lagrangian by fields
$h\ H_1\ H_1$	$-v\left((\lambda_{23}+\lambda'_{23})({s_{\theta_c}}^2+n{c_{\theta_c}}^2)-2\lambda_3 c_{\theta_h}s_{\theta_c}\right)$
$h\ H_1\ H_2$	$v\left((\lambda_{23}+\lambda'_{23})(n+1)c_{\theta_c}s_{\theta_c}-\lambda_3 c_{2\theta_c}\right)$
$h\ H_2\ H_2$	$-v\left((\lambda_{23}+\lambda'_{23})(n{s_{\theta_c}}^2+{c_{\theta_c}}^2)+2\lambda_3 c_{\theta_h}s_{\theta_c}\right)$
$h\ H_1^{\pm}\ H_1^{\mp}$	$-v\lambda_{23}\left(s_{\theta_c}^2+n{c_{\theta_c}}^2\right)$
$h\ H_1^{\pm}\ H_2^{\mp}$	$v\lambda_{23}\left(1-n\right)c_{\theta_c}s_{\theta_c}$
$h\ H_2^{\pm}\ H_2^{\mp}$	$-v\lambda_{23}\left(c_{\theta_c}^2+n{s_{\theta_c}}^2\right)$
$A_1\ A_1\ H_1$	$-v\lambda_2\left(\lambda_1 c_{\theta_a}(c_{\theta_a}s_{\theta_c}-2c_{\theta_h}s_{\theta_a})-\lambda_2 s_{\theta_a}(s_{\theta_a}c_{\theta_h}-2c_{\theta_a}s_{\theta_c})\right)$
$A_1\ A_1\ H_2$	$v\left(\lambda_1 c_{\theta_a}(c_{\theta_a}c_{\theta_h}+2s_{\theta_a}s_{\theta_c})+\lambda_2 s_{\theta_a}(s_{\theta_a}s_{\theta_c}+2c_{\theta_a}c_{\theta_h})\right)$
$A_1\ A_2\ H_1$	$-v\left(\lambda_1(c_{\theta_a}s_{\theta_a}s_{\theta_c}+c_{2\theta_a}c_{\theta_h})+\lambda_2(c_{\theta_a}s_{\theta_a}c_{\theta_h}-c_{2\theta_a}s_{\theta_c})\right)$
$A_1\ A_2\ H_2$	$v\left(\lambda_1(c_{\theta_a}c_{\theta_h}s_{\theta_a}-c_{2\theta_a}s_{\theta_c})-\lambda_2(c_{\theta_a}s_{\theta_a}s_{\theta_c}+c_{2\theta_a}c_{\theta_h})\right)$
$A_2\ A_2\ H_1$	$-v\left(\lambda_1 s_{\theta_a}(s_{\theta_a}s_{\theta_c}+2c_{\theta_a}c_{\theta_h})-\lambda_2 c_{\theta_a}(c_{\theta_a}c_{\theta_h}+2s_{\theta_a}s_{\theta_c})\right)$
$A_2\ A_2\ H_2$	$v\left(\lambda_1 s_{\theta_a}(s_{\theta_a}c_{\theta_h}-2c_{\theta_a}s_{\theta_c})+\lambda_2 c_{\theta_a}(c_{\theta_a}s_{\theta_c}-2s_{\theta_a}c_{\theta_h})\right)$
$H_1\ H_1\ H_1$	$3v\lambda_2\left(nc_{\theta_h}-s_{\theta_c}\right)s_{\theta_c}c_{\theta_h}$
$H_1\ H_1\ H_2$	$-v\lambda_2\left(nc_{\theta_h}(1-3s_{\theta_c}^2)-s_{\theta_c}(2-3s_{\theta_c}^2)\right)$
$H_1\ H_2\ H_2$	$-v\lambda_2\left(ns_{\theta_c}(2-3s_{\theta_c}^2)+c_{\theta_h}(1-3s_{\theta_c}^2)\right)$
$H_2\ H_2\ H_2$	$-3v\lambda_2\left(ns_{\theta_c}+c_{\theta_h}\right)s_{\theta_c}c_{\theta_h}$

The case $n = 1$

$$\text{If} \qquad n = 1, \qquad \tan 2\theta \to \infty \qquad \Rightarrow \qquad \theta = \pm\pi/4$$

for $\theta = \theta_h, \theta_a, \theta_c$.
If we assume $\theta_h = \theta_c = -\theta_a = -\pi/4$:

$$\begin{aligned}
m^2_{H_1} &= \frac{1}{2}v^2(\lambda_{23} + \lambda'_{23} + \lambda_3) - \mu^2_{12} - \mu^2_2 \\
m^2_{A_1} &= \frac{1}{2}v^2(\lambda_{23} + \lambda'_{23} + \lambda_3) + \mu^2_{12} - \mu^2_2 \\
m^2_{H_2} &= \frac{1}{2}v^2(\lambda_{23} + \lambda'_{23} - \lambda_3) + \mu^2_{12} - \mu^2_2 \\
m^2_{A_2} &= \frac{1}{2}v^2(\lambda_{23} + \lambda'_{23} - \lambda_3) - \mu^2_{12} - \mu^2_2 \\
m^2_{H_1^\pm} &= \frac{1}{2}v^2\lambda_{23} - \mu^2_{12} - \mu^2_2 \\
m^2_{H_2^\pm} &= \frac{1}{2}v^2\lambda_{23} + \mu^2_{12} - \mu^2_2 \qquad (8)
\end{aligned}$$

Fields in the vertex	Variational derivative of Lagrangian by fields
$h\ H_1\ H_1$	$-v\left(\lambda_{23} + \lambda'_{23} + \lambda_3\right)$
$h\ H_1\ H_2$	0
$h\ H_2\ H_2$	$-v\left(\lambda_{23} + \lambda'_{23} - \lambda_3\right)$
$A_1\ A_1\ H_1$	$-\frac{1}{\sqrt{2}}v\lambda_2$
$A_1\ A_1\ H_2$	0
$A_1\ A_2\ H_1$	0
$A_1\ A_2\ H_2$	$-\frac{1}{\sqrt{2}}v\lambda_2$
$A_2\ A_2\ H_1$	$\frac{3}{\sqrt{2}}v\lambda_2$
$A_2\ A_2\ H_2$	0
$H_1\ H_1\ H_1$	$-\frac{3}{\sqrt{2}}v\lambda_2$
$H_1\ H_1\ H_2$	0
$H_1\ H_2\ H_2$	$\frac{1}{\sqrt{2}}v\lambda_2$
$H_2\ H_2\ H_2$	0

Note that in this case $hH_1H_2 \to 0$, do we have two DM candidates in this case?

Parameters in the $n = 1$ case

The following equations relate different parameters:

$$\mu_{12}^2 = \frac{\Delta_+}{2}, \qquad \lambda_{23} = \frac{3\Delta_1 - \Delta_2}{v^2} + \lambda_3,$$
$$\lambda'_{23} = -\frac{\Delta_1}{v^2} - \lambda_3, \qquad \mu_2^2 = -m_{H_1}^2 - \frac{2\Delta_+ - \Delta_0}{2} + \frac{v^2}{2}\lambda_3, \quad (9)$$

with $\Delta_i > 0$, where:

$$\Delta_0 = m_{H_2}^2 - m_{H_1}^2, \qquad \Delta_{1,2} = m_{H_{1,2}^\pm}^2 - m_{H_{1,2}}^2, \qquad \Delta_+ = m_{H_2^\pm}^2 - m_{H_1^\pm}^2$$

And λ_3 relate the DM-higgs couplings of the two sectors,

$$\lambda_3 = \frac{g_{hH_1H_1} - g_{hH_2H_2}}{2}, \quad (10)$$

where $vg_{hH_iH_i}$ is the coefficient of the H_iH_ih term in the potential. Therefore, our input parameters are: $m_{H_1}, m_{H_2}, m_{H_1^\pm}, m_{H_2^\pm}, \lambda_3$ and also: $\lambda_{11}, \lambda_{22}, \lambda_{12}, \lambda'_{12}, \lambda_2$.

Relic density

Three different processes can be identified that could impact the dark matter relic abundance of the two DM sectors:

- Semi-annihilation processes: These are (assuming $m_{H_2} > m_{H_1}$) $S_2 S_2 \to h S_1$ $(S = H, A)$, and all of these vertices are proportional to λ_2.
- Partial DM conversion: These are $S_2 S_2 \to S_2 S_1$ $(S = H, A)$, and all of these vertices are proportional to $\lambda_{11} - \lambda_{22}$.
- Total DM conversion: These are $S_2 S_2 \to S_1 S_1$ $(S = H, A)$, and all of these vertices are proportional to $(\lambda_{11} + \lambda_{22})$ and $(\lambda_{12} + \lambda'_{12})$.

in order to keep these processes under control we need small lambdas, most of all λ_2 should be small to avoid the heavier DM candidate having a small relic density.

Two possible benchmarks

A

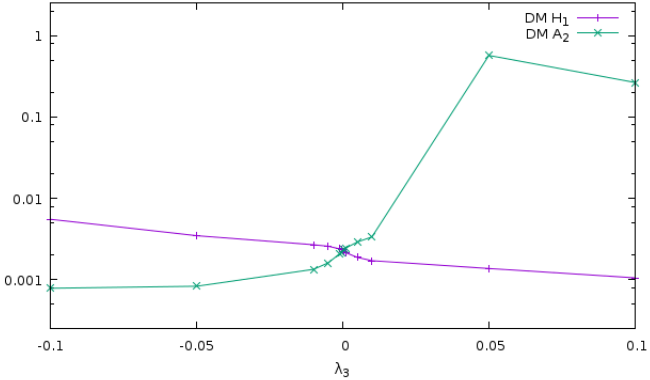
$m_{H_1} = 75$	$\lambda_{11} = 0.02$
$m_{H_2} = 205$	$\lambda_{22} = 0.01$
$m_{H_1^\pm} = 320$	$\lambda_{12} = 0.02$
$m_{H_2^\pm} = 360$	$\lambda'_{12} = 0.01$
$m_{A_1} = 181.2$	$m_{A_2} = 74.6$
$\Omega_1 h^2 = 3.75 \times 10^{-2}$	
$\Omega_2 h^2 = 7.67 \times 10^{-2}$	

B

$m_{H_1} = 90$	$\lambda_{11} = 0.3$
$m_{H_2} = 120$	$\lambda_{22} = 0.3$
$m_{H_1^\pm} = 210$	$\lambda_{12} = 0.3$
$m_{H_2^\pm} = 225$	$\lambda'_{12} = 0.3$
$m_{A_1} = 120.9$	$m_{A_2} = 160.6$
$\Omega_1 h^2 = 0.125$	
$\Omega_2 h^2 = 2.51 \times 10^{-4}$	

Masses in GeV, $\lambda_2 = 0.0001$

A test plot



In this plot we take the values from scenario B and change the value of λ_3. Note that for $\lambda_3 < 0 \rightarrow m_{A_2} > m_{H_1}$ and for $\lambda_3 > 0 \rightarrow m_{A_2} < m_{H_1}$

Testing inert interacions

We can see how the relic density depends on the lambdas by fixing the masses[2].

- Test 1: All lambdas equal to zero. Then, both DM sectors are completely independent.

$$\Omega_1 h^2 = 1.62 \times 10^{-4}, \qquad \Omega_2 h^2 = 4.90 \times 10^{-4}.$$

- Test 2: $\lambda_{11} = \lambda_{22} = \lambda_{12} = \lambda'_{12} = 0.1$, $\lambda_2 = 0$. Then, only total DM conversion processes are present.

$$\Omega_1 h^2 = 1.63 \times 10^{-4}, \qquad \Omega_2 h^2 = 5.29 \times 10^{-4}.$$

- Test 3: $\lambda_{11} = -\lambda_{22} = 0.1$, $\lambda_{12} = \lambda'_{12} = \lambda_2 = 0$. Then, only partial DM conversion processes are present.

$$\Omega_1 h^2 = 1.28 \times 10^{-4}, \qquad \Omega_2 h^2 = 2.24 \times 10^{-10}.$$

[2]We assumed: $m_{H_1} = m_{A_1} = 100\text{GeV}$, $m_{H_2} = m_{A_2} = 200\text{GeV}$, $m_{H_1^\pm} = m_{H_2^\pm} = 400\text{GeV}$

- Test 4: $\lambda_{11} = 2\lambda_{22} = 0.2$, $\lambda_{12} = \lambda'_{12} = 0.1$, $\lambda_2 = 0$. Then, all DM conversion processes are present, but no semi-annihilation.

$$\Omega_1 h^2 = 1.28 \times 10^{-4}, \qquad \Omega_2 h^2 = 3.15 \times 10^{-9}.$$

- Test 5: $\lambda_{11} = \lambda_{22} = \lambda_{12} = \lambda'_{12} = 0$, $\lambda_2 = 0.25$. Then, semi-annihilation processes are present, but no DM conversion.

$$\Omega_1 h^2 = 4.69 \times 10^{-6}, \qquad \Omega_2 h^2 = 2.46 \times 10^{-11}.$$

- Test 6: All lambdas different from zero: $\lambda_{11} = 2\lambda_{22} = \lambda_{12} = 2\lambda'_{12} = 0.2$, $\lambda_2 = 0.25$. Now all these interactions are present.

$$\Omega_1 h^2 = 4.70 \times 10^{-6}, \qquad \Omega_2 h^2 = 2.20 \times 10^{-11}.$$

  - Now with $\lambda_2 = 0.025$:

$$\Omega_1 h^2 = 1.01 \times 10^{-4}, \qquad \Omega_2 h^2 = 2.52 \times 10^{-9}.$$

What's next?

- Study DM phenomenology
- Constraints on parameters
- Direct and indirect DM detection
- Comparation with Z_2 model
- Colliders signatures: LHC and ILC

Thank you for your attention!