New features in the $Z2 \times Z2$ 3HDM two component DM model

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Motivation

N-Higgs Doublet models (NHDM) provide:

- Simple extensions of the SM that allow for CP violation;
- Viable Dark Matter (DM) candidates;
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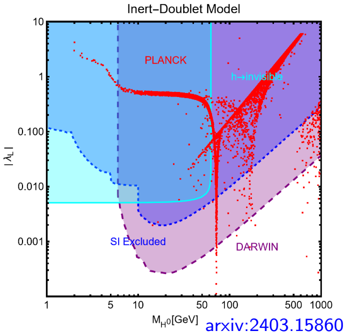
- The simplest form adds one scalar doublet with a $\mathbb{Z}_2$ symmetry that leaves the SM fields unchanged - IDM;
- DM particle states were in thermal equilibrium and decoupled - freeze-out - from the primordial plasma;
- $\Omega_{\mathrm{DM}} h^2 \approx 0.12$ [Planck, 2021] is determined with $\langle \sigma v \rangle$;
- Available region $M_h/2 \lesssim M_{DM} \lesssim M_h$ or $500 GeV \lesssim M_{DM}$



arxiv:2403.15860

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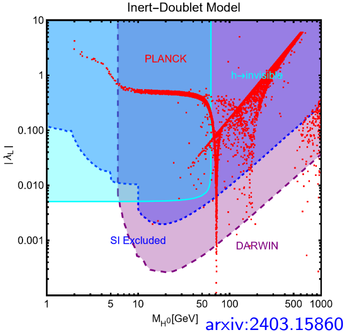

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Two inert 3HDM

- $\mathbb{Z}_2 \times \mathbb{Z}_2$ symmetry which does not alter the SM fields;
- Forbids the decay of one sector to the other.

Collaborators: P.N. Figueiredo, J. C. Romão, J. P. Silva, arxiv:2407.15933 [JHEP in print]

Model consistency

Every doublet can develop a VEV resulting in different scenarios. The most general vacuum may be parametrized [Faro, Ivanov, 2019]

$$\phi_1 = \sqrt{r_1}\begin{pmatrix}\sin\alpha_1 \\ \cos\alpha_1 \; e^{i\beta_1}\end{pmatrix}, \quad \phi_2 = \sqrt{r_2}e^{i\gamma}\begin{pmatrix}\sin\alpha_2 \\ \cos\alpha_2 \; e^{i\beta_2}\end{pmatrix}, \quad \phi_3 = \sqrt{r_3}\begin{pmatrix}0 \\ 1\end{pmatrix}.$$

We are interested in a `2-Inert` minimum, $(0, 0, v)$. Need to identify the parameter space with the `2-Inert` configuration as the global minimum, having for all other minima,

$$V_{\texttt{2Inert}} < V_{\texttt{X}}\,.$$

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BFB:

- The necessary and sufficient conditions for the $\mathbb{Z}_2 \times \mathbb{Z}_2$ 3HDM to be bounded from below are only known along neutral directions [Grzadkowski, Ogreid, Osland, 2009], $\alpha_1 = \alpha_2 = 0$.
- Only sufficient when considering charge breaking directions [Faro, Ivanov, 2019].
- Derived method of obtaining sufficient conditions for 3HDMs [Boto, Romão, Silva, 2022].

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Global minima:

- Identify all possible minima;
- Numerically minimize the potential with Minuit for random initial conditions;
- Apply BFB and conditions for 2-Inert to be global minima;
- Confirm none of the points ever give a lower vacuum.

Name	vevs	Symmetry of vacuum
EWs	$(0,0,0)$	$\mathbb{Z}_2\times\mathbb{Z}_2'$
2-Inert	$(0,0,v_3)$	$\mathbb{Z}_2\times\mathbb{Z}_2'$
DM1	$(0,v_2,v_3)$	$\mathbb{Z}_2$
DM2	$(v_1,0,v_3)$	$\mathbb{Z}_2'$
FODM1	$(0,v_2,0)$	$\mathbb{Z}_2$
FODM2	$(v_1,0,0)$	$\mathbb{Z}_2'$
FODM0	$(v_1,v_2,0)$	None
N	(v_1,v_2,v_3)	None
sCPv	$(v_1e^{i\xi_1},v_2e^{i\xi_2},v_3)$	None
FODM0'	$(v_1,iv_2,0)$	None

Name	vevs		
CB1	$\begin{pmatrix}u_1\\ c_1\end{pmatrix}$	$\begin{pmatrix}u_2\\ c_2\end{pmatrix}$	$\begin{pmatrix}0\\ c_3\end{pmatrix}$
CB2	$\begin{pmatrix}u_1\\ 0\end{pmatrix}$	$\begin{pmatrix}u_2\\ c_2\end{pmatrix}$	$\begin{pmatrix}0\\ c_3\end{pmatrix}$
CB3	$\begin{pmatrix}u_1\\ c_1\end{pmatrix}$	$\begin{pmatrix}u_2\\ 0\end{pmatrix}$	$\begin{pmatrix}0\\ c_3\end{pmatrix}$
CB4	$\begin{pmatrix}u_1\\ c_1\end{pmatrix}$	$\begin{pmatrix}u_2\\ c_2\end{pmatrix}$	$\begin{pmatrix}0\\ 0\end{pmatrix}$
CB5	$\begin{pmatrix}0\\ c_1\end{pmatrix}$	$\begin{pmatrix}u_2\\ c_2\end{pmatrix}$	$\begin{pmatrix}0\\ c_3\end{pmatrix}$
CB6	$\begin{pmatrix}u_1\\ c_1\end{pmatrix}$	$\begin{pmatrix}0\\ c_2\end{pmatrix}$	$\begin{pmatrix}0\\ c_3\end{pmatrix}$
CB7	$\begin{pmatrix}u_1\\ 0\end{pmatrix}$	$\begin{pmatrix}u_2\\ 0\end{pmatrix}$	$\begin{pmatrix}0\\ c_3\end{pmatrix}$
CB8	$\begin{pmatrix}u_1\\ 0\end{pmatrix}$	$\begin{pmatrix}0\\ 0\end{pmatrix}$	$\begin{pmatrix}0\\ c_3\end{pmatrix}$
CB9	$\begin{pmatrix}0\\ 0\end{pmatrix}$	$\begin{pmatrix}u_2\\ 0\end{pmatrix}$	$\begin{pmatrix}0\\ c_3\end{pmatrix}$
FOCB	$\begin{pmatrix}u_1\\ c_1\end{pmatrix}$	$\begin{pmatrix}u_2\\ -\frac{u_1^* u_2}{c_1^*}\end{pmatrix}$	$\begin{pmatrix}0\\ 0\end{pmatrix}$

The model

The potential is written as [notation of Boto, Romão, Silva, 2022]

$$
\begin{aligned}
V =& m_{11}^2\phi_1^\dagger\phi_1 + m_{22}^2\phi_2^\dagger\phi_2 + m_{33}^2\phi_3^\dagger\phi_3 + \lambda_1(\phi_1^\dagger\phi_1)^2 + \lambda_2(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_3^\dagger\phi_3)^2 + \lambda_4(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) \\
&+ \lambda_5(\phi_1^\dagger\phi_1)(\phi_3^\dagger\phi_3) + \lambda_6(\phi_2^\dagger\phi_2)(\phi_3^\dagger\phi_3) + \lambda_7(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \lambda_8(\phi_1^\dagger\phi_3)(\phi_3^\dagger\phi_1) \\
&+ \lambda_9(\phi_2^\dagger\phi_3)(\phi_3^\dagger\phi_2) + \left[\lambda_{10}''(\phi_1^\dagger\phi_2)^2 + \lambda_{11}''(\phi_1^\dagger\phi_3)^2 + \lambda_{12}''(\phi_2^\dagger\phi_3)^2 + \text{h.c.}\right] .
\end{aligned}
$$

Parameter space of 15 to scan,

$$
\{v^2, \mathrm{m}_{\mathrm{H}_1}^2, \mathrm{m}_{\mathrm{H}_2}^2, m_{H_3}^2 = m_{SM}^2, m_{A_1}^2, m_{A_2}^2, m_{H_1^\pm}^2, m_{H_2^\pm}^2, \Lambda_1, \Lambda_2, \Lambda_3, \lambda_1, \lambda_2, \lambda_4, \lambda_7\},
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$$V = m_{11}^2\phi_1^\dagger\phi_1 + m_{22}^2\phi_2^\dagger\phi_2 + m_{33}^2\phi_3^\dagger\phi_3 + \lambda_1(\phi_1^\dagger\phi_1)^2 + \lambda_2(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_3^\dagger\phi_3)^2 + \lambda_4(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2)$$
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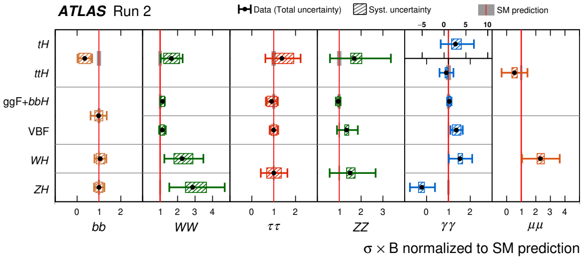
The remaining restrictions to consider include,

- the S matrix must satisfy perturbative unitarity, [Bento et al., 2022] for all 3HDMs;
- Agreement with the S, T and U electroweak parameters [Grimus et al., 2008];
- Coupling modifiers and cross section ratios μ_{if}^h from [ATLAS Collaboration, 2022];
- `HiggsTools` 1.1.3 [Bahl et al., 2023] that uses the experimental cross section limits from the LEP, the Tevatron and the LHC (at 95% C.L).

We built a FORTRAN program for each model to calculate all the quantities for a randomly generated set of parameters and test all the constraints. We then generate the FeynRules and CalcHEP model files in order to implement the model in micrOMEGAs 6.0.5.

Collider constraints

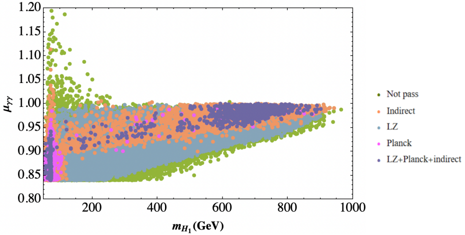


Coupling modifiers and cross section ratios μ^h_{if} from [ATLAS, arxiv:2207.00092]

$\mu_{\gamma\gamma}$ **and** $\mu_{z\gamma}$

- $\mu_{\gamma\gamma}$ applied at 3σ, very close to SM;
- $\mu_{\gamma\gamma}$ correlated to $\mu_{Z\gamma}$ in this model;
- Currently $\mu_{z\gamma}$ at [CMS, 2023]

$$\mu_{Z\gamma} = 2.2 \pm 0.7$$



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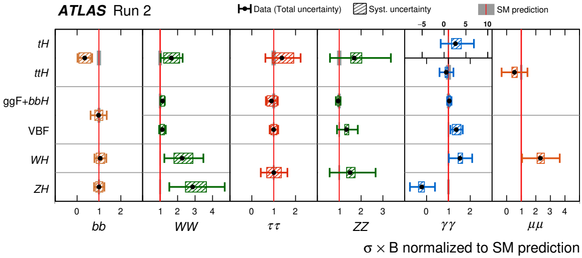

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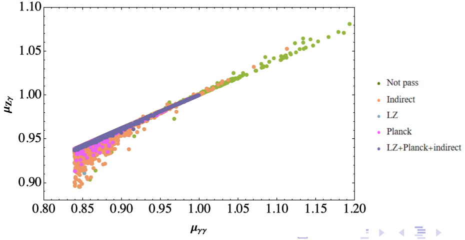


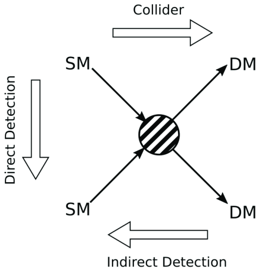
Dark matter detection

The total relic density is given by the sum of the contributions from the DM candidates,

$$\Omega_T h^2 = \Omega_{H_1} h^2 + \Omega_{H_2} h^2 = 0.1200 \pm 0.0012, \quad \text{[Planck, 2021]}$$

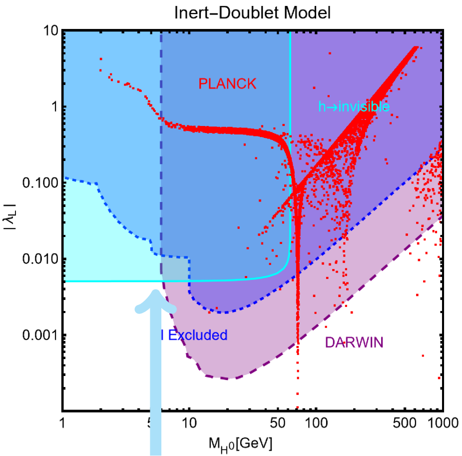
DM detection:

- Collider - $Br(h \to \text{invisible}) < 0.11$ [ATLAS, 2023]
- Direct detection - Spin-independent (SI) scattering cross section [LZ, 2023] with future DARWIN/XLZD and PandaX-xT,
  Rescale the calculated σ by the relative relic density;
- Indirect detection - detect gamma rays, cosmic rays or neutrinos from DM annihilation,
  For GeV scale, [Fermi-LAT, 2015] $\gamma' s$ in dwarf galaxies, [AMS-02, 2015] with antiproton flux and [H.E.S.S., 2015] $\gamma' s$ in Galactic Center.



Collider constraints

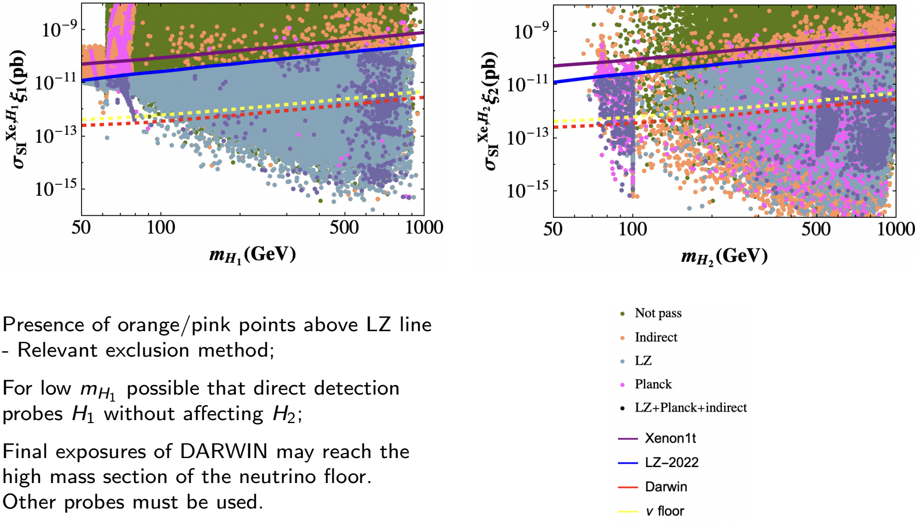
Bound from invisible Higgs decays $Br(h \to \text{invisible}) < 0.11$ [ATLAS Collaboration, 2023] also almost entirely excludes inert scalars lighter than $m_h/2$ for this model.



arxiv:2403.15860

Direct detection Results

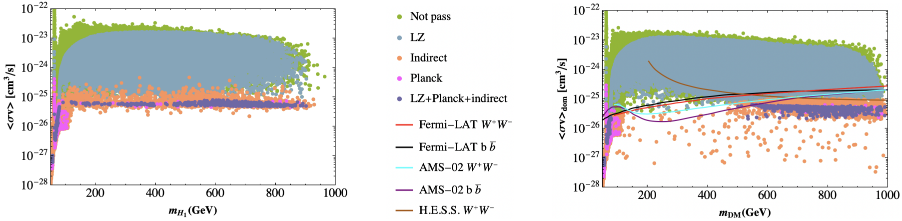
The points pass all previous constraints, including collider. $m_{H_2} > m_{H_1}$ always.



- Presence of orange/pink points above LZ line - Relevant exclusion method;
- For low m_{H_1} possible that direct detection probes H_1 without affecting H_2;
- Final exposures of DARWIN may reach the high mass section of the neutrino floor. Other probes must be used.

Indirect detection

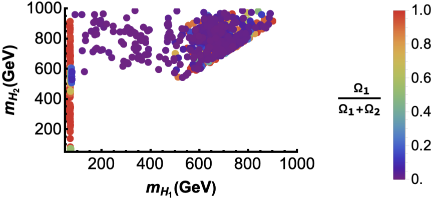
The left figure shows the total $\langle \sigma v \rangle$ as a function of m_{H_1}. The right figure shows the dominant contribution to $\langle \sigma v \rangle$ as a function of the mass of the DM candidate. NFW DM density profile.

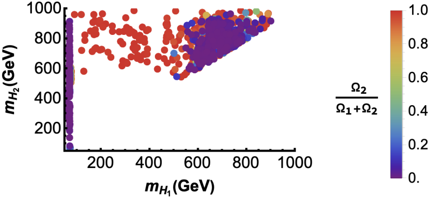


- We calculate the contributing channels and take the upper limit from the reconstruction of the experimental signal for the dominant channel;
- Above the *w* threshold, the annihilation proceeds mostly into WW. It occurs into $b\bar{b}$ otherwise;
- The Planck constraints (almost) guarantee indirect detection to not have effect.

Relic density

Points that satisfy all constraints, including direct and indirect detection, and have the correct relic density.





- Possible to have a DM candidate mass at any value $[\frac{1}{2}m_h, 1000GeV]$. In the intermediate mass range, by requiring that it is H_2 which is mostly responsible for the relic density
- Equal abundance is possible for either $\frac{1}{2}m_h < m_{H_1} < 80GeV$ or $m_{H_1} \gtrapprox 500GeV$.

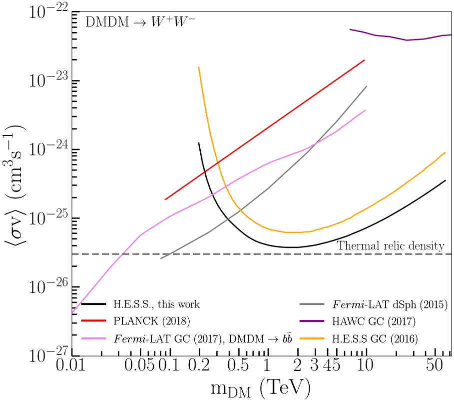
Summary

1. Studied a 3HDM with two DM candidates;
2. Complete classification of the minimum vacuum with numerical method;
3. Combined all avaliable experimental data in a wide scan;
4. Possible to populate the whole *GeV* mass range for a scalar DM candidate;
5. Future direct detection and collider data will further restrict the model.

The End

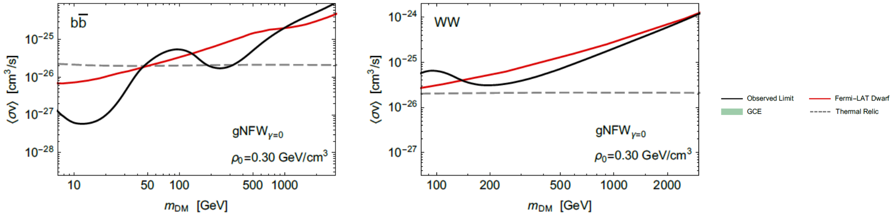
Extra Slides

Indirect detection



Comparison of present constraints in the W^+W^- channel. H.E.S.S. arxiv:2207.10471

Indirect detection



Comparison of AMS-02 and Fermi-LAT constraints. [arxiv:1712.00002](https://arxiv.org/abs/1712.00002)