A model of two dark matter candidates with equal abundance

Rafael Boto

CFTP, Lisboa, Portugal

Collaboration: Jorge C. Romão, João P. Silva, Pedro Figueiredo

FCT grant: PRT/BD/152268/2021

June 5, 2024

The model

3HDM with the $\mathbb{Z}_2 \times \mathbb{Z}_2$ symmetry [Weinberg, 1976]

$$\mathbb{Z}_2 : \phi_1 \to -\phi_1, \quad \phi_2 \to \phi_2, \quad \phi_3 \to \phi_3\,, \tag{1}$$

$$\mathbb{Z}_2' : \phi_1 \to \phi_1, \quad \phi_2 \to -\phi_2, \quad \phi_3 \to \phi_3\,. \tag{2}$$

The quadratic part of the potential is

$$V_2 = m_{11}^2 \phi_1^\dagger \phi_1 + m_{22}^2 \phi_2^\dagger \phi_2 + m_{33}^2 \phi_3^\dagger \phi_3\,, \tag{3}$$

while its quartic part reads [notation of Boto, Romão, Silva, 2022]

$$\begin{aligned} V_4 =& \lambda_1 (\phi_1^\dagger \phi_1)^2 + \lambda_2 (\phi_2^\dagger \phi_2)^2 + \lambda_3 (\phi_3^\dagger \phi_3)^2 + \lambda_4 (\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) + \lambda_5 (\phi_1^\dagger \phi_1)(\phi_3^\dagger \phi_3) \\ & + \lambda_6 (\phi_2^\dagger \phi_2)(\phi_3^\dagger \phi_3) + \lambda_7 (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1) + \lambda_8 (\phi_1^\dagger \phi_3)(\phi_3^\dagger \phi_1) + \lambda_9 (\phi_2^\dagger \phi_3)(\phi_3^\dagger \phi_2) \\ & + \left[\lambda_{10}'' (\phi_1^\dagger \phi_2)^2 + \lambda_{11}'' (\phi_1^\dagger \phi_3)^2 + \lambda_{12}'' (\phi_2^\dagger \phi_3)^2 + \text{h.c.} \right]\,. \end{aligned} \tag{4}$$

Extended to the full Lagrangian by assigning an even $\mathbb{Z}_2 \times \mathbb{Z}_2$ to all SM gauge bosons and fermions - "Type-I" interactions with ϕ_3.

Model consistency

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

$$\phi_1 = \sqrt{r_1}\begin{pmatrix} \sin\alpha_1 \\ \cos\alpha_1 \ e^{i\beta_1} \end{pmatrix}, \quad \phi_2 = \sqrt{r_2}e^{i\gamma}\begin{pmatrix} \sin\alpha_2 \\ \cos\alpha_2 \ e^{i\beta_2} \end{pmatrix}, \quad \phi_3 = \sqrt{r_3}\begin{pmatrix} 0 \\ 1 \end{pmatrix}. \tag{5}$$

We are interested in a two-component DM with a 2-Inert minimum configuration, $(0, 0, v)$, with two inert doublets, ϕ_1 and ϕ_2, and one active ϕ_3. Need to identify the parameter space with the 2-Inert configuration as the global minimum, having

$$V_{\texttt{2Inert}} < V_{\texttt{X}}\,, \tag{6}$$

for all other possible minima.

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]. Only sufficient when considering charge breaking directions [Faro, Ivanov, 2019]. Derived method of obtaining sufficient conditions for 3HDMs [Boto, Romão, Silva, 2022].

Constraints on the Model

The remaining restrictions to consider when performing parameter scans for a given model with DM 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^h_{if} from [ATLAS Collaboration, 2022];
- Upper limit on the Higgs total decay width is set by [CMS, 2019] at:

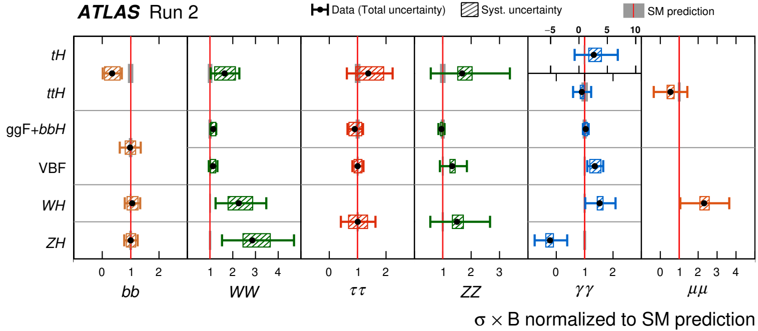
$$\Gamma_{tot} \leq 9.1\, MeV \,. \tag{7}$$

- `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 that numerically calculates all the necessary quantities for a randomly generated set of parameters and then tests the restrictions implemented. We then generate the FeynRules and CalcHEP model files in order to implement the model in micrOMEGAs 6.0.5.

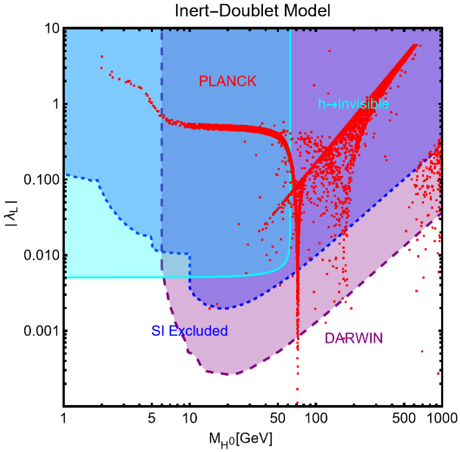
Collider constraints

- Coupling modifiers and cross section ratios μ_{if}^{h} from [ATLAS Collaboration, 2022],



Collider constraints

- Bound from invisible Higgs decays $Br(h \to \text{invisible}) < 0.11$ [ATLAS Collaboration, 2023] has significant impact for inert scalars lighter than $m_h/2$,



The Waning of the WIMP: Endgame?[Arcadi et al., 2024]

Astrophysical constraints

The total relic density is given by the sum of the contributions from both DM candidates H_1 and H_2,

$$\Omega_T h^2 = \Omega_{H_1} h^2 + \Omega_{H_2} h^2, \tag{8}$$

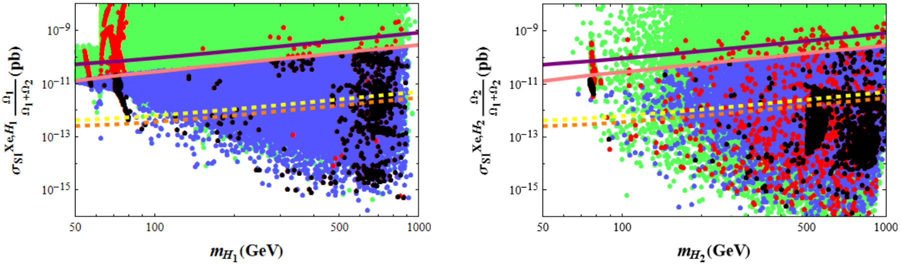
and is constrained by [Planck, 2021] data to be:

$$\Omega_T h^2 = 0.1200 \pm 0.0012. \tag{9}$$

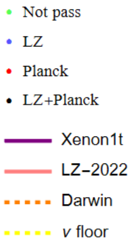
The current upper limit on the scattering cross-section of DM (direct detection) are given by the LUX-ZEPLIN (LZ) experiment [LZ, 2023]. In a model with two DM candidates, we rescale the calculated cross section by the relative relic density and compare with the experimental upper-limit.

The current indirect detection limits through photons given by Fermi-LAT start at $< \sigma v > \approx 3 \times 10^{-26}\, cm^3/s$ for $m_{DM} \lesssim 100\, GeV$ to $\langle \sigma v \rangle \approx 10^{-25} cm^3/s$ for heavier DM. The searches through anti-protons with AMS-02 provide competing constraints.

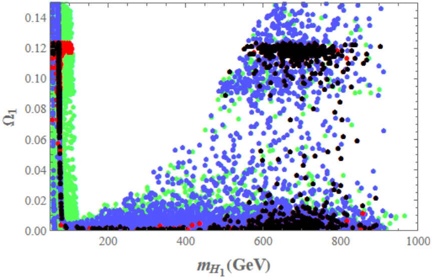
Direct detection Results

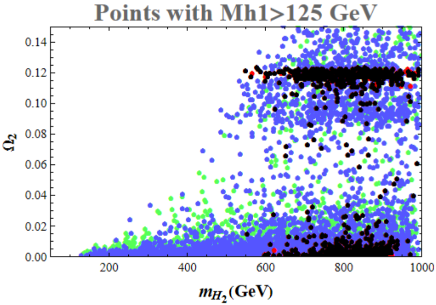


The final exposures of experiments like DARWIN and Argo, may reach the high mass section of the neutrino floor.



Relic density Results

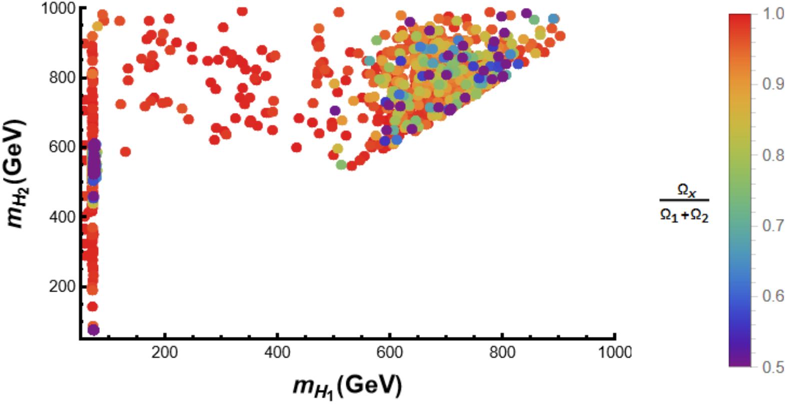


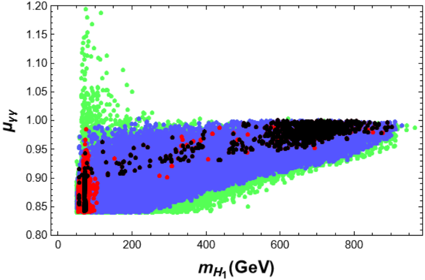


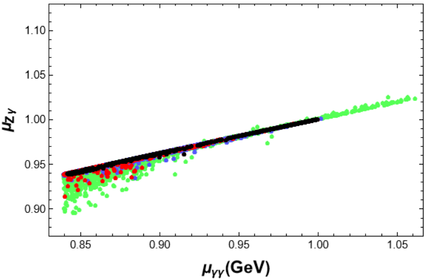
- Not pass
- LZ
- Planck
- LZ+Planck

- Possible to have a DM candidate mass at any value $[\frac{1}{2}m_h, 1000 GeV]$;
- Equal abundance is possible for $\frac{1}{2}m_h < m_{H_1} < 80 GeV$ and $m_{H_1} \gtrsim 500 GeV$

Equal abundance







$\mu_{\gamma\gamma}$ correlated to $\mu_{Z\gamma}$ in this model.
$\mu_{\gamma\gamma}$ measured close to SM expectation.
Currently measured $\mu_{z\gamma}$ at [CMS, 2023]

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

- Not pass
- LZ
- Planck
- LZ+Planck

The End