Collider Probes of Two-Component Dark Matter and its Characterisation

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Introduction

There is strong evidence showing the existence of a large abundance of matter which does not interact with the electromagnetic force in the universe, named dark matter (DM). DM constitutes 85% of the total matter mass while the remaining 15% is the matter that can be explained by the Standard Model (SM). In particle physics, the mass spectrum of possible DM models can be from meV to TeV, including axion-like particles, Weakly Interacting Massive Particles (WIMPs), etc. There are also various approaches and experiments for DM searching. This poster will introduce a two-component DM model, discussed in [1] and [2], which predicts DM masses around the EW scale, and also their collider searching analysis.

Detection Methods

For the WIMPs, there are several experimental approaches to search for DM signals, and they can mainly be classified into 3 categories:

1. Direct Detection: Searching for the DM scattering recoil from nuclei of some liquid, e.g. LZ, XENONnT, PandaX, etc.
2. Indirect Detection: Looking for the products created by the DM (co)-annihilation or decay in the centre of galaxies, spheroidal galaxies, galaxy halos, etc.
3. Collider Searches: Attempting to search for the missing transverse energy, $\not{E}_T$, from the DM creation in the events of the colliders.

Inert (2+1) Higgs Doublet Model (I(2+1)HDM)

By introducing two Higgs doublets into the SM and applying discrete symmetries on these, we can obtain a two-component DM model, with the Higgs fields being

$$\phi_1 = \begin{pmatrix} H_1^+ \\ \frac{H_1 + iA_1}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} H_2^+ \\ \frac{H_2 + iA_2}{\sqrt{2}} \end{pmatrix}, \quad \phi_3 = \begin{pmatrix} H_3^+ \\ \frac{v + h + iA_3}{\sqrt{2}} \end{pmatrix},$$

where the ϕ_3 is the doublet in the SM which gives the 125 GeV Higgs boson. Then, by adding extra discrete symmetries to the ϕ_1 and ϕ_2 doublets, one can make their physical fields inert. Considering adding a $Z_2 \times Z_2$ such that

$$g_{Z_2} = \text{diag}(-1, 1, 1), \quad g_{Z_2'} = \text{diag}(1, -1, 1),$$

the model will make each new doublet inert per se and also prevent each of these to interact with the other. By choosing the neutral CP-even states H_1 and H_2 to be the lightest ones in each doublet, we will have a two-component DM model. The theory will have 13 new free parameters, i.e. masses of the new particles and the coupling constants.

Model Constraints

There are several constraints to make the model provide two-component dark matter.

Avoiding the EW gauge boson decay into new scalars with $i = 1, 2$:

$$m_{H_i/A_i} + m_{H^\pm} \geq m_{W^\pm}, \quad m_{H_i} + m_{A_i} \geq m_Z, \quad 2m_{H^\pm} \geq m_Z.$$

Excluded region from LEP2 SUSY particle search re-interpreted for the I(1+1)HDM with $i = 1, 2$:

$$m_{A_i} \leq 100 \text{ GeV}, \quad m_{H_i} \leq 80 \text{ GeV}, \quad \Delta m = |m_{A_i} - m_{H_i}| \geq 8 \text{ GeV}.$$

Sufficiently short lifetime for charged states:

$$m_{H^\pm} > 70 \text{ GeV}.$$

DM constraints:

$$\Omega_{H_1} h^2 + \Omega_{H_2} h^2 = \Omega_{DM} h^2 = 0.1200 \pm 0.0012.$$

Then the model should also satisfy the theoretical constraints on aspects of perturbative unitarity, EW precision observable, the stability of the potential and the global minimum condition, and the model should also satisfy the experimental observation on mass, width and branching ratio of the SM-like Higgs bosons.

Model Parameter Space

By applying the constraints above, the allowed parameter space can be found in figure 1.

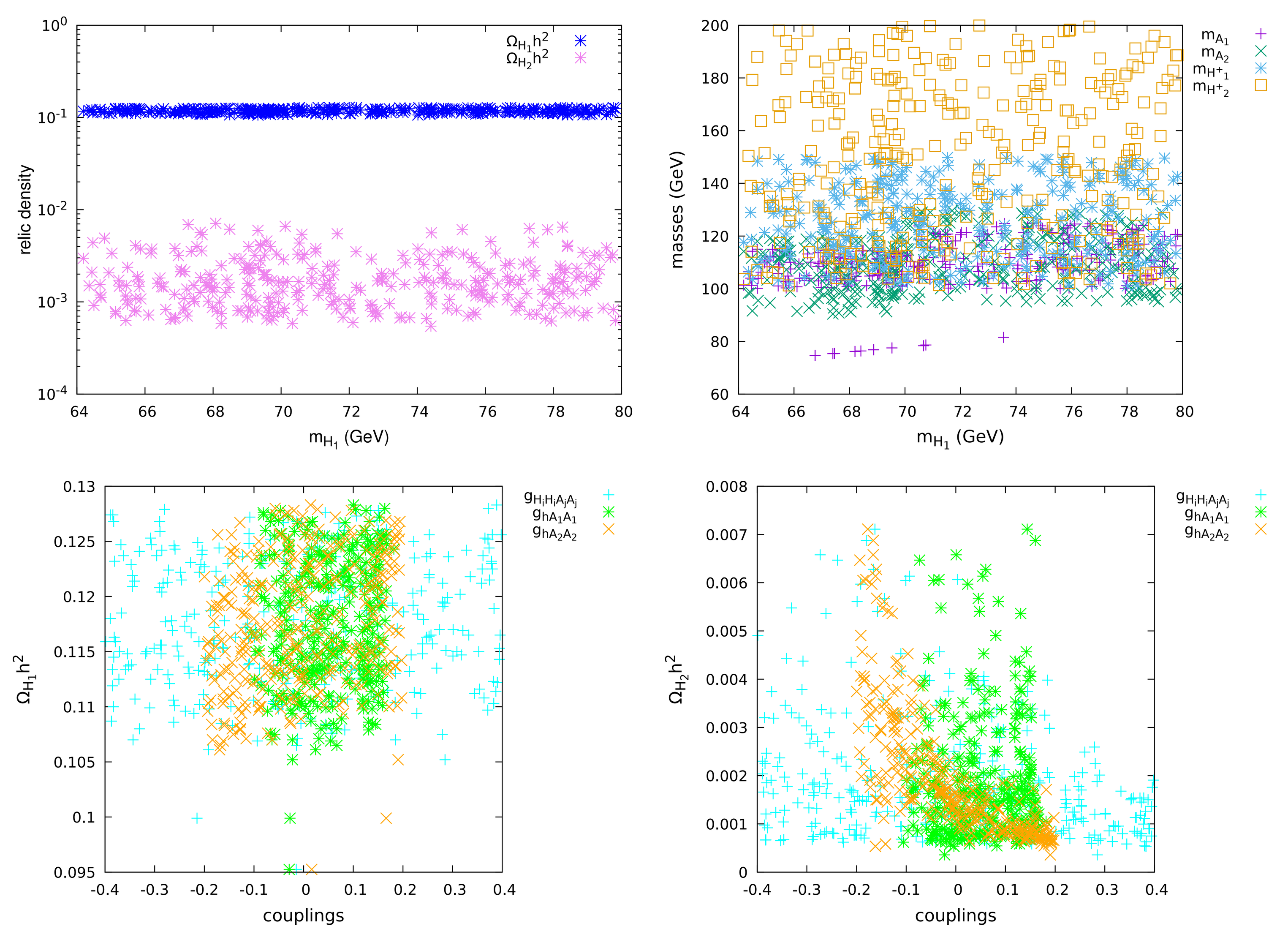

Figure 1. Parameter space for the H_1 mass with respect to the relic densities and other Higgs boson masses, and also for the coupling constants with respect to the relic densities of H_1 and H_2, as generated by MicrOMEGA in reference [1].

The chosen mass range in figure 1 is $\frac{1}{2}m_h < m_{H_1} < 80$ GeV, $H_2 \approx 100$ GeV and total relic density $\Omega_T h^2 = \Omega_{H_1} h^2 + \Omega_{H_2} h^2$ is within 3σ deviation of the observation.

$2\ell + \not{E}_T$ Signal Analysis

To search for a two-component DM signal in the $Z_2 \times Z_2$ symmetric I(2+1)HDM, dilepton + $\not{E}_T$ signals can be targeted at the LHC and these will come from the diagrams in figure 2,

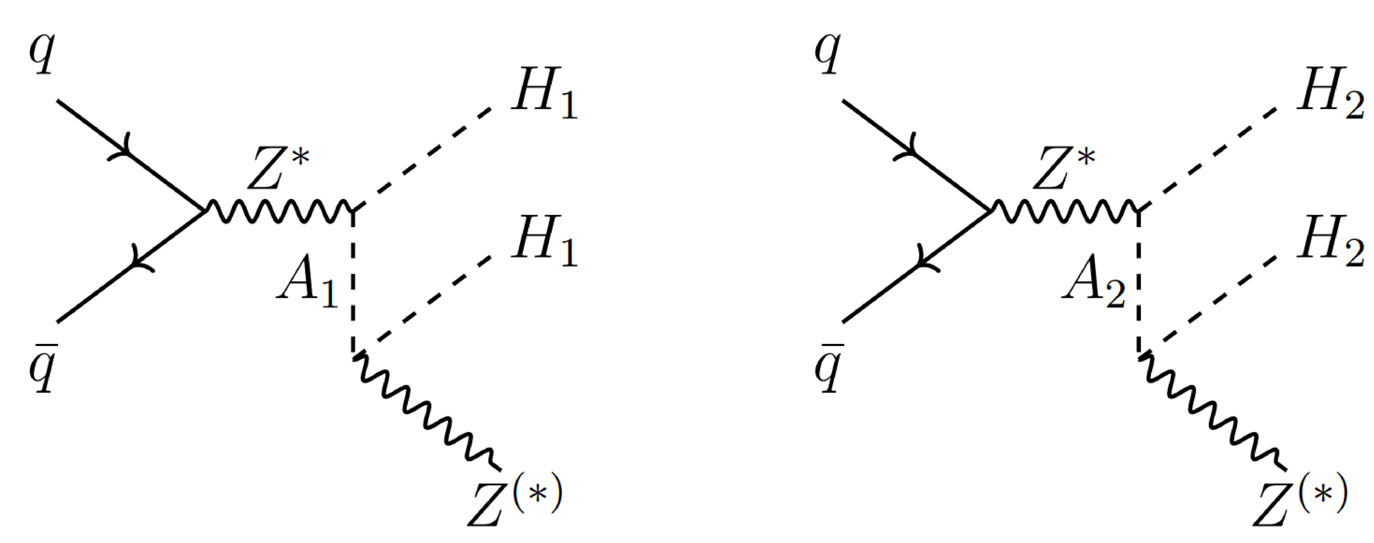

Figure 2. Representative Feynman diagrams producing a $2\ell + \not{E}_T$ final state when the off-shell Z decays to electrons and muons.

Herein, a small mass gap between the CP-odd and CP-even neutral states only allows off-shell Z bosons. To generate the events, the following benchmark point was chosen as: $m_{H_1} = 50$ GeV, $m_{H_2} = 100$ GeV, $m_{A_1} = 59.3$ GeV, and $m_{A_2} = 130.06$ GeV, and the Higgs vertices come from the gauge coupling with

$$g_{H_i A_i Z} = \frac{1}{2}(g \cos\theta_W + g' \sin\theta_W).$$

Then the obtained cross-sections of the two diagrams are around 1.058 fb and 1.929 fb respectively.

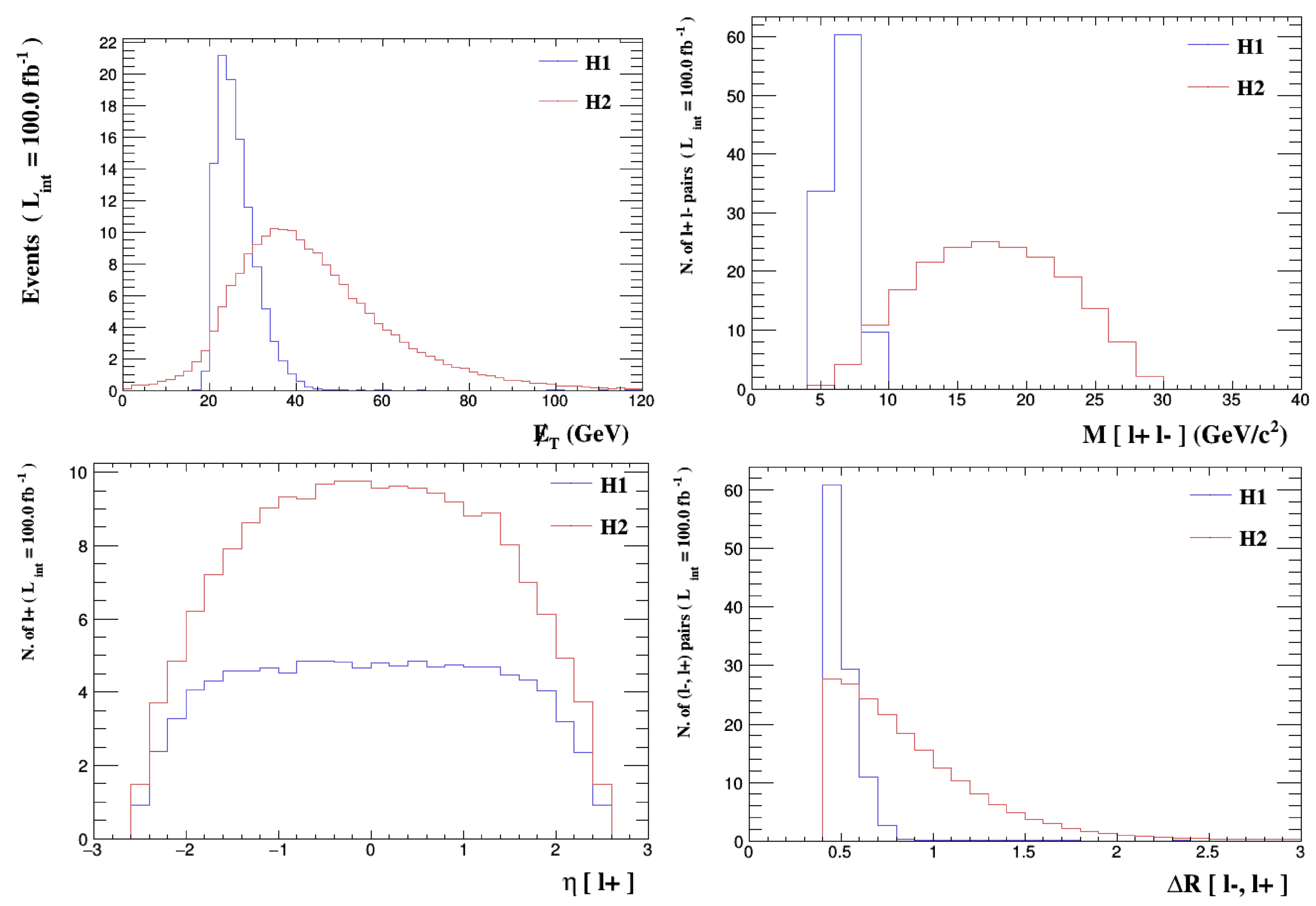

Figure 3. Distributions in missing transverse energy, as well as invariant mass, pseudorapidity and separation of dilepton pairs from reference [2].

By looking at the distributions, we can clearly see there will be two different patterns for this two-component DM model, and there would be sizable signals for LHC Run 3 luminosities. It not only allows us to prove the existence of two DM states at the same time, but also confirms the mass spectrum of the inert particles by associating the experimental observations to the model predictions.

Discussion and Plan

Dark matter searching is always a popular topic in high-energy physics, and collider physics plays a crucial role in DM detection. By introducing extra Higgs doublets and applying discrete symmetries to these, one can have a DM model with multiple components. Specifically, a $Z_2 \times Z_2$ symmetric I(2+1)HDM can provide us with two-component DM, and it also motivates one to search for two DM signals simultaneously with detectable rates at the LHC Run 3.

Our plan for the next step in investigating this model will be in two bullets:

- Validate the observability of the dilepton + $\not{E}_T$ signals in the presence of backgrounds doing a full Monte Carlo analysis at the detector level - which Manimala Chakraborti is leading on.
- Establish the LHC sensitivity to the I(2+1)HDM parameter space - which Shu Chen will be leading on.

References

[1] J Hernandez-Sanchez, V Keus, S Moretti, D Rojas-Ciofalo, and D Sokolowska. Complementary probes of two-component dark matter. *arXiv preprint arXiv:2012.11621*, 2020.

[2] Jaime Hernandez-Sanchez, Venus Keus, Stefano Moretti, and D Sokołowska. Complementary collider and astrophysical probes of multi-component dark matter. *Journal of High Energy Physics*, 2023(3):1–22, 2023.