Dilepton plus $\not{E}_T$ Signature from Two-component Dark Matter at the LHC

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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. As the SM shows a rich variety of particles and interactions, we would naturally consider that the dark sectors beyond the SM could show their diversity as well, and therefore we should also consider a universe with multiple-component DM. Herein, this poster will present a two-component DM model with two scalar DM candidates coming from two separate Higgs-like dark sectors and its detector-level Monte-Carlo simulations with possible backgrounds at the LHC.

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 from interacting with the other, so that the model contains two inert Higgs doublets and one active doublet, therefore an I(2+1)HDM .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 DM.

Avoiding the Electroweak (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 Supersymmetry particle search re-interpreted for the I(1+1)HDM with $i = 1, 2$ [1]:

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

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 [2], and the model should also satisfy the experimental observation on mass, width and branching ratio of the SM-like Higgs boson in the direct Higgs searches.

$2\ell + \not{E}_T$ Signal and Parton-level Distributions

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

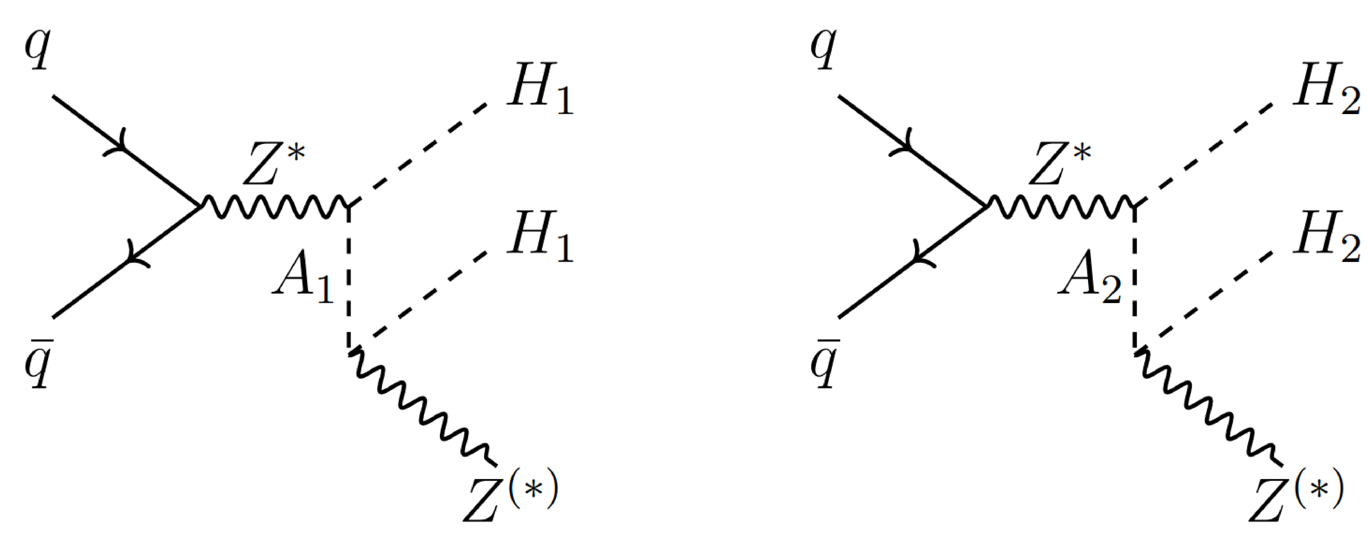

Figure 1. Representative Feynman diagrams producing a $2\ell + \not{E}_T$ final state when the off-shell Z decays to electrons and muons.

Herein, the vertices are all from EW gauge interactions, and a small mass gap between the CP-odd and CP-even neutral states only allows off-shell Z bosons.

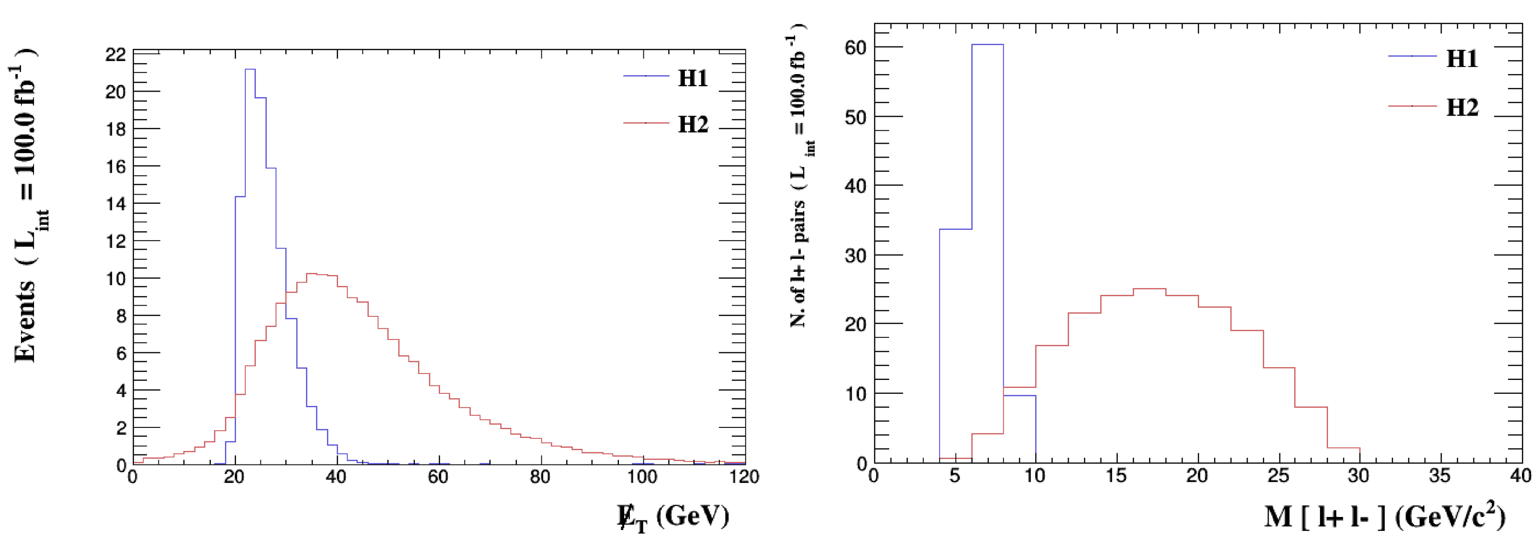

Figure 2. Parton level distributions on missing transverse energy and invariant mass of dilepton pairs for $Z_2 \times Z_2$ i3HDM in [3]

The parton level simulations were studied in [3], in which the benchmark point (BP) 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 cross-sections are 1.058 fb and 1.929 fb respectively. By looking at the plots in figure 2 we can clearly see there will be two different patterns for this two-component DM model. 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. It motivates us to study possible observations with the detector-level simulation in a high luminosity.

Detector-level Distributions for DM plus one Jet

We are now working on the detector-level distributions for the $2\ell + \not{E}_T$ DM signals with one extra jet coming from the initial states under a different BP of $m_{H_1} = 57.92$ GeV, $m_{H_2} = 93.98$ GeV, $m_{A_1} = 103.19$ GeV, and $m_{A_2} = 115.7$ GeV. Table 1 shows cutflows for the DM and all the possible background events, and also figures 3 and 4 show some detector-level distributions before and after cuts.

Cuts	DM	DY	$Z^*/\gamma^*(\to\tau\tau)$	$t\bar{t}$	tW	WW	$Z\gamma$
All :	1880	1.5×10^7	4×10^7	5.7×10^5	1.6×10^5	7.6×10^4	6649
SFOS + b-veto	718	5×10^6	5×10^5	9×10^3	9×10^3	1.6×10^4	1054
$\not{E}_T > 110$ GeV	280	2839	4.4×10^4	1712	1536	4190	315
$\Delta R_{ll} < 1.5$	218	2761	3.4×10^4	1067	963	2492	253
$P_T^{J_1} > 120$ GeV	120	1057	27635	325	411	1521	105
$\Delta\Phi[J_1 - \not{E}_T] > 1.5$	117	305	27635	289	398	1496	100
$m_{ll} < 50$ GeV	117	295	26434	261	295	1236	94
τ-veto	98	222	4098	226	249	1066	80

Total DM	Total SM	$S/\sqrt{B}$ at HL-LHC (3ab^{-1})
98	5941	4.02

Table 1. The top table shows the cutflows for DM and background under 300 fb^{-1} luminosity at LHC 13.6 TeV, and the below shows the significance for HL-LHC.

In table 1, the cutflows provide an overall significance of 1.27 for the 300 fb^{-1} at LHC 13.6 TeV. By multiplying by a factor of $\sqrt{10}$, we can obtain a significance of 4.02 for a high luminosity of 3000 fb^{-1} for future HL-LHC experiments. To increase the significance to a higher value, we are now considering cutting off the fake and non-prompt leptons in our final signals, which could allow us to have a significance value greater than 5.

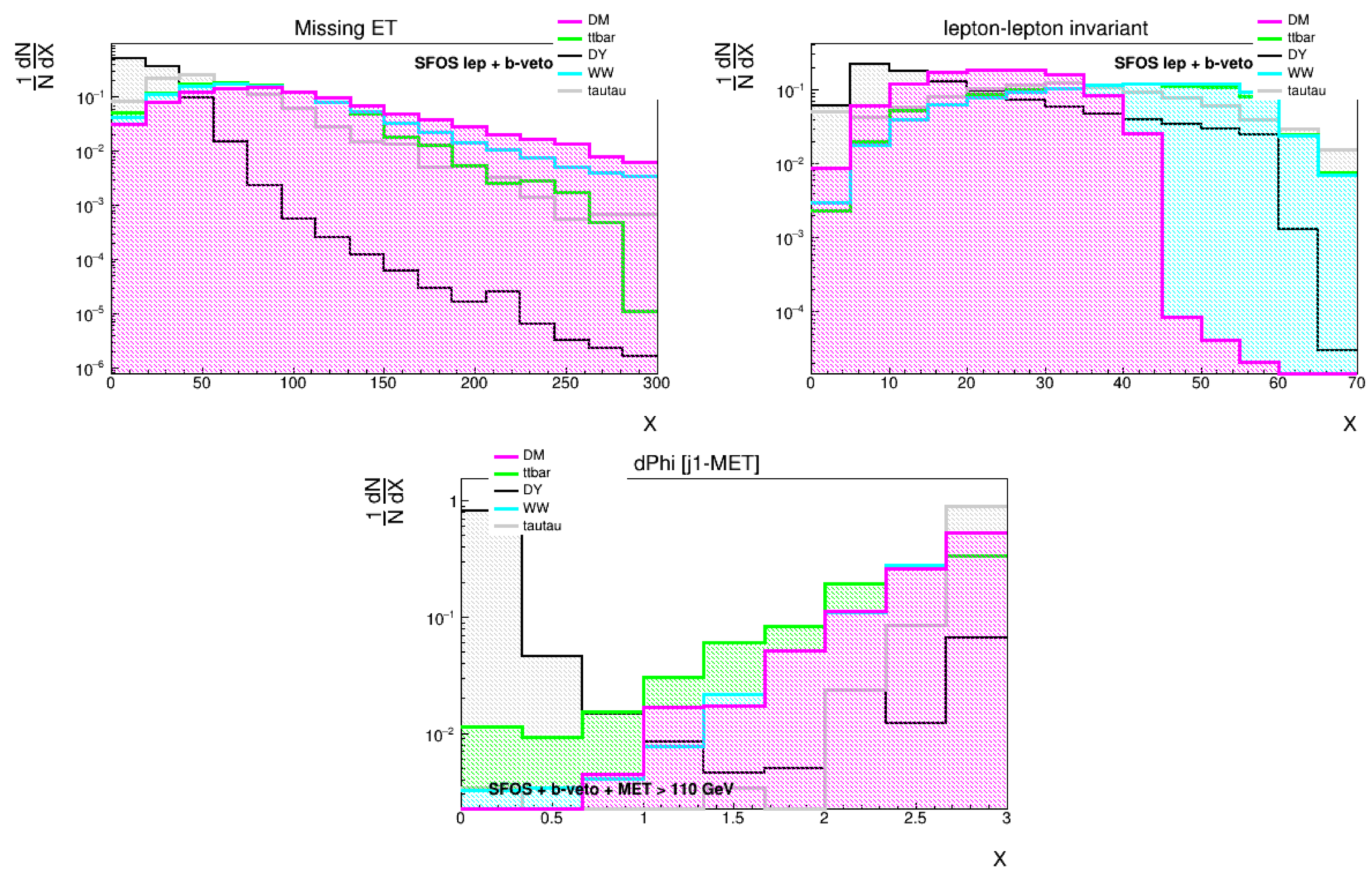

Figure 3. Detector-level distributions on missing transverse energy, dilepton invariant masses and separations between jet and $\not{E}_T$ for both signals and background events

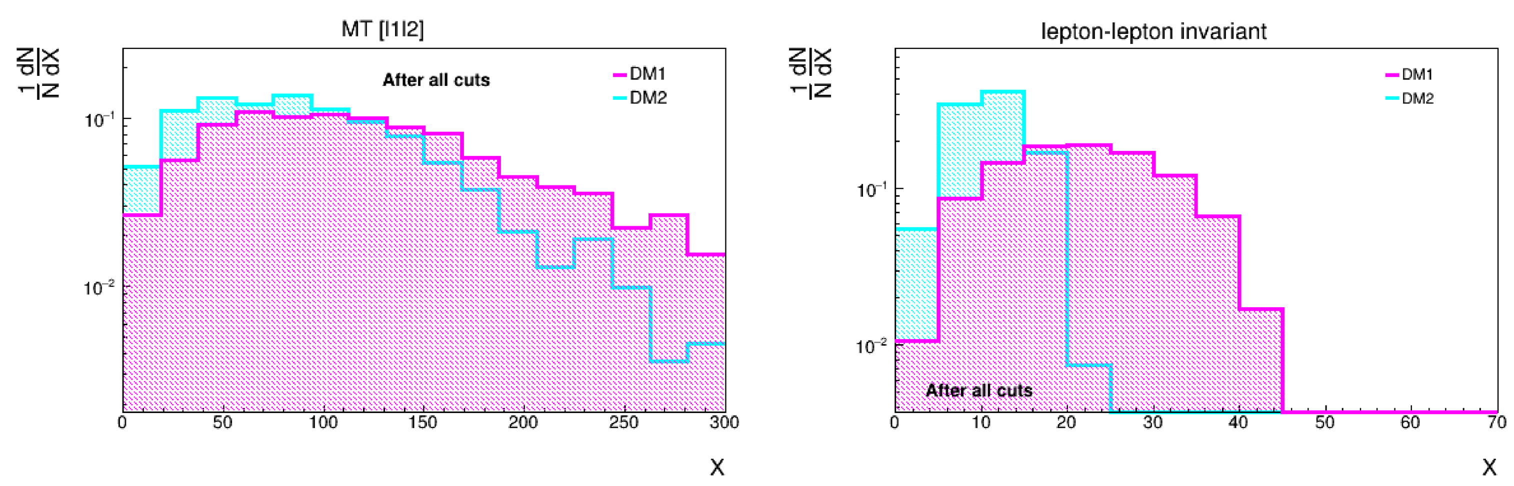

Figure 4. Detector-level distributions for dilepton pairs after all cuts in table1 for H_1 and H_2

We also considered the contribution from charged Higgs in each dark sector, i.e. $H^\pm_{1/2}$, which will provide around 25% extra cross-section of the process in figure 1 for $2\ell + \not{E}_T$ signals at detector level, but it becomes negligible after the cutflows in table 1.

Discussion

DM 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. 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 future LHC experiments. Also, this method can be largely model-independent and thus suitable for interpretations in other two-component scalar DM models providing dilepton plus $\not{E}_T$ signals.

References

[1] Erik Lundström, Michael Gustafsson, and Joakim Edsjö. Inert doublet model and lep ii limits. *Physical Review D*, 79(3), February 2009.

[2] 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.

[3] 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.

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