Searching for dark matter in 2HDM + complex singlet at lepton colliders

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Based on 2504.14529 with Gudrid Moortgat-Pick, Juhi Dutta, Cheng Li, Julia Ziegler and Farah Tabira Sheikh

Motivation

- SM, though a very successful theory, still does not answer many questions.
- 2HDM is one of the most popular extensions of Standard Model scalar sector.
- However, it is not easy to accommodate a dark matter candidate in the 2HDM.
- The singlet extension of 2HDM, can give rise to a viable dark matter candidate, when a discrete Z_2 symmetry is introduced.
- In addition, recently observed 95 GeV excess, can be explained if we consider complex singlet extension of 2HDM.
- We explore the prospect of probing dark matter signal stemming from such a scenario at the future (lepton)colliders.

Scalar potential

2HDM (type-II) scalar potential with imposed softly broken $\mathcal{Z}_2$-symmetry + complex singlet with $\mathcal{Z}_2'$ symmetry :

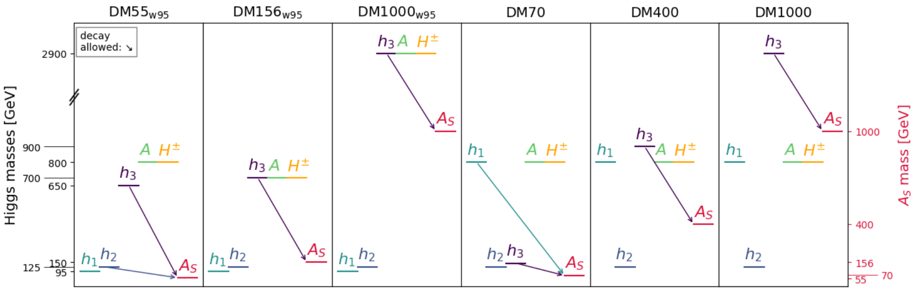
$$\begin{aligned}
V_{2HDMS} &= -m_{11}^2\Phi_1^\dagger\Phi_1 - m_{22}^2\Phi_2^\dagger\Phi_2 - [m_{12}^2\Phi_1^\dagger\Phi_2 + h.c.] + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 \\
&+ \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 \\
&+ m_S^2 S^\dagger S + \left[\frac{m_S'^2}{2}S^2 + h.c.\right] + \left[\frac{\lambda_1''}{24}S^4 + h.c.\right] + \left[\frac{\lambda_2''}{6}(S^2 S^\dagger S) + h.c.\right] \\
&+ \frac{\lambda_3''}{4}(S^\dagger S)^2 + S^\dagger S[\lambda_1'\Phi_1^\dagger\Phi_1 + \lambda_2'\Phi_2^\dagger\Phi_2] + [S^2(\lambda_4'\Phi_1^\dagger\Phi_1 + \lambda_5'\Phi_2^\dagger\Phi_2) + h.c.]
\end{aligned}$$

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ v_i + \rho_i + i\eta_i \end{pmatrix}, \quad \langle\Phi_i\rangle = \begin{pmatrix} 0 \\ v_i \end{pmatrix}$$

$$S = \frac{1}{\sqrt{2}}(v_S + \rho_S + iA_S), \quad \langle S\rangle = v_S$$

Three scalars h_1, h_2, h_3, charged scalars $H^\pm$, pseudoscalar A and dark matter A_S.

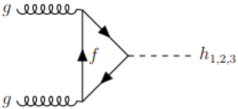
Benchmarks - probing different mass regions

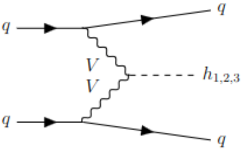


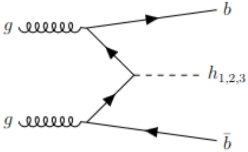
- Our benchmark choices are motivated by the prospect of detecting them in the future colliders, therefore different mass ranges are focussed on.
- We are interested in the topology DM+X in the final state (X=γ, Z, jets etc) and DM pair actually comes from the onshell decay of one of the scalars (h_1, h_2, h_3) in the theory.
- Made sure to satisfy all the theoretical, experimental constraints and dark matter constraints such as direct and indirect detection bounds also entire observed relic in some cases.
- Some BPs also accommodate the 95 GeV scalar as the lightest scalar.

LHC analysis of the benchmarks

- We explore the possibility of probing low and intermediate mass DM at the HL-LHC.







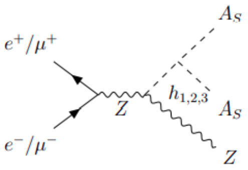
Benchmark	m_χ (GeV)	m_{h_i} (GeV)	Ωh^2	$BR(h_i \to \chi\chi)$	channel	Significance
DM55$_{\mathbf{w95}}$	55 GeV	125 GeV	0.11	2%	GGF	0.33 σ
DM70	70 GeV	150 GeV	0.11	100%	VBF	1.94 σ
DM156$_{\mathbf{w95}}$	156 GeV	700 GeV	1.610^{-6}	69%	$b\bar{b}h_i$	1.95 σ

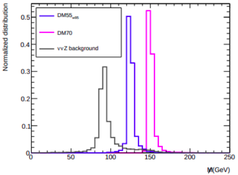
Low mass region - probe at ILC/FCC-ee/CEPC

We considered mono-photon, mono-Z, $b\bar{b}$-associated production and VBF modes.

Low mass region

- For the low mass region with our representative BP's $\mathbf{DM55_{w95}}$ and **DM70**, ILC/FCC-ee/CEPC would be the best choice.
- Mono-Z final state with Higgs strahlung production of Higgs and its decay to DM-pair has the largest cross-section.



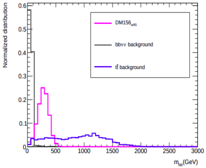


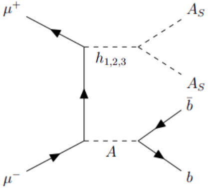
$$\not{M}^2 = (p_{in} - p_{out})^2,$$

Benchmark	$\sqrt{s}$ (GeV)	Cut	Significance
$\mathbf{DM55_{w95}}$	250 GeV	$\not{M} > 100$ GeV	$11\sigma(1\ \text{ab}^{-1})$
DM70	250 GeV	$\not{M} > 130$ GeV	$3\sigma(3\ \text{ab}^{-1})$

Benchmarks at muon collider - intermediate and heavy mass DM

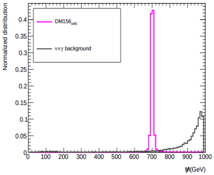
- For **intermediate mass range** (mediator mass ~ 1 TeV and DM mass few hundred GeV), $b\bar{b}$+MET final state yields the best event rate at $\sqrt{s} = 3$ TeV muon collider.





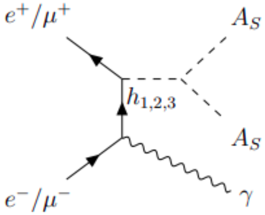
Benchmark	Cut	Significance
DM156$_{w95}$	100 GeV $< m_{bb} <$ 500 GeV	6.3σ $(3ab^{-1})$

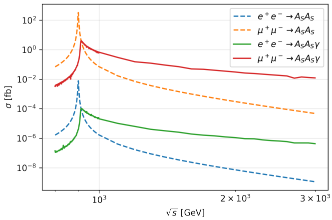
- Interestingly, 1 TeV muon collider will be able to probe this benchmark in the mono-photon final state.

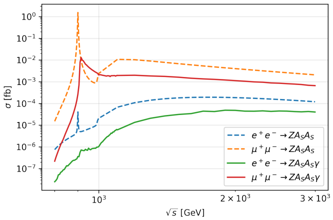


Benchmark	Cut	Significance
DM156$_{w95}$	690 GeV $< \not{M} <$ 710 GeV	3σ $(3ab^{-1})$, 5.3σ $(10ab^{-1})$

The cross-sections of mono-photon and mono-Z processes involves the Yukawa couplings.

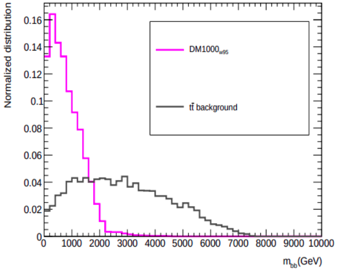






- The muon-collider has larger cross-section of the mono-photon and mono-Z processes than the e^+e^- collider, due to larger muon Yukawa coupling compared to electron Yukawa.

- **High mass DM** (~ 1 TeV) can be probed only at muon collider with $\sqrt{s} = 10$ TeV.
- The best signal yield is obtained with $t\bar{t}$+MET final state.
- For heavy h_i(~ 3 TeV), the largest BR to $t\bar{t}$ causes overall enhanced signal rate.



Benchmark	$\sqrt{s}$ (GeV)	Cut	Significance
$\mathbf{DM1000_{w95}}$	10 TeV	$m_{bb} < 2$ TeV	$3\sigma(10\ \text{ab}^{-1})$

Some challenges along the way

- There are scenarios where a benchmark can be allowed by all constraints, and give rise to the total observed relic density. Also the the BR of the heavier scalar to DM pair can be very large.
- Such scenarios invariably favors the heavy scalar h_i to be almost completely singlet-like.
- Our chosen benchmark **DM400**, **DM1000** fall under this category.
- Their production becomes a challenge, even at 10 TeV muon collider.
- FCC-hh may be helpful.

Summary

- The purpose of our study is to explore the possibility of detecting DM at future (lepton)collider experiments, when the DM pair comes from a heavy scalar.
- In this context we consider 2HDM + a complex singlet model, but our findings will be valid for a broad class of models.
- The benchmarks that are under-relic, easier to probe at the collider, due to larger portal coupling and invisible branching.
- The DM mass above a few hundred GeV will be difficult to probe at the LHC, ILC or muon collider will be more sensitive.
- Low mass DM $\lesssim \frac{m_{h_2}}{2}$ can be best probed at the mono-Z final state, at a e^+e^- collider with $\sqrt{s}\approx$250 GeV.
- Intermediate and heavy mass region is best probed at the muon-collider.
- 1 TeV muon collider can have stronger physics case compared to a 1 TeV ILC or even 3 TeV CLIC due to enhanced Yukawa coupling. Low $\sqrt{s}$ muon collider if possible?
- Conventional VBF channel may not work in a broad class of models and associated $b\bar{b}/t\bar{t}$ can be important channels to look for.
- There are still regions of the parameter space where the scalar, i.e portal to the dark sector is singlet-like, difficult to produce, FCC-hh might be helpful.

Back-up

Basis transformation

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R(\alpha_1, \alpha_2, \alpha_3) \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \end{pmatrix},$$

Interaction basis parameters :
$\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, m_{12}^2, \tan\beta, v_S, m_S'^2,$
$\lambda_1', \lambda_2', \lambda_4', \lambda_5', \lambda_1'' = \lambda_2'', \lambda_3''$

Mass basis parameters :
$m_{h_1}, m_{h_2}, m_{h_3}, m_{H^\pm}, m_A, m_{A_S}, \tan\beta, v_S,$
$\lambda_1' - 2\lambda_4', \lambda_2' - 2\lambda_5', \lambda_1'' - \lambda_3'', c_{h_1 bb}, c_{h_1 tt},$
$alignm, m_{12}^2$

$$v = \sqrt{v_1^2 + v_2^2}, \qquad \tan\beta = \frac{v_2}{v_1}$$

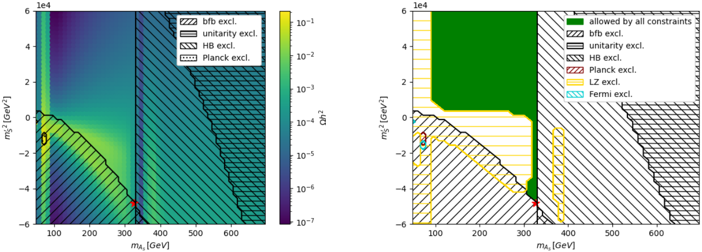
$$c_{h_1 bb} = \frac{R_{11}}{\cos\beta}, \quad c_{h_1 tt} = \frac{R_{12}}{\sin\beta}, \quad alignm = \sin(\beta - \alpha_1 - \alpha_3 sgn(\alpha_2)) \approx 1$$

Trilinear coupling:

$$\frac{\lambda_{h_j A_S A_S}}{v} = -[(\lambda_1' - 2\lambda_4')c_\beta R_{j1} + (\lambda_2' - 2\lambda_5')s_\beta R_{j2} - \frac{v_S}{2v}(\lambda_1'' - \lambda_3'')R_{j3}]$$

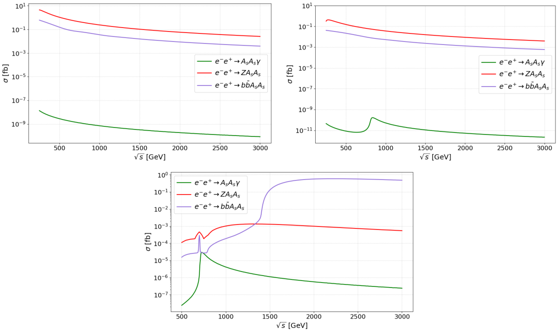
Quartic coupling:

$$\lambda_{h_j h_k A_S A_S} = -[(\lambda_1' - 2\lambda_4')R_{j1}R_{k1} + (\lambda_2' - 2\lambda_5')R_{j2}R_{k2} - \frac{1}{2}(\lambda_1'' - \lambda_3'')R_{j3}R_{k3}]$$



- The DM relic density has a dip at $2m_{A_S} \sim m_{h_3}$, where the resonant annihilation channel via h_3 opens up.
- The direct detection bound gets relaxed in certain regions of the parameter space where cancellation between various contribution takes place.
- The DM direct detection limits from LZ relaxes for underabundant DM due to the rescaling factor $\zeta = \Omega h^2/(\Omega h^2_{\rm PLANCK})$ rescaled by DM relic density.

Cross-section plots-ILC



Cross-section plots-muon collider