Dark matter phenomenology in 2HDM + complex singlet, probe at lepton colliders

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Motivation

- 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, inert doublet scenario is quite strongly constrained by the data.
- The singlet extension of 2HDM, can give rise to a viable dark matter candidate.
- In addition, recently observed 95 GeV excess, can be explained if we consider complex singlet extension of 2HDM, simultaneously having the possibility of dark matter.
- We have considered all the constraints (experimental and theoretical) on the model, studied the dark matter phenomenology and the prospect of detecting such a scenario at the future colliders.

Scalar potential

2HDM scalar potential with imposed softly broken $\mathcal{Z}_2$-symmetry and 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. In our analysis h_1 is the 95 GeV scalar and h_2 is the observed Higgs at 125 GeV.

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

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:

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

Testing against the Constraints

The model is written in SARAH and spectrum is generated via SPheno.

Theoretical constraints

- Boundedness from below, unitarity, vacuum stability

Oblique parameters

- Constraints from S,T,U parameters are taken into account.

Collider constraints

- Constraints from collider checked via HiggsBounds and HiggsSignals

Dark matter constraints

Dark matter observables such as relic density, direct and indirect detection cross-section are generated via micrOMEGAs.

- Observed relic density from Planck Experiments.
- Upper bound on direct detection cross-section from LUX-ZEPPLIN (LZ) experiments.
- Upper limit on indirect detection cross-section from FERMI-LAT experiments.

BP1

m_{h_1}	m_{h_2}	m_{h_3}	m_A	$m_{H\pm}$	m_{12}^2	m_{A_S}	v_S
95	125.09	900	900	900	8.0456×10^4	325.86	239.86
$\tan\beta$	$c_{h_1 bb}$	$c_{h_1 tt}$	alignm	$\lambda'_1 - 2\lambda'_4$	$\lambda'_2 - 2\lambda'_5$	$\lambda''_1 - \lambda''_3$	Ωh^2
10	0.2096	0.4192	0.98	12.3327	-0.3109	-1.3645	8.71×10^{-3}

BP2

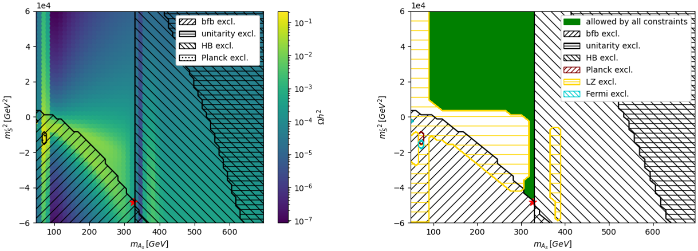
m_{h_1}	m_{h_2}	m_{h_3}	m_A	$m_{H\pm}$	m_{12}^2	m_{A_S}	v_S
95	125.09	700	700	700	7.2576×10^4	325.86	239.86
$\tan\beta$	$c_{h_1 bb}$	$c_{h_1 tt}$	alignm	$\lambda'_1 - 2\lambda'_4$	$\lambda'_2 - 2\lambda'_5$	$\lambda''_1 - \lambda''_3$	Ωh^2
6.6	0.258	0.372	0.98	12.75	-0.3135	-1.0112	3.16×10^{-4}

BP55

m_{h_1}	m_{h_2}	m_{h_3}	m_A	$m_{H\pm}$	m_{12}^2	m_{A_S}	v_S
95	125.09	650	800	800	1.69×10^5	55.596	300
$\tan\beta$	$c_{h_1 bb}$	$c_{h_1 tt}$	alignm	$\lambda'_1 - 2\lambda'_4$	$\lambda'_2 - 2\lambda'_5$	$\lambda''_1 - \lambda''_3$	Ωh^2
2	0.2323	0.3105	0.97	0.00209	0.000746	-0.025735	0.11

BP2900

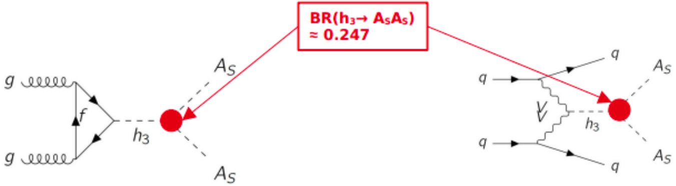
m_{h_1}	m_{h_2}	m_{h_3}	m_A	$m_{H\pm}$	m_{12}^2	m_{A_S}	v_S
95	125.09	2900	2900	2900	1.6173×10^6	1000	1000
$\tan\beta$	$c_{h_1 bb}$	$c_{h_1 tt}$	alignm	$\lambda'_1 - 2\lambda'_4$	$\lambda'_2 - 2\lambda'_5$	$\lambda''_1 - \lambda''_3$	Ωh^2
5	0.3669	0.3393	0.99995	7.616	0.0	-0.4632	0.111



- 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.

Search for BP1 at HL-LHC

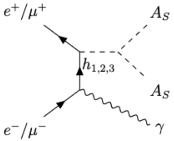
BP1 corresponds to $m_{h_3} = 900$ GeV and $m_{A_S} = 326$ GeV



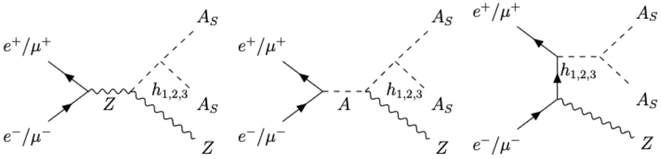
Process	Signal Significance
Gluon fusion	1.36 σ
Vector boson fusion	0.007 σ

Dark matter search at lepton colliders

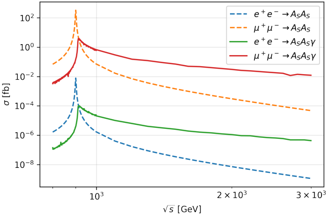
Mono-γ

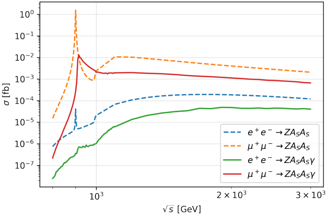


Mono-Z



The cross-sections of mono-photon and mono-Z processes



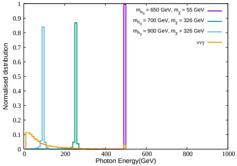


- The muon-collider has larger cross-section of the mono-photon and mono-Z processes than the e^+e^- collider, due to larger muon Yukawa coupling compared to electron Yukawa.

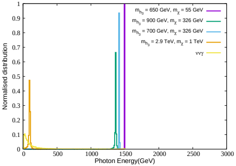
We have used WHIZARD for the analysis.

Kinematic distributions

$\sqrt{s} = 1$ TeV at ILC



$\sqrt{s} = 3$ TeV at muon-collider



	m_{h_3} (GeV)	m_χ (GeV)	Ωh^2	$BR(h_3 \to \chi\chi)$	$BR(h_2 \to \chi\chi)$
BP1	900	325.86	8.71×10^{-3}	0.25	-
BP2	700	325.86	3.16×10^{-4}	0.48	-
BP3	700	156.0	1.61×10^{-4}	0.69	-
DM55	650	55.6	0.11	3.81×10^{-9}	0.0199
BP2900	2900	1000	0.111	0.0359	-

Process	Production cross-section (pb) at $\sqrt{s} =$	
	1 TeV	3 TeV
$\gamma\nu\bar{\nu}$	2.447	2.964

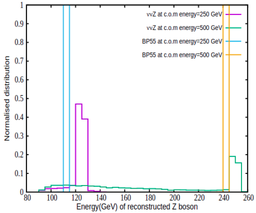
Table: Whizard cross sections for SM background at $\sqrt{s} = 1$ and 3 TeV.

Benchmark	$S(1\ ab^{-1})$	$S(10\ ab^{-1})$
BP1	0.76	2.4
BP2	0.59	2.2
BP3	1.7	5.3

Table: 1 TeV mono-γ+missing energy signal

Analysis of low mass dark matter-DM55

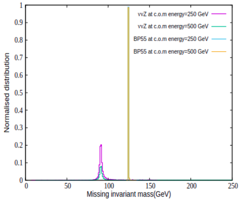
- In this benchmark the the dark matter comes from the decay of 125 GeV Higgs boson h_2.
- We will look into mono-Z (in the dilepton final state), Higgsstrahlung is the major production.



At low $\sqrt{s}$, required for the low mass DM scenario, the major background comes from $\nu\nu Z$ where $\nu\nu$ comes from Z-boson.

To reduce this background, we construct the variable $\not{M}$ missing-mass which is the invariant mass of the missing particles.

$$\begin{aligned} \not{M} &= E_{inv}^2 - |\vec{p_{inv}}|^2 \\ &= (\sqrt{s} - E_Z)^2 - |\vec{p_Z}|^2 \\ &= (\sqrt{s} - E_Z)^2 - (E_Z^2 - m_Z^2) \\ &= s - 2\sqrt{s}E_Z + m_Z^2 \end{aligned}$$



After applying a cut $\not{M} > 100$ GeV we achieve :

Benchmark	$S(\sqrt{s}$=250 GeV)	$S(\sqrt{s}$=500 GeV)
BP55	4.3 ($1ab^{-1}$), 7.4 ($3ab^{-1}$)	1.2 ($1ab^{-1}$), 2.0 ($3ab^{-1}$)

Table: At ILC

Benchmark	$S(\sqrt{s}$=1 TeV)	$S(\sqrt{s}$=3 TeV)
BP55	5.4 ($10ab^{-1}$),	0.38 ($10ab^{-1}$)

Table: At muon collider

Summary

- We perform a scan of the 2HDMS parameter space, choose benchmarks with varied masses and portal couplings.
- 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 ILC or muon collider.

Further things to do

- The high mass DM BP2900, can be probed only at muon collider, analysis still to be done, VBF production process looks most promising.
- We would like to establish a complementarity between different machines as well as final states.
- The impact of polarization is also under study.