Phenomenology of dark matter in complex scalar singlet extensions of Two Higgs doublet models

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Mini workshop on BSM at ILC and other e^+e^- colliders

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Motivation

- Requisite dark matter candidates $\rightarrow$ neutral, colorless and stable over the lifetime of the universe.

- Scalar singlets under the SM gauge group are potential dark matter candidates with the right quantum numbers.

  Barger et.al , Phys.Rev.D79:015018,2009

- Stringent constraints from direct detection cross-sections to the SM Higgs portal scenarios.

- Extensions of the Two Higgs Doublet model (2HDM) with scalar singlets under SM accomodates a dark matter (DM) candidate, baryogenesis and gravitational waves.

Dorsch et.al JCAP05 (2017) 052,
Drozd et.al JHEP11 (2014) 105,
Dey et.al JHEP 09 (2019) 004,
T.Bioketter et.al JHEP 10 (2021) 215

The Model

- Consider a softly broken Z_2 symmetric 2HDM and conserved Z_2' symmetric singlet potential.
- The quantum numbers of the fields are

Particles	Z_2	Z_2'
Φ_1	$+1$	$+1$
Φ_2	-1	$+1$
S	$+1$	-1

Table: The quantum numbers of the Higgs doublets Φ_1, Φ_2 and complex singlet S under $Z_2 \times Z_2'$.

- Free parameters of the model are

$$\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, m_{12}^2, \tan\beta, \lambda_1', \lambda_2', \lambda_4', \lambda_5', \lambda_1'', \lambda_3'', m_S^2, m_{S'}^2$$

- The Higgs sector same as in the 2HDM, i.e, $h, H, A, H^{\pm}$ where h, H are the two CP-even scalars, A, the pseudoscalar and charged Higgs $H^{\pm}$.
- Our focus on Type II 2HDM where the up-type quarks couple to Φ_2 and down-type quarks and leptons couple to Φ_1.

Higgs(es) as portal to dark matter

- The CP-even higgses couple to the DM at tree-level.
- Relevant couplings of the higgses to the DM,

$$\lambda_{hSS^*} \propto i\frac{1}{\sqrt{1+\tan^2\beta}}(\lambda_1' \sin\alpha - \lambda_2' \cos\alpha \tan\beta)$$

$$\lambda_{HSS^*} \propto -i\frac{1}{\sqrt{1+\tan^2\beta}}(\lambda_1' \cos\alpha + \lambda_2' \sin\alpha \tan\beta)$$

Here, v is the vacuum expectation value (*vev*) such that $v^2 = v_1^2 + v_2^2$ where v_i $(i = 1, 2)$ refers to the vev's of the Higgs doublets Φ_i and $\tan\beta = \frac{v_2}{v_1}$.

Phenomenological constraints

- Relic density constraint from `Planck`.
- Spin independent (SI) DM-nucleon direct detection cross section from `XENON-1T`.
- The lightest CP-even Higgs mass from LHC.
- Collider limits on heavy higgses from LHC and LEP.
- Flavour physics constraints: BR(B$\rightarrow s\gamma$), BR(B$\rightarrow \mu^+\mu^-$).

Simulation details

Model implementation/adoption in the following codes:

- Model building: `SARAH`
- Spectrum Generator: `SARAH-SPheno`
- DM constraints: `micrOMEGAs`
- Higgs constraints: `HiggsBounds` and `HiggsSignals`
- Flavour constraints and tree-level unitarity constraints: `SPheno`
- `Madgraph-Pythia-Delphes` for event generation, showering and detector simulation. `Madanalysis5` for performing signal background analysis.

Dark matter constraints: Relic density

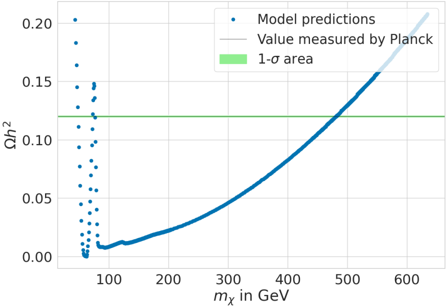


Figure: Variation of the relic density with the mass of the DM candidate, m_χ. Here, the mass parameter m_S^2 is varied.

SI direct detection cross-section

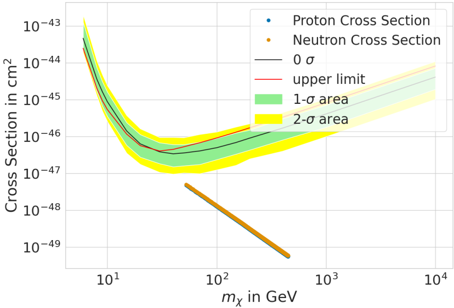


Figure: Variation of the direct detection cross-section with m_χ for $\lambda_2' = 0.001$ and $\tan\beta = 12$.

low λ_2' favoured from direct detection constraints.

Representative benchmarks

Parameters	BP1	BP2	BP3
λ_1	0.23	0.1	0.23
λ_2	0.25	0.26	0.26
λ_3	0.39	0.10	0.2
λ_4	-0.17	-0.10	-0.14
λ_5	0.001	0.10	0.10
m_{12}^2	-1.0×10^5	-1.0×10^5	-1.0×10^5
λ_1''	0.1	0.1	0.1
λ_3''	0.1	0.1	0.1
λ_1'	0.042	0.04	2.0
λ_2'	0.042	0.001	0.01
λ_4'	0.1	0.1	0.1
λ_5'	0.1	0.1	0.1
m_h	125.09	125.09	125.09
m_H	724.4	816.4	821.7
m_A	724.4	812.6	817.9
$m_{H^\pm}$	728.3	816.3	822.2
$\tan\beta$	4.9	6.5	6.5
m_{DM}	338.0	76.7	357.1
Ωh^2	0.058	0.119	0.05
$\sigma_{SI}^p \times 10^{10}$ (pb)	0.76	0.052	2.9
$\sigma_{SI}^n \times 10^{10}$ (pb)	0.78	0.054	3.1

Decay Channels	Branching ratios for		
	BP1	**BP2**	**BP3**
$H \to b\bar{b}$	0.14	0.29	0.24
$H \to t\bar{t}$	0.83	0.66	0.68
$H \to \tau\bar{\tau}$	0.02	0.45	0.04
$H \to \chi\bar{\chi}$	0.0	0.0	0.05
$A \to b\bar{b}$	0.12	0.27	0.27
$A \to t\bar{t}$	0.86	0.69	0.69
$A \to \tau\bar{\tau}$	0.02	0.04	0.04
$H^{\pm} \to t\bar{b}$	0.97	0.96	0.96
$H^{\pm} \to \tau\bar{\nu_{\tau}}$	0.022	0.03	0.03

Table: Dominant decay modes of the heavy Higgses for the benchmarks **BP1**, **BP2** and **BP3**. The branching ratios are rounded up to the second decimal place.

Collider signatures at e^+e^- colliders

- Presence of a dark matter candidate opens up new decay modes of the Higgses to χ.
- In the CP-even case, $h/H \to \chi\bar{\chi}$ with $h \to \chi\bar{\chi}$ severely constrained from Higgs invisible decay width measurements from LHC. We focus on $m_\chi > 62.5$ GeV such that only the heavy Higgs can decay to χ.
- Heavy Higgs H acts as the portal to the dark matter. Its production and decay at colliders to a dark matter candidate lead to signals with SM particles along with missing energy in the final state.

Results

- We perform a signal background analyses at e^+e^- colliders for $\sqrt{s} = 3$ TeV in the final state $2b + \not{E}_T$.
- Dominant signal processes: HA, $b\bar{b}H$, $t\bar{t}H$.
- Dominant SM backgrounds: $b\bar{b}\nu\bar{\nu}$, $t\bar{t}$, $t\bar{t}Z$,$b\bar{b}$, ZZZ.

Some important kinematic variables

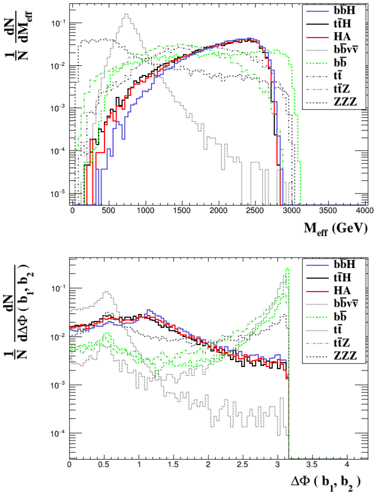


Figure: Normalized distributions for M_{eff} and $\Delta\Phi(b_1, b_2)$for **BP3**.

- Important kinematic variables: $p_T(b_1) > 100$ GeV, $p_T(b_2) > 80$ GeV, $\not{E}_T > 650$ GeV, $M_{eff} > 1.2$ TeV, $M_{b\bar{b}}$,$\Delta\Phi(b_1, b_2) < 1.6$ instrumental in reducing backgrounds.

Process	$p_T(b)$ $> 100, 80$GeV	$M_{b\bar{b}}! =$ $(80, 130)$ GeV	M_{eff} > 1.2 TeV	$\not{E}_T$ > 650 GeV	$\Delta\Phi(b_1, b_2)$ < 1.6
$b\bar{b}H$	27	26	26	25	21
$t\bar{t}H$	13	12	12	11	10
HA	28	24	24	22	20
BP3	51				
$b\bar{b}\nu\bar{\nu}$ 159	15738	2040.9	330.3	147.6	124.3
$b\bar{b}$	8432.5	8387.2	6697.5	65.6	4.07
ZZZ	3.75	3.07	1.5	0.51	0.28
WWZ	3.14	1.1	0.14	0.02	-
$t\bar{t}Z$	5.68	5.6	4.04	0.71	0.35
$t\bar{t}$ (semi-leptonic)	2843.9	2818.8	2500.6	338.5	16.61
$t\bar{t}$ (leptonic)	481.5	478.3	401.9	29.65	1.13
WW	0.28	0.28	-	-	-
hZ	1.26	0.023	-	-	-
ZZ	42.81	13.0	-	-	-
Total background	146.4				
Significance	3.99				

Table: The cut-flow table for the signal and background process for **BP3**.

Summary

- Extensions of 2HDM with complex scalar singlet provides a potential dark matter candidate.
- The higgs sector consists of two CP-even scalar h,H, a pseudoscalar A, and a pair of charged higgses as in the THDM.The DM candidate interacts with the SM via the CP-even scalar higgses at tree-level.
- Stringent constraints on the parameter space from direct detection cross-section with low λ_2' favoured from current data.
- Possible to obtain suitable parameter points allowed by DM and higgs constraints, with representative benchmark points in light and heavy mass regions along with potential observation of signal excess at high energy e^+e^- colliders.

Thank you!

Backup

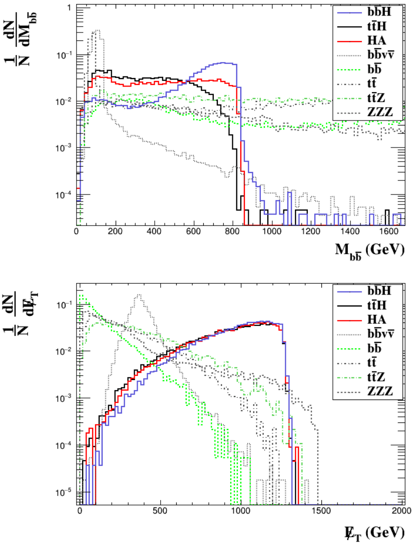


Figure: Normalized distribution for $M_{b\bar{b}}$ and $\not{E}_T$ for **BP3**.

The Scalar Potential

$$V_{THDMCS} = V_{THDM} + V_S + V_{HS}$$

$$V_{THDM} = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 + (m_{12}^2\Phi_1^\dagger\Phi_2 + h.c) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2$$
$$+\frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + (\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + h.c.)$$

$$V_S = m_S^2 S^\dagger S + (\frac{m_{S'}^2}{2}S^2 + h.c) + (\frac{\lambda_1''}{24}S^4 + h.c) + \frac{\lambda_1''}{6}(S^2(S^\dagger S)$$
$$+ h.c) + \frac{\lambda_3''}{4}(S^\dagger S)^2$$

$$V_{HS} = [S^\dagger S(\lambda_1'\Phi_1^\dagger\Phi_1 + \lambda_2'\Phi_2^\dagger\Phi_2)] + [S^2(\lambda_4'\Phi_1^\dagger\Phi_1 + \lambda_5'\Phi_2^\dagger\Phi_2) + h.c]$$

Baum,Shah JHEP 12 (044) 2018

Variation of other parameters

- Recall, the higgs couples to the DM via the portal couplings $\lambda_1', \lambda_2', \lambda_4', \lambda_5'$ and $\tan\beta$.
- We vary each of these parameters to determine the allowed region of parameter space.

Strongest effect on the direct-detection cross section of λ_2' and $\tan\beta$.

Variation of direct detection cross-section with λ_2'

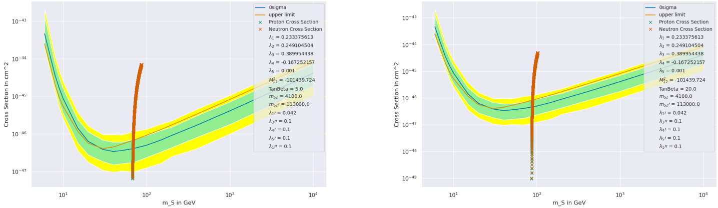
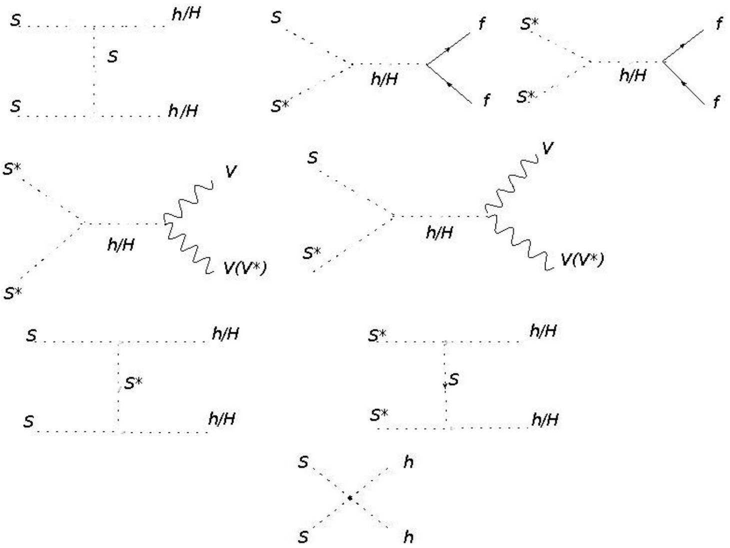


Figure: Variation of the direct detection cross section with m_χ for varying λ_2' for two values of $\tan\beta = 5, 20$ (left,right).

$\Longrightarrow$ low λ_2' satisfies σ^{SI}.

Relic Density



Parameters	**BPA**
λ_1	0.23
λ_2	0.25
λ_3	0.39
λ_4	-0.17
λ_5	0.001
m_{12}^2	-1.0×10^5
λ_1''	0.1
λ_3''	0.1
$\lambda_1' = \lambda_2'$	0.042
$\lambda_4' = \lambda_5'$	0.1
$m_S^{2\prime}$	1.13×10^5
m_h	125.1
m_H	724.4
m_A	724.4
$m_{H^\pm}$	728.3
m_χ	338.9
$\tan\beta$	5