Phenomenology of dark matter in the Two higgs doublet with complex scalar singlet extension

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(arXiv:2203.05509)

33rd Reconstrious de Blois: Exploring the Dark Universe

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May 25, 2022

Motivation

- Presence of dark matter has been unequivocally established from experimental observations.
- Requisite Dark Matter (DM) candidate $\rightarrow$ electrically neutral, colorless and stable (over the lifetime of the Universe).

- Standard Model (SM) gauge singlet scalars provide a natural candidate for dark matter in extended Higgs sectors such as the Two Higgs doublet model.
- Also explains matter-antimatter asymmetry and potential source of gravitational waves.

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

The Model: 2HDMS

- We consider a softly broken Z_2 symmetric Two Higgs Doublet Model (2HDM) and conserved Z_2' symmetric singlet scalar 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 $Z_2 \times Z_2'$.

Scalar Potential

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

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

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

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

Baum,Shah JHEP 12 (044) 2018

- Free parameters of the model are

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

- In absence of a vev for the complex singlet, the Higgs sector, after electroweak symmetry breaking, consists of two scalars h, H, pseudoscalar A, and charged higgses $H^\pm$.

- We focus on Type II THDM 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

- 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

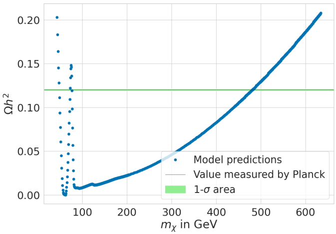
- Relic density upper bound from `Planck`.
- Spin independent (SI) DM-nucleon direct detection cross section from `XENON-1T`.
- The lightest CP-even Higgs mass constraints from LHC.
- Collider limits on heavy higgses from LHC and LEP.
- Flavour physics constraints: BR(B$\rightarrow s\gamma$), BR(B$\rightarrow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

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-Madanalysis` chain for the collider studies.

Constraints from dark matter observables



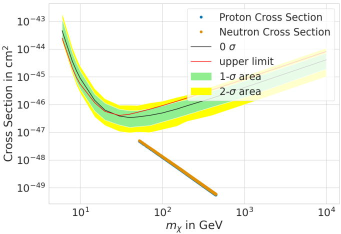


Figure: Variation of the relic density and direct detection cross-section with the mass of the DM candidate, m_χ.

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 (GeV^2)	-1.0$\times 10^5$	-1.0$\times 10^5$	-1.0$\times 10^5$
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 (GeV)	125.09	125.09	125.09
m_H (GeV)	724.4	816.4	821.7
m_A (GeV)	724.4	812.6	817.9
$m_{H^\pm}$ (GeV)	728.3	816.3	822.2
$\tan\beta$	4.9	6.5	6.5
m_{DM} (GeV)	338.0	76.7	323.6
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 modes of the Higgses

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**.

Collider probes: At LHC

- Important production modes: gluon fusion, VBF
- Possible collider channels: Mono-j + $\not{E}_T$, $jj + \not{E}_T$
- Dominant SM backgrounds: $V + j$,$t\bar{t}$+j, VV where $V = W, Z$ are the SM gauge bosons.

So far, for **BP3** Mono-j and VBF channels beyond HL-LHC reach owing to the low invisible branching ratio and heavy scalar mass.

Collider probes at e^+e^- colliders

Production channels: $b\bar{b}H$,HA,$t\bar{t}H$ (with $H \to \chi\bar{\chi}$)

- Signal channel: $2b + \not{E}_T$
- SM Backgrounds: $bb\nu\bar{\nu}$,$b\bar{b}$, $t\bar{t}$, $t\bar{t}Z$, ZZ,hZ,WWZ,ZZZ

For **BP3**, nearly 4σ significance (at leading order signal-backgrounds) for $\sqrt{s} = 3$ TeV and integrated luminosity $\mathcal{L} = 5$ ab^{-1}.

Some useful kinematic variables

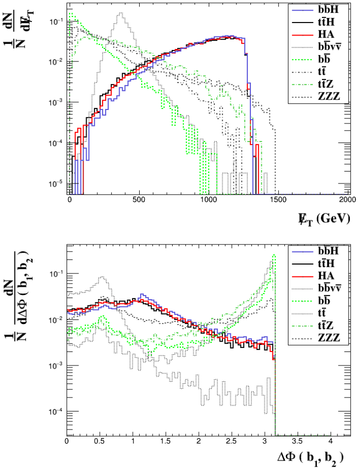


Figure: Normalised distributions for missing transverse energy $\not{E}_T$ and $\Delta\Phi$ between the two b-jets.

Results

Process	$p_T(b), M_{bb}$	$M_{Eff} > 1.2$ TeV	$\not{E}_T$ >650	$\Delta\Phi < 1.6$
$b\bar{b}H$	27	26	25	21
$t\bar{t}H$	12	12	11	10
HA	25	24	22	20
BP3	51			
$bb\nu\bar{\nu}$	2040.9	330.3	147.6	124.3
$b\bar{b}$	8387.2	6697.5	65.6	4.1
ZZZ	3.1	1.5	0.51	0.3
WWZ	1.1	0.14	0.02	-
$t\bar{t}Z$	5.6	4.04	0.71	0.35
$t\bar{t}$	478.3	401.9	29.6	1.13
$t\bar{t}$(semi-lep)	2818.8	2500.6	338.5	16.61
Total background	146.4			

Table: The number of events after cuts for $\sqrt{s} = 3$ TeV at $\mathcal{L} = 5$ ab^{-1}.

$$\mathcal{S} = \sqrt{2 \times \left[(s+b)\ln(1+\frac{s}{b}) - s\right]} \simeq 3.99. \tag{1}$$

where s and b are the total signal and background event numbers after the cuts

Summary

- Extensions of THDM with complex scalar singlet provides a potential dark matter candidate.
- 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. Low λ_2' favoured from current data.
- Possible to obtain suitable parameter points allowed by DM and higgs constraints and potential excess signals at future e^+e^- colliders.

Thank you!