Phenomenology of the Dark Matter sector in the Two Higgs Doublet with Complex Scalar Singlet extension

Juhi Dutta

with G. Moortgat-Pick, M. Schreiber

(based on arXiv:2203.05509)

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II. Institute of Theoretical Physics, University of Hamburg.

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Dark matter

- Presence of dark matter is unequivocally established from experimental confirmations via gravitational interactions.

- Pertinent questions still remain on nature of DM as well as interactions.

- Basic requirements (so far):
  - electrically neutral,
  - colorless under SM gauge group,
  - stable (at leastover the lifetime of the Universe),
  - (very) weakly interacting

Standard Model singlets as Dark Matter

- Standard Model (SM) gauge singlet scalars provide a natural candidate for dark matter.

- While such extensions to the SM are stringently constrained from direct detection searches, there is potential for such cases in extended Higgs sectors such with the heavy Higgses as portal to the dark sector $\rightarrow$ the Two Higgs doublet model+ (real/complex) scalar singlet (2HDMS).

- Presence of extra singlet also address matter-antimatter asymmetry and potential source of gravitational waves.

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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

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The Model: 2HDMS

- We consider a softly broken Z_2 symmetric Two Higgs Doublet Model (2HDM) (Branco et.al,hep-ph/1106.0034) 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 $Z_2 \times Z_2'$.

The Scalar Potential

$$V_{2HDMS} = V_{2HDM} + V_S + V_{HS}$$

$$V_{2HDM} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + (m_{12}^2 \Phi_1^\dagger \Phi_2 + h.c) + \frac{\lambda_1}{2}(\Phi_1^\dagger \Phi_1)^2$$

$$+ \frac{\lambda_2}{2}(\Phi_2^\dagger \Phi_2)^2 + \lambda_3(\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + (\frac{\lambda_5}{2}(\Phi_1^\dagger \Phi_2)^2 + h.c.)$$

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

$$+ h.c) + \frac{\lambda_3''}{4}(S^* S)^2$$

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

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 vacuum expectation value 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$\to s\gamma$), BR(B$\to \mu^+\mu^-$).

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.
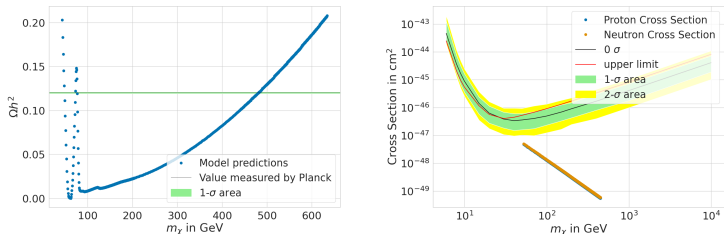
Constraints from Dark Matter observables

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

$\rightarrow$ Stringent constraints on λ'_2 to satisfy direct detection data from Xenon-1T.

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)	-1.0×10^5	-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 (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
$\sigma_p^{SI}\times10^{10}$ (pb)	0.76	0.052	2.9
$\sigma_n^{SI}\times10^{10}$ (pb)	0.78	0.054	3.1

Higgs invisible decay

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**.

$\implies$ invisible branching of the heavy Higgs stringently constrained.

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

Dominant irreducible background arises from $b\bar{b}\nu\bar{\nu}$ and semi-leptonic $t\bar{t}$ events. However, signal events are characterised by high p_T b jets and large missing transverse momentum which potentially help in signal background discrimination.
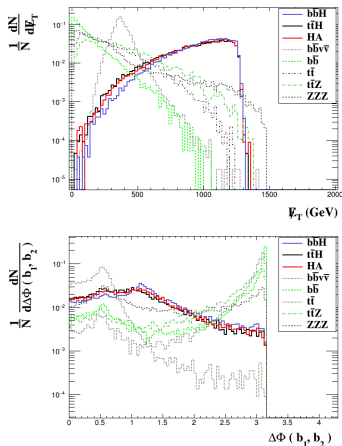
Some useful kinematic variables

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	0.2
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	2500.3	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 applying cuts.

Summary

- Extension of the Two Higgs Doublet Model with a complex scalar singlet provides a potential dark matter candidate.

- The Higgs sector consists of two CP-even scalars h, H, a pseudoscalar A, and a pair of charged Higgses $H^{\pm}$ as in the 2HDM.

- 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.

- Possible to obtain suitable parameter points allowed by DM and higgs constraints and potential excess at future e^+e^- colliders for $2b + \not{E}_T$ final state.
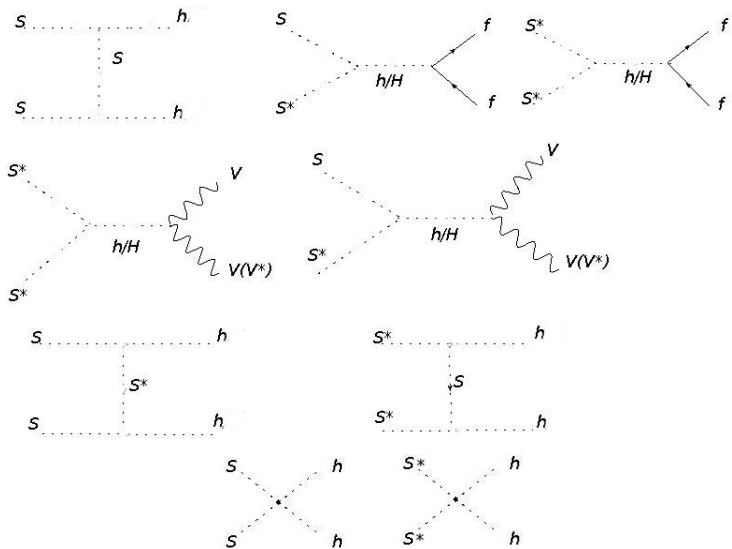
Thank you!

Backup

Scan parameters

Parameters	Values
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
λ_1'	0.042
λ_2'	0.042
λ_4'	0.1
λ_5'	0.1
$m_S^{2'}$	1.13×10^5
m_h	125.1
m_H	724.4
m_A	724.4
$m_{H^\pm}$	728.3
$\tan \beta$	5

Table: List of parameters kept fixed for the scans for relic density.

Relic Density

Kinematic cuts

- Transverse momenta (p_T) of the two leading b-jets > 100, 80 GeV respectively.

- The invariant mass of the two b-jets within the mass window $80 < M_{b_1 b_2} < 130$ is rejected to remove contributions from Z and h bosons.

- $M_{eff} > 1.2$ TeV where $M_{eff} = \sum_i (p_{T_i}) + \not{E}_T$

- $\not{E}_T > 650$ GeV

- $\Delta\Phi(b_1, b_2) < 1.60$ reduces background from $t\bar{t}$ and $t\bar{t}Z$ sharply.