

Dark matter phenomenology of the Two higgs doublet with complex scalar singlet model

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- Presence of dark matter has been unequivocally established from experimental observations.
- Requisite Dark Matter (DM) candidate → 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, provides potential source of CP-violation and 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

- Consider a softly broken Z_2 symmetric Two Higgs doublet model 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

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

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

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

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

- Free parameters of the model are

$$\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, m_{12}^2, \alpha, \tan \beta, \lambda'_1, \lambda'_2, \lambda'_4, \lambda'_5, \lambda''_1, \lambda''_3, m_S^2, m_{S'}^2,$$

- The Higgs sector, after electroweak symmetry breaking, consists of two scalars h, H , pseudoscalar A , and charged higgses H^\pm .
- Our 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

- The dark matter candidate couples to the CP-even higgses 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 $\tan \beta = \frac{v_2}{v_1}$.

- 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: $\text{BR}(B \rightarrow s\gamma)$, $\text{BR}(B \rightarrow \mu^+ \mu^-)$.

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

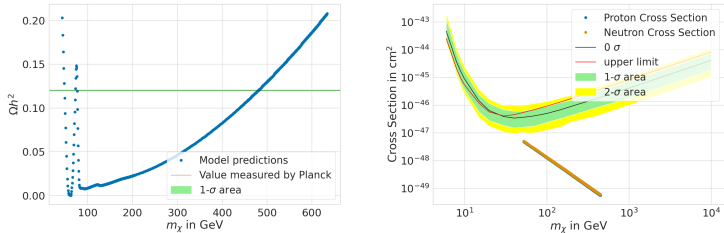


Figure: Variation of the relic density and direct detection cross-section with the mass of the DM candidate, m_χ .

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)	-1.0×10^5	-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
$\sigma_{SI}^p \times 10^{10}$ (pb)	0.76	0.052	2.9
$\sigma_{SI}^n \times 10^{10}$ (pb)	0.78	0.054	3.1

Table: Relevant parameters of the benchmark used for the study.

Decay modes of the Higgses

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

Table: Dominant decay modes of the heavy higgses for the benchmarks **BP1**, **BP2** and **BP3**.

- Important production modes: gluon fusion, VBF
- Possible collider channels: Mono-j + \cancel{E}_T , $jj + \cancel{E}_T$

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

Collider probes at e^+e^- colliders (ongoing)

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

- Signal channel: $2b + \cancel{E}_T$
- SM Backgrounds: $bb\nu\bar{\nu}, b\bar{b}, t\bar{t}, t\bar{t}Z, ZZ, hZ, WWZ, ZZZ$
- Key kinematic variables for signal-background discrimination: large M_{Eff} , \cancel{E}_T and low $\Delta\Phi(b_1, b_2)$.

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

- 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, with representative benchmark points in light and heavy mass regions.

Thank you!

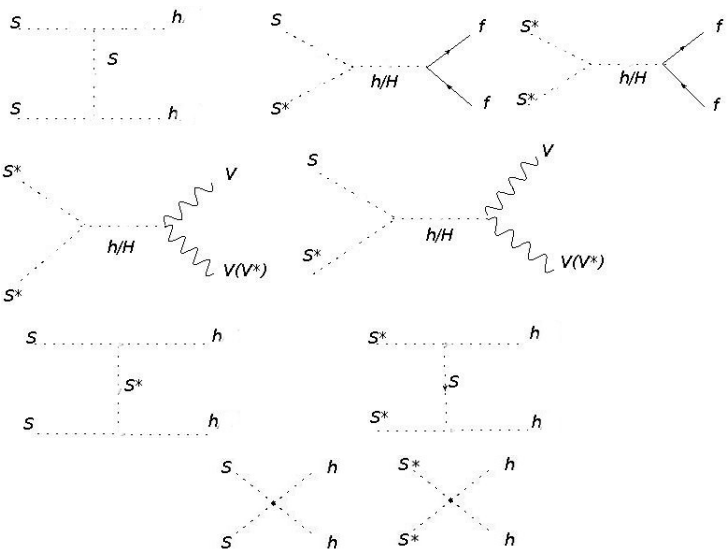
Backup

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
$\lambda_1^{//}$	0.1
$\lambda_3^{//}$	0.1
λ_1^{\prime}	0.042
λ_2^{\prime}	0.042
λ_4^{\prime}	0.1
λ_5^{\prime}	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
$\tan \beta$	5

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

Relic Density



Process	$p_T(b), M_{bb}$	$M_{Eff} > 1.2 \text{ TeV}$	$\cancel{E}_T > 650$	$\Delta\Phi < 1.6$
$b\bar{b}H$	27	26	25	21
$t\bar{t}H$	12	12	11	10
HA	25	24	22	20
BP3	51			
$bb\nu\bar{\nu}$	2222.3	324.7	142.1	131.9
$b\bar{b}$	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
Total background	137.5			

Table: Signal-background analyses cutflow at $\sqrt{s} = 3 \text{ TeV}$ at $\mathcal{L} = 5 \text{ ab}^{-1}$.

$$\mathcal{S} = \sqrt{2 \times \left[(s + b) \ln\left(1 + \frac{s}{b}\right) - s \right]} \simeq 4.1. \quad (1)$$

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