Dark Matter Phenomenology in Two Higgs Doublet Model with Complex Scalar Singlet

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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, 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

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

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

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

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

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

Baum,Shah JHEP 12 (044) 2018

- 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

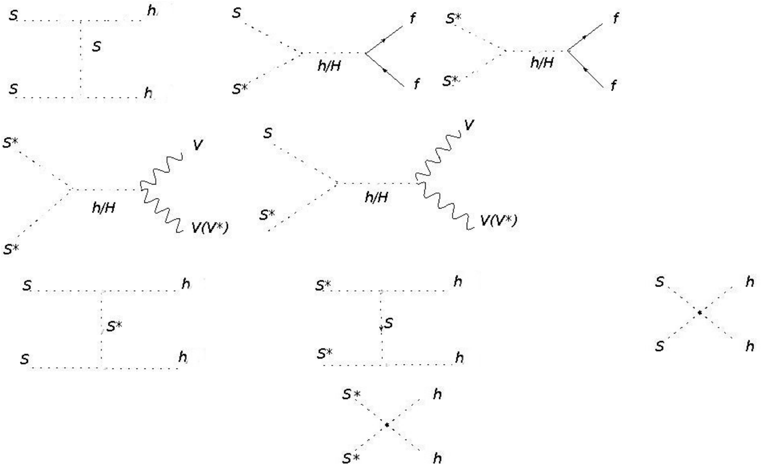


Figure: Some Feynmann diagrams contributing to relic density.

Phenomenological constraints

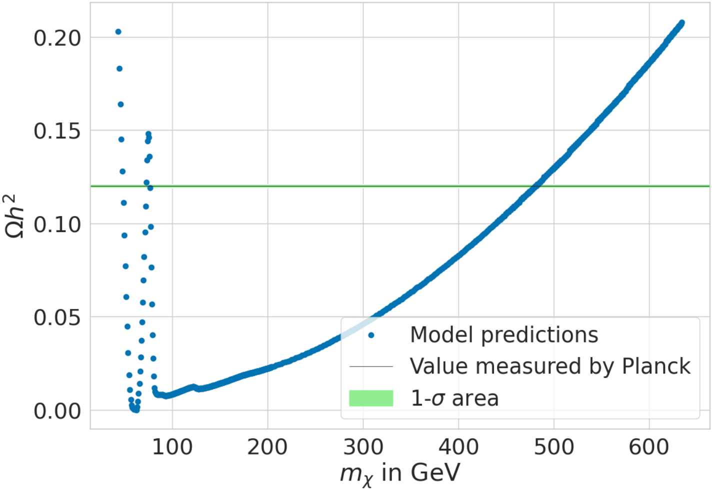
- Relic density upper bound from `Planck`.
- Spin independent (SI) DM-nucleon direct detection cross section from `XENON-1T`.
- The lightest CP-even Higgs mass constraints from LHC.
- Collider limits on heavy higgses from LHC and LEP.
- Flavour physics constraints: BR(B$\to s\gamma$), BR(B$\to \mu^+\mu^-$).

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`

Constraints from relic density



Direct detection cross-section

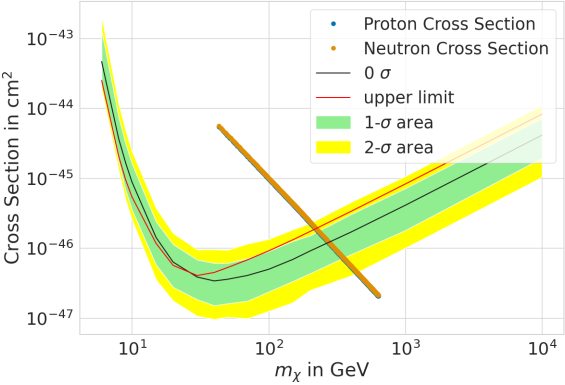
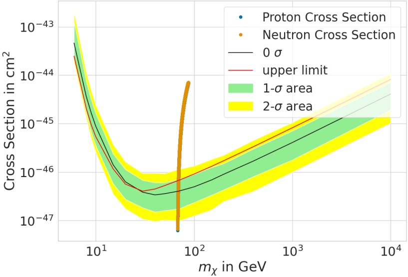


Figure: Variation of the direct detection cross-section against mass of the dark matter candidate, m_χ.

Variation of other parameters

- Low DM mass regions severely constrained from `Xenon-1T` data.
- Recall, the higgs couples to the DM via the portal couplings λ'_1, λ'_2 and $\tan\beta$.
- 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 $\tan\beta$.



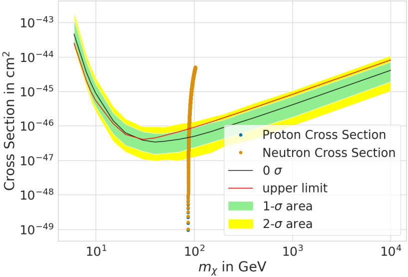


Figure: Variation of the direct detection cross section with m_χ for varying λ_2' for two values of $\tan\beta = 5, 20$ (left,right).

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

Direct detection cross-section

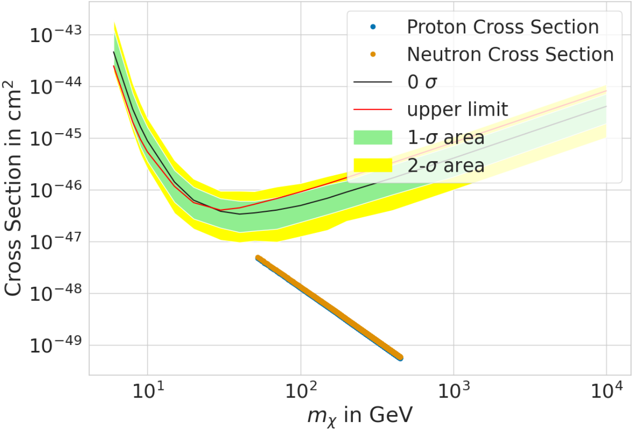


Figure: Variation of Direct detection cross-sections with the mass of the DM.

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

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**.

Presence of invisible modes $\to$ source of missing energy at colliders.

Collider probes: At LHC (ongoing)

- Important production modes: gluon fusion (ggF), vector boson fusion (VBF), ZH
- Possible collider channels: Mono-j + $\not{E}_T$, $jj + \not{E}_T$
- Dominant SM backgrounds: $W + j$,$Z + j$, QCD, $t\bar{t}$, $h + jj$, diboson channels

Summary

- We explore models with two higgs doublet and extra SM singlet complex scalar dark matter (DM) as compared to the SM.
- Such a model is motivated from baryogenesis, gravitational waves, dark matter and inflationary point of view.
- The Higgs sector consists of $h, H, A, H^{\pm}$ where h, H is the CP-even scalar and A, pseudoscalar and the singlet as the DM candidate.
- The DM candidate interacts with the SM particles only via the higgses.
- Possible to obtain suitable parameter points allowed by DM, Higgs and flavour 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
λ_1''	0.1
λ_3''	0.1
λ_1'	0.042
λ_2'	0.042
λ_4'	0.1
λ_5'	0.1
$m_S^{2\prime}$	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.