

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

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CLUSTER OF EXCELLENCE  
QUANTUM UNIVERSE

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- 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

- 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	$Z_2$	$Z'_2$
$\Phi_1$	+1	+1
$\Phi_2$	-1	+1
$S$	+1	-1

**Table:** The quantum numbers of the Higgs doublets  $\Phi_1, \Phi_2$  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  $\Phi_2$  and down-type quarks and leptons couple to  $\Phi_1$ .

# Higgs(es) as portal to dark matter

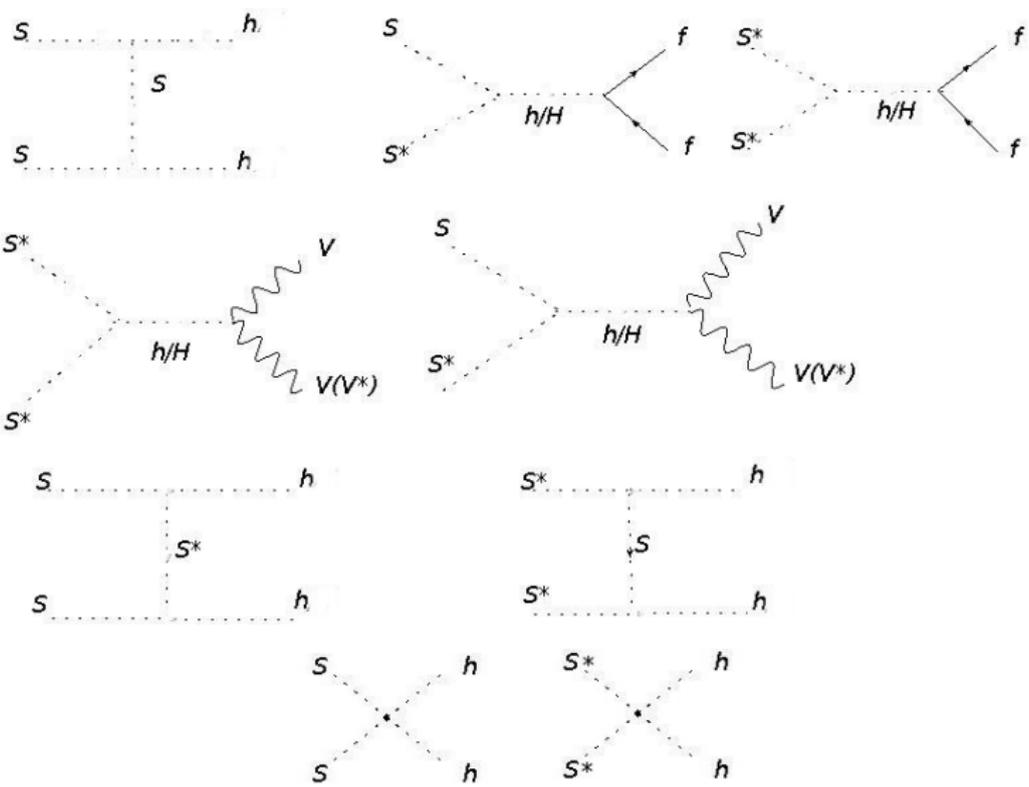
- The dark matter candidate couples to the CP-even higgses at tree-level.
- Relevant couplings of the higgses to the DM,

$$\lambda_{hSS^*} \propto i \frac{1}{\sqrt{1 + \tan^2 \beta}} (\lambda'_1 \sin \alpha - \lambda'_2 \cos \alpha \tan \beta)$$

$$\lambda_{HSS^*} \propto -i \frac{1}{\sqrt{1 + \tan^2 \beta}} (\lambda'_1 \cos \alpha + \lambda'_2 \sin \alpha \tan \beta)$$

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  $\Phi_i$  and  $\tan \beta = \frac{v_2}{v_1}$ .

# Relic Density



- 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

# Constraints from relic density

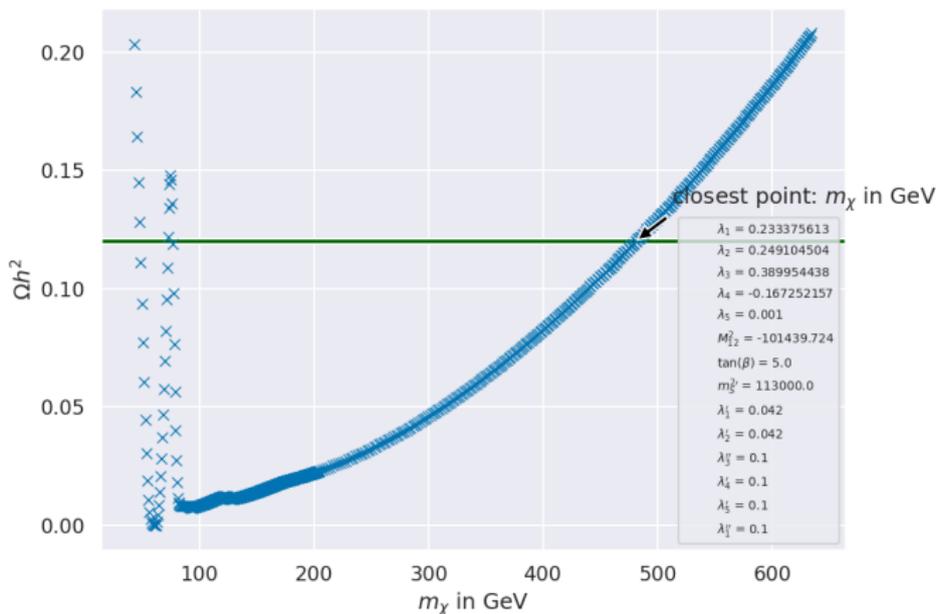


Figure: Variation of the relic density with the mass of the DM candidate,  $m_\chi$ .

# 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  $\lambda'_2$  and  $\tan \beta$ .

# Variation of direct detection cross-section with $\lambda'_2$

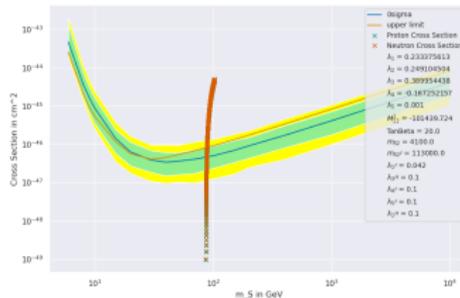
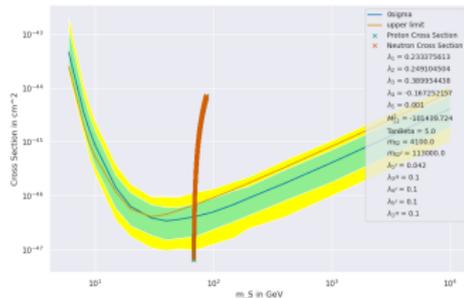


Figure: Variation of the direct detection cross section with  $m_\chi$  for varying  $\lambda'_2$  for two values of  $\tan \beta = 5, 20$  (left, right).

$\implies$  low  $\lambda'_2$  satisfies  $\sigma^{SI}$  easily.



# Representative benchmarks

Parameters	BP1	BP2	BP3
$\lambda_1$	0.23	0.1	0.23
$\lambda_2$	0.25	0.26	0.26
$\lambda_3$	0.39	0.10	0.2
$\lambda_4$	-0.17	-0.10	-0.14
$\lambda_5$	0.001	0.10	0.10
$m_{12}^2$ (GeV <sup>2</sup> )	$-1.0 \times 10^5$	$-1.0 \times 10^5$	$-1.0 \times 10^5$
$\lambda_1''$	0.1	0.1	0.1
$\lambda_3''$	0.1	0.1	0.1
$\lambda_1'$	0.042	0.04	2.0
$\lambda_2'$	0.042	0.001	0.01
$\lambda_4'$	0.1	0.1	0.1
$\lambda_5'$	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
$\Omega h^2$	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		
	<b>BP1</b>	<b>BP2</b>	<b>BP3</b>
$H \rightarrow b\bar{b}$	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, ZH.
- Possible collider channels: Mono-j +  $\cancel{E}_T$ ,  $jj + \cancel{E}_T$ ,  $l^+l^- + \cancel{E}_T$

- 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  $\lambda'_2$  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.



Backup

# Scan parameters

Parameters	Values
$\lambda_1$	0.23
$\lambda_2$	0.25
$\lambda_3$	0.39
$\lambda_4$	-0.17
$\lambda_5$	0.001
$m_{12}^2$	$-1.0 \times 10^5$
$\lambda_1''$	0.1
$\lambda_3''$	0.1
$\lambda_1'$	0.042
$\lambda_2'$	0.042
$\lambda_4'$	0.1
$\lambda_5'$	0.1
$m_S^{2'}$	$1.13 \times 10^5$
$m_h$	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.