Phenomenology of Dark Matter in Two Higgs doublet and complex singlet model

Juhi Dutta
in collaboration with Prof. Gudrid Moortgat-Pick and Merle Schreiber

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II. Institute of Theoretical Physics, University of Hamburg
Cluster of Excellence, Quantum Universe
juhi.dutta@desy.de

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Introduction

- Extensions of the two higgs doublet models with complex singlet scalar (THDM-CS) motivated from baryogenesis, gravitational waves, dark matter and inflation.

- The complex scalar singlet serves as the dark matter (DM) candidate and interacts with the SM particles only via the higgses.

The Model

- We consider a softly broken Z_2 symmetric two higgs doublet model (THDM) extended with a complex singlet scalar (S), the DM candidate stabilised under Z_2'.
- 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 scalar singlet S under $Z_2 \times Z_2'$.

The Scalar Potential

$$\mathcal{V}_{THDMCS} = \mathcal{V}_{THDM} + \mathcal{V}_S$$

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

$$\mathcal{V}_S = m_S^2 S^\dagger S + (\frac{m_{S'}^2}{2} S^2 + h.c.) + (\frac{\lambda_1''}{24} S^4 + h.c.) + \frac{\lambda_1''}{6}(S^2 (S^\dagger S) + h.c.) + \frac{\lambda_3''}{4}(S^\dagger S)^2 + [S^\dagger S(\lambda_1' \Phi_1^\dagger \Phi_1 + \lambda_2' \Phi_2^\dagger \Phi_2)] + [S^2(\lambda_4' \Phi_1^\dagger \Phi_1 + \lambda_5' \Phi_2^\dagger \Phi_2) + h.c.]$$

Baum,Shah JHEP 12 (044) 2018

Particle Spectrum

- The higgs sector for the CP-conserving THDM-CS is the same as in the THDM since the singlet S doesnot obtain a vev.
- It consists of $h, H, A, H^{\pm}$ where h, H are the CP-even scalars, A is the pseudoscalar and $H^{\pm}$, the charged higgses.
- 16 parameters in the model

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

where $\tan\beta = \frac{v_2}{v_1}$ is the ratio of the vacuum expectation values of Φ_2, Φ_1 respectively while α is the mixing angle in the CP-even higgs sector.

Phenomenological constraints

- Relic density upper bound from Planck.
- Spin-independent DM-nucleon direct detection cross section from XENON-1T.
- Lightest CP-even Higgs mass 125 GeV.
- Collider limits on heavy higgses from colliders.
- 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`

Benchmark scenario

Parameters	**BP1**
m_{12}^2	-1.014×10^5
λ_1	0.233
λ_2	0.249
λ_3	0.389
λ_4	-0.167
λ_5	0.001
λ_1''	0.1
λ_3''	0.1
λ_1'	0.04
λ_2'	0.04
λ_4'	0.1
λ_5'	0.1
m_h	125.1
m_H	724.4
m_A	724.4
$m_{H^\pm}$	728.3
$\tan\beta$	5
m_χ	338.9
Ωh^2	0.059
$\sigma_{SI}^n \times 10^{11}$ (pb)	7.55

Table: Relevant parameters of the benchmark.Mass parameters are in GeV units.

Some favourable regions of the parameter space: Relic Density

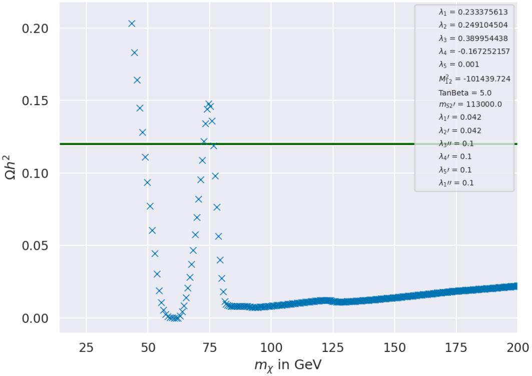

Figure: Variation of the relic density with the mass of the DM candidate, m_χ. Here, the mass parameter m_S^2 is varied.

Spin-independent direct detection cross section

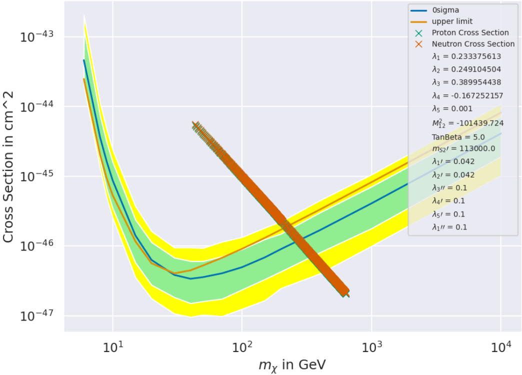

Figure: Variation of the spin-independent direct detection cross section with the mass of the DM candidate, m_χ and compared to the limits from XENON-1T. Here, the mass parameter m_S^2 is varied.

Variation of other parameters

- Some relevant couplings of the higgs to the DM candidate are:

$$\lambda_{hSS} = \lambda_{hS^*S^*} = 2i\frac{v}{\sqrt{1+\tan^2\beta}}(\lambda'_4 \sin\alpha - \lambda'_5 \tan\beta\cos\alpha)$$

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

- We vary the other parameters in the scalar potential for the singlet: $\lambda'_1, \lambda'_2, \lambda'_4, \lambda'_5$ and $\tan\beta$ individually.

Variation of direct detection cross section with λ_2'

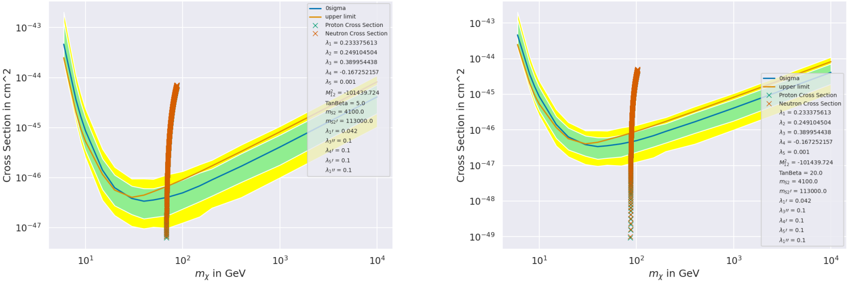

Figure: Variation of the direct detection cross section with mass of the DM, m_χ for varying λ_2' for two values of $\tan\beta = 5, 20$ (left,right).

- so far observed strongest effect on the cross section via λ_2'.
- low λ_2' favoured for agreement with direct detection limits

Variation of relic density on $\tan\beta$

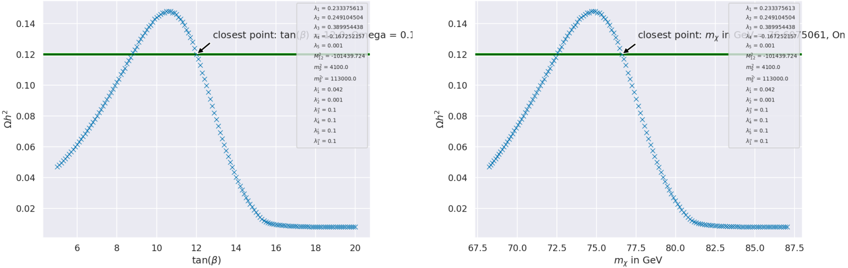

Figure: Variation of relic density with $\tan\beta$ (left) and mass of the DM, m_χ (right) for $\lambda_2' = 0.001$.

Benchmark point with DM mass, $m_\chi \sim 77$ GeV satisfies both thermal relic and direct detection cross section.

Summary

- Extensions of THDM with complex scalar singlet provide a potential DM candidate.
- We explore the parameter space satisfying DM constraints and accomodating a light 125 GeV Higgs.
- Possibility of obtaining light and heavy DM with mass ~ 77 GeV and heavy DM ~ 339 GeV respectively.

Ongoing work

- Comparison with another existing DM code `madDM`.
- Constraints from the Higgs signal strengths in the light DM mass range.
- Collider phenomenology on model determination and distinction $\rightarrow$ LHC, LC, and beyond.

Thank You!