Dark Matter Phenomenology in THDM-CS

Juhi Dutta, Merle Schreiber and Gudrid Moortgat-Pick

THDM Working group report (ongoing)

January 14, 2021

Motivation and aim

- Extensions of the THDM with a complex scalar singlet are motivated from baryogenesis, gravitational waves, dark matter and inflationary point of view.
- Our study aims to study the prospects for dark matter in the context of THDM-CS model.

The Model

- We consider a softly broken Z_2 symmetric THDM and conserved Z_2' symmetric singlet potential.
- The quantum numbers of the fields are

Scalar Fields	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

$$\mathcal{V}_{THDMCS} = \mathcal{V}_{2HDM} + \mathcal{V}_S + \mathcal{V}_{HS}$$

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

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

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

(Baum,Shah, *JHEP 12 (2018) 044*)

Mass spectrum

- The Higgs sector same as in the THDM,i.e, $h, H, A, H^{\pm}$ since the singlet S has $v_s = 0$.
- The mass of the dark matter S at tree-level is

$$m_{\chi}^2 = 2m_S^2 + 2m_S^{2\prime} + (\lambda_1' + 2\lambda_4')\frac{v_1^2}{2} + (\lambda_2' + 2\lambda_5')\frac{v_2^2}{2}.$$

where $\tan\beta = \frac{v_1}{v_2}$.

16 free parameters of the model

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

Benchmark scenario

Parameters	**BP1**
m_{12}^2	-1.014$\times 10^5$
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'	0.042
λ_2'	0.042
λ_4'	0.1
λ_5'	0.1
m_h	125.07
m_H	724.4
m_A	724.4
$m_{H\pm}$	728.3
$\tan\beta$	5
m_{DM}	338.9
Ωh^2	0.059
$\sigma_{DD}^n \times 10^{11}$ (pb)	7.55

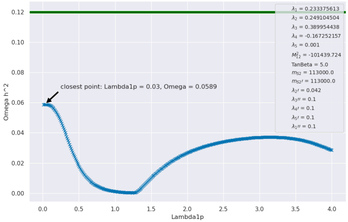
Relevant parameters of the benchmark used for the study. All mass parameters have units GeV except for m_{12}^2 in GeV^2

The Plan

- Start from Benchmark point BP1
- Vary potential parameters one at a time
- See their influence on DM relic density and Direct Detection
- Look for interesting regions

- Interesting DM observables
  - Relic density
  - Direct detection cross section
  - singlet DM mass

- Varied Parameters:
  - $\tan(\beta)$
  - λ'_1, λ'_2, λ'_4, λ'_5
  - m_S^2
  - λ''_1, λ''_3



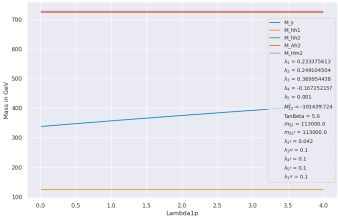
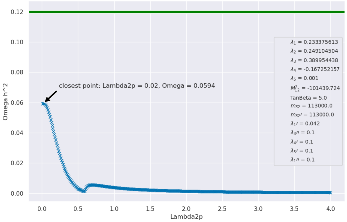


Figure: Relic density (left) and mass spectrum (right) in dependence of λ_1'



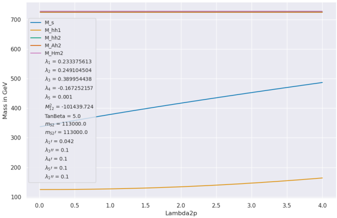
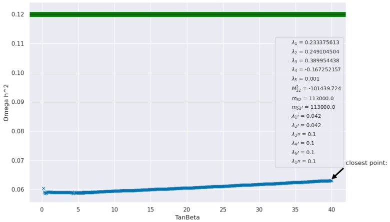


Figure: Relic density (left) and mass spectrum (right) in dependence of λ_2'



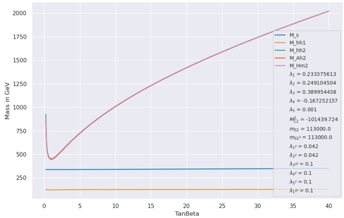


Figure: Relic density (left) and mass spectrum (right) in dependence of $\tan(\beta)$

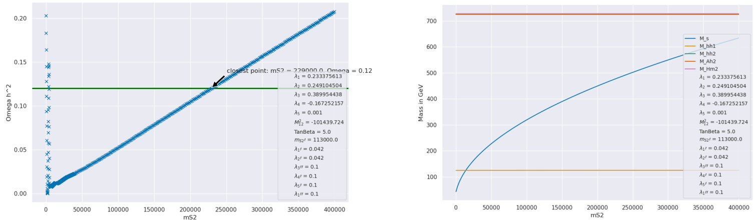


Figure: Relic density (left) and mass spectrum (right) in dependence of m_S^2

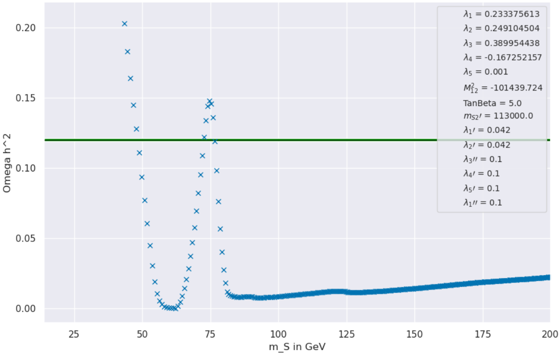


Figure: Relic density in dependence of the Singlet mass controlled by m_S^2

- Interesting changes for low m_S^2
- For Singlet mass around $\frac{m_h}{2}$ pair annihilation channel via SM Higgs opens up

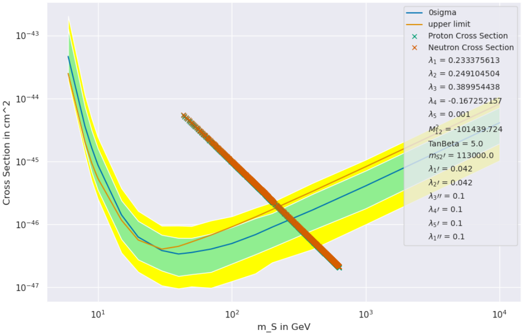


Figure: Direct detection cross section in comparison to upper bounds of XENON. Cross section in dependence of m_S^2. Data from: [XENON Collaboration 2018. arXiv-1805.12562, Phys. Rev. Lett. 121, 111302]

For low m_S^2 (also low singlet mass) the nuclear cross section in Direct Detection exceeds the upper bounds by Xenon measurements

How to find a fitting parameter point?

- Want to keep Light Singlet
- Focus on direct detection limits
- See which parameters influences Direct Detection most
- See if very low λ_1'' and λ_3'' change the picture
- See how $\lambda_i',\ i = 1, 2, 4, 5$ dependencies change for extreme $\tan(\beta)$

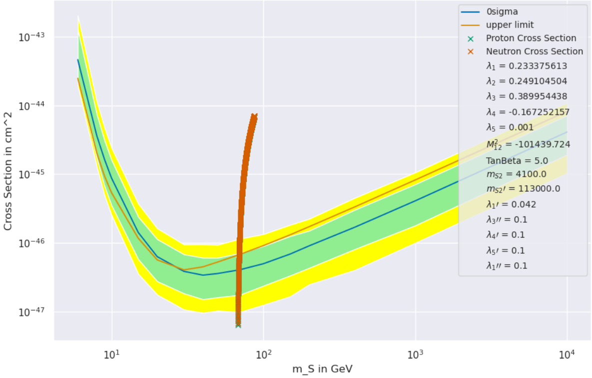
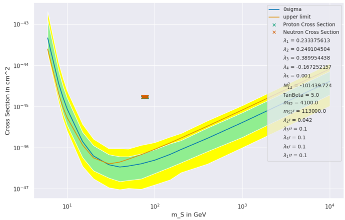
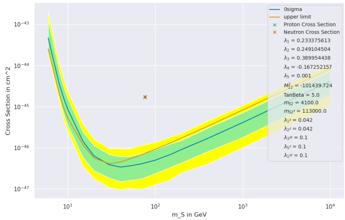


Figure: Direct detection cross section in dependence of λ_2'

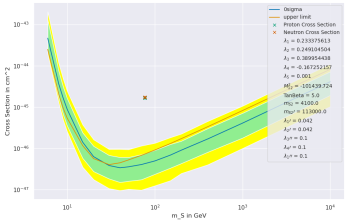
λ_2' has strongest impact on direct detection. Independent of $\tan(\beta)$



(a) λ_1' dependence



(b) λ_4' dependence



(c) λ_5' dependence

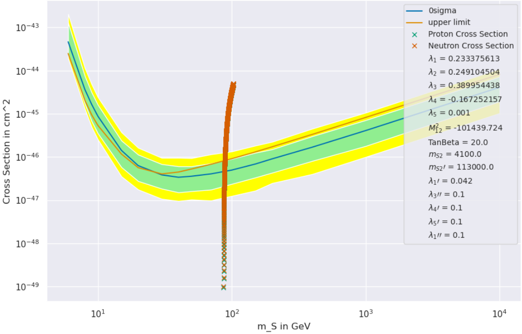


Figure: λ_2' dependence of direct detection cross section for $\tan(\beta) = 20$

Agreement with upper bounds gets better for high $\tan(\beta)$
$\rightarrow$ choose low $\lambda_2' = 0.001$ and see which $\tan(\beta)$ fulfils the direct detection bounds and fits the measured relic density best

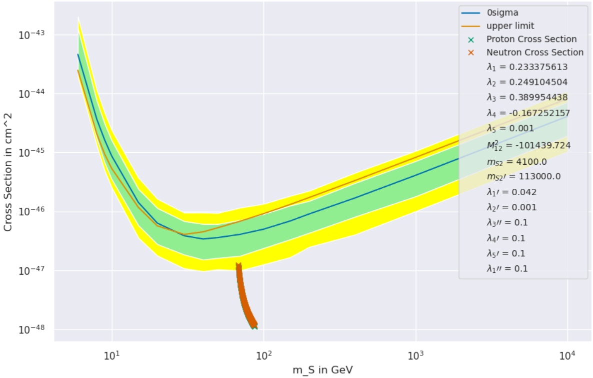


Figure: Direct Detection cross section for $\lambda_2' = 0.001$ depending on the singlet mass controlled by $\tan(\beta)$

Direct detection limit is fulfilled for all $\tan(\beta)$

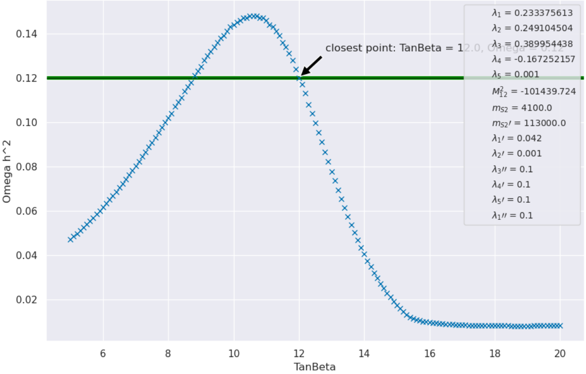


Figure: Relic density in dependence of $\tan(\beta)$ for $\lambda_2' = 0.001$

$\rightarrow$ Choose $\tan(\beta) = 12$

Finally there is a parameter point with a light singlet which fulfils the upper bound on Direct Detection and that features a relic density slightly below the value measured by Planck. The parameters λ_i $i = 1, 2, 3, 4$ stay the same as for the starting point

Table: Parameter point light singlet

$\tan(\beta)$	m_S^2	$m_S'^2$	λ_1'	λ_2'	λ_3''	λ_4'	λ_5'	λ_1''
12.0	4.1×10^3	1.13×10^5	0.042	0.001	0.1	0.1	0.1	0.1

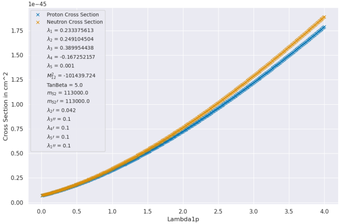
With a Singlet mass of 77GeV

Ongoing work

- Checking the collider constraints on the light singlet DM
- Comparison of real and complex scalar DM

Thank you for your attention!

Backup



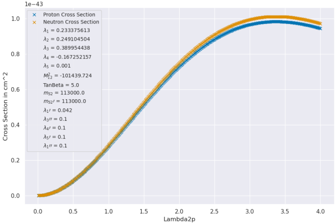


Figure: Direct detection cross section in dependence of λ_1' (left) and λ_2' right

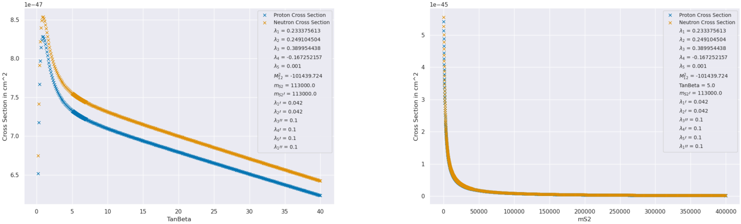


Figure: Direct detection cross section in dependence of $\tan(\beta)$ (left) and m_S^2 (right)

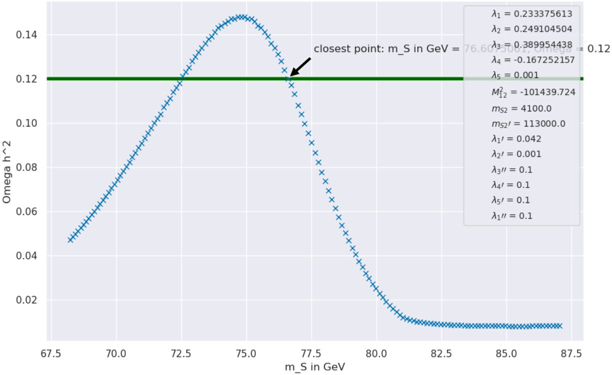


Figure: Direct detection cross section in dependence of the singlet mass controlled by m_S^2 in th light singlet case

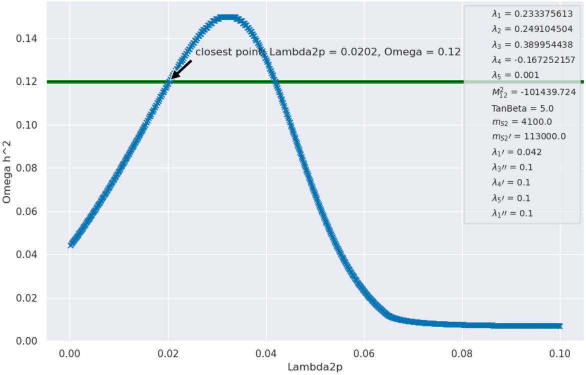


Figure: Direct detection cross section in dependence of λ_2' in the light singlet case