Phenomenology of the Dark Matter sector in the Two Higgs Doublet Model with Complex Scalar Singlet extension

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Extensions of the Two Higgs Doublet model with a complex scalar singlet (2HDM) may accommodate all current experimental constraints and are highly motivated candidates for Beyond Standard Model Physics. In this work, we focus on the phenomenology of the 2HDM with the complex scalar singlet as the dark matter candidate. We study variations of dark matter observables with respect to the model parameters and present representative benchmark points allowed by existing experimental constraints from dark matter, flavour physics and collider searches. Further, we discuss the discovery potential of observing such scenarios at future colliders.
1. Introduction

Dark Matter (DM) remains a pertinent puzzle at the interface of particle physics and cosmology. In the absence of a suitable DM candidate in the Standard Model (SM), it is imperative to look beyond the SM. Several Beyond Standard Model (BSM) extensions have been proposed to accommodate DM candidates ranging from scalar, fermion to vector candidates. The simplest choice of a SM gauge singlet scalar has been extensively considered as minimal extensions to the SM [1, 14–16]. With the 125 GeV Higgs as the portal to the dark sector, these models are constrained stringently by results from DM-nucleon direct detection searches [10].

Extended Higgs sector models, such as the Two Higgs Doublet model (2HDM)[5], provide additional portals to the dark sector via the heavy CP-even Higgses in addition to the 125 GeV SM-like Higgs. While special cases of the 2HDM, namely the Inert Doublet model can account for dark matter, an alternate candidate for dark matter in multi-Higgs models, in general, are minimal extensions with SM gauge singlet scalars as the DM candidate. Extended versions of 2HDM dark matter, an alternate candidate for dark matter in multi-Higgs models, in general, are minimal SM-like Higgs. While special cases of the 2HDM, namely the Inert Doublet model can account for additional portals to the dark sector via the heavy CP-even Higgses in addition to the 125 GeV Higgs as the portal to the dark sector, these models are constrained stringently by results from DM-nucleon direct detection searches [10].

Extended Higgs sector models, such as the Two Higgs Doublet model (2HDM)[5], provide additional portals to the dark sector via the heavy CP-even Higgses in addition to the 125 GeV SM-like Higgs. While special cases of the 2HDM, namely the Inert Doublet model can account for dark matter, an alternate candidate for dark matter in multi-Higgs models, in general, are minimal extensions with SM gauge singlet scalars as the DM candidate. Extended versions of 2HDM involving real scalar singlet have been extensively studied[3, 8, 9] while complex scalar extensions to the 2HDM are also recently studied in the context of modified Higgs sectors[6] and some specific cases of dark matter study in the U(1) symmetric case[13]. In this work, we discuss the dark matter sector in the Two Higgs Doublet model extended with a complex scalar singlet (2HDMs) under a conserved $Z'_2$ symmetry stabilising the dark matter candidate.

2. The Model

We consider the CP-conserving Type II Two Higgs Doublet model augmented with a complex scalar singlet (2HDMs)[6] to avoid flavour changing neutral currents (FCNCs) at tree-level. We consider the soft $Z_2$ symmetry breaking consistent with flavour changing neutral currents (FCNCs) while explicit $Z_2$ breaking terms are absent. The complex scalar singlet $S$ is stabilised by a $Z'_2$ symmetry such that $S$ is odd under $Z'_2$ while the SM fields are even under the new $Z'_2$ symmetries as given in Table 1. The $Z'_2$ is assumed to remain unbroken both explicitly and dynamically, i.e., the singlet does not obtain a vev. Therefore, the scalar potential $V$ with a softly broken $Z'_2$- and a conserved $Z'_2$-symmetry is

$$V = V_{2HDM} + V_S$$

where, the softly broken $Z_2$-symmetric 2HDM potential is

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

$$+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{\lambda_6}{2} (\Phi_1^2 \Phi_2^2 + h.c.)$$

and the $Z'_2$-symmetric singlet potential, $V_S$, is

$$V_S = m_S^2 S^\dagger S + \left( \frac{m_{12}^2}{2} S^2 + h.c. \right) + \left( \frac{\lambda'}{2} (S^2 S^\dagger S + h.c.) \right) + \frac{\lambda''}{4} (S^\dagger S)^2$$

$$+ S^\dagger S [\lambda'_1 \Phi_1^\dagger \Phi_1 + \lambda'_2 \Phi_2^\dagger \Phi_2] + [S^2 (\lambda''_1 \Phi_1^\dagger \Phi_1 + \lambda''_2 \Phi_2^\dagger \Phi_2) + h.c.]$$.

After electroweak symmetry breaking (EWSB), the free parameters in the model are

1. The positive sign convention is used for $m_{12}^2$ as used for Type II 2HDM implementation in SARAH.
2. For simplicity, we set $\lambda''_1 = \lambda''_2$ without loss of generality throughout our study.
\[
\begin{array}{c|cc}
\text{Fields} & Z_2 & Z'_2 \\
\hline
\Phi_1 & +1 & +1 \\
\Phi_2 & -1 & +1 \\
S & +1 & -1 \\
\end{array}
\]

**Table 1:** The quantum numbers of the Higgs doublets and the singlet under the \(Z_2\)- and \(Z'_2\)-symmetry.

\[
\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, m^2_{12}, \tan \beta, \alpha, \lambda'_1, \lambda''_1, m^2_S, m^2_S', \lambda'_2, \lambda'_3, \lambda'_4.
\]

Here, \(\tan \beta = \frac{v_2}{v_1}\) is the ratio of the vev’s of the up-type and down-type Higgs doublet denoted by \(v_1 = v \cos \beta\) and \(v_2 = v \sin \beta\) respectively where \(v(= v_1^2 + v_2^2) \approx 246 \text{ GeV}\) is the electroweak vev while \(\alpha\) is the mixing angle in the CP-even Higgs sector.

### 3. Results

We examine the case when the complex singlet scalar does not develop a vacuum expectation value (vev), i.e., imposing \(v_s = 0\) where \(v_s\) is the singlet scalar vev and the complex scalar \(S\) acts as a dark matter candidate. Since the only tree-level interactions of the dark matter to the SM particles is via the Higgses which act as scalar mediators, stringent constraints arise from spin independent DM-nucleon direct detection searches from XENON-1T\[10\]. In Fig. 1, we show the variation of the relic density and spin-independent direct detection cross-sections against the mass of the dark matter candidate, \(m_\chi\). We observe that the large fraction of the parameter space is under-abundant except for \(m_\chi = 76 \text{ GeV}\) and \(m_\chi = 480 \text{ GeV}\) where thermal relic density may be achieved. However such low dark matter mass regions face stringent constraints from direct detection searches thus requiring the portal coupling \(\lambda'_2\) to be restricted to low values. Based on these results, we select a representative benchmark point as shown in Table. 2 satisfying the DM constraints along with constraints from the Higgs sector, namely bounds on the heavy Higgses as well as the mass and signal strengths of the 125 GeV-like Higgs.

![Figure 1](image-url): Relic density and direct detection cross-section predicted by the model depending on the DM mass \(m_\chi\)[4].
In presence of the dark matter, there are additional decay channels opening up for the heavy Higgs, $H \rightarrow \chi \bar{\chi}$. The presence of the invisible DM candidate in the final state ensures the presence of missing energy in the final state signal at colliders. We consider this case in BP where the allowed invisible branching of the Higgses is $\sim 4.8\%$ being severely constrained from direct detection searches. Owing to the small invisible branching ratio and heavy Higgs masses $\sim 820$ GeV (and hence small production cross section), the final states are inaccessible at the upcoming HL-LHC run using a simple cut-and count analysis[4]. Therefore, we discuss the prospects of observing such a benchmark at the $e^+e^-$ collider. We consider the final state $2b + E_T$ where $E_T$ is the missing transverse energy carried by the invisible dark matter candidate at future $e^+e^-$ collider at $\sqrt{s} = 3$ TeV. Dominant SM contributions to these arise from $b\bar{b} \nu \bar{\nu}, t\bar{t}, ZZZ, t\bar{t}Z$. Since the signal is characterised by large missing transverse energy, kinematic variables such as $E_T$, effective mass $M_{eff}(= \Sigma_j p_{Tj} + E_T)$ (where $j$ runs over the jets) and the azimuthal separation angle $\Delta \Phi$ between the two $b$-jets are instrumental in suppressing the SM background as shown in Fig. 2. We summarise the cut-flow table in Table 3.

Table 2: Relevant parameters of the benchmark point used for the study[4].

| Parameters | BP |
|-----------|----|
| $\tan \beta$ | 6.5 |
| $m_h$ (GeV) | 125.09 |
| $m_H$ (GeV) | 821.7 |
| $m_A$ (GeV) | 817.9 |
| $m_{H^+}$ (GeV) | 822.2 |
| $m_\chi$ (GeV) | 323.6 |
| $BR(H \rightarrow \chi \bar{\chi})$ | 4.8% |
| $\Omega h^2$ | 0.05 |
| $\sigma^S_{p} \times 10^{10}$ (pb) | 2.9 |
| $\sigma^S_{n} \times 10^{10}$ (pb) | 3.1 |

Table 3: The cut-flow table showing the change in the number of events for for benchmark BP for the unpolarised electron and positron at $\sqrt{s} = 3$ TeV at $L = 5$ ab$^{-1}$.

| Process | $p_T(b) > 100$, 80 GeV | $t = [80 < M_{bb} < 130]$ | $M_{eff} > 1.2$ TeV | $E_T > 650$ GeV | $\Delta \Phi(b_1, b_2) < 1.60$ |
|---------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| $bbH$ | 27 | 26 | 26 | 25 | 21 |
| $t\bar{t}H$ | 13 | 12 | 12 | 11 | 10 |
| $HA$ | 28 | 24 | 24 | 22 | 20 |
| $BP$ | | | | | 51 |
| $b\bar{b} \nu \bar{\nu}$ | 15738 | 2040.9 | 330.3 | 147.6 | 124.3 |
| $b\bar{b}$ | 8432.5 | 8387.2 | 6697.5 | 65.6 | 4.07 |
| $ZZZ$ | 3.75 | 3.07 | 1.5 | 0.51 | 0.28 |
| $t\bar{t}Z$ | 5.68 | 5.6 | 4.04 | 0.71 | 0.35 |
| $t\bar{t}$ (semi-leptonic) | 2843.9 | 2818.8 | 2500.6 | 338.5 | 16.61 |
| $t\bar{t}$ (leptonic) | 481.5 | 478.3 | 401.9 | 29.65 | 1.13 |
| Total background | | | | | 146.4 |
| Significance | | | | | 3.99 |
4. Summary and Conclusions

We consider the Two Higgs Doublet model extended with a complex singlet scalar (2HDMS) and focus on a Type II softly broken $Z_2$ symmetric 2HDM scalar potential augmented with a complex scalar symmetric under $Z'_2$ stabilizing the dark matter candidate. Under the assumption that the complex scalar singlet does not develop a vacuum expectation value, the singlet scalar acts as the dark matter candidate, while the Higgs spectrum remains the same as in 2HDM with the CP-even Higgses act as a portal to the dark matter. We explore the parameter space allowed by current experimental data. We observe that direct detection results stringently constrain the parameter space and therefore requiring low values of $\lambda'_2$. Presence of the singlet also leads to new invisible decay modes for the Higgses leading to the presence of missing energy at colliders. We choose a representative benchmark BP with $m_H \approx 820 \text{ GeV}$ consistent with all experimental data in order to demonstrate the prospects of observing such a signal at HL-LHC and future $e^+e^-$ colliders. We perform a signal-background analysis at the $e^+e^-$ collider with $\sqrt{s} = 3 \text{ TeV}$ with unpolarised beams and observe that the $2b + E_T$ channel is observable with $a = 3.99\sigma$ significance at integrated luminosity $L = 5 \text{ ab}^{-1}$.

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