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

Juhi Dutta,[a,*] **Gudrid Moortgat-Pick**[a,b] **and Merle Schreiber**[a]

[a] *II.Institute of Theoretical Physics, University of Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany*

[b] *Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany*

E-mail: juhi.dutta@desy.de, gudrid.moortgat-pick@desy.de, merle.schreiber@desy.de

Extensions of the Two Higgs Doublet model with a complex scalar singlet (2HDMS) 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 2HDMS 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.

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*Speaker

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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 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' symmetryas given in Table 1. The Z_2' is assumed to remain unbroken both explicitly and dynamically, i.e,the singlet doesnot obtain a vev. Therefore, the scalar potential V with a softly broken Z_2- and a conserved Z_2'-symmetry is

$$V = V_{2HDM} + V_S \tag{1}$$

where, the softly broken Z_2-symmetric 2HDM potential is[1]

$$\begin{aligned} V_{2HDM} &= m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 + (m_{12}^2\Phi_1^\dagger\Phi_2 + h.c) + \tfrac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \tfrac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 && (2)\\ &\quad +\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + [\tfrac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + h.c] && (3)\end{aligned}$$

and the Z_2'-symmetric singlet potential, V_S, is

$$\begin{aligned} V_S &= m_S^2 S^*S + (\tfrac{m_S^{2\prime}}{2}S^2 + h.c) + (\tfrac{\lambda_1''}{24}S^4 + h.c) + (\tfrac{\lambda_2''}{6}(S^2S^*S) + h.c) + \tfrac{\lambda_3''}{4}(S^*S)^2 && (4)\\ &\quad +S^*S[\lambda_1'\Phi_1^\dagger\Phi_1 + \lambda_2'\Phi_2^\dagger\Phi_2] + [S^2(\lambda_4'\Phi_1^\dagger\Phi_1 + \lambda_5'\Phi_2^\dagger\Phi_2) + h.c.]. && (5)\end{aligned}$$

After electroweak symmetry breaking (EWSB), the free parameters in the model are[2]

[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.

Fields	Z_2	Z_2'
Φ_1	+1	+1
Φ_2	-1	+1
S	+1	-1

Table 1: The quantum numbers of the Higgs doublets and the singlet under the Z_2- and Z_2'-symmetry.

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

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 $v (= v_1^2 + v_2^2) \simeq 246$ GeV is the electroweak *vev* while α 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_χ. We observe that the large fraction of the parameter space is under-abundant except for $m_\chi = 76$ GeV and $m_\chi = 480$ 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 λ_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.

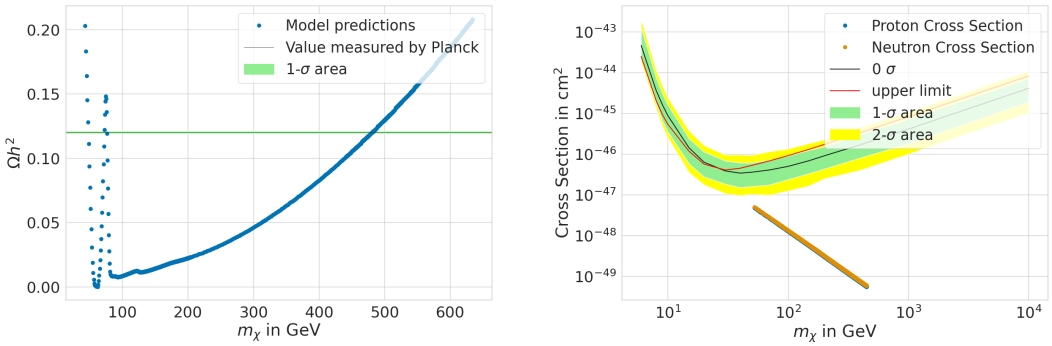

Figure 1: Relic density and direct detection cross-section predicted by the model depending on the DM mass m_χ[4].

Parameters	**BP**
$\tan\beta$	6.5
m_h (GeV)	125.09
m_H(GeV)	821.7
m_A(GeV)	817.9
$m_{H^\pm}$ (GeV)	822.2
m_χ(GeV)	323.6
$BR(H \to \chi\bar{\chi})$	4.8%
Ωh^2	0.05
$\sigma_p^{SI} \times 10^{10}$ (pb)	2.9
$\sigma_n^{SI} \times 10^{10}$ (pb)	3.1

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

In presence of the dark matter, there are additional decay channels opening up for the heavy Higgs, $H \to \chi\bar{\chi}$. 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 ~4.8% being severely constrained from direct detection searches. Owing to the small invisible branching ratio and heavy Higgs masses ~ 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 $M_{eff}(= \Sigma_j p_{T_j} + E_T)$ (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.

Process	$p_T(b) > 100, 80$ GeV	! = [80 < M_{bb} < 130]	$M_{eff} > 1.2$ TeV	$E_T > 650$ GeV	$\Delta\Phi(b_1, b_2) < 1.60$
$b\bar{b}H$	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				

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 $\mathcal{L}$ = 5 ab^{-1}.

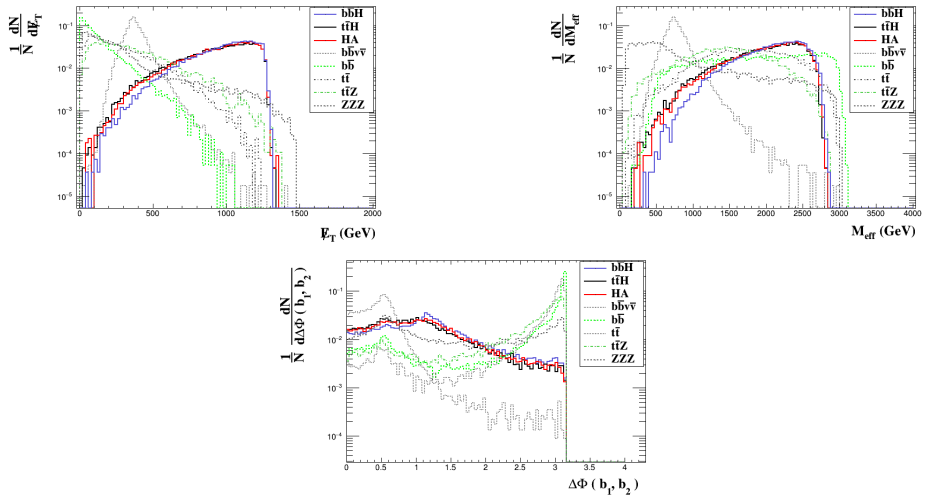

Figure 2: Normalized distribution of missing transverse energy(E_T), effective mass (M_{eff}) and $\Delta\Phi$ between the two b-jets for signal vs. dominant SM backgrounds.

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 λ_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 $m_H \simeq 820$ 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 $\sqrt{s} = 3$ TeV with unpolarised beams and observe that the $2b + E_T$ channel is observable with a = 3.99σ significance at integrated luminosity $\mathcal{L} = 5$ ab^{-1}.

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