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Dark Matter searches in models with extended Higgs sector at lepton colliders

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The Two Higgs Doublet model extended with a complex scalar singlet (2HDMS) is a well-motivated Beyond Standard Model candidate addressing several open problems of nature. In this work, we focus on the dark matter (DM) phenomenology of the complex scalar singlet where the real part of the complex scalar obtains a vacuum expectation value. The model is characterized by an enlarged Higgs spectrum comprising six physical Higgs bosons and a pseudoscalar DM candidate. We address the impact of accommodating the 95 GeV excess on the 2HDMS parameter space and DM observables after including all theoretical and experimental constraints. Finally, we look into the prospects of this scenario at different lepton colliders such as electron-positron colliders as well as a muon collider.

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PoS(ICHEP2024)772

1. The 2HDM with complex singlet extension

The 2HDM with complex singlet extension can accommodate the 95 GeV excess at LHC and LEP as well as the dark matter candidate [3]. This model has two gauge doublet fields Φ_i, Φ_2 and the singlet field S. After the electroweak symmetry breaking, this model generate one charged Higgs boson $H^\pm$ and five neutral Higgs bosons, including three neutral CP-even scalars $m_{h_{1,2,3}}$, and two neutral pseudoscalars A, A_S. The Higgs potential of this model has the $\mathbb{Z}_2'$ symmetry (see Ref. [3]).This $\mathbb{Z}_2'$ symmetry forbid the mixing terms between the singlet pseudoscalar and the doublet pseudoscalar. Consequently, the singlet pseudoscalar would not decay to the other particles, and can be stable in the universe. Eventually, the singlet pseudoscalar A_S becomes the dark matter candidate in this model. The dark matter can still couple to other Higgs bosons, where the dark matter to Higgs portal couplings are given by

$$\frac{\lambda_{h_j A_S A_S}}{v} = -i[(\lambda_1' - 2\lambda_4')c_\beta R_{j1} + (\lambda_2' - 2\lambda_5')s_\beta R_{j2} - \frac{v_S}{2v}(\lambda_1'' - \lambda_3'')R_{j3}], \tag{1a}$$

$$\lambda_{h_j h_k A_S A_S} = -i[(\lambda_1' - 2\lambda_4')R_{j1}R_{k1} + (\lambda_2' - 2\lambda_5')R_{j2}R_{k2} - \frac{1}{2}(\lambda_1'' - \lambda_3'')R_{j3}R_{k3}]. \tag{1b}$$

These two couplings can be both parameterized by the three parameter combinations $\lambda_1'' - \lambda_3''$, $\lambda_1' - 2\lambda_4'$ and $\lambda_2' - 2\lambda_5'$. Therefore the free input parameters of this model are

$$m_{h_{1,2,3}}, m_A, m_{H^\pm}, m_{A_S}, m_{12}, v_S, \tan\beta, \alpha_{1,2,3}, \lambda_1'' - \lambda_3'', \lambda_1' - 2\lambda_4', \lambda_2' - 2\lambda_5' \tag{2}$$

We obtain some interesting benchmark points for our study, which are shown in Tab. 1. The BP55 has a dark matter with the mass around 55 GeV, where the 125 GeV Higgs can decay to the dark matter. The BP2900 has a much heavier dark matter with 1 TeV mass, and the heavy Higgs boson with 2.9 TeV can decay to the dark matter in such benchmark. Both benchmark can accommodate the 95 GeV excess [2], and can be allowed by the theoretical constraints as well as by the experimental constraints, including unitarity, boundedness from below, vacuum stability, BSM Higgs searches, precision measurements of Higgs and the dark matter searches. Particularly, the relic abundance of both points fulfilled the cosmological observation. We perform the scan around the BP2, and the exclusions regions are presented in Figs. 1, which shows a large viable parameter space.

	$\tan\beta$	m_{h_3} (GeV)	m_{A_S} (GeV)	Ωh^2
BP2	6.6	700	325.86	3.16×10^{-4}
BP55	2	650	55.596	0.11
BP2900	5	2900	1000	0.111

Table 1: The input parameters of the benchmark points.

2. Dark matter searches at lepton colliders

We would like to probe the two benchmark scenarios that satisfy the observed relic density, at the lepton colliders, e.g. the electron-positron colliders (ILC [1]) and the muon collider [4]. For the

PoS(ICHEP2024)772

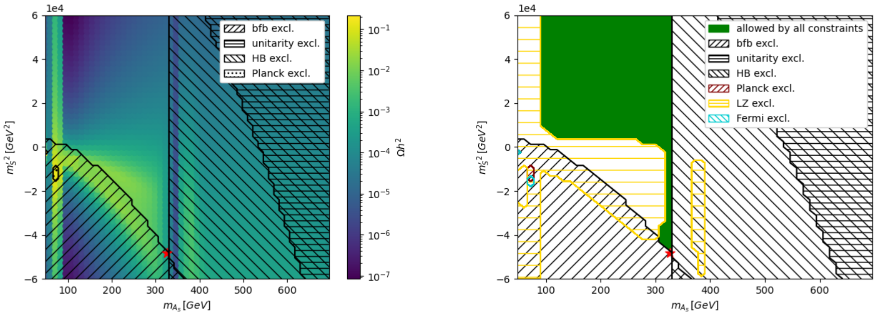

Figure 1: The parameter space of m_{A_S}-$m_S'^2$, where the color code of the left panel denote for the dark matter relic density.

Benchmark	$\mathcal{S}(\sqrt{s}$=250 GeV)	$\mathcal{S}(\sqrt{s}$=500 GeV)	$\mathcal{S}(\sqrt{s}$=1 TeV)	$\mathcal{S}(\sqrt{s}$=3 TeV)
BP2900			–	0.14 (10 ab^{-1})
BP55	4.3 (1 ab^{-1}), 7.4 (3 ab^{-1})	1.2 (1 ab^{-1}), 2.0 (3 ab^{-1})	5.4 (10 ab^{-1}),	0.38 (10ab $^{-1}$)

Table 2: The signal significance of BP2900 mono-photon process at 3 TeV muon collider, and the Signal significance of BP55 at 250 GeV (ILC), 500 GeV (ILC) and 1 TeV (muon collider), 3 TeV (muon collider) in the mono-Z(leptonic) final state.

BP55, the dark matter is light and can be generated via 125 GeV Higgs decay from $e^+e^- \to HZ$. Hence, the future e^+e^- machine can provide a precise measurement via the mono-Z process at 250 GeV. For the BP2900 with the heavy dark matter, the production rate of dark matter at e^+e^- machine would not be ideal, while the muon collider can provide a better prospect to produce the dark matter.

At the muon collider, the heavy dark matter can be produced by $\mu^+\mu^- \to h_3 \to A_S A_S$, and we can measure the corresponding mono-photon process $\mu^+\mu^- \to h_3\gamma \to A_S A_S \gamma$ using the cuts $E_\gamma > 10$ GeV and $|\eta_\gamma| < 2.5$. We have estimated the dominant background $\gamma\nu\bar{\nu}$ cross-section to be 2.447 pb and 2.964 pb at $\sqrt{s} = 1$ and 3 TeV, respectively. The light dark matter scenario BP55 can be probed best via the mono-Z+missing energy in final state, when Z decays into two-leptons. The major contribution to the signal comes from the Higgs-Strahlung process, and the dominant background here comes from $\nu\nu Z$ final state. The signal significances that can be achieved for BP55 and BP2900 at the ILC and the muon collider are given in Table 2.

As we see in Tables 2, both the ILC and the muon collider can provide a very nice sensitivity for the light dark matter scenario, while sensitivity to the heavier dark matter scenario is only achieved by the muon collider and still needs to be improved by more dedicated study.

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PoS(ICHEP2024)772

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PoS(ICHEP2024)772