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Theoretical Overview on novel BSM models

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In this short work, an overview of some BSM Dark Matter models, which can be useful benchmarks for interpreting a broad variety of collider signatures, will be presented.

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1. Introduction

Dark Matter is one of the cornerstones of the program of New Physics searches conducted by LHC. It is crucial to elaborating theoretical benchmark models to interpret the experimental outcomes. Such models should possess the following features: be a good compromise between predictivity (limited amount of free parameters) and theoretical consistency; provide a broad variety of collider signatures; feature an interesting DM phenomenology. Models with SM singlet fermionic DM interacting with SM via extended Higgs sector have such features. We will illustrate below some examples.

2. 2HDM+S/PS

This class of models consists into DM interacting with a Higgs sector composed by two SU(2) doublets, $\Phi_{1,2}$ and a scalar (S) or pseudoscalar (PS) singlet state. See e.g. [1] for more details. After EW symmetry breaking, the neutral components of the doublets and the singlet mix. In the case of the 2HDM+S, the physical spectrum of neutral scalars is made by three CP-even states, h, S_1, S_2 with h being identified with the 125 GeV Higgs and one pseudoscalar state A. In the case of the 2HDM+PS we have two CP-even, h, H, and two CP-odd, a, A states (by convention $M_a < M_A$). In all models the Higgs spectrum is completed by charged states $H^{\pm}$. The couplings, in the mass basis, of the neutral Higgs sector and the SM fermions are described by the following lagrangians:

$$\mathcal{L}^{\text{yuk}}_{2HD+S} = \sum_f \frac{m_f}{v}\left[h\bar{f}f + \cos\theta\epsilon^H_f S_1\bar{f}f - \sin\theta\epsilon^H_f S_2\bar{f}f - i\epsilon^A_f A\bar{f}\gamma_5 f\right]$$
$$\mathcal{L}^{\text{yuk}}_{2HD+PS} \sum_f \frac{m_f}{v}\left[h\bar{f}f + \epsilon^H_f H\bar{f}f - i\cos\theta\epsilon^A_f A\bar{f}\gamma_5 f + i\sin\theta\epsilon^A_f a\bar{f}\gamma_5 f\right] \quad (1)$$

where θ is the mixing angle between the Higgs states (notice that we have assumed the so-called alignment limit. This implies that h is a purely SM states while only $S_{1,2}$ are singlet-doublet mixtures). $\epsilon^{A,H}_f$ are Yukawa scaling factors. The Lagrangians above are obtained assuming the so called Flavor-Aligned Yukawa model [2] which automatically avoids FCNC at tree level. The neutral Higgs bosons are, in turn, coupled with a pair of fermionic DM candidates χ as:

$$\mathcal{L}^{\text{DM}}_{2HD+S} = -y^S_\chi\left(\sin\theta S_1 + \cos\theta S_2\right)\bar{\chi}\chi, \quad \mathcal{L}^{\text{DM}}_{2HD+PS} = -iy^P_\chi\left(\sin\theta A + \cos\theta a\right)\bar{\chi}\gamma_5\chi \quad (2)$$

The 2HDM+S/PS are characterized by a broad ranges of characteristic signatures. In this work we will focus mostly on the mono-X, $X = Z, h$ signatures.
Their detection prospects are shown in fig.1 [1] in the bidimensional planes (M_a, M_A) and (M_{S_1}, M_{S_2}) respectively. While having similar sensitivity to mono-Z events, the 2HDM+S/PS might be discriminated in case of an hypothetical detection of mono-h event. For illustration, the figure shows also the sensitivity to associated production of $\bar{t}t$ pairs.
The 2HDM+PS is an interesting case of study also in the regime of a light a, i.e with mass below 100 GeV. As evidenced by fig. 2, it is possible to obtain the correct DM relic density for a light

[1] An extensive study of the collider prospects of the 2HDM+PS has been also done in [3].

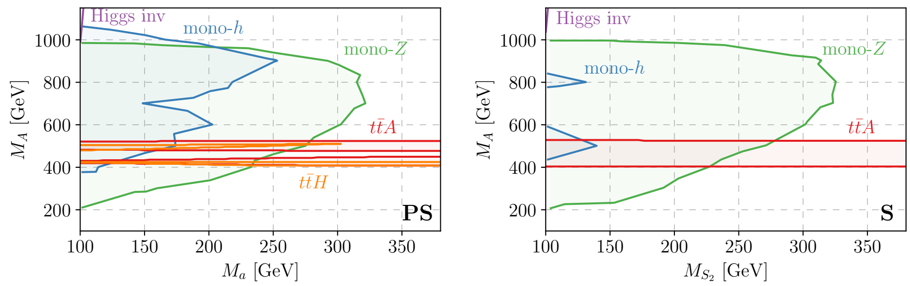

Figure 1: 2σ exclusion limits from searches of mono-h and mono-Z events, as well as, $t\bar{t}$ for the 2HDM+PS (left panel) and $2HDM + S$ (right panel)in the $(M_{S_2,a}, M_A)$ bidimensional planes (assuming $\tan\beta = 1$).

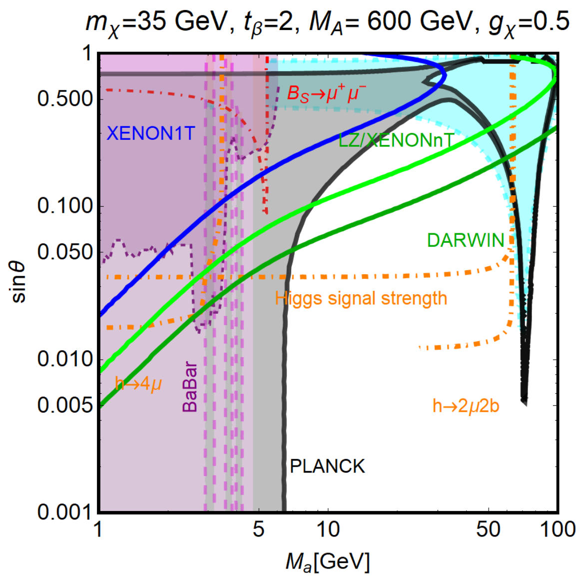

Figure 2: Summary of constraints of a 2HDM+PS, in the light a regime, in the $(M_a, \sin\theta)$ bidimensional plane. See [4] for details.

DM candidate, 35 GeV in the figure, either through the $\chi\chi \to aa$ or the $\chi\chi \to \bar{f}f$ processes (mostly via light pseudoscalar exchange). Contrary to many WIMP models, this scenario is not yet ruled-out by Direct Detection since Spin Independent interactions arise only at the one loop level for the considered setup (see [5, 6] for the most up-to-date computations). Very light masses of a, namely below 5 GeV, can be probed by looking at deviations, with respect to the SM prediction, in the rate of B-meson decays, like e.g. $B_s \to \mu^+\mu^-$ [7]. More interestingly, LHC can probe the light a regime through searches of the exotic decays of the SM Higgs $h \to aa$. More recently ref. [8] pinpointed that also searches of light resonances decaying into muon pairs can also effectively probe the parameters space of the model.

3. 2HDM+$U(1)_X$

A second class of interesting models have Higgs sectors again made by two SU(2) doublets and a Higgs singlet. This time $U(1)_X$ gauge symmetry is present, spontaneously broken by the vev of the

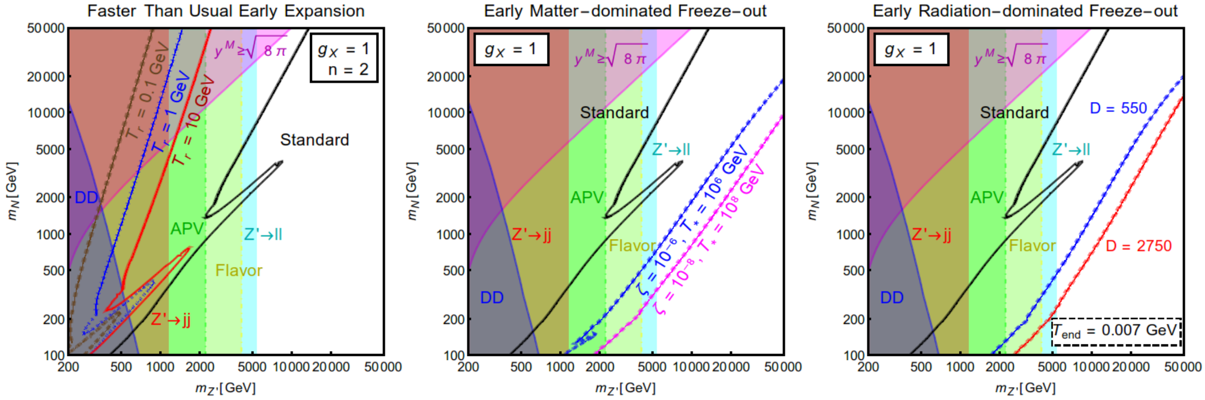

Figure 3: Summary of constraints for the $2HDM + U(1)_X$ model in the $(m_{Z'}, m_{N_1})$ bidimensional plane.

Higgs singlet. This gives majorana masses to right-handed neutrinos, the lightest of which is the DM candidate. The latter is coupled with the gauge boson of this new symmetry which, in turn, features mass and kinetic mixing with the SM Z. The relevant lagrangian for the phenomenology reads (for more details see e.g.[9, 10]):

$$\mathcal{L}_{\rm NC} = -eJ^{\mu}_{em}A_{\mu} - \frac{g_Z}{2\cos\theta_W}J^{\mu}_{NC}Z_{\mu} - \left(\epsilon e J^{\mu}_{em} + \frac{\epsilon_Z g}{2\cos\theta_W}J^{\mu}_{NC}\right)Z'_{\mu} - \frac{g_X}{2}Q_{X_f}\left(\bar{\psi}_f\gamma^{\mu}\psi_f\right)Z'_{\mu} \quad (3)$$

$$+\frac{1}{4}g_X\left(N_{1R}\gamma^{\mu}\gamma_5 N_{1R}\right)Z'_{\mu},$$

$$J^{\mu}_{NC} = \left(T_{3f} - 2Q_{Yf}\sin^2\theta_W\right)\bar{\psi}_f\gamma^{\mu}\psi_f - T_{3f}\bar{\psi}_f\gamma^{\mu}\gamma_5\psi_f. \quad (4)$$

g_Z and g_X represent, respectively, the gauge couplings associated to $U(1)_Y$ and $U(1)_X$. ϵ_Z is the Z/Z' mass mixing parameter.

Fig.3 shows, in the $(m_{Z'}, m_{N_1})$ bidimensional plane for a fixed assignation of the new gauge coupling g_X, the strong complementarity between different kind of constraints which characterize the model. The colored regions correspond to different kinds of experimental exclusions. The most prominent come from LHC searches of dijet and dilepton resonances, typically the most important ones in the case of Z' portal. In the 2HDM+$U(1)_X$ the mass of the charged Higgs is related to the mass of the Z'. A good complementary constraint is hence provided by the bound from $b \to s$ transition on the mass of the charged Higgs. The aforementioned constrains have been compared in [11] not only with the prediction for the DM relic density from the WIMP paradigm (black solid line in all the panels) but also with the case of three non-standard cosmological histories, dubbed, respectively, faster than usual early expansion, early matter domination and early radiation domination (we refer to [11] for details).

4. Conclusions

We have illustrated a series of models showing how extended Higgs sectors connected to DM offer interesting phenomenology and peculiar collider signatures.

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