PROCEEDINGS OF SCIENCE

Dark Matter and Gravitational Waves in the 2HD+a model

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We provide an overview of the two-Higgs-doublet model plus a light pseudoscalar a boson, 2HD+a, with a focus on the Dark Matter phenomenology and the prospects of having Gravitational Wave signals from a first order phase transition in the Early Universe. This talk is based on Ref. [1].

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1. The Model

The 2HD+a model plus a singlet fermion Dark Matter (DM) can be characterized by specifying the scalar potential which is written as $V_{\rm 2HDMa} = V_{\rm 2HDM} + V_{a_0}$, with $V_{\rm 2HDM}$ representing the customary Z_2 invariant CP conserving potential of a model with two Higgs doublets $\Phi_{1,2}$:

$$V_{\rm 2HDM} = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \text{h.c.}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2$$
$$+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5[\,(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\,]\,, \quad (1)$$

while V_{a_0} contains additional contributions from a Standard Model (SM) singlet CP-odd state a_0:

$$V_{a_0} = \frac{1}{2}m_{a^0}^2(a^0)^2 + \frac{\lambda_a}{4}(a^0)^4 + \left(i\kappa a^0\Phi_1^\dagger\Phi_2 + \text{h.c.}\right) + \left(\lambda_{1P}(a^0)^2\Phi_1^\dagger\Phi_1 + \lambda_{2P}(a^0)^2\Phi_2^\dagger\Phi_2\right)\,. \quad (2)$$

Upon symmetry breaking, the two doublets get vev $\langle\Phi_i\rangle = v_i$ with $i = 1, 2$ and mass mixing arises among the SU(2) doublets and the singlet. Such a mixing is characterized by three angles: α (mixing between CP-even scalars), β (defined by $\tan\beta = v_1/v_2$) and θ (mixing among the CP-odd scalars). It is possible to eliminate the angle α via the so-called alignment limit $\beta - \alpha = \pi/2$ which automatically ensures that a CP-even scalar has SM-like couplings and can be identified with the Higgs boson discovered at LHC. The set of physical states is commonly labelled $(h, H, H^\pm, A, a)$ with h, H being electrically neutral CP-even states (h is identified with the 125 GeV Higgs), $H^\pm$ electrically charged Higgs bosons while finally (a, A) is a set of CP-odd electrically neutral states. The electrically neutral bosons couple with the SM fermions via the following Yukawa Lagrangian:

$$\mathcal{L}_{\rm Yuk} = \sum_f \frac{m_f}{v}\left[g_{hff}h\bar f f + g_{Hff}H\bar f f + ig_{Aff}A\bar f\gamma_5 f - ig_{aff}a\bar f\gamma_5 f\right], \quad (3)$$

where $g_{Aff} = \cos\theta\, g_{A^0ff}$ and $g_{aff} = \sin\theta\, g_{A^0ff}$. We have normalized the couplings to their SM values m_f/v. In principle, the coefficients $g_{h/H/A^0ff}$ are functions of the angles α, β and can be grouped in four specific configurations, dubbed Type-I,-II,-X,-Y, in order to avoid flavor changing neutral currents at tree-level. In the alignment limit, one has $g_{hff} = 1$ (i.e. h is purely SM-like) and the others are either $g_{H/A^0/ff} \propto \tan\beta$ or $\propto \cot\beta$. The 2HDM+a has to comply with a broad variety of constraints, including perturbative unitarity and boundness from below of the scalar potential, electroweak precision tests, Higgs signal strengths at the LHC and B-meson physics constraints.

These constraints have been spelled in detail in Ref. [1]. We illustrate their impact in Fig. 1.

As can bee seen, they lead to a rather small mass splitting among the $H, A, H^\pm$ states while, with the exception of the case of B-physics, no strong limit is present on their overall mass scale M. On an analogous footing, the additional pseudoscalar a can lie at a substantially lower mass scale.

2. DM Phenomenology

The DM candidate is represented by a fermion χ that is a singlet with respect to the SM gauge group and couples only with the pseudoscalar states through:

$$\mathcal{L}_{\rm DM} = y_\chi\,(\cos\theta a + \sin\theta A)\,\bar\chi i\gamma_5\chi\,. \quad (4)$$

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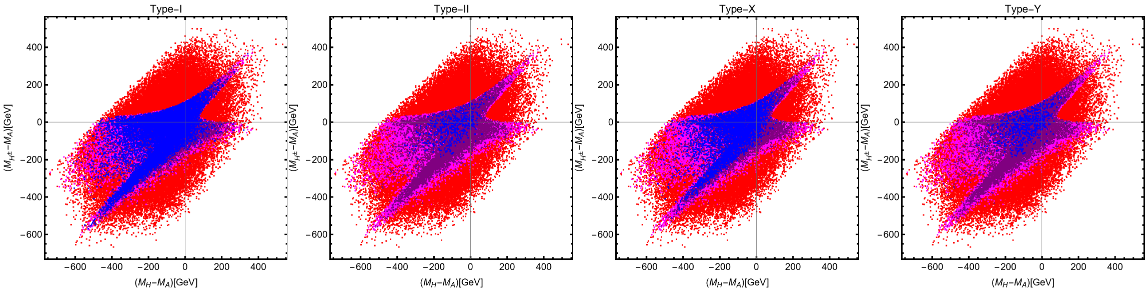

Figure 1: Assignments of the 2HD+a model parameters compatible with theoretical constraints (red points)+ constraints form electroweak precision tests (magenta points) + Higgs signal strength constraints (purple points)+ B-physics constraints (blue points) in the $[M_H - M_A, M_{H^\pm} - M_A]$ plane. The four panels correspond to the four Yukawa configurations forbidding flavor changing neutral currents at the tree level.

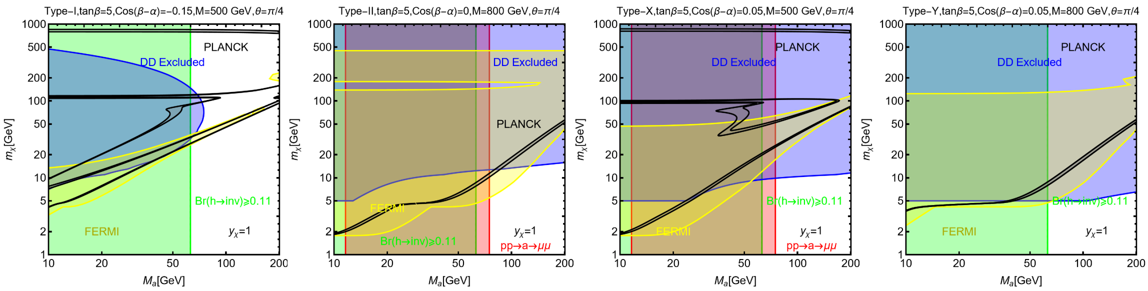

Figure 2: Combination of DM constraints, in the $[M_a, m_\chi]$ plane, for four benchmark assignments of the 2HD+a parameters. The black contours correspond to the correct DM relic density. The blue (yellow) regions are excluded by Direct (Indirect) Detection constraints. The green region correspond to $BR(h \to aa)$ above the experimental limits while the red region is excluded by searches at the LHC for the $pp \to a \to \mu^+\mu^-$ process.

Its cosmological relic density can be achieved via the conventional freeze-out paradigm mostly via annihilation processes into SM fermion pairs, via s-channel exchange of the pseudoscalars, or, if kinematically allowed, annihilations into aa and ha final states. Furthermore, some of the most relevant annihilation channels, as for example into $\bar{f}f$ and ha final states, have s-wave dominated cross-sections; consequently Indirect Detection signals, possibly detected by γ-ray observatories, are generated. Direct Detection is, nevertheless the most interesting feature. The coupling of fermionic DM with a pseudoscalar mediator leads, at tree-level, to a cross-section suppressed with the tiny momentum exchange in the non-relativistic scattering of the DM. Sizable Spin Independent interactions, which can be probed by Xenon based experiments, emerge however at one loop.

The combination of the DM constraints is shown, for some benchmark scenarios in Fig. 2.

3. First order phase transition and a Gravitational Wave signal

To assess the capability of the 2HD+a model of triggering a first order phase transition we have computed the one-loop thermal effective potential:

$$V_{\text{eff}}(h^0, H^0, T) = V_0 + V_{\text{CW}} + V_{\text{CT}} + V_T. \tag{5}$$

with V_0 being the three level potential:

$$V_0 = \frac{m_{11}^2}{2}(h^0)^2 + \frac{m_{22}^2}{2}(H^0)^2 - m_{12}^2 h^0 H^0 + \frac{\lambda_1}{8}(h^0)^4 + \frac{\lambda_2}{8}(H^0)^4 + \frac{\lambda_3+\lambda_4+\lambda_5}{4}(h^0)^2(H^0)^2\,, \quad (6)$$

where h^0, H^0 stem for the CP-even components of the two Higgs doublets. $V_{\rm CW}$ represents the Coleman-Weinberg potential:

$$V_{\rm CW} = \frac{1}{64\pi^2}\sum_i n_i m_i^4 \left(\ln\frac{m_i^2}{\mu^2} - c_i\right), \quad (7)$$

accounting for one-loop quantum corrections, while

$$V_{\rm CT} = \delta m_{11}^2 (h^0)^2 + \delta m_{22}^2 (H^0)^2 + \delta m_{12}^2 h^0 H^0 + \delta\lambda_1 (h^0)^4 + \delta\lambda_2 (H^0)^4, \quad (8)$$

contains the counter terms needed to compensate the shifts in the vevs, masses and mixing of the doublets induced by $V_{\rm CW}$. Finally, we have the contributions from thermal corrections:

$$V_T = \frac{T^4}{2\pi^4}\sum_i n_i J\left(\frac{m_i^2}{T^2}\right), \quad J(y^2) = \int_0^\infty dx\, x^2 \ln\left(1 + (-1)^B e^{-\sqrt{x^2+y^2}}\right)\,. \quad (9)$$

We have performed a scan over the following model parameters:

$$\begin{aligned} & M_H, M_A, M_{H^\pm} \in [500, 1250]\ \text{GeV}, \quad M_a \in [10, 200]\ \text{GeV}, \quad \tan\beta \in [0.1, 50], \\ & \sin\theta \in [\sqrt{2}/2, 1]\,, \quad \lambda_a \in [0, 4\pi], \quad \lambda_{1P}, \lambda_{2P} \in [-\pi, 4\pi], \end{aligned} \quad (10)$$

and computed, for each model point, the effective potential and the strength of the phase transition via the package `CosmoTransitions` [2]. The parameter space leading to strong first order phase transition is shown in Fig. 3. Having determined the conditions for such a transition, we have computed the stochastic Gravitational Wave background via the conventional expression [3]: $h^2\Omega_{\rm GW} \simeq h^2\Omega_{\rm col} + h^2\Omega_{\rm sw} + h^2\Omega_{\rm turb}$ with $h^2\Omega_{\rm col}(f) = h^2\Omega_{\rm col}^{\rm peak} S_{\rm col}(f)$ representing the contribution from bubble collisions in the envelope approximation by [4], while $h^2\Omega_{\rm sw}$ and $h^2\Omega_{\rm turb}$ represent, respectively, the contributions from sound-waves and MHD turbulence.

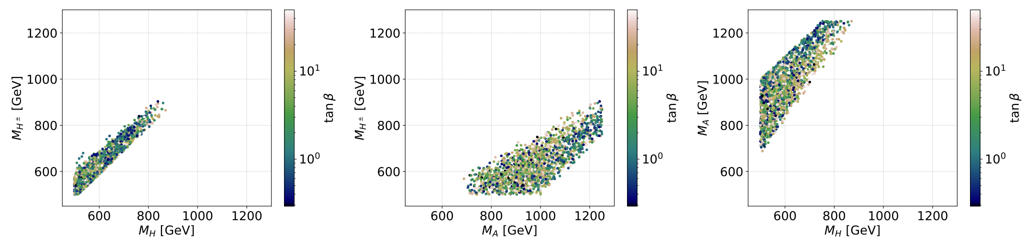

Figure 3: Parameter space of the 2HD+a leading to a strong first order phase transition.

Fig. 4 shows the peak amplitude of the Gravitational Wave signal as a function of the peak frequency for the model points, leading to strong first order phase transition, already shown in Fig.3. The results is compared with power-law integrate sensitivity curves constructed for an observation time of four years for LISA (solid line), BBO (dashed line) and DECIGO (dotted line) and Gravitational Waves are considered to be detectable if the signal-to-noise ratio is above 10 [5].

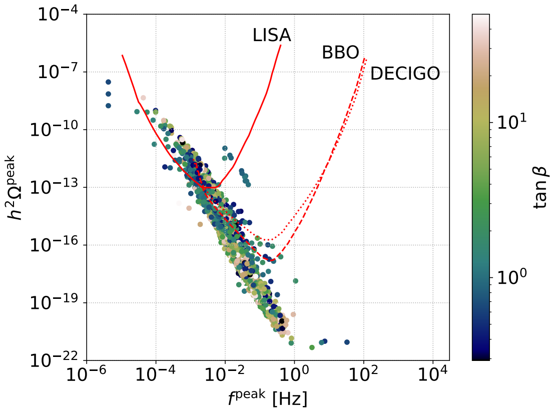

Figure 4: Peak amplitude of the Gravitational Wave signal as a function of frequency for model points leading to a strong first order phase transition. The outcome is compared with the expected sensitivity of LISA, BBO and DECIGO.

4. Conclusions

We have provided a brief overview of the 2HD+a model which features and interesting DM phenomenology and can accommodate, in the early Universe, a strong first order phase transition that could lead to a stochastic Gravitational Wave background in the detection reach of future facilities. A detailed account may be found in Ref. [1].

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