The THDMa and possible $e^+e^-$ signatures

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Abstract

I here discuss the THDMa, a type II two Higgs doublet model that is enhanced by an additional pseudoscalar which serves as a portal to the dark matter sector containing a fermionic dark matter candidate. I present a recent scan of the models parameter space where all parameters are allowed to float freely, and discuss prospects for this model at future $e^+e^-$ colliders for cases that are not covered in standard THDM searches.

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I. INTRODUCTION

I discuss a new physics models that extends the Standard Model (SM) particle sector by an additional scalar and provides a dark matter candidate. The models is confronted with current theoretical and experimental constraints, including the minimization of the vacuum as well as the requirement of vacuum stability and positivity. I also require perturbative unitarity to hold, and perturbativity of the couplings at the electroweak scale.

From the experimental side, I include the agreement with current measurements of the properties of the 125 GeV resonance discovered by the LHC experiments, as well as agreement with the null-results from searches for additional particles at current or past colliders. Furthermore, I consider bounds from electroweak precision observables (via $S$, $T$, $U$ parameters), B-physics observables ($B \to X_s \gamma$, $B_s \to \mu^+\mu^-$, $\Delta M_s$), as well as agreement with astrophysical observables (relic density and direct detection bounds). In my scan, I use a combination of private and public tools; the latter include HiggsBounds [1], HiggsSignals [2], SPheno [3], Sarah [4], micrOMEGAs [5, 6], and MadDM [7]. Experimental numbers are taken from [8, 9] for electroweak precision observables, [10] for $B_s \to \mu^+\mu^-$, [11] for $\Delta M_s$ and [12] and [13] for relic density and direct detection, respectively. Bounds from $B \to X_s \gamma$ are implemented using a fit function from [14, 15]. For predictions of production cross sections I am using Madgraph5 [16].

II. THDMA

The THDMA is a type II two-Higgs-doublet model (THDM), extended by an additional pseudoscalar $a$ mixing with the "standard" pseudoscalar $A$ of the THDM. In the gauge-eigenbasis, the additional field serves as a portal to the dark sector, where I consider a fermionic dark matter candidate $\chi$. This model has extensively been studied in light of hadron colliders, and more details can e.g. be found in [17–24].

The model contains, besides the new scalars from the standard THDM, an additional pseudoscalar and the dark matter candidate, leading to the following particle content: $h, H, H^\pm, a, A, \chi$. It contains in 12 additional new physics parameters, which can be chosen e.g. as

\[ v, m_h, m_H, m_a, m_A, m_{H^\pm}, m_\chi, \cos(\beta - \alpha), \tan \beta, \sin \theta, y_\chi, \lambda_3, \lambda_{P_1}, \lambda_{P_2}. \]

Here $v$ and either $m_h$ or $m_H$ are fixed by current measurements in the electroweak sector. I refer the reader to [23] for a more thorough discussion, including the concrete form of the potential.

I here report on results of a scan that allows all of the above novel parameters float in specific predefined ranges [23]. Due to the large number of free parameters, it is not always straightforward to display bounds from specific constraints in 2-dimensional planes. In some cases, however, displaying these in such setups is straightforward. Two examples
are shown in figure 2. The first plot shows bounds in the \((m_{H^\pm}, \tan \beta)\) plane from B-physics observables. The result is similar to a simple THDM, and shows that in general low masses \(m_{H^\pm} \lesssim 800\) GeV as well as values \(\tan \beta \lesssim 1\) are excluded. The second plot displays the relic density as a function of the mass difference \(m_a - 2m_\chi\). Here, a behaviour can be observed that is typical in many models with dark matter candidates: in the region where this mass difference remains small, relic density annihilates sufficiently to stay below the observed relic density bound, leading to a so-called "funnel" region. Too large differences lead to values \(\Omega h^2 \gtrsim 0.12\) and therefore are forbidden from dark matter considerations.

Finally, it is interesting to consider which production cross-section values would still be feasible for points that fulfill all constraints at \(e^+e^-\) colliders. I concentrate on signatures that include missing energy and therefore do not exist in a THDM without a portal to the dark sector. Processes that include the lighter CP-even scalar, as e.g. \(e^+e^- \rightarrow hA, ha\) are suppressed due to alignment, which makes \(e^+e^- \rightarrow HA, H\) the most interesting channel that contains novel signatures. Due to the interplay of B-physics and electroweak constraints, such points typically have mass scales \(\gtrsim 1\) TeV. Therefore, the first interesting scenario are production cross sections for an \(e^+e^-\) collider with a center-of-mass energy of 3 TeV. The corresponding production cross sections are shown in figure 3. Here, I display predictions for \(t\bar{t}t\bar{t}\) and \(t\bar{t} + \cancel{E}_T\) final states using a factorized approach. There is a non-negligible number of points where the second channel is dominant. A "best" point with a large rate for \(t\bar{t} + \cancel{E}_T\) has been presented in [23]:

\[
\begin{align*}
\sin \theta &= -0.626, \quad \cos (\beta - \alpha) = 0.0027, \quad \tan \beta = 3.55 \\
&= 643 \text{ GeV}, \quad m_A = 907 \text{ GeV}, \quad m_{H^\pm} = 814 \text{ GeV}; \\
&= 653 \text{ GeV}, \quad m_\chi = 277 \text{ GeV}, \\
&= -1.73, \quad \lambda_{P_1} = 0.18, \quad \lambda_{P_2} = 2.98, \quad \lambda_3 = 8.63.
\end{align*}
\]

For this point, all width/ mass ratios are \(\lesssim 6\%\). In addition, branching ratios for various final states as a function of the mass sum for the \(HA\) channel are given in figure 1.

III. CONCLUSION AND OUTLOOK

In this work, I presented a model that extend the particle content of the SM and also provides a dark matter candidate. In particular, I defined signatures that do not exist in models without dark matter candidates. I have presented production cross sections for various standard pair-production modes. A more dedicated investigation of the corresponding signatures, including background simulation and cut optimization, is in the line of future work.
FIG. 1. Branching ratios into various final states for $A H$ production, as a function of the mass sum.

FIG. 2. Left: Bounds on the $(m_{H^\pm}, \tan \beta)$ plane from B-physics observables. The contour for low $(m_{H^\pm}, \tan \beta)$ values stems from [14, 15]. Right: Dark matter relic density as a function of $m_a - 2 m_\chi$, where $m_\chi$ defines the color coding. The typical resonance-enhanced relic density annihilation is clearly visible. Figures taken from [23].

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FIG. 3. Production cross sections for $t\bar{t}t\bar{t}$ (x-axis) and $t\bar{t} + \bar{E}$ (y-axis) final state in a factorized approach at 3 TeV center-of-mass energy. Left: mediated via $HA$, right: mediated via $HA$ and $Ha$ intermediate states. Color coding refers to $m_H + m_A$ (left) and $m_H + 0.5 \times (m_A + m_a)$ (right). Figures taken from [23].

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