BSM scenarios with missing energy at future lepton colliders

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I will briefly discuss the signatures and discovery prospects of several new physics models containing dark matter candidates at future lepton colliders. In particular, I will discuss the two models that, among other signatures, lead to electroweak gauge bosons and missing energy: the Inert Doublet Model, as well as the THDM\textsubscript{a}, a two Higgs doublet model with an additional pseudoscalar that serves as a portal to the dark sector. Results are mainly based on a Snowmass Whitepaper [1].

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1. Introduction

I briefly discuss two models that enhance the scalar sector of the Standard Model by additional particle content, including dark matter candidates. These models lead to signatures with missing energy. I present current bounds on these models as well as perspectives and rates at future lepton colliders.

2. Inert Doublet Model

The Inert Doublet Model (IDM) [2–4] is a two Higgs Doublet Model (THDM) with a discrete exact $Z_2$ symmetry containing a dark matter candidate. The model features 7 free parameters, which we chose in the so-called physical basis [5]: $v, M_h, M_H, M_A, M_{H^\pm}, \lambda_2, \lambda_{345}$, where the $\lambda$s correspond to potential parameters. As two parameters (the vacuum expectation value (vev) $v$ and $M_h \sim 125 \text{ GeV}$) are fixed by experimental measurements, we end up with a total number of 5 free parameters. Here, we consider the case where $H$ is the dark matter candidate, which implies $M_{A, H^\pm} \geq M_H$.

The model is subject to a large number of theoretical and experimental constraints [1, 5–9]. These lead to a large reduction of the allowed parameter space. As an example, the masses are usually quite degenerate, as can be seen from figure 1. We also consider the case when $M_H \leq\frac{M_h}{2}$, where constraints from $h \rightarrow$ invisible start to play an important role and an interesting interplay arises, between bounds from signal strength measurements, and bounds from dark matter relic density, see figure 2. In [5], it was found that this in general leads to a lower bound of $M_H \sim 50 \text{ GeV}$, with exceptions presented in [9]. The discovery potential of ILC and CLIC was investigated in [11–16] for several benchmark points proposed in [8], for varying center-of-mass energies from 250 GeV up to 3 TeV. We focus on $A H$ and $H^+ H^-$ production with $A \rightarrow Z H$ and $H^\pm \rightarrow W^\pm H$, with leptonic decays of the electroweak gauge bosons. Event generation was done using WHizard 2.2.8 [17, 18], with an interface via SARAH [19] and SPheno 4.0.3 [20, 21] for model implementation. For CLIC results energy spectra [22] were also taken into account.

\footnote{Note that BP11 from [8] is by now excluded from the newest direct detection constraints [10].}
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Figure 2: Interplay of signal strength and relic density constraints in the \((M_H, \lambda_{345})\) plane. Using XENON1T results, with golden points labelling those points that produce exact relic density (taken from [6]). Note that all points displayed here also pass the new LUX-Zeppelin bounds [10].

The investigated final states were \(e^+ e^- \rightarrow \mu^+ \mu^- + E, \quad e^+ e^- \rightarrow \mu^+ e^- + E\) for \(HA\) and \(H^+ H^-\) production, respectively. Results for the discovery reach of CLIC, including center-of-mass energies of 1.5 TeV and 3 TeV, are shown in figure 3. In general, production cross sections \(\gtrsim 0.5\) fb and mass sums up to 1 TeV seem accessible, where the \(\mu^\pm e^\mp\) channel seems to provide a larger discovery range.

3. THDMa

The THDMa is a type II two-Higgs-doublet model that is extended by an additional pseudoscalar \(a\). In the gauge-eigenbasis, the additional scalar serves as a portal to the dark sector, with a fermionic dark matter candidate, denoted by \(\chi\). More details can e.g. be found in [23–29].

The model contains the following particles in the scalar and dark matter sector: \(h, H, H^\pm, a, A, \chi\). It depends on 12 additional new physics parameters

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

where \(v\) and either \(m_h\) or \(m_H\) are fixed by current measurements in the electroweak sector.

I here report on results of a scan that allows all of the above novel parameters float in specific predefined ranges [29]. Two examples for direct bounds in 2-dimensional planes are displayed in figure 4. Note that for this proceeding, on contrast to the results presented in [1, 29], we have now updated the value of \(B_s \rightarrow \mu^+ \mu^-\) to the current PDG value [30], we have \(B_s \rightarrow \mu^+ \mu^- = \frac{3.01 \pm 0.35}{10^{-9}}\). Following the logic explained in [29], this leads to \((B_s \rightarrow \mu^+ \mu^-)_{\text{Spheno}} \in [1.52; 3.34] \times 10^{-9}\). Note that the \(\Delta M_s\) experimental value has also been updated [31] and now reads \(\Delta M_s \left(\text{ps}^{-1}\right) = 17.765 \pm 0.004 \pm 0.004\). However, this basically leads to similar bounds as the previous value [32], so we did not update the respective bounds.

If, for consistency, now taking again a 3\(\sigma\) allowed range for \(B_s \rightarrow \mu^+ \mu^-\), the bounds from this branching ratio and \(\Delta M_s\) basically overlap. In turn, it means that now tan \(\beta\) values \(\lesssim 1\) are still allowed. The second plot displays the relic density as a function of the mass difference \(m_a - 2m_\chi\).

I also present cross section values for production at \(e^+e^-\) colliders for points that pass all bounds considered in [29] at a 3 TeV collider in figure 5.
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Figure 3: Discovery prospects at CLIC for the IDM in $\mu^+ \mu^- + E_T$ (left) and $\mu^\pm e^\mp + E_T$ (right) final states, as a function of the respective production cross-sections (top) and mass sum of the produced particles (bottom). Taken from [11].

4. Conclusion

I briefly presented two scenarios for models with dark matter candidates and their prospective signatures and rates/discovery ranges at future lepton colliders, with a focus on larger ($O(\text{TeV})$) center-of-mass energies. For the IDM, a detailed study shows that many still viable parameter points should be accessible, depending on the specifics of the particular benchmark points. For the THDMa, regions in parameter space exist where $t\bar{t} + E_T$ is the dominant production mode.

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Figure 4: Left: Bounds on the \((m_{H^\pm}, \tan \beta)\) plane from B-physics observables, implemented via the SPheno [21]//Sarah [33] interface, and compared to experimental bounds [34, 35]. The contour for low \((m_{H^\pm}, \tan \beta)\) values stems from [36, 37]. Right: Dark matter relic density as a function of \(m_a - 2m_\chi\), with \(m_\chi\) defining the color coding. The typical resonance-enhanced relic density annihilation is clearly visible. Right figure taken from [29].

Figure 5: Production cross sections for \(t\bar{t}H\) (x-axis) and \(t\bar{t} + E\) (y-axis) final state in a factorized approach, for an \(e^+e^-\) collider with a 3 TeV center-of-mass energy. Left: mediated via \(H_A\), right: mediated via \(H_A\) and \(H_a\) intermediate states. Color coding refers to \(m_H + m_A\) (left) and \(M_H + 0.5 \times (m_A + m_\chi)\) (right). Figures taken from [29], with an update including results from [38].

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