Inert Doublet Model signatures at future e^+e^- colliders

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The Inert Doublet Model (IDM) is one of the simplest extensions of the Standard Model (SM), providing a dark matter candidate. It is a two Higgs doublet model with a discrete Z_2 symmetry, that prevents the scalars of the second doublet (inert scalars) from coupling to the SM fermions and makes the lightest of them stable. We study a large group of IDM scenarios, which are consistent with current constraints on direct detection, including the most recent bounds from the XENON1T experiment and relic density of dark matter, as well as with all collider and low-energy limits. We propose a set of benchmark points with different kinematic features, that promise detectable signals at future e^+e^- colliders. Two inert scalar pair-production processes are considered, $e^+e^- \to H^+H^-$ and $e^+e^- \to AH$, followed by decays of $H^\pm$ and A into final states which include the lightest and stable neutral scalar dark matter candidate H. Significance of the expected observations is studied for different benchmark models and different running scenarios, for centre-of-mass energies up to 3 TeV. Numerical results are presented for the signal signatures with two muons or an electron and a muon in the final state. For high mass scenarios, when the significance is too low for the leptonic signatures, the semi-leptonic signature can be used as the discovery channel.

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1. Inert Doublet Model

The Inert Doublet Model (IDM) is one of the simplest extensions of the Standard Model (SM) which can provide a dark matter (DM) candidate [1, 2, 3]. In addition to the SM doublet ϕ_S, the scalar sector contains a second $SU(2)$ doublet, ϕ_D. A discrete Z_2 symmetry is imposed on the model, with the following transformation rules for the fields: $\phi_S \to \phi_S$, $\phi_D \to -\phi_D$, SM $\to$ SM. Therefore, the additional doublet ϕ_D, called dark or inert, is the only Z_2-odd field. The resulting Z_2-symmetric potential has a following form:

$$V = -\frac{m_{11}^2}{2}(\phi_S^\dagger \phi_S) - \frac{m_{22}^2}{2}(\phi_D^\dagger \phi_D) + \frac{\lambda_1}{2}(\phi_S^\dagger \phi_S)^2 + \frac{\lambda_2}{2}(\phi_D^\dagger \phi_D)^2$$
$$+\lambda_3(\phi_S^\dagger \phi_S)(\phi_D^\dagger \phi_D) + \lambda_4(\phi_S^\dagger \phi_D)(\phi_D^\dagger \phi_S) + \frac{\lambda_5}{2}\left[(\phi_S^\dagger \phi_D)^2 + (\phi_D^\dagger \phi_S)^2\right].$$

Exact Z_2-symmetry implies that only ϕ_S can acquire a non-zero vacuum expectation value (v). As a result the scalar fields in ϕ_D do not mix with the SM-like fields from ϕ_S, and the lightest particle of the dark sector is stable. Therefore, there are five physical scalars after electroweak symmetry breaking: the SM Higgs boson h and four dark scalars: two neutral, H and A, and two charged, $H^\pm$. We here consider the case where the neutral particle H is the lightest and therefore the DM candidate.

After electroweak symmetry breaking, the model contains seven free parameters. Agreement with the Higgs boson discovery and electroweak precision observables fixes the SM-like Higgs mass m_h and v, and we are left with five free parameters:

$$m_H, \ m_A, \ m_{H^\pm}, \ \lambda_2, \ \lambda_{345} \equiv \lambda_3 + \lambda_4 + \lambda_5.$$

The model is a subject to various theoretical and experimental constraints, as described in detail in [4]. Among the theoretical constraints we include positivity of the potential, the condition to be in the inert vacuum and perturbative unitarity. Furthermore, we demand agreement with electroweak precision tests, electroweak gauge boson widths, no long-lived charged scalars, agreement with recasts of LEP and LHC searches, agreement with measurements of Higgs signal strengths and branching ratios, as well as null-results for additional scalar searches at the LHC. The DM candidate H is constrained through results from direct and indirect detection experiments and measurements of DM relic density. Based on these considerations, two sets of benchmark points (BPs) in agreement with all theoretical and experimental constraints were proposed in [4], covering different possible signatures at e^+e^- colliders, with masses of inert particles extending up to 1 TeV. Distributions of the scalar masses for these benchmark scenarios are shown in Fig. 1.

2. Analysis strategy

Prospects for the discovery of IDM scalars using leptonic channels at CLIC were described in detail in [5]. In this contribution we summarize these results and extend them to the case of the ILC running at 250 GeV and 500 GeV centre-of-mass energy. We furthermore discuss the increased discovery reach we obtained from semi-leptonic channels at 3 TeV CLIC.

We consider the following tree-level production processes of inert scalars at e^+e^- collisions: $e^+e^- \to A H$ and $e^+e^- \to H^+H^-$. The dark neutral scalar A decays to a (real or virtual) Z boson and the neutral scalar H, $A \to Z^{(\star)}H$, while the charged boson $H^\pm$ decays predominantly to a (real or virtual) $W^\pm$ boson and the neutral scalar H, $H^\pm \to W^{\pm(\star)}H$. The lightest neutral particle H is stable, and therefore escapes detection, contributing to the missing transverse energy ($\not{E}_T$).
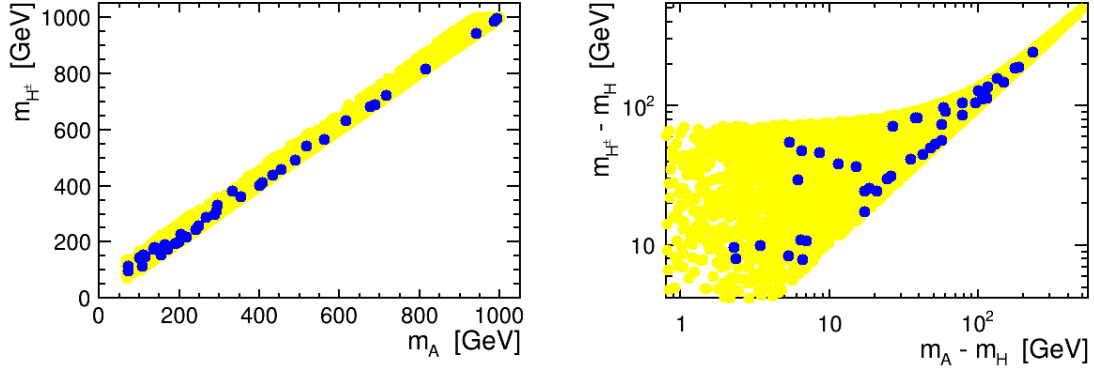
Figure 1: Distribution of benchmark candidate points (yellow) and selected benchmark points (blue) in the $(m_A; m_{H^\pm})$ plane (left) and in the $(m_A - m_H; m_{H^\pm} - m_H)$ plane (right) [4].

We first focus on leptonic decays of Z and $W^\pm$, as isolated leptons (electrons and muons) can be identified and reconstructed with very high efficiency and purity. These processes lead to a signature of leptons and missing transverse energy. The $\mu^+\mu^-$ final state predominantly arises from neutral scalar pair-production, while the different flavour lepton pairs, μ^+e^- and $e^+\mu^-$ are considered a signature for the production of charged inert scalars, see Fig. 2. However, during the simulation we do not constrain the intermediate states, but consider all processes leading to $ll^{(')} + \not{E}_T$; both signatures include contributions from AH and H^+H^- production. Especially processes with additional neutrinos, e.g. from τ (pair) production and their successive leptonic decays, have to be taken into account. For the background, SM processes leading to charged lepton pair ($\mu^\pm e^\mp$ and $\mu^+\mu^-$) and neutrinos (which constitute $\not{E}_T$) have been considered. As with the signal, topologies with intermediate τ leptons were also included.
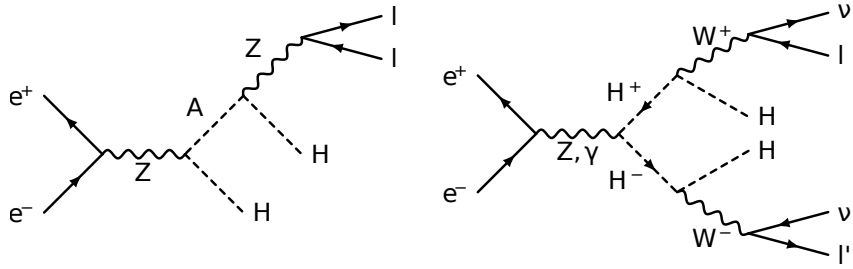
Figure 2: Signal Feynman diagrams for the considered production and decay process for: *(left)* neutral scalar production, $e^+e^- \to HA \to HHll$, and *(right)* charged scalar production, $e^+e^- \to H^+H^- \to HHll'\nu\nu'$.

In the processes involving charged scalar pair production, one of the $W^\pm$ bosons can decay hadronically, leading to a semi-leptonic signature with $l\nu$ and two jets, as seen in Fig. 3. The hadronic branching ratio is significantly larger than the leptonic one, leading to a significant increase in the discovery reach.

Details of the simulation, including cuts selection, are described in [5]. Signal and background samples were generated with WHizard 2.2.8 [6]. Generator level cuts reflecting detector acceptance for leptons and ISR photons were applied. For the final selection of signal-like events, a multivariate
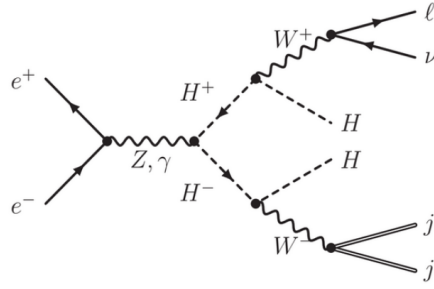
Figure 3: Signal Feynman diagram for the semi-leptonic decay process for charged scalar production: $e^+e^- \to H^+H^- \to HHl\nu jj$.

analysis is performed using a Boosted Decision Tree (BDT) classifier [7] with 8 input variables, both for the HA and H^+H^- analysis. The BDT is trained using all accessible (at given energy) benchmark points in a given category ($\mu^+\mu^-$ or $e^\pm\mu^\mp$ signature; virtual or real W/Z).

## 3. Results for leptonic decay channels

For both analysed signatures, the expected significance of the signal is mainly related to the production cross-section for the considered channel.

Low $\sqrt{s}$ at ILC and CLIC Fig. 4 shows the expected significance for low centre-of-mass energy stages of ILC and CLIC. In all cases, the integrated luminosity is set to $1\,\text{ab}^{-1}$. For the centre-of-mass energies of $250\,\text{GeV}$, $380\,\text{GeV}$ and $500\,\text{GeV}$, the expected discovery reach of e^+e^- colliders extends up to sum of neutral scalar masses of $220\,\text{GeV}$, $300\,\text{GeV}$ and $330\,\text{GeV}$, respectively, and for charged scalar pair-production up to charged scalar masses of $110\,\text{GeV}$, $160\,\text{GeV}$ and $200\,\text{GeV}$. Note, that as charged scalars are usually heavier than their neutral partners, fewer scenarios are accessible at a given energy in the electron-muon pair-production channel.

We usually do not observe strong dependence of the expected significance on the mass splitting between inert scalars, $m_{H^\pm} - m_H$ or $m_A - m_H$, within the considered range of parameters. However, a possibility of significant contribution of cascade decays, $H^\pm \to W^\pm A \to W^\pm ZH$, which were not considered in the signal event selection, can reduce the signal, as is indeed the case with one of the benchmarks in the muon-electron channel (BP2 with $m_{H^\pm} = 112.8$ GeV).

High $\sqrt{s}$ at CLIC If a scenario is not kinematically accessible at low energy stages of CLIC and ILC, it can be searched for at high-energy CLIC stages, with centre-of-mass energies 1.5 TeV and 3 TeV. After the kinematic threshold, the signal production cross-section for both considered channels decreases significantly with energy, much faster than for the corresponding background. As shown in Fig. 5, for $2.5\,\text{ab}^{-1}$ of data and energy of 1.5 TeV, only a moderate increase in discovery reach is expected. The neutral scalar pair-production in the $\mu^+\mu^-$ channel can be discovered for $m_A + m_H < 450\,\text{GeV}$. A better reach was observed for charged scalar production in the $e^\pm\mu^\mp$ channels, leading to $m_{H^\pm} < 500\,\text{GeV}$.

For the scenarios considered here, increasing the centre-of-mass energy to 3 TeV does not significantly improve the sensitivity. Therefore, the observation of the inert scalar production in the leptonic channels might be challenging at high-energy CLIC.
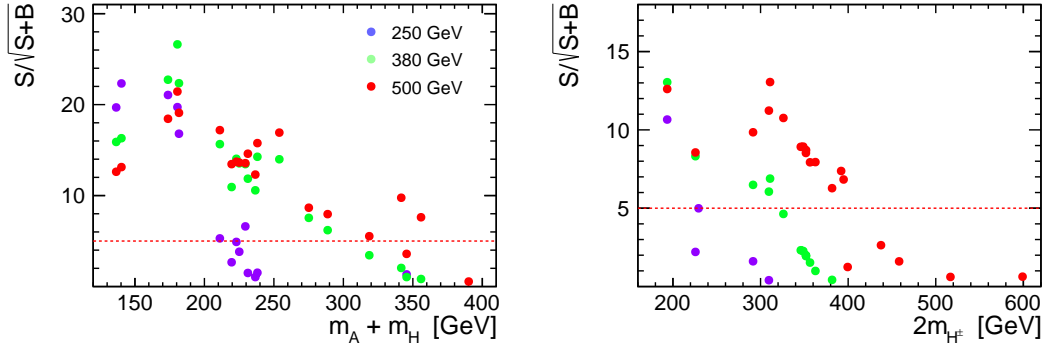
Figure 4: Significance of the deviations from the Standard Model predictions, expected for $1\,\text{ab}^{-1}$ of data collected at centre-of-mass energy of $250\,\text{GeV}$, $380\,\text{GeV}$ and $500\,\text{GeV}$, for: *(left)* events with two muons in the final state ($\mu^+\mu^-$) as a function of the sum of neutral inert scalar masses and *(right)* events with an electron and a muon in the final state ($e^+\mu^-$ or $e^-\mu^+$) as a function of twice the charged scalar mass.
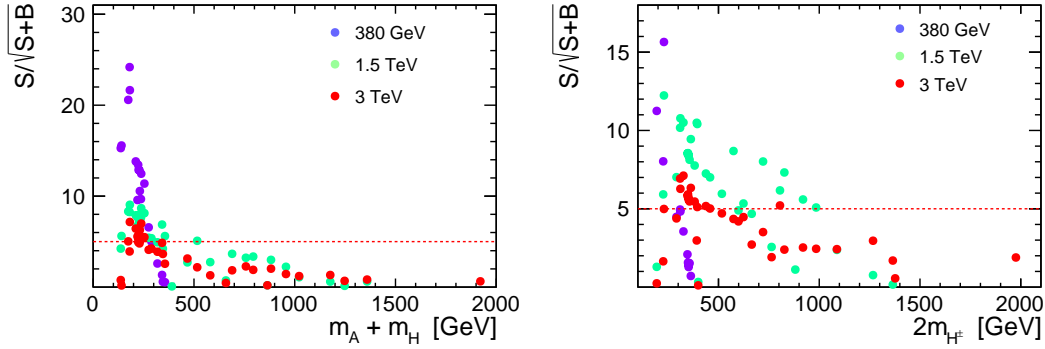

Figure 5: As in Fig. 4 but for target integrated luminosity of CLIC: $1\,\text{ab}^{-1}$ of data collected at $380\,\text{GeV}$, $2.5\,\text{ab}^{-1}$ at $1.5\,\text{TeV}$ and $5\,\text{ab}^{-1}$ at $3\,\text{TeV}$.

4. Results for semi-leptonic decay channels

Due to the much larger branching ratios (28.6% for $H^+H^- \to HHl^\pm\nu qq$, with $l = e, \mu$ compared to 2.3% for $H^+H^- \to HH\mu^\pm e^\mp\nu\nu$) the expected number of H^+H^- signal events in the semi-leptonic final state is over an order of magnitude larger than for the electron-muon signature. Considering a similar scaling for the background processes (dominated by the W^+W^- production), the expected significance of the observation in the semi-leptonic channel compared to purely leptonic one increases by a factor of 3-6, as presented in Fig. 6. For $2.5\,\text{ab}^{-1}$ at $1.5\,\text{TeV}$ all proposed benchmarks with charged scalar masses up to $600\,\text{GeV}$ can be discovered. Discovery reach is further expanded with increased energy and luminosity: for $5\,\text{ab}^{-1}$ at $3\,\text{TeV}$ all benchmarks but one with charged scalar masses up to $1\,\text{TeV}$ reach 5σ significance.

5. Conclusions

A large part of the parameter space of the Inert Doublet Model can be tested at future e^+e^-
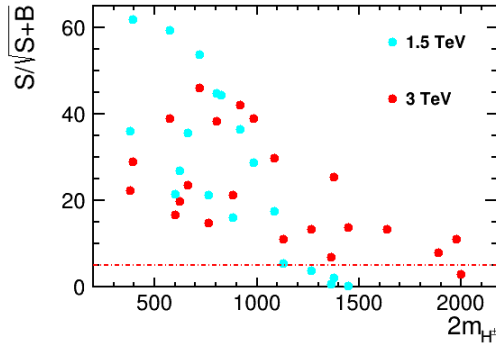
Figure 6: Significance of the deviations from the Standard Model predictions in the semi-leptonic channel as a function of twice the charged scalar mass expected for 2.5 ab^{-1} at 1.5 TeV and 5 ab^{-1} at 3 TeV.

colliders. Low mass scenarios can be observed with high significance in $\mu^+\mu^-$ or $e^\pm\mu^\mp$ channels already at the low energy stages of CLIC and ILC, up to $m_A + m_H \approx 330$ GeV and $m_{H^\pm} \approx 200$ GeV. The discovery reach is extended to $m_A + m_H \approx 500$ GeV and $m_{H^\pm} \approx 500$ GeV for $\sqrt{s} = 1.5$ TeV. There is no improvement in searches in leptonic channels with 3 TeV run at CLIC, however there is a significant increase in discovery reach while using semi-leptonic final states, providing 5σ significance for inert scalar masses up to 1 TeV.

Acknowledgements

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