

Inert Doublet Model Signatures at Future e^+e^- Colliders

Aleksander Filip Żarnecki*, Jan Kalinowski, Jan Klamka, Paweł Sopicki

Faculty of Physics, University of Warsaw

E-mail: filip.zarnecki@fuw.edu.pl, jan.kalinowski@fuw.edu.pl,
j.klamka@student.uw.edu.pl, pawel.sopicki@fuw.edu.pl

Wojciech Kotlarski

Institut für Kern- und Teilchenphysik, TU Dresden

E-mail: wojciech.kotlarski@tu-dresden.de

Tania Robens

Theoretical Physics Division, Rudjer Boskovic Institute, Zagreb

E-mail: trobens@irb.hr

Dorota Sokolowska

International Institute of Physics, Universidade Federal do Rio Grande do Norte, Brasil

E-mail: dsokolowska@iip.ufrn.br

The Inert Doublet Model is one of the simplest extensions of the Standard Model, 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 Standard Model fermions and makes the lightest of them stable. We study a large number of Inert Doublet Model 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 collider and low-energy limits. We use 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, $e^+e^- \rightarrow AH$ and $e^+e^- \rightarrow H^+H^-$, followed by decays of H^\pm and A into the 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, while the qualitative conclusions can also be drawn for the semi-leptonic signatures.

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1. Inert Doublet Model benchmark points

One of the simplest extensions of the Standard Model (SM) which can provide a dark matter (DM) candidate is the Inert Doublet Model (IDM) [1, 2, 3]. In this model, the scalar sector is extended by a so-called inert or dark doublet Φ_D (the only field odd under Z_2 symmetry) in addition to the SM Higgs doublet Φ_S . This results in five physical states after electroweak symmetry breaking: the SM Higgs boson h and four dark scalars: two neutral, H and A , and two charged, H^\pm . Two sets of benchmark points in agreement with all theoretical and experimental constraints were proposed in [4], covering different possible signatures at e^+e^- colliders, with masses of IDM particles extending up to 1 TeV. Distributions of the scalar masses for the IDM benchmark scenarios considered in [4] are shown in Fig. 1. For the considered benchmark scenarios H is the lightest, stable neutral scalar and may serve as a good DM candidate.

2. Analysis strategy

Prospects for the discovery of IDM scalars at CLIC were described in detail in [5]. In this contribution we summarize these results and extend them to ILC running at 250 GeV and 500 GeV. The following tree-level production processes of inert scalars at e^+e^- collisions are considered: $e^+e^- \rightarrow A H$ and $e^+e^- \rightarrow H^+H^-$. In the scenarios considered in this paper the produced dark scalar A decays to a (real or virtual) Z boson and the (lighter) neutral scalar H , $A \rightarrow Z^{(*)}H$, while the produced charged boson H^\pm decays predominantly to a (real or virtual) W^\pm boson and the neutral scalar H , $H^\pm \rightarrow W^{\pm(*)}H$, where the DM candidate H escapes detection. Since isolated leptons (electrons and muons) can be identified and reconstructed with very high efficiency and purity, we concentrate on Z and W^\pm leptonic decays, leading to a signature of leptons and missing transverse energy. In the presented study, we considered the $\mu^+\mu^-$ final state as a signature of the neutral scalar pair-production, while the different flavour lepton pairs, μ^+e^- and $e^+\mu^-$, were considered as a signature for production of charged inert scalars, see Fig. 2.

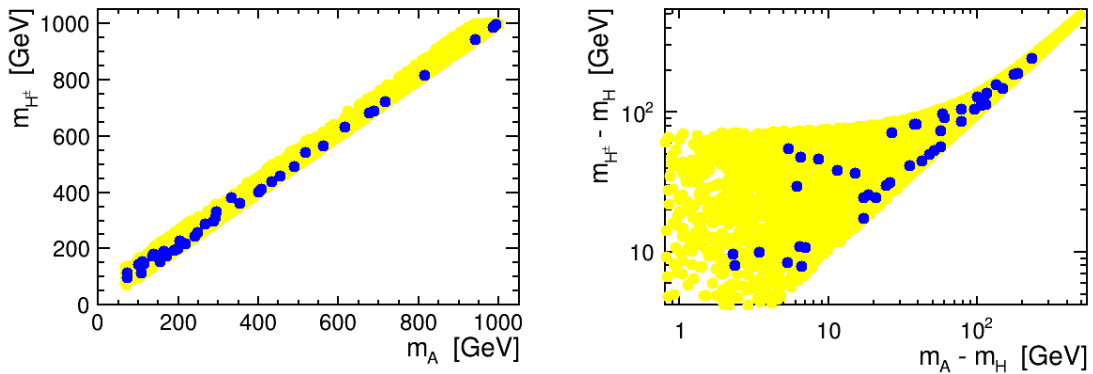


Figure 1: Distribution of benchmark candidate points (yellow) in the $(m_A; m_{H^\pm})$ plane (left) and in the $(m_A - m_H; m_{H^\pm} - m_H)$ plane (right), after all constraints are taken into account, as well as selected benchmark points (blue) in the same planes [4].

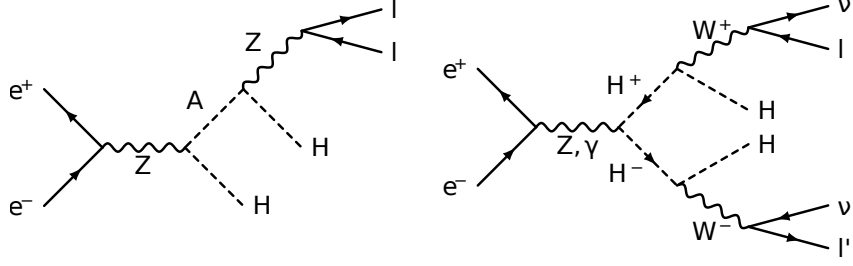


Figure 2: Signal Feynman diagrams for the considered production and decay process for: (left) neutral scalar production, $e^+e^- \rightarrow HA \rightarrow HHll$, and (right) charged scalar production, $e^+e^- \rightarrow H^+H^- \rightarrow HHll' \nu\nu'$.

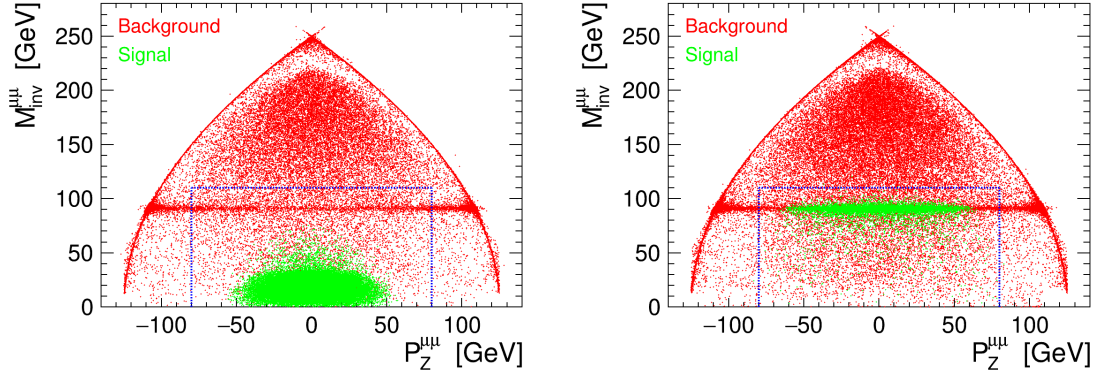


Figure 3: Distribution of the lepton pair invariant mass, $M_{\mu\mu}$, as a function of the lepton pair longitudinal momentum, $P_Z^{\mu\mu}$, for IDM signal (green points) and Standard Model background (red points). Signal events were simulated for BP1 scenario (left) and BP9 scenario (right), for centre-of-mass energy of 250 GeV. The blue box indicates the cut used to remove the dominant background from $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$ process.

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 neutral inert scalar pair production, $e^+e^- \rightarrow AH$, the invariant mass of the lepton pair from (virtual) Z decay depends on the mass splitting between A and H and is relatively small, $M_{\mu\mu} \leq M_Z$. We apply pre-selection cuts on the invariant mass and the longitudinal boost of the lepton pair to suppress the dominant background process $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$, see Fig. 3. Distributions of selected kinematic variables describing the leptonic final state in AH analysis, after the pre-selection cuts, are presented in Fig. 4. Presented in Fig. 5 (left) is the lepton pair invariant mass distribution after pre-selection cuts and additional selection based on lepton pair energy, transverse momentum, production angle (polar angle of the Z boson) and the difference of the lepton azimuthal angles. Already with this simplest, cut-based approach, the IDM signal would result in the visible excess in the invariant mass distribution for the number of benchmark scenarios. For the final selection of signal-like events, a multivariate analysis is performed using a Boosted Decision Tree (BDT) classifier [7] with 8 input variables, both for HA and H^+H^- analysis (no pre-selection cuts are applied for H^+H^-). The BDT is trained using all accessible (at given energy) benchmark points in given category ($\mu^+\mu^-$ or $e^\pm\mu^\mp$ signature; virtual or real W/Z). Response distributions of the BDT classifier used for the selection of AH production events for the benchmark scenario BP1 are presented in Fig. 5 (right).

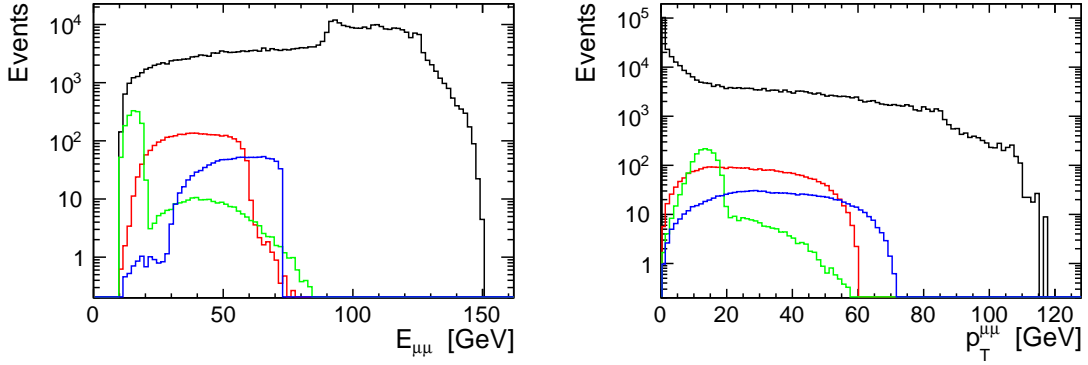


Figure 4: Distributions of the kinematic variables describing the leptonic final state in AH analysis: lepton pair energy, $E_{\mu\mu}$ and total transverse momentum, $p_T^{\mu\mu}$. Expected distributions for representative benchmarks BP1 (red histogram), BP2 (green) and BP7 (blue) are compared with expected background (black histogram) simulated for 1 ab^{-1} collected at 250 GeV.

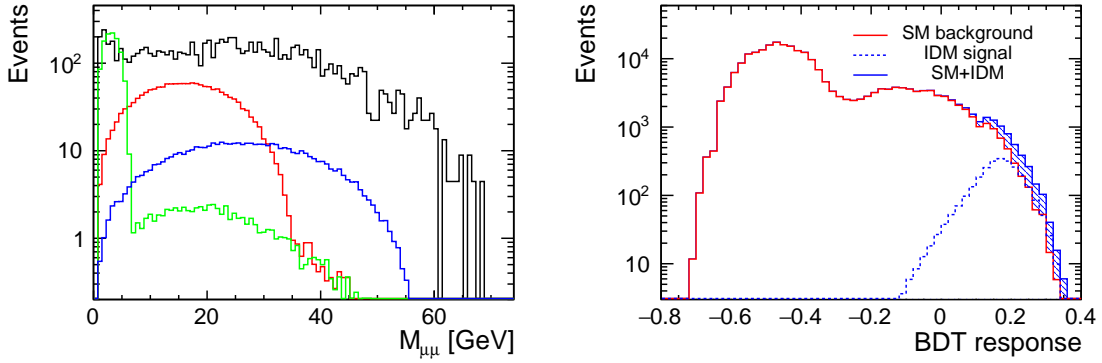


Figure 5: Left: distribution of the lepton pair invariant mass, $M_{\mu\mu}$, for BP1 (red histogram), BP2 (green) and BP7 (blue) signal scenarios, compared with the expected Standard Model background (black histogram), after event selection cuts (see text for details). Right: response distributions of the BDT classifiers used for the selection of AH production events, for BP1. Samples are normalised to 1 ab^{-1} collected at 250 GeV.

3. Results

Expected significance of the deviations from the Standard Model predictions, assuming 1 ab^{-1} of data collected at centre-of-mass energy of 250 GeV, 380 GeV and 500 GeV, for AH and H^+H^- signatures, are shown in Figs. 6 and 7, respectively. Only scenarios resulting in the significances above 5σ are shown¹. We found that for scenarios accessible at a certain energy, high significances can be expected at future e^+e^- colliders. They are mainly related to the inert scalar production cross sections. We display the dependence of the expected significances on the inert scalar masses in Fig. 8. With 1 ab^{-1} of integrated luminosity collected at 250 GeV, 380 GeV and 500 GeV, the expected discovery reach of e^+e^- colliders extends up to neutral scalar mass sum of 220 GeV, 300 GeV and 330 GeV, respectively, and for charged scalar pair-production up to charged scalar

¹We omit BP5 and BP17, which are excluded by the updated Xenon1T limits.

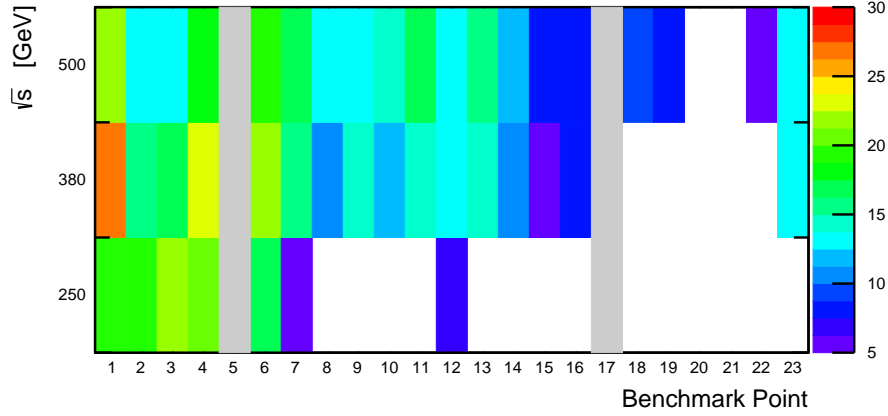


Figure 6: Significance of the deviations from the Standard Model predictions, expected for 1 ab^{-1} of data collected at centre-of-mass energy of 250 GeV, 380 GeV and 500 GeV, for events with two muons in the final state, for all considered low mass benchmark scenarios. Only significance above 5σ is shown.

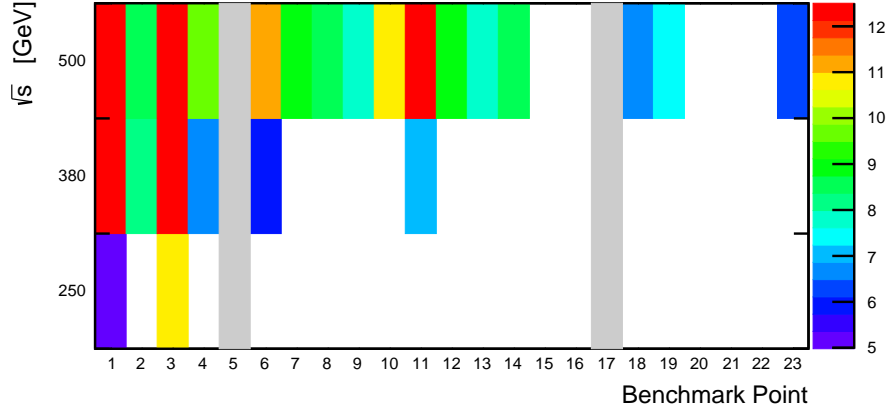


Figure 7: As in Fig. 6 but for events with an electron and a muon in the final state.

masses of 110 GeV, 160 GeV and 200 GeV. For CLIC running at 1.5 TeV, only a moderate increase in discovery reach is expected, even with 2.5 ab^{-1} of data, see Fig. 9. The neutral scalar pair-production can be discovered in the leptonic channel for $m_A + m_H < 450 \text{ GeV}$ and the charged scalar production for $m_{H^\pm} < 500 \text{ GeV}$. Marginal improvement is expected when running at 3 TeV. Low significance expected at high CLIC energies is related to the decrease of the signal cross sections with energy. However, we found that significant improvement of the discovery reach for high mass scenarios could be achieved using the semi-leptonic final state, as the signal cross section increases by an order of magnitude. The corresponding study is in progress and the preliminary results are very promising.

Acknowledgements

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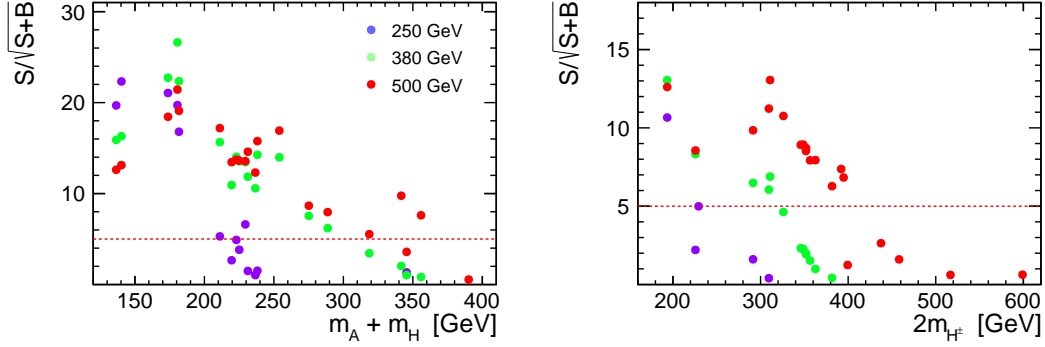


Figure 8: Significance of the deviations from the Standard Model predictions, expected for 1 ab^{-1} of data collected at centre-of-mass energy of 250 GeV, 380 GeV and 500 GeV, for: (left) events with two muons in the final state ($\mu^+\mu^-$) as a function of the sum of neutral inert scalar masses 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.

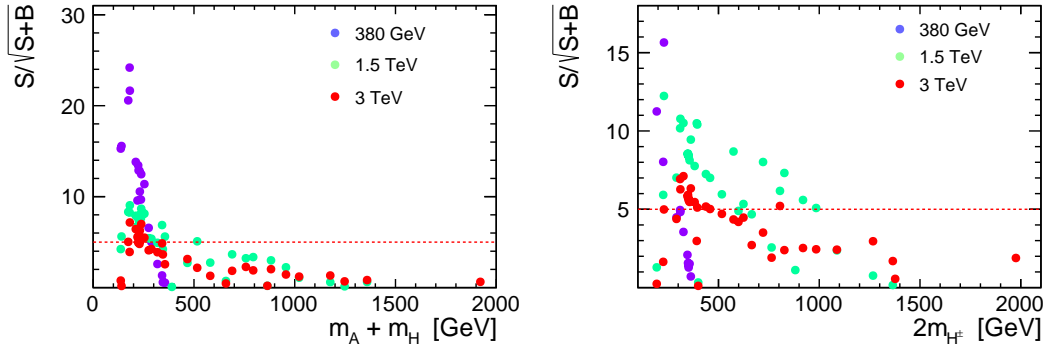


Figure 9: As in Fig. 8 but for expected CLIC running scenario: 1 ab^{-1} of data collected at 380 GeV, 2.5 ab^{-1} at 1.5 TeV and 5 ab^{-1} at 3 TeV.

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