PROCEEDINGS OF SCIENCE

Dark matter searches at future e^+e^- linear colliders

Jan Kalinowski,[a,b,*] **Wojciech Kotlarski**[c] **and Aleksander Filip Żarnecki**[a]

[a] *Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland*
[b] *CERN, Theoretical Physics Department, Geneva, Switzerland*
[c] *National Centre for Nuclear Physics, Pasteura 7, 02-093 Warsaw, Poland*

E-mail: jan.kalinowski@fuw.edu.pl

The future linear e^+e^- colliders offer a number of unique opportunities for searches for dark matter and dark sector particles. The collider program itself will offer important capabilities on three frontiers: (i) the precision frontier with measurements at the Higgs factory, (ii) the energy frontier with direct investigations of the scalar sector, and (iii) the intensity frontier with fixed-target and beam-dump measurements. This contribution presents some of the possible experiments, which address various dark sector portals.

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1. Introduction

While there are many hints for existence of Dark Matter (DM), its nature is basically not known. Many possible scenarios need to be considered with different possible connections between Standard Model (SM) and DM sectors, a wide range of DM particle masses, coupling values and other model parameters. The International Linear Collider (ILC) and Compact Linear Collider (CLIC), with their high energy reach, clean environment and kinematic constraints of e^+e^- collisions, are unique machines offering many options for DM searches. Additional capabilities of the ILC also open with the use of single high-intensity electron or positron beams in a fixed target mode.

The ILC will make use of the superconducting accelerating cavities. In the assumed, staged construction scheme, it will start as a 250 GeV Higgs factory, followed by the 500 GeV machine, with a possible upgrade even to 1 TeV [1]. The unique feature of the ILC is the possibility of having both beams polarized: electrons at 80% and positrons at 30%. This is crucial for many precision measurements as well as for beyond SM searches. By combining data collected with four different polarization combinations accuracy of precision measurements is significantly increased, more constraints can be imposed in global fits and analyses, ambiguity between different scenarios can be removed in many BSM studies and the sensitivity to systematic effects can be significantly reduced.

The CLIC will use a novel two-beam accelerating technique. It is foreseen to operate at three stages: as a Higgs factory at 380 GeV and as a discovery machine at 1.5 TeV and 3 TeV [2]. At CLIC only the electron beam can be polarized with 80%.

The future linear e^+e^- colliders offer a number of unique opportunities for searches for dark matter and dark sector particles. They include precision measurements at the Higgs factory, direct investigations of the scalar sector at high energies, while the extreme intensities of the high-energy electron and positron beams will also enable new fixed-target measurements, both beam dump experiments and dedicated experiments using extracted beams at ILC. This contribution summarizes the expectations for these programs, which address various possible dark sector portals.

2. The precision frontier

2.1 Higgs precision measurements

The first ILC running stage at 250 GeV will clearly focus on precision measurements of the Higgs boson. Since its production is dominated by the Higgs-strahlung process, $e^+e^- \to ZH$, the Z-tagging method can be used for unbiased selection of Higgs production events by reconstructing the recoil mass. This allows for fully model independent analysis avoiding any dependence on the Higgs decay channel. The recoil mass technique results also in high sensitivity to invisible Higgs boson decays [3, 4]. For 2 ab^{-1} collected at 250 GeV ILC the expected 95% C.L. limit on the invisible Higgs boson decays is 0.23% [3], an order of magnitude better than the estimated HL-LHC sensitivity. The expected recoil mass distribution for the ILC running at 250 GeV, assuming an invisible Higgs boson branching ratio of 10%, is shown in Fig. 1 (left).

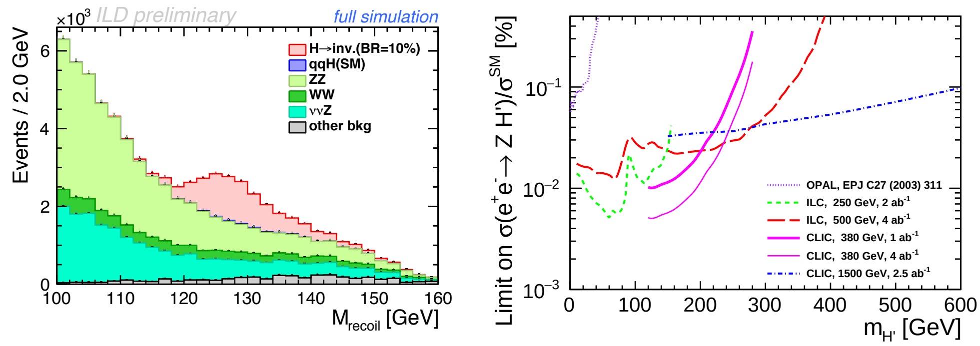

Figure 1: Left: recoil mass distribution after event selection for ILC running at 250 GeV and invisible Higgs branching ratio of 10% [3]. Right: limit on $\sigma(e^+e^- \to ZH')/\sigma^{SM}$ as a function of H' mass [5].

2.2 Searches for new scalars

In Higgs-portal models, new scalar fields coupled to DM particles can mix with the SM Higgs field. If the mixing angle θ is small, one of the mass eigenstates is SM-like (the observed 125 GeV scalar). If the second mass eigenstate is also light, it can be produced in e^+e^- collisions in the same way as the SM-like Higgs boson and should be visible as an additional resonance in the recoil mass distribution. Such scenarios can be probed at the ILC and CLIC down to $\sin^2\theta \sim 10^{-2}$, see Fig. 1 (right) [5, 6].

3. Energy frontier

3.1 Inert doublet model

The Inert Doublet Model (IDM) is one of the simplest extensions of the SM with two SU(2) scalar doublets Φ_S, Φ_D [7–9]. By imposing a discrete Z_2 symmetry under which the doublet Φ_S and all the other SM fields are even, whereas Φ_D is odd, $\Phi_D \to -\Phi_D$, the doublet Φ_S is the SM-like, while the Φ_D is inert (or dark). After the electroweak symmetry breaking the scalar sector of IDM has five physical states: apart from the SM Higgs boson h it has two neutral ones, H and A, as well as two charged scalars, $H^\pm$. As a result of Z_2, the lightest neutral component of Φ_D becomes a candidate for dark matter; without loss of generality the H can be taken as a DM particle.

At e^+e^- collisions the DM particles can be produced via pair-production of charged scalars (H^+H^-) or neutral scalars (HA) followed by decay predominant decay chains as $H^+ \to W^+H$ and $A \to ZH$, leading to a signature of gauge boson(s) and missing transverse energy, with on- or off-shell electroweak gauge bosons depending on the kinematic configuration and available phase space. Such production processes with leptonic decays of gauge bosons have been analyzed using the proposed benchmarks of [10] which satisfy all theoretical requirements and current experimental constraints. Production cross sections for the above channels can reach up to 150 fb for collider scenarios with center-of-mass energies in the 250 – 500 GeV range. In [11] a detailed analysis was presented for the potential of CLIC running at center-of-mass energies of 380 GeV with an integrated luminosity of 1 ab^{-1} as well as 1.5 and 3 TeV with 2.5 ab^{-1} and 5 ab^{-1}, respectively, including luminosity spectra and beamsstrahlung. The results are summarized in Fig. 2, where the expected signifcance as a function of the relevant mass scales are plotted. At a center-of-mass energy of 380 GeV, scales up to 300 GeV are accessible. An increase in collider energy enhances this reach up to 550 GeV for the dimuon and 1 TeV for the different flavour final states. Sensitivity of high energy e^+e^- collider to pair production of massive charged scalars can be further increased when the semi-leptonic final state is considered. For high energy CLIC, the accessible scalar mass range increases by about a factor of two, to about 2 TeV [12–14].

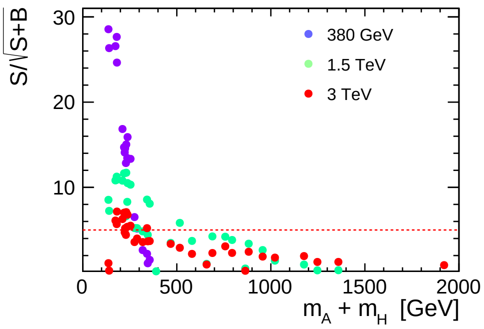

Figure 2: Projected signifcances, as a function of the relevant masses, for benchmark points of [10] after full simulation and BDT analysis for various center-of-mass energies, taken from [11] . Left: For dimuon and missing transverse energy (HA channel). Right: For different flavour final states (H^+H^- channel).

3.2 Mono-photon events

DM particles can be pair produced in the e^+e^- collisions via exchange of a new mediator particle, which couples to both electrons and DM particles, χ. This process can be detected, if additional hard photon radiated from the initial state, $e^+e^- \to \chi\chi + \gamma$, is observed in the detector. The mono-photon signature is considered to be the most general approach to search for DM particle production at e^+e^- colliders, as it is largely independent on the BSM scenario. Signal events have a striking signature: single high-energy photon and no other activity in the detector. "Irreducible" background in this channel comes from the radiative neutrino pair-production, $e^+e^- \to \nu\bar{\nu} + \gamma$, while huge background from the radiative Bhabha scattering, $e^+e^- \to e^+e^- + \gamma$, can be efficiently suppressed by the selection cuts.

Scenarios with DM pair-production via heavy mediator exchange were considered in a full simulation study [15], using an EFT approach and assuming coupling values $O(1)$. For light DM particles mediator masses up to about 3 TeV can be excluded at the ILC, as shown in Fig. 3 (left). DM production via light mediator exchange is still not excluded if very small mediator couplings to SM particles (electrons) are considered. Within a simplified DM model [16] limits on the DM pair-production were studied as a function of mediator mass and width. A dedicated simulation procedure was used [17], where all "detectable" photons generated on a matrix element level were matched to soft ISR. With 2 dimensional distributions of $(p_T^\gamma, \eta^\gamma)$ used to constrain DM production it is found that the ILC running at 500 GeV is sensitive to mediator couplings down to $O(10^{-3})$, as shown in Fig. 3 (right).

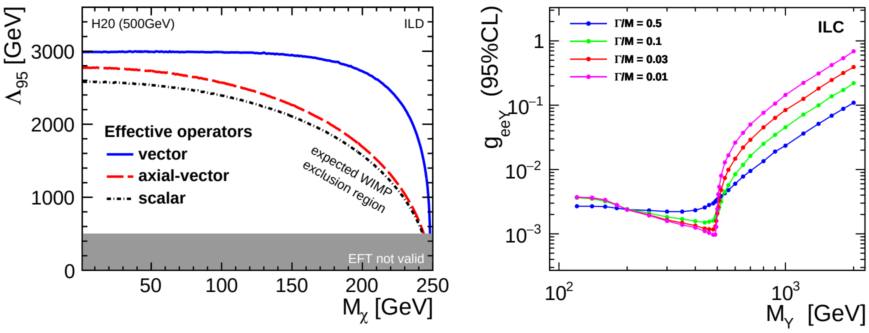

Figure 3: The expected sensitivity of ILC running at 500 GeV to DM pair production. Left: EFT limits on mediator mass, as a function of the DM particle mass, for different mediator types [15]. Right: mediator coupling limits as a function of the vector mediator mass and DM particle mass of 50 GeV [16].

4. Intensity frontier

Extreme intensities of electron and positron beams at the ILC, $\mathcal{O}(10^{22})$ particles per year, open unique options for fixed-target experiments focused on rare processes. General concept of main beam dump experiments searching for axion-like particles or new scalars is presented in Fig. 4 [18]. Light axion-like particles (a) could be copiously produced in the beam dump and decay only after

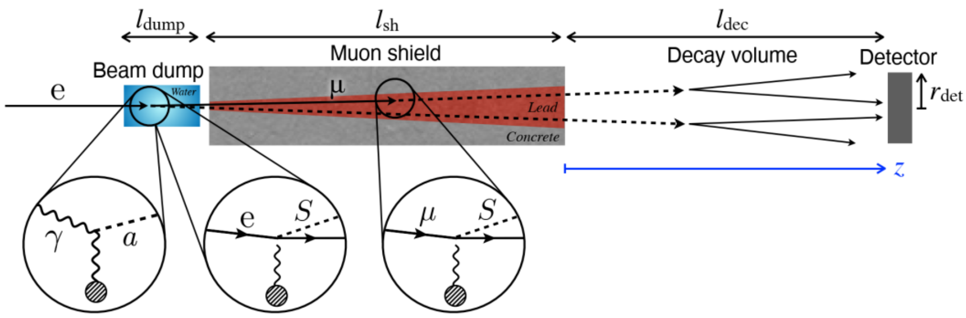

Figure 4: An experimental setup proposed for new light particle searches at the ILC [18].

passing the massive muon shield. Expected sensitivity of ILC running at 250 GeV to $a\gamma\gamma$ coupling as a function of its mass, resulting from the search for two-photon decay, $a \to \gamma\gamma$, is presented in Fig. 5 (left). Thanks to the extreme beam intensities the ILC sensitivity is an order of magnitude better than those expected at other experiments. A similar increase in sensitivity is expected for models with new light scalars coupling to charged leptons. Expected sensitivity of the ILC to the scenario with scalar coupling proportional to the lepton mass is shown in Fig. 5 (right).

Other options for light DM particle searches in fixed-target experiments at the ILC were considered in [19, 20]. If DM particles are light, dark photon A′ production in the beam dump could result in a collimated stream of DM χ particles from A′ decay, $\mathrm{A}' \to \chi\chi$, which can be probed by looking for elastic DM interactions in the dedicated detector. This approach, previously used in SLAC Beam Dump Experiment E137 [21], will offer a huge improvement in sensitivity for $m_{A'} \lesssim 1$ GeV thanks to much higher statistics at the ILC. Experiments with extracted positron

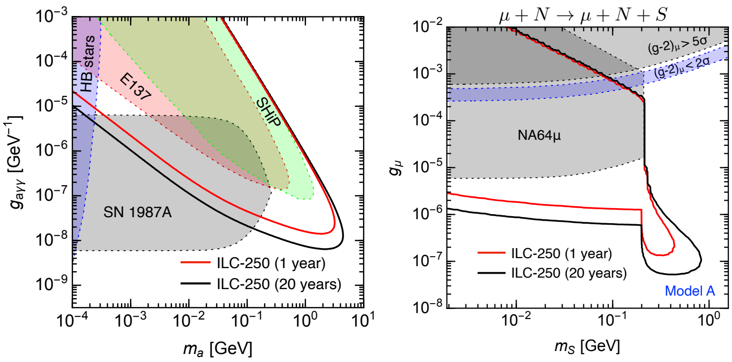

Figure 5: Expected sensitivity of main beam dump experiments at the 250 GeV ILC after one year (red lines) and 20 years (black lines) of running to processes with light axion-like particle production (left) and light scalar production (right). Results taken from [18].

beams can search for dark photon production independent on its decays. Associated production, $e^+e^- \to A'\gamma$ can be searched for with thick active target reconstructing the missing energy (idea based on LDMX experiment for SLAC [22]) or in thin target detectors reconstructing the missing mass (as in the PADME experiment at Frascati [23]). As shown in [19, 20], in both approaches sensitivity of the fixed-target experiments at the ILC can probe the dark photon couplings down to the minimum couplings allowed by relic density bounds.

5. Conclusions

Linear e^+e^- colliders will offer many complementary options for DM searches. Different scenarios can be constrained via precision Higgs studies. Direct searches for DM pair-production are possible in the di-lepton or the mono-photon channels with missing energy. Sensitivity to heavy mediator exchange can reach TeV mass scales, order of magnitude higher than the collision energy, and sensitivity to couplings of $\mathcal{O}(10^{-3})$ in the case of light mediator exchange. The ILC will also offer high energy electron and positron beams, with unprecedented intensities, for beam dump and extracted beam experiments. Fixed-target experiments offer many interesting opportunities for dark sector searches in the low mass domain and other science goals.

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PoS(DISCRETE2020-2021)013

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PoS(DISCRETE2020-2021)013