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# New approach to dark matter searches with mono-photon signature

**Jan Kalinowski,**[a] **Wojciech Kotlarski,**[b] **Krzysztof Mekala,**[a,*]
**Aleksander Filip Żarnecki**[a] **and Kamil Zembaczynski**[a]

[a] *Faculty of Physics, University of Warsaw*
*Pasteura 5, 02-093 Warsaw, Poland*
[b] *National Centre for Nuclear Research*
*Pasteura 7, 02-093 Warsaw, Poland*
*E-mail:* jan.kalinowski@fuw.edu.pl, wojciech.kotlarski@ncbj.gov.pl, k.mekala@uw.edu.pl, filip.zarnecki@fuw.edu.pl, k.zembaczynski@student.uw.edu.pl

High energy $e^+e^-$ colliders offer a unique possibility for the most general dark matter (DM) search based on the mono-photon signature. Analysis of the energy spectrum and angular distributions of photons from the initial state radiation can be used to search for hard processes with invisible final state production. Most studies in the past focused on scenarios assuming heavy mediator exchange. We notice, however, that scenarios with light mediator exchange are still not excluded by existing experimental data, if the mediator coupling to Standard Model (SM) particles is very small. We proposed a novel approach, where the experimental sensitivity to light mediator production is defined in terms of both the mediator mass and mediator width. This approach is more model independent than the approach assuming given mediator coupling values to SM and DM particles. Presented in this contribution are results on the expected sensitivity of the International Linear Collider (ILC) and Compact Linear Collider (CLIC) experiments to dark matter production. The use of beam polarisation can largely improve the sensitivity to DM production scenarios and reduce the impact of systematic uncertainties. Precision of mediator mass, width, and coupling structure determination, in the case of signal observation, are also derived.

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[*] Speaker





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## 1. Introduction

Any $e^+e^-$ scattering process can be accompanied by a hard photon emission from the initial state radiation. In particular, analysis of the energy spectrum and angular distributions of those photons can be used to search for hard processes with an invisible final state. For this reason, high energy $e^+e^-$ colliders and the mono-photon signature, when only a single hard photon radiated from the initial state is observed in the detector, are considered perfect tools for the most general search for pair-production of DM particles.

Considered in this contribution is the DM pair production at future linear $e^+e^-$ colliders, 500 GeV ILC [1] and 3 TeV CLIC [2]. A total of 4000 fb$^{-1}$ of data is expected to be collected at 500 GeV stage at the ILC, with polarisation of 80% and 30% for $e^-$ and $e^+$ beams, respectively [3]. For CLIC, a total integrated luminosity of 5000 fb$^{-1}$ is expected at 3 TeV stage, with 80% electron beam polarisation only [4]. For details of the results presented here the reader is referred to [5–7].

## 2. Simulating mono-photon events

A dedicated procedure [5] allows for consistent simulation of BSM processes and of the SM backgrounds processes with mono-photon signature in Whizard [8, 9]. Matching of the soft ISR radiation with the matrix element (ME) level simulation of detectable hard photons is based on two variables, calculated separately for each emitted photon, describing its kinematics:

$$\begin{aligned} q_- &= \sqrt{4E_0 E_\gamma} \cdot \sin\frac{\theta_\gamma}{2} , \\ q_+ &= \sqrt{4E_0 E_\gamma} \cdot \cos\frac{\theta_\gamma}{2} , \end{aligned}$$

where $E_0$ is the nominal electron or positron beam energy, while $E_\gamma$ and $\theta_\gamma$ are the energy and scattering angle of the emitted photon in question. The detector acceptance in the $(q_+, q_-)$ plane expected for the ILC experiment is presented in Fig. 1 (left). The red dashed line indicating the cut used to separate "soft ISR" and "hard ME" emission regions shows that with this procedure only the photons generated on the ME level can enter the detector acceptance region. The matching procedure can result in up to 50% correction to the DM production cross section.

While radiation of one or more photons (on the ME level) is expected in up to 50% of DM pair-production events, most of these photons go along the beam line and only a small fraction is reconstructed as mono-photon events in the detector. The fraction of "tagged" events depends significantly on the mediator mass and width, as shown in Fig. 1 (right).

The presented results are based on the fast detector simulation framework Delphes [10] in which two detector models were implemented, including a detailed description of the calorimeter systems in the very forward region.

## 3. Analysis approach

The analysis [6] considered pair-production of DM particles at the ILC and CLIC for scenarios with both light and heavy mediators. The study focused on scenarios with very small mediator couplings to SM, which are still not excluded by the existing experimental data, when the total

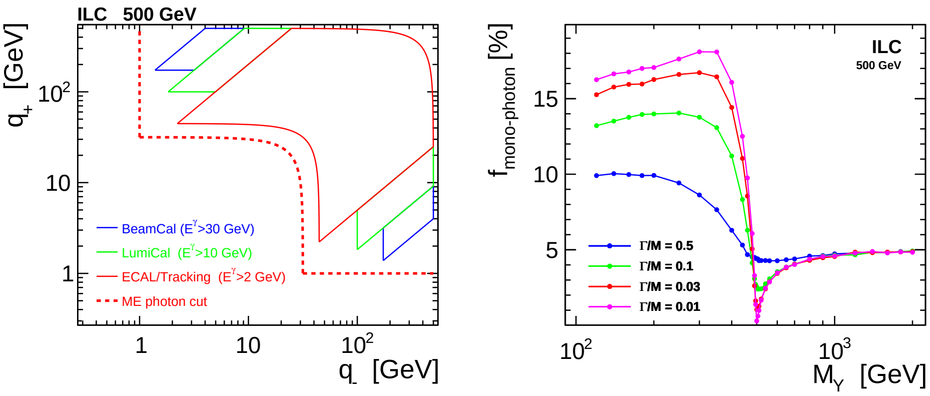


**Figure 1:** Left: detector acceptance in the $(q_+, q_-)$ plane expected for the future experiments at 500 GeV ILC. Red dashed lines indicate the cut used to restrict the phase space for ME photon generation [6]. Right: fraction of dark matter pair-production events, which are reconstructed as mono-photon events in the detector, as a function of the assumed mediator mass for the ILC running at 500 GeV and different fractional mediator widths, as indicated in the plot.

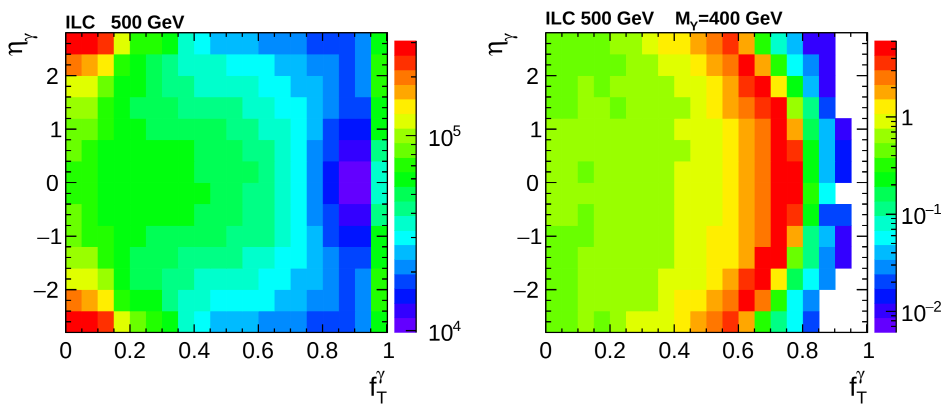


**Figure 2:** Pseudorapidity vs transverse momentum fraction for mono-photon events at 500 GeV ILC running with –80%/+30% electron/positron beam polarisation. Left: for sum of considered SM backgrounds. Right: for pair-production of Dirac fermion DM particles with $m_\chi$ = 50 GeV and vector mediator mass of $M_Y$ = 400 GeV, assuming total production cross section of 1 fb [6].

mediator width is dominated by invisible decays, $\Gamma_{SM} \ll \Gamma_{DM} \approx \Gamma_{tot}$. An "experimental-like" approach is adopted, focused on setting the DM pair-production cross section limits as a function of the mediator mass and width, assuming DM particles are light (the mass of fermionic DM is fixed to $m_\chi$ = 50 GeV for all results presented in the following). Limits on the production cross section are extracted from the two-dimensional distributions of the reconstructed mono-photon events in pseudorapidity and transverse momentum fraction. Distributions expected at 500 GeV ILC, for the SM backgrounds and an example DM production scenario, are compared in Fig. 2. The transverse momentum fraction, $f_T^\gamma$, is a logarithm of the transverse momentum scaled to span the range between the minimum and maximum photon transverse momentum for given rapidity. Cross section limits for DM pair-production are extracted from the combined analysis of data taken with different beam polarisations, resulting in the strongest limits, also reducing the impact of systematic uncertainties.

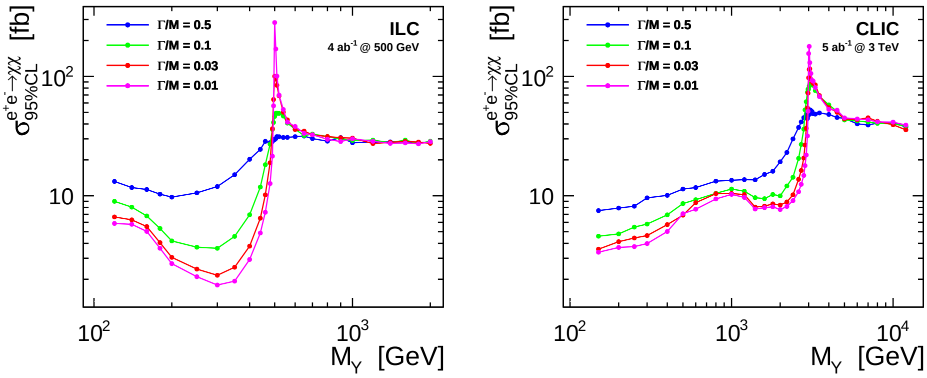


**Figure 3:** Limits on the cross section for light fermionic DM pair-production processes with *s*-channel mediator exchange for the ILC running at 500 GeV (left) and CLIC running at 3 TeV (right), for the vector mediator exchange and different fractional mediator widths. Combined limits corresponding to the assumed running scenarios are presented with systematic uncertainties taken into account [6].

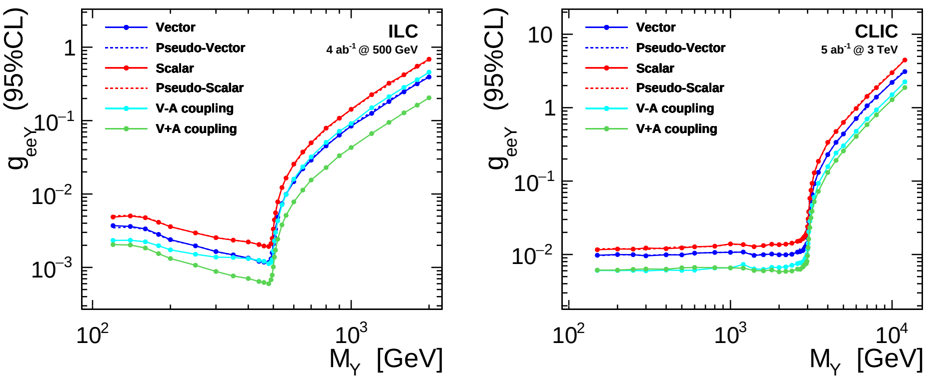


**Figure 4:** Limits on the mediator coupling to electrons for the ILC running at 500 GeV (left) and CLIC running at 3 TeV (right) for different mediator coupling scenarios and relative mediator width, $\Gamma/M = 0.03$. Combined limits corresponding to the assumed running scenarios are presented with systematic uncertainties taken into account [6].

## 4. Results

After correcting for the hard photon tagging probability (refer Fig. 1), limits for the total DM pair-production cross section can be extracted. Presented in Fig. 3 are limits expected from the combined analysis of data taken with different beam polarisations, for different fractional mediator widths assuming vector mediator exchange. The strongest limits are obtained for processes with light mediator exchange and for narrow mediator widths, whereas for heavy mediator exchange ($\mathrm{M_Y} \gg \sqrt{s}$) cross section limits no longer depend on the mediator width.

Shown in Fig. 4 are limits on the mediator coupling to electrons expected for different mediator coupling scenarios and relative mediator width, $\Gamma/M = 0.03$. For heavy mediator exchange, the coupling limits increase with the mediator mass squared, $\mathrm{g_{eeY}} \sim \mathrm{M_Y^2}$, as expected in the Effective Field Theory (EFT) approach. As shown in [11], presented results [6] are in very good agreement

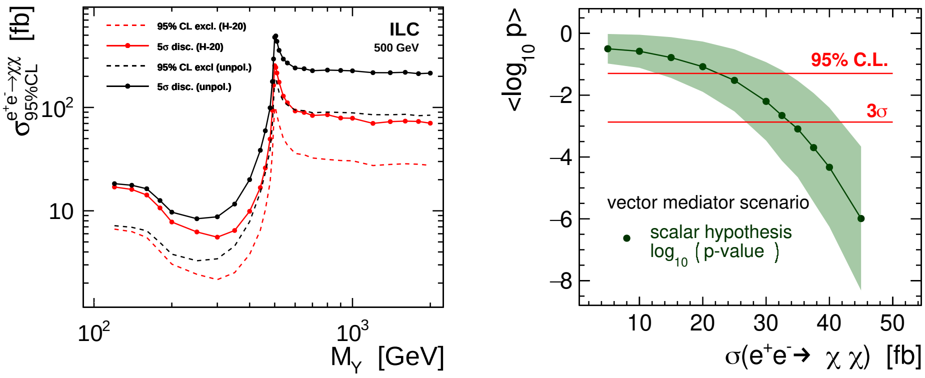


**Figure 5:** Left: expected 95% C.L. limits and $5\sigma$ discovery threshold for DM pair production cross section with vector mediator exchange, as a function of mediator mass, for relative mediator width, $\Gamma/M = 0.03$. Right: expected probability of the scalar mediator hypothesis from the model fit to vector mediator scenario, as a function of the assumed DM pair-production cross-section. Mediator mass of 300 GeV and width of 30 GeV are assumed.

with the limits from the ILD analysis [12] based on the full detector simulation and EFT formalism.

Light mediator scenarios can be discovered at future $e^+e^-$ colliders already for DM production cross sections of $\mathcal{O}(10$ fb). The possibility of running with both electron and positron beam polarisation significantly increases experimental sensitivity, for heavy mediator exchange scenarios in particular, see Fig. 5 (left). It also allows us to establish the mediator coupling structure to electrons (SM fermions) based on the polarisation dependence of the DM pair-production cross section. As shown in Fig. 5 (right), different coupling structures can be easily distinguished at the ILC. Already at the discovery threshold, the light mediator mass can be measured with few percent precision, and sub-percent precision is possible as well as the precise determination of the mediator width, if the production cross section is large enough [13].

## 5. Conclusions

Future $e^+e^-$ colliders offer many complementary options for DM searches. Searches based on the mono-photon signature are believed to be the most general and least model-dependent way to look for DM production. A dedicated procedure has been proposed for a proper simulation of mono-photon events in Whizard [5] and the mono-photon analysis framework was developed for scenarios with light mediator exchange and very small mediator couplings to SM [6]. Future experiments at 500 GeV ILC or 3 TeV CLIC will result in limits on the cross section for the radiative DM pair-production, $e^+e^- \to \chi\chi\gamma_{tag}$, of the order of 1 fb. Limits on the mediator coupling to electrons of the order of $g_{eeY} \sim 10^{-3} - 10^{-2}$ can be set up to the kinematic limit, $M_Y \leq \sqrt{s}$. For processes with light mediator exchange, limits expected from the analysis of mono-photon spectra on the mediator couplings to SM fermions are stronger than those expected from the direct searches in SM decay channels. If discovered, the new mediator can be precisely studied at $e^+e^-$ colliders. Its coupling structure can be easily determined at the ILC thanks to the polarisation of both electron and positron beams.

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