# New approach to DM searches with mono-photon signature

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March 15, 2022

### Abstract

High energy $e^+e^-$ colliders offer unique possibility for the most general dark matter 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 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.

Summarised in this contribution are published results of our studies concerning simulation of mono-photon events with WHIZARD and the expected sensitivity of the International Linear Collider (ILC) and Compact Linear Collider (CLIC) experiments to dark matter production.

# 1    Introduction

Direct pair-production of DM particles can be searched for at high energy $e^+e^-$ colliders. This process can be detected, if additional hard photon radiated from the initial state, see Fig. 1, is observed in the detector. This so called mono-photon signature is considered as the most general approach to search for DM particle production.
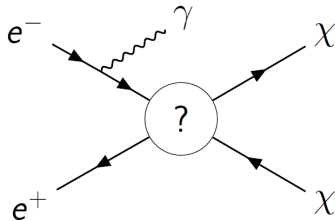


Figure 1: Diagram describing DM particle pair production process with additional ISR photon radiation.

Presented in this contribution are results concerning the DM pair production with mono-photon signature at future linear $e^+e^-$ colliders, ILC [1] and CLIC [2]. Baseline ILC design assumes initial stage at $250\,\mathrm{GeV}$, followed by $500\,\mathrm{GeV}$ and $1\,\mathrm{TeV}$ as the possible upgrade [3]. Polarisation is assumed for both $e^-$ and $e^+$ beams, of 80% and 30%, respectively. Total of $4000\,\mathrm{fb}^{-1}$ of data is expected to be collected at $500\,\mathrm{GeV}$ stage, with 80% of the integrated luminosity taken with LR and RL beam polarisation combinations ($2{\times}1600\,\mathrm{fb}^{-1}$), and only 20% with RR and LL beam polarisation combinations ($2{\times}400\,\mathrm{fb}^{-1}$). Novel two-beam acceleration scheme proposed for CLIC opens the possibility of reaching the collision energy of up to $3\,\mathrm{TeV}$. Total integrated luminosity of $5000\,\mathrm{fb}^{-1}$ is expected at $3\,\mathrm{TeV}$ stage, with 80% ($4000\,\mathrm{fb}^{-1}$) collected with left-handed electron beam polarisation and 20% ($4000\,\mathrm{fb}^{-1}$) with right-handed electron beam [4]. Positron beam polarisation is not included in the CLIC baseline design.

# 2    Simulating mono-photon events

Precise and consistent simulation of BSM processes and of the SM backgrounds is crucial for proper estimate of the experimental sensitivity to processes with mono-photon signature. Procedure developed for simulating these processes with WHIZARD [5, 6] is described in a dedicated paper [7]. We summarise our main results below.

WHIZARD program, which is widely used for $e^+e^-$ collider studies, provides the ISR structure function option that includes all orders of soft and soft-collinear photons as well as up to the third order in high-energy collinear photons. However, photons generated by WHIZARD in this approximation can not be considered as ordinary final state particles, as they represent all photons radiated in the event from a given lepton line. Nor the ISR structure function can properly account for hard non-collinear photon radiation. The proper solution is to generate all "detectable" photons on the Matrix Element (ME) level. This however requires a proper procedure for matching the soft ISR radiation with the hard ME simulation, to avoid double-counting.

The procedure for matching ISR and ME regimes proposed in [7] is based on two variables, calculated separately for each emitted photon, used to describe kinematics of the photon
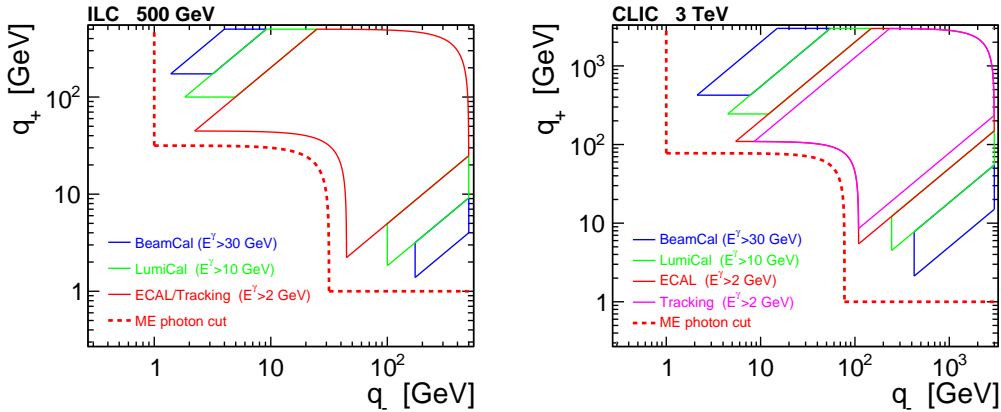
Figure 2: Detector acceptance in the $(q_+, q_-)$ plane expected for the future experiments at 500 GeV ILC (left) and 3 TeV CLIC (right). Red dashed lines indicate the cut used to restrict the phase space for ME photon generation [8].

emission:

$$q_- = \sqrt{4E_0 E_\gamma} \cdot \sin\frac{\theta_\gamma}{2} ,$$

$$q_+ = \sqrt{4E_0 E_\gamma} \cdot \cos\frac{\theta_\gamma}{2} ,$$

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 future ILC and CLIC experiments is presented in Fig. 2. Red dashed lines indicating the cut used to separate "soft ISR" emission region (to the left and below the dashed line) from the region described by ME calculations (to the right and above the dashed line) shows that with this procedure only the photons generated on the ME level can enter the detector acceptance region. Validity of the proposed matching procedure was verified by comparing results of the WHIZARD simulation with those from the semi-analytical $\mathcal{KK}$ MC code [9, 10], for the radiative neutrino pair-production events. Details can be found in [7].

Results concerning sensitivity of future linear $e^+e^-$ colliders to processes of dark matter production with light mediator exchange were presented in [8]. Dedicated model [11] was encoded into FEYNRULES [12, 13] for calculating the DM pair-production cross section and generating signal event samples with WHIZARD. We consider mediator mass, width and coupling to electrons as the independent model parameters, with the total mediator width assumed to be dominated by its decay to the DM particles. In this approximation, cross section dependence on the DM particle couplings is absorbed in the total mediator width and the results hardly depend on the DM particle type or coupling structure.

The matching procedure described in [7], removing events with ISR photons emitted in the ME phase space region (so called "ISR rejection") can result in up to 50% correction to the DM production cross section, as shown in Fig. 3. Most of the DM pair-production events will remain "invisible" in the detector. While radiation of one or more photons (on the ME level) is expected in up to 50% of these 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 also depends significantly on the mediator mass and width, as shown in Fig. 4.
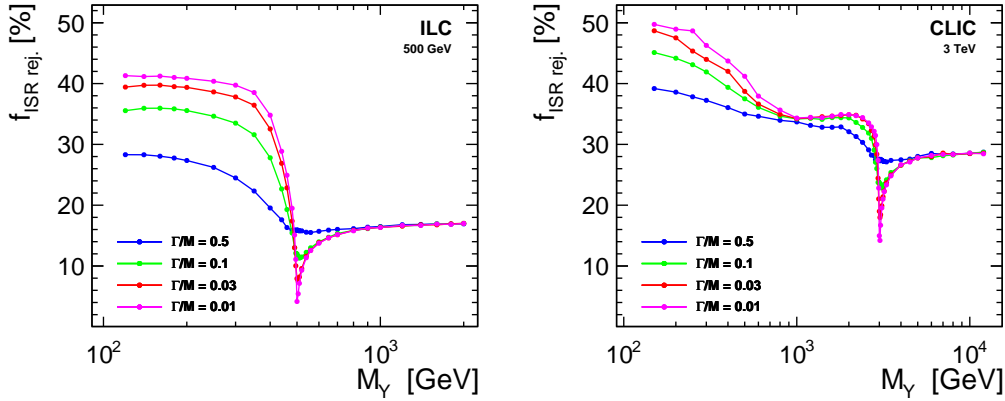
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Figure 3: Fraction of WHIZARD events, which are removed by the ISR rejection procedure, as described in [7]. Figure taken from [8].
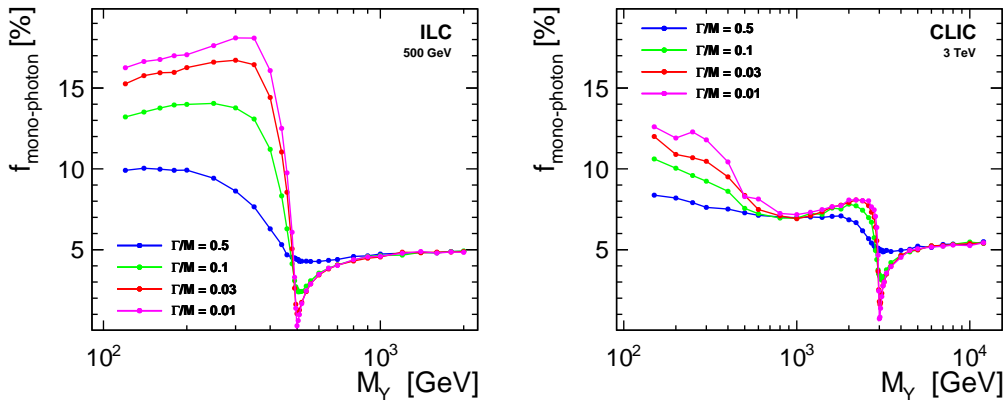


Figure 4: Fraction of dark matter pair-production events, which are reconstructed as mono-photon events in the detector, as a function of the assumed mediator mass, for the ILC running at 500 GeV (left) and CLIC running at 3 TeV (right) and different fractional mediator widths, as indicated in the plot.

Presented results are based on the fast detector simulation framework DELPHES [14] in which the two detector models were implemented, including detailed description of the calorimeter systems in the very forward region.

# 3 Sensitivity to dark matter production

Summarised below are results of [8] addressing pair-production of DM particles at the ILC and CLIC for scenarios with both light and heavy mediators. Scenarios with light mediator exchange are still not excluded by the existing experimental data. Limits on the mediator coupling to electrons which were set at LEP and by the LHC experiments, are of the order of 0.01 or above. The study focused on scenarios with very small mediator couplings to SM, when the total mediator width is dominated by invisible decays, $\Gamma_{SM} \ll \Gamma_{DM} \approx \Gamma_{tot}$. "Experimental-like" approach is adopted, focused on setting the DM pair-production cross section limits as a

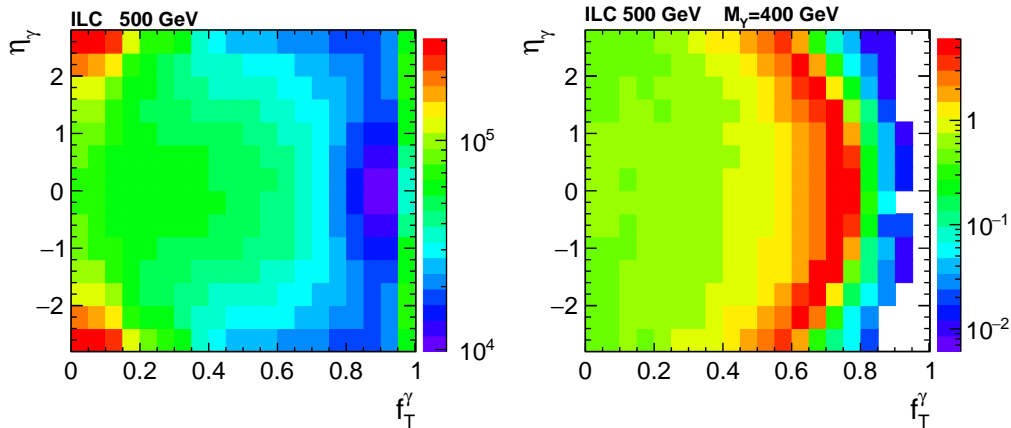Figure 5: Pseudorapidity vs transverse momentum fraction for mono-photon events at $500\,\text{GeV}$ ILC running with $-80\%/+30\%$ electron/positron beam polarisation and integrated luminosity of $1.6\,\text{ab}^{-1}$. Left: for sum of considered SM backgrounds. Right: for pair-production of Dirac fermion DM particles with $m_\chi = 50\,\text{GeV}$ and vector mediator mass of $M_Y = 400\,\text{GeV}$, assuming total production cross section of $1\,\text{fb}$ [8].

function of the mediator mass and width, assuming DM particles are light (the mass of fermionic DM is fixed to $m_\chi = 50\,\text{GeV}$ 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 $500\,\text{GeV}$ ILC, for SM backgrounds and example DM production scenario, are compared in Fig. 5. 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 allowed for given rapidity.

Cross section limits for radiative DM production (for events with the tagged photon) at $500\,\text{GeV}$ ILC and $3\,\text{TeV}$ CLIC, for vector mediator exchange scenario, are compared in Fig. 6. Combined analysis of data taken with different beam polarisation combinations results in strongest limits, also reducing the impact of systematic uncertainties. Systematic effects are also suppressed when searching for on-shell production of narrow mediator, i.e. for $M_Y < \sqrt{s}$ (assuming $\Gamma/M \ll 1$).

After correcting for the hard photon tagging probability (refer Fig. 4), limits for the total DM pair-production cross section can be extracted. Presented in Fig. 7 are limits expected from the combined analysis of data taken with different beam polarisations, for different fractional mediator widths assuming vector mediator exchange. Strongest limits are obtained for processes with light mediator exchange and for narrow mediator widths, whereas for heavy mediator exchange ($M_Y \gg \sqrt{s}$) cross section limits no longer depend on the mediator width. Limits are significantly weaker for narrow mediator with $M_Y \approx \sqrt{s}$, when photon radiation is significantly suppressed.

Shown in Fig. 8 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, coupling limits increase with the mediator mass squared, $g_{eeY} \sim M_Y^2$, as expected in the EFT limit. Results of study [8] are in very good agreement with the limits resulting from the ILD analysis [15] based on the full detector simulation and EFT approach [16].
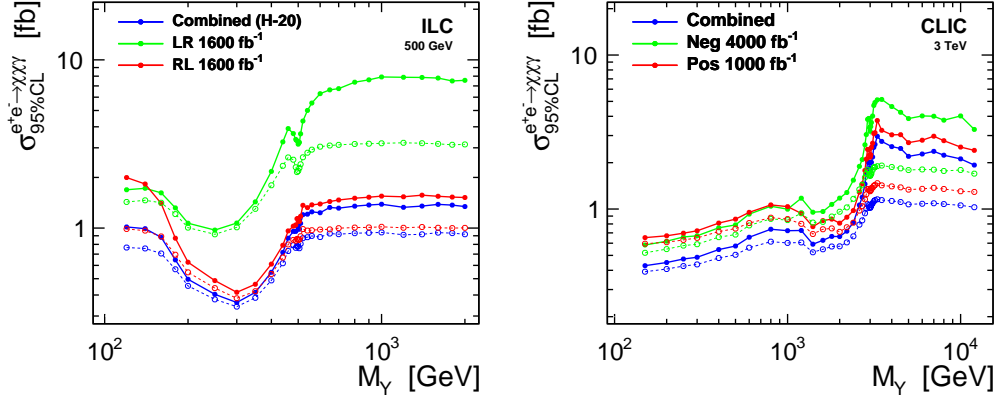
Figure 6: Limits on the cross section for the radiative light DM pair-production processes with vector mediator exchange at $500\,\mathrm{GeV}$ ILC (left) and $3\,\mathrm{TeV}$ CLIC (right), for mediator width $\Gamma/M = 0.03$, with (solid line) and without (dashed line) taking into account systematic uncertainties [8].
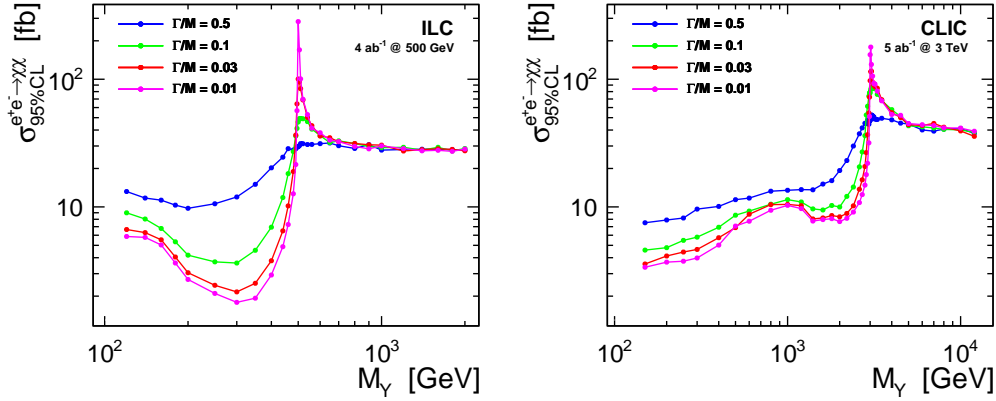


Figure 7: Limits on the cross section for light fermionic DM pair-production processes with $s$-channel mediator exchange for the ILC running at $500\,\mathrm{GeV}$ (left) and CLIC running at $3\,\mathrm{TeV}$ (right), for the vector mediator exchange and different fractional mediator widths. Combined limits corresponding to the assumed running scenarios are presented with systematic uncertainties taken into account [8].
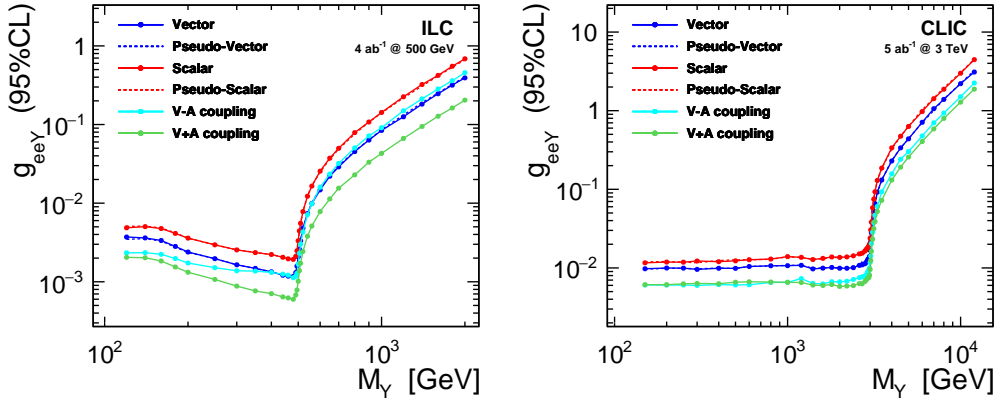
Figure 8: Limits on the mediator coupling to electrons for the ILC running at 500 GeV (left) and CLIC running at 3 TeV (right) for different mediator coupling scenarios and relative mediator width, $\Gamma/M = 0.03$. Combined limits corresponding to the assumed running scenarios are presented with systematic uncertainties taken into account [8].

# 4   Impact of polarisation

The sensitivity to processes of radiative DM production is mainly limited by the "irreducible" background from radiative neutrino pair-production events, $e^+e^- \to \nu\bar{\nu} + \gamma$. With proper polarisation choice, this background can be strongly suppressed and mass scale limits can improve significantly, see Fig. 9 (left). As the structure of mediator couplings is unknown, data taken with different polarisation combinations needs to be collected to obtain the best sensitivity in all possible scenarios. Moreover, by combining four independent data sets the impact of systematic uncertainties is significantly reduced. This is shown in Fig. 9 (right), where the expected limits from mono-photon analysis are compared for the combined analysis of polarised data and for an unpolarised data set with the same integrated luminosity, without and with systematic uncertainties taken into account. When beam polarisation is not used, systematic uncertainties reduce the ILC reach in EFT mass scale by almost a factor of two. When combining data taken using different polarisation combinations, systematic effects can be significantly constrained based on the predicted polarisation dependence of the SM backgrounds. For scenarios with light mediator exchange, the impact of systematic uncertainties is reduced but combined analysis of data taken with different polarisation combinations still results in significant limit improvement.

# 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. Dedicated procedure has been proposed for a proper simulation of mono-photon events in WHIZARD [7] and the mono-photon analysis framework was developed for scenarios with light mediator exchange and very small mediator couplings to SM [8]. Future experiments at 500 GeV ILC or 3 TeV CLIC will results in limits on the cross section for the radiative DM pair-production, $e^+e^- \to \chi\chi\gamma_{\text{tag}}$, of the order of 1 fb. Limits on the mediator
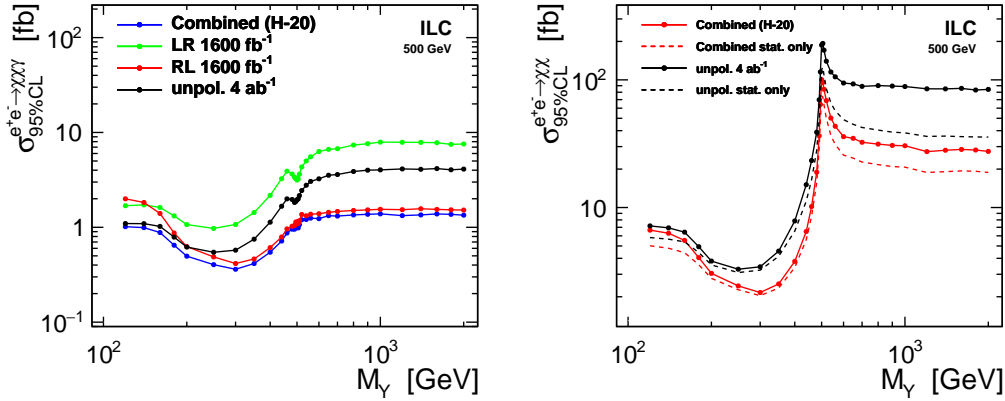
Figure 9: Impact of beam polarisation on the expected limits on the DM pair-production cross section as a function of vector mediator mass [8]. Left: limits from data collected with different beam polarisations are compared with limits from the combined data analysis and limits expected from unpolarised data set with the same integrated luminosity. Right: limits from the combined analysis are compared with limits expected for unpolarised data set with (solid lines) and without (dashed lines) taking into account systematic uncertainties.

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, coupling limits expected from the analysis of mono-photon spectra are stronger than those expected from the direct searches in SM decay channels. In the heavy mediator limit, sensitivity of future $e^+e^-$ colliders extends to the mediator mass scales of the order of 10 TeV.

# Acknowledgements

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