Dark matter production with light mediator exchange at future e^+e^- colliders

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July 13, 2022

Abstract

One of the primary goals of the proposed future collider experiments is to search for dark matter (DM) particles using different experimental approaches. High energy e^+e^- colliders offer unique possibility for the most general search based on the mono-photon signature. As any e^+e^- scattering process can be accompanied by a hard photon emission from the initial state radiation, analysis of the energy spectrum and angular distributions of those photons can be used to search for hard processes with invisible final state production and to test the nature and interactions of the DM particles.

Production of DM particles at the International Linear Collider (ILC) and Compact Linear Collider (CLIC) experiments was studied using dedicated simulation procedure developed for Whizard and the Delphes fast simulation framework. Limits on the light DM production cross section in a generic model are set as a function of the mediator mass and width, and translated into the limits on the mediator coupling to electrons. If deviations from the Standard Model predictions are observed, mediator mass, width and coupling structure can be constrained from the reconstructed mono-photon event distributions.

Presented at DIS2022:
XXIX International Workshop on Deep-Inelastic Scattering and Related Subjects,
Santiago de Compostela, Spain, May 2-6 2022.

1 Introduction

High energy e^+e^- colliders are well suited for observation of direct DM particle pair-production. As any e^+e^- scattering process can be accompanied by a hard photon emission from the initial state radiation, analysis of the energy spectrum and angular distributions of those photons can be used to search for hard processes with invisible final state production. Study of this so called mono-photon signature, when only single hard photon radiated from the initial state is observed in the detector, is considered as the most general approach to search for pair-production of DM particles.

Results presented in this contribution [1–3] concern the DM pair production with mono-photon signature at future linear e^+e^- colliders, ILC [4] and CLIC [5]. Baseline ILC design assumes initial stage at 250 GeV, followed by 500 GeV and 1 TeV as the possible upgrade [6]. Polarisation is assumed for both e^- and e^+ beams, of 80% and 30%, respectively. Total of 4000 fb^{-1} of data is expected to be collected at 500 GeV stage, with 80% of the integrated luminosity taken with LR and RL beam polarisation combinations ($2\times1600\,\text{fb}^{-1}$), and only 20% with RR and LL beam polarisation combinations ($2\times400\,\text{fb}^{-1}$). Novel two-beam acceleration scheme proposed for CLIC opens the possibility of reaching the collision energy of up to 3 TeV. Total integrated luminosity of 5000 fb^{-1} is expected at 3 TeV stage, with 80% (4000 fb^{-1}) collected with left-handed electron beam polarisation and 20% (4000 fb^{-1}) with right-handed electron beam [7]. 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 [8, 9] is described in a dedicated paper [1]. The procedure for matching the soft ISR radiation with the ME simulation of detectable hard photons is based on two variables, calculated separately for each emitted photon, used to describe kinematics of the photon emission:

$$\begin{aligned} q_- &= \sqrt{4E_0E_\gamma}\cdot\sin\frac{\theta_\gamma}{2}\ , \\ q_+ &= \sqrt{4E_0E_\gamma}\cdot\cos\frac{\theta_\gamma}{2}\ , \end{aligned}$$

where E_0 is the nominal electron or positron beam energy, while E_γ and θ_γ 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. 1. 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.

A dedicated model [10] was encoded into FEYNRULES [11, 12] for calculating the DM pair-production cross section and generating signal event samples with WHIZARD. We consider the 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, the cross section dependence on the DM particle couplings is absorbed in

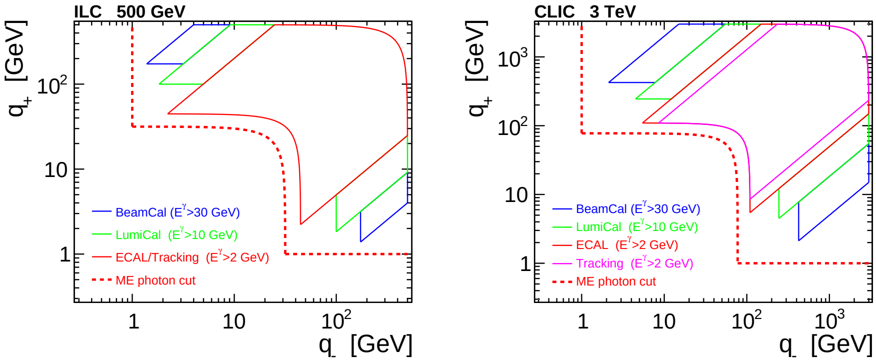

Figure 1: Detector acceptance in the (q_+, q_-) plane expected for the future experiments at 500 GeV ILC (left) and 3 TeV CLIC (right). Red dashed lines indicate the cut used to restrict the phase space for ME photon generation [2].

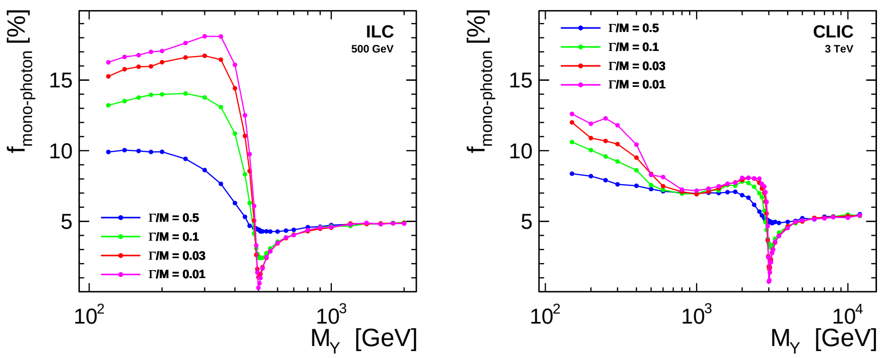

Figure 2: Fraction of dark matter pair-production events, which are reconstructed as mono-photon events in the detector, as a function of the assumed mediator mass, for the ILC running at 500 GeV (left) and CLIC running at 3 TeV (right) and different fractional mediator widths, as indicated in the plot.

the total mediator width and the results hardly depend on the DM particle type or coupling structure.

The matching procedure described in [1], 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. 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. 2. Presented results are based on the fast detector simulation framework DELPHES [13] in which the two detector models were implemented, including detailed description of the calorimeter systems in the very forward region.

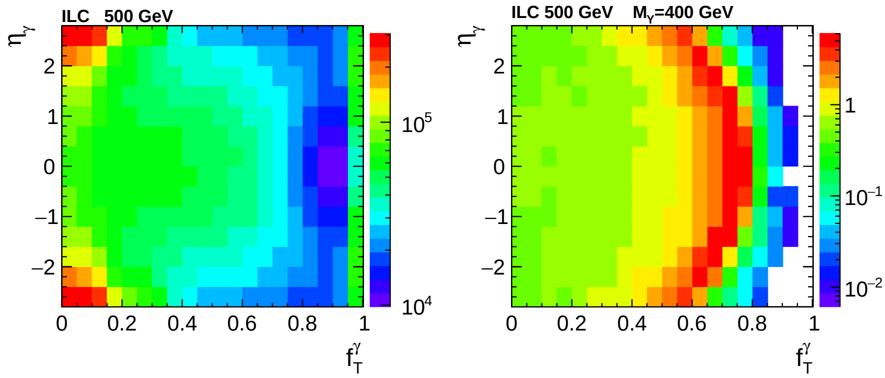

Figure 3: Pseudorapidity vs transverse momentum fraction for mono-photon events at 500 GeV ILC running with –80%/+30% electron/positron beam polarisation. Left: for sum of considered SM backgrounds. Right: for pair-production of Dirac fermion DM particles with $m_\chi = 50$ GeV and vector mediator mass of $M_Y = 400$ GeV, assuming total production cross section of 1 fb [2].

3 Analysis approach

The analysis procedure outlined below was developed in [2] to consider 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, if their couplings are small: 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, $\Gamma_{\mathrm{SM}} \ll \Gamma_{\mathrm{DM}} \approx \Gamma_{\mathrm{tot}}$. "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. 3. The transverse momentum fraction, f_{T}^{γ}, 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 DM pair-production are extracted from combined analysis of data taken with different beam polarisations. This results in strongest limits, also reducing the impact of systematic uncertainties.

4 Results

After correcting for the hard photon tagging probability (refer Fig. 2), limits for the total DM pair-production cross section can be extracted. Presented in Fig. 4 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.

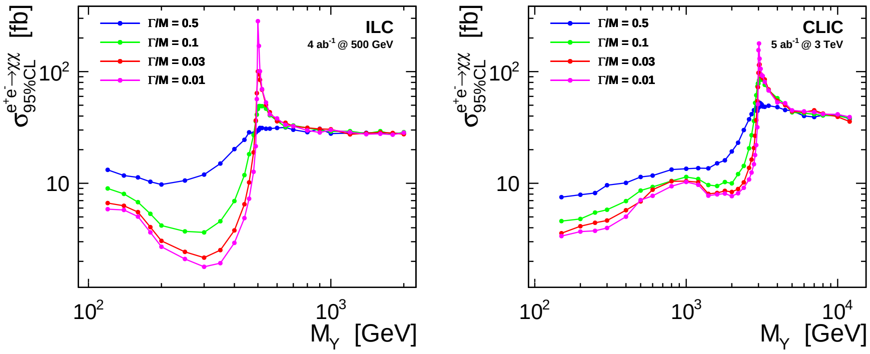

Figure 4: Limits on the cross section for light fermionic DM pair-production processes with s-channel mediator exchange for the ILC running at 500 GeV (left) and CLIC running at 3 TeV (right), for the vector mediator exchange and different fractional mediator widths. Combined limits corresponding to the assumed running scenarios are presented with systematic uncertainties taken into account [2].

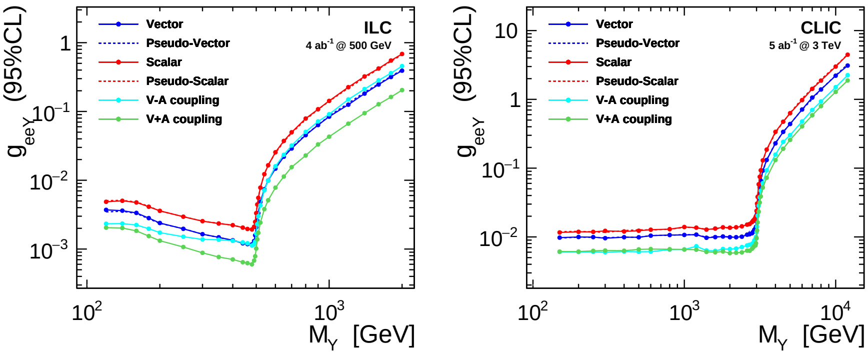

Figure 5: Limits on the mediator coupling to electrons for the ILC running at 500 GeV (left) and CLIC running at 3 TeV (right) for different mediator coupling scenarios and relative mediator width, $\Gamma/M = 0.03$. Combined limits corresponding to the assumed running scenarios are presented with systematic uncertainties taken into account [2].

Shown in Fig. 5 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, $\mathrm{g}_{\mathrm{eeY}} \sim \mathrm{M}_{\mathrm{Y}}^2$, as expected in the EFT limit. As shown in [14], presented results [2] are in very good agreement with the limits from the ILD analysis [15] based on the full detector simulation and EFT approach.

Light mediator scenarios can be discovered at future $\mathrm{e}^+\mathrm{e}^-$ colliders already for DM production cross sections of $\mathcal{O}(10\text{ fb})$, see Fig. 6 (left). The polarisation dependence of the DM pair-production cross section reflects the mediator coupling structure to electrons (SM fermions). As shown in Fig. 6 (right), different coupling structures can be easily distinguished at the ILC, thanks to running with both electron and positron beam polarisations. Already at the discovery threshold, the light mediator mass can be measured with percent-level precision, see Fig. 7 [16]. Also the mediator width can be precisely determined, if the production cross section is large enough.

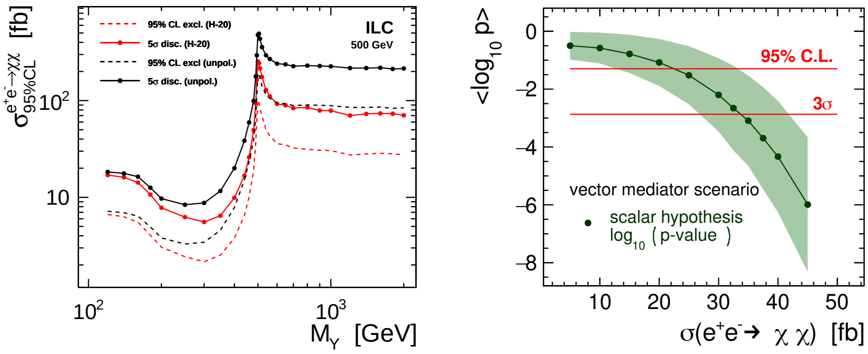

Figure 6: Left: expected 95% C.L. limits and 5σ discovery threshold for DM pair production cross section with vector mediator exchange, as a function of mediator mass, for relative mediator width, $\Gamma/M = 0.03$. Right: expected probability of the scalar mediator hypothesis from the model fit to vector 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.

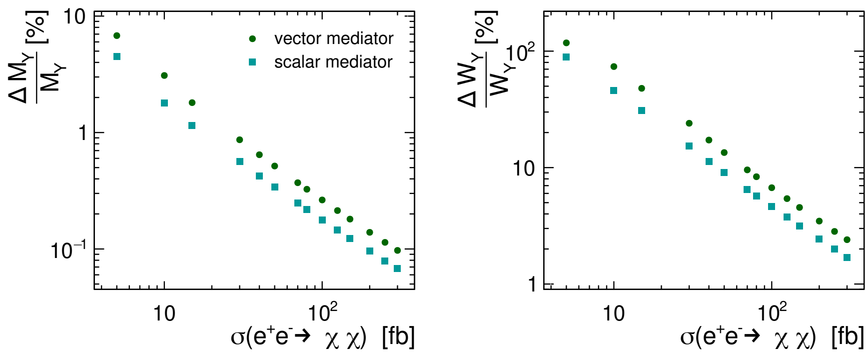

Figure 7: Expected relative precision of mediator mass (left) and width (right) determination for scalar and vector mediator scenarios, as a function of the DM pair-production cross section. Mediator mass of 300 GeV and width of 30 GeV are assumed [16].

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 [1] and the mono-photon analysis framework was developed for scenarios with light mediator exchange and very small mediator couplings to SM [2]. Future experiments at 500 GeV ILC or 3 TeV CLIC will results in limits on the cross section for the radiative DM pair-production, $e^+e^- \to \chi\chi\gamma_{\rm tag}$, of the order of 1 fb. Limits on the mediator coupling to electrons of the order of $g_{\rm eeY} \sim 10^{-3} - 10^{-2}$ can be set up to the kinematic limit, $M_Y \le \sqrt{s}$. 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. 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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