CLICdp-Conf-2021-006
10 November 2021

Dark matter searches with mono-photon signature at future e^+e^- colliders

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Abstract

As any e^+e^- scattering process can be accompanied by a hard photon emission from the initial state radiation, the analysis of the energy spectrum and angular distributions of those photons can be used to search for hard processes with an invisible final state. Thus high energy e^+e^- colliders offer a unique possibility for the most general search of Dark matter based on the mono-photon signature.

We consider production of DM particles via a mediator at the International Linear Collider (ILC) and Compact Linear Collider (CLIC) experiments taking into account detector effects within the DELPHES fast simulation framework. Limits on the light DM production in a generic model are set for a wide range of mediator masses and widths. For mediator masses up to the centre-of-mass energy of the collider, results from the mono-photon analysis are more stringent than the limits expected from direct resonance searches in Standard Model decay channels.

Talk presented at the XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects, Stony Brook University, New York, USA, 12-16 April 2021

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July 27, 2021

Proceedings for the XXVIII International Workshop
on Deep-Inelastic Scattering and Related Subjects,
Stony Brook University, New York, USA, 12-16 April 2021
doi:10.21468/SciPostPhysProc.?

Abstract

As any e^+e^- scattering process can be accompanied by a hard photon emission from the initial state radiation, the analysis of the energy spectrum and angular distributions of those photons can be used to search for hard processes with an invisible final state. Thus high energy e^+e^- colliders offer a unique possibility for the most general search of Dark matter based on the mono-photon signature.

We consider production of DM particles via a mediator at the International Linear Collider (ILC) and Compact Linear Collider (CLIC) experiments taking into account detector effects within the DELPHES fast simulation framework. Limits on the light DM production in a generic model are set for a wide range of mediator masses and widths. For mediator masses up to the centre-of-mass energy of the collider, results from the mono-photon analysis are more stringent than the limits expected from direct resonance searches in Standard Model decay channels.

1 Introduction

The most general approaches to search for the dark matter (DM) production at future e^+e^- colliders is based on the mono-photon signature, which is expected when the production of the invisible final state is accompanied by a hard photon from initial state radiation (ISR). We proposed the procedure [1] which allows for consistent, reliable simulation of mono-photon events in WHIZARD for both Beyond the Standard Model (BSM) signal and Standard Model (SM) background processes, based on merging the matrix element calculations with the lepton ISR structure function. For precise kinematic description of photons entering the detector, emission of up to three photons is included in the matrix element (ME) calculation. Soft and collinear photons are simulated with the WHIZARD built-in lepton ISR structure function and a dedicated ISR rejection procedure is applied to avoid double counting, removing all events with any of the ISR photons entering the ME photon phase space. In this contribution, we exploit the proposed procedure [1] in estimating the sensitivity of future e^+e^- colliders to different DM scenarios in which DM particles couple to the SM ones via a mediator. We propose a novel approach, where the experimental sensitivity is defined in terms of both the mediator

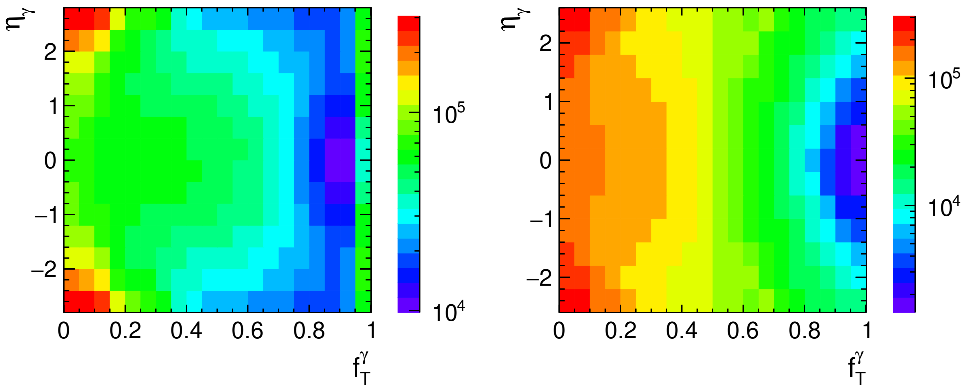

Figure 1: Distribution of the Standard Model background events in the $(f_T^\gamma, \eta_\gamma)$ plane for 500 GeV ILC running with –80%/+30% electron/positron beam polarisation (left) and 3 TeV CLIC running with –80% electron beam polarisation (right).

mass and mediator width. This approach is more model independent than the approaches presented so far, which assume given mediator coupling values to SM and DM particles [2,3].

2 Analysis framework

We consider DM pair-production for ILC running at 500 GeV, with total integrated luminosity of 4 ab^{-1} [4], and for CLIC running at 3 TeV, with total integrated luminosity of 5 ab^{-1} [5]. Polarisation of both electron and positron beams is considered for the ILC while only electron beam polarisation is included for CLIC .

Signal and background samples generated with WHIZARD are processed with the fast simulation framework DELPHES [6] in which the generic ILC and the CLIC detector models were implemented. Both models include detailed description of the forward calorimeter systems which is crucial for proper modeling of the background constribution. Limits on the light DM pair-production cross section are set based on the expected two-dimensional distributions of the reconstructed mono-photon events in the rapidity and transverse momentum fraction defined as $f_T^\gamma = \log\left(\frac{p_T^\gamma}{p_T^{min}}\right)/\log\left(\frac{p_T^{max}}{p_T^{min}}\right)$, where p_T^{min} is the minimum photon transverse momentum required in the event selection procedure and p_T^{max} is the maximum transverse momentum of the photon allowed for the given scattering angle [7]. Expected distributions of the Standard Model (SM) background events, coming from the radiative Bhabha scattering and radiative neutrino pair production, are shown in Figure 1. Example distributions of signal events, for a dark matter mass of M_χ=50 GeV and mediator mass of M_Y=400 GeV at the ILC and M_Y=2.4 TeV at CLIC are shown in Figure 2.

3 Results

Signal and background distributions in the $(f_T^\gamma, \eta_\gamma)$ plane are used to extract the expected 95% C.L. cross section limits for radiative DM pair-production. Limits for the DM production with exchange of a narrow (Γ/M=0.03) vector mediator, expected for the ILC and CLIC running with different beam polarisations, are shown in Figure 3 as a function of the mediator mass. While the expected limits strongly depend on the assumed beam polarisation, both colliders will be sensitive to radiative production cross sections of the order of 1 fb for a wide

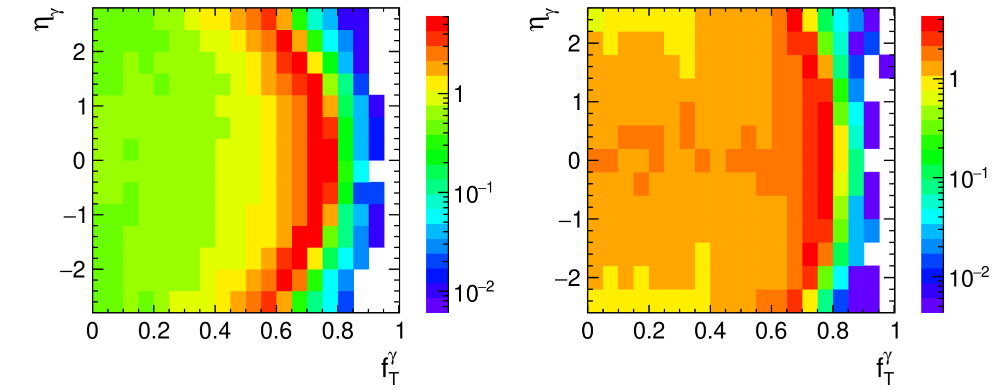

Figure 2: Distribution of the DM pair-production events in the $(f_T^{\gamma}, \eta_{\gamma})$ plane for a fermion DM with M_{χ}=50 GeV and a vector mediator mass of M_Y=400 GeV at 500 GeV ILC (left) and M_Y=2.4 TeV at 3 TeV CLIC (right).

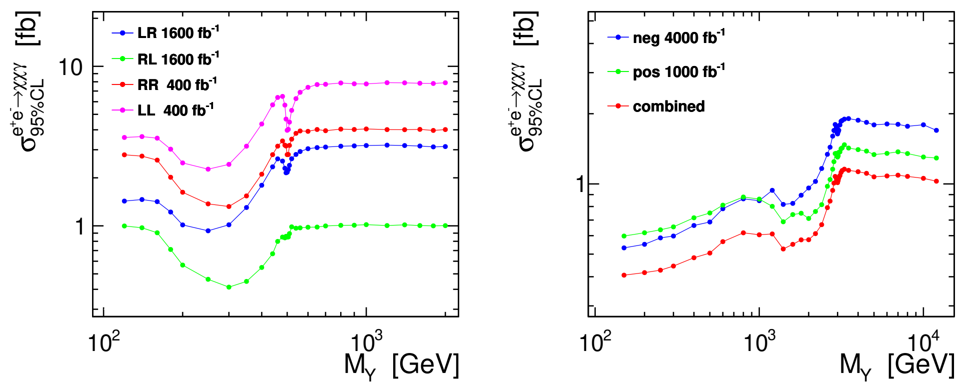

Figure 3: Limits on the radiative DM pair-production cross section for processes with the vector mediator exchange, for different beam polarisations, at 500 GeV ILC (left) and 3 TeV CLIC (right).

range of mediator masses. These results can be corrected for the probability of hard photon radiation in the detector acceptance region, which significantly depends on the assumed mediator mass. It is of the order of 10–15% for light mediator scenarios and about 5% for large mediator masses. However, for mediator masses close to the nominal collision energy, hard photon radiation is significantly suppressed, in particular for narrow mediator scenarios. Resulting limits on the total DM pair-production cross section are presented in Figure 4 as a function of mediator mass, for different fractional mediator widths. Total cross section limits are of the order of 10 fb for the light mediator, $M_Y < \sqrt{s}$, and about 20 fb for a heavy one, $M_Y > \sqrt{s}$. Only for the resonant mediator production, $M_Y \sim \sqrt{s}$, when the hard photon emission is suppressed, the cross section limits are much weaker.

The impact of systematic uncertainties was considered following the approach presented in [2] and the results are shown in Figure 5 for a scenario with a narrow vector mediator exchange. While systematic uncertainties deteriorate the expected cross section limits by about 50% for heavy mediator scenarios, their impact is significantly reduced for light mediator exchange, when a resonance-like structure is expected in the mono-photon spectra (see Figure 2).

Cross section limits corresponding to the combined analysis of the ILC or CLIC data taken with different beam polarisations, after taking systematic uncertainties into account, were

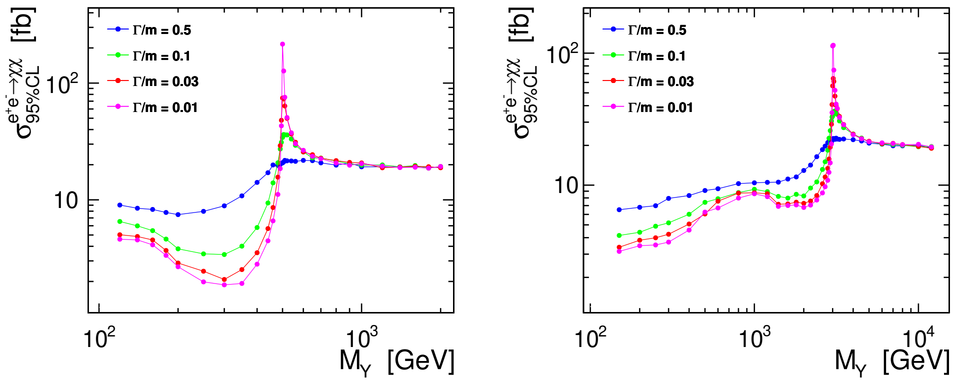

Figure 4: Limits on the total DM pair-production cross section for processes with vector mediator exchange, for different mediator widths, at 500 GeV ILC (left) and 3 TeV CLIC (right).

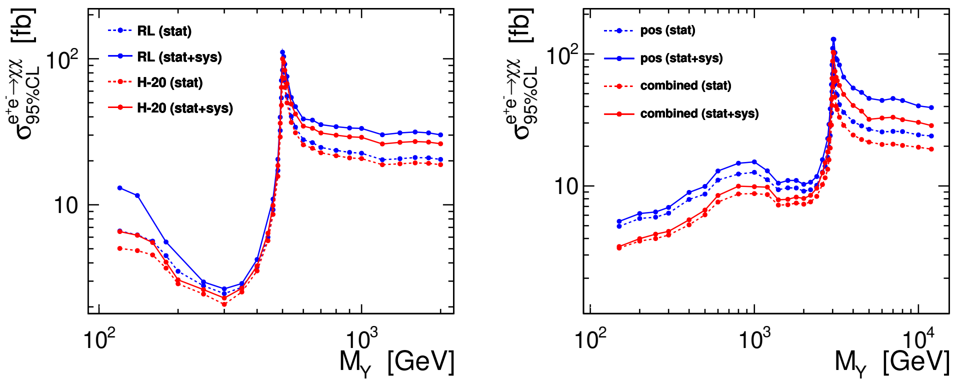

Figure 5: Limits on the total DM pair-production cross section for vector mediator width, Γ/M=0.03, at 500 GeV ILC (left) and 3 TeV CLIC (right) without (stat) and with (stat+sys) systematic uncertainties taken into account.

used to extract the expected limits on the mediator coupling to electrons, g_{eeY}. Results are presented in Figure 6 for different vector mediator widths at 500 GeV ILC and for different mediator couplings at 3 TeV CLIC. The sensitivity of e^+e^- colliders to g_{eeY} is almost uniform up to the kinematic limit, $M_Y \leq \sqrt{s}$. Coupling limits are about 0.003 at the ILC and about 0.01 at CLIC, and weakly depend on the assumed coupling structure.

4 Conclusion

Mono-photon production at e^+e^- colliders is sensitive to a wide range of DM pair-production scenarios. A new framework for mono-photon analyses [7] focuses on scenarios with light mediator exchange and very small mediator couplings to SM particles. Limits of the order of 1 fb and 10 fb are expected from the mono-photon analysis for the radiative DM pair-production cross section and for the total DM pair-production crossection, respectively, at both the ILC and CLIC, except for the resonance region, $M_Y \approx \sqrt{s}$. Limits on the mediator coupling to electrons in the range $10^{-3} - 10^{-2}$ are obtained up to the kinematic limit. These limits are more stringent than those expected from direct resonance search in SM decay channels.

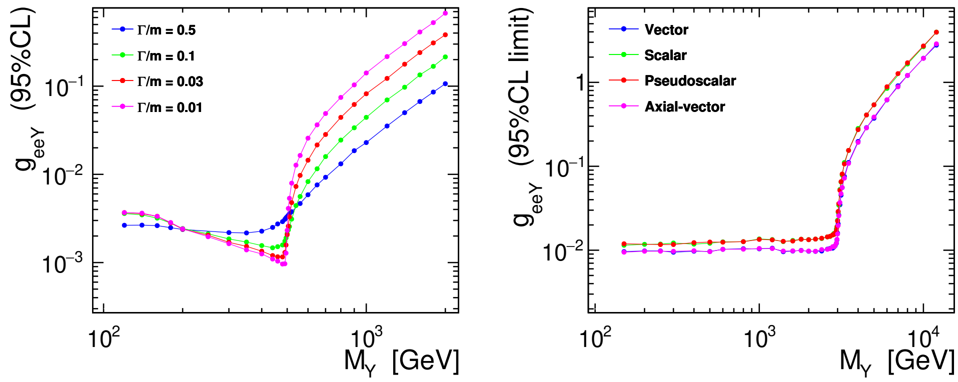

Figure 6: Limits on the mediator coupling to electrons for different relative widths of vector mediator at 500 GeV ILC (left) and for mediator width of Γ/M=0.03 and different mediator types at 3 TeV CLIC (right).

Acknowledgements

We thank members of the CLIC detector and physics (CLICdp) collaboration and the International Large Detector (ILD) concept group for the ILC for fruitful discussions, valuable comments and suggestions. This contribution was supported by the National Science Centre, Poland, the OPUS project under contract UMO-2017/25/B/ST2/00496 (2018-2021) and the HARMONIA project under contract UMO-2015/18/M/ST2/00518 (2016-2021), and by the German Research Foundation (DFG) under grant number STO 876/4-1 and STO 876/2-2.

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