PROCEEDINGS OF SCIENCE

Sensitivity to dark matter production at future e^+e^- colliders

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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. Dedicated procedure of merging the matrix element calculations with the lepton ISR structure function was developed to model the Standard Model background processes contributing to mono-photon signature with Whizard.

We consider production of DM particles at the International Linear Collider (ILC) and Compact Linear Collider (CLIC) experiments. Detector effects are taken into account within the Delphes fast simulation framework. Limits on the light DM production in a generic model are set as a function of the mediator mass and width based on the expected two-dimensional distributions of the reconstructed mono-photon events. Limits on the mediator coupling to electrons are presented for a wide range of mediator masses and widths. For light mediators, for 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 search in SM decay channels.

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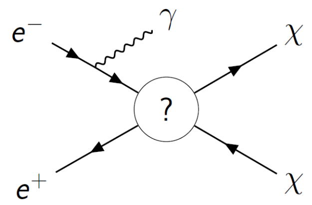
1. Introduction

There are many hints for existence of physics Beyond the Standard Model (BSM). The existence of dark matter (DM) is supported by many astrophysical and cosmological observations. The SM alone is not able to explain the barion asymmetry in our Universe nor the fact that neutrinos have mass. There are also numerous deviations from the SM predictions observed in precision measurements like $g_\mu - 2$, B meson decays or W boson mass. Many theoretical scenarios are considered, with wide range of masses and couplings for dark matter particles. With no direct evidence within the LHC energy reach, two general approaches can be considered: models with new physics mass scales in $\mathcal{O}(10)$ TeV range and models where new particles are light, but their couplings to SM are very small. While the direct search for heavy BSM scenarios require new energy frontier machines (FCC-hh), the latter option requires rather precision measurements in a clean environment.

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. This so called mono-photon signature, with only single hard photon radiated from the initial state observed in the detector, is considered as the most general approach to search for pair-production of DM particles.



Results presented in this contribution [1–5] concern the DM pair production with mono-photon signature at future linear e^+e^- colliders, ILC [6] and CLIC [7]. Baseline ILC design assumes initial stage at 250 GeV, followed by 500 GeV and 1 TeV as the possible upgrade [8]. 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 (2×1600 fb^{-1}), and only 20% with RR and LL beam polarisation combinations (2×400 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 [9]. Positron beam polarisation is not included in the CLIC baseline design.

Detector designs for experiments at ILC and CLIC are based on the concept of Particle Flow [10], with very high detector granularity and measurement precision allowing for single particle reconstruction and identification. This approach is also expected to result in the best possible jet energy measurement based on combining calorimeter measurements for neutral particles with much more precise track momentum reconstruction for the charged ones.

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 [11, 12] is described in a dedicated paper [1]. 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 [1] is based on two variables, calculated separately for each emitted photon, used to describe kinematics of the photon 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_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 the "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.

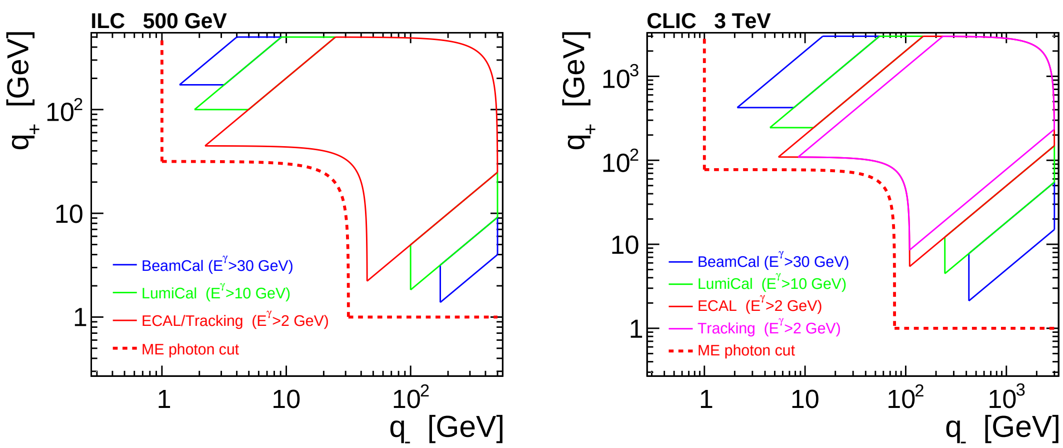


Figure 1: Detector acceptance in the (q_+, q_-) plane expected for the future experiments at 500 GeV ILC (left) and 3 TeV CLIC (right). Red dashed lines indicate the cut used to restrict the phase space for ME photon generation [4].

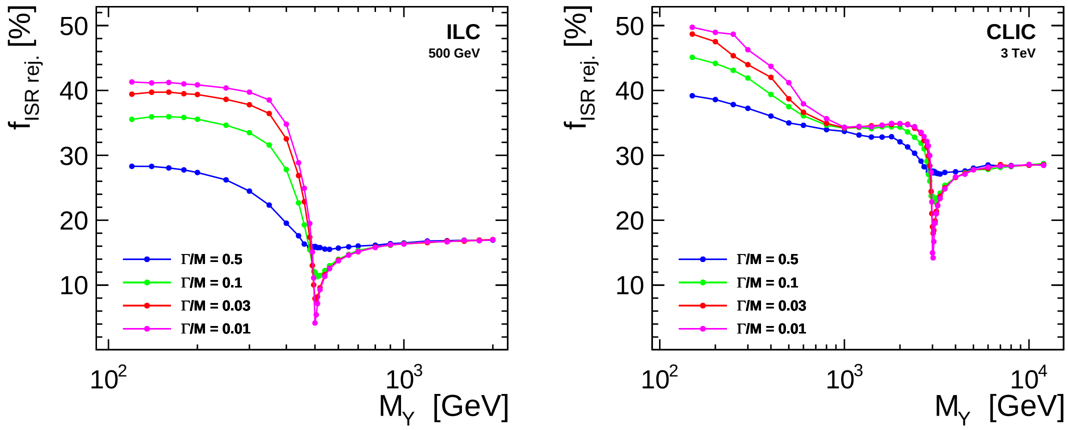


Figure 2: Fraction of WHIZARD events, which are removed by the ISR rejection procedure, as described in [1]. Figure taken from [4].

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 [13, 14], for the radiative neutrino pair-production events. Details can be found in [1].

Results concerning sensitivity of future linear e^+e^- colliders to processes of dark matter production with light mediator exchange were presented in [4]. A dedicated model [15] was encoded into FEYNRULES [16, 17] 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 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, as shown in Fig. 2. 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. 3. Presented results are based on the fast detector simulation framework DELPHES [18] in which the two detector models were implemented, including detailed description of the calorimeter systems in the very forward region.

3. Previous studies

Prospects for detecting DM production with mono-photon signature were previously studied for both ILC [2] and CLIC [3] in the heavy mediator approximation. The study performed for the ILD detector at the ILC [2] was based on the full detector simulation. After proper event selection and background suppression cuts, the expected SM background is dominated by radiative

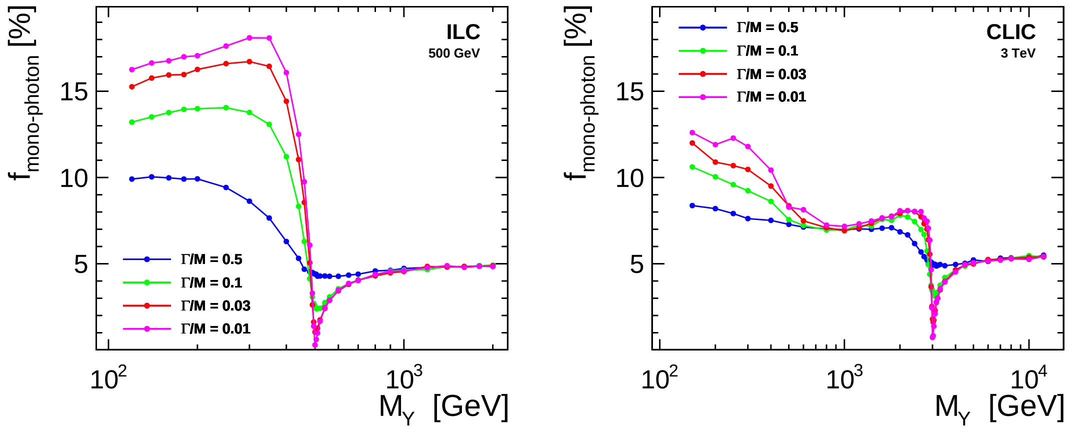


Figure 3: Fraction of dark matter pair-production events, which are reconstructed as mono-photon events in the detector, as a function of the assumed mediator mass, for the ILC running at 500 GeV (left) and CLIC running at 3 TeV (right) and different fractional mediator widths, as indicated in the plot.

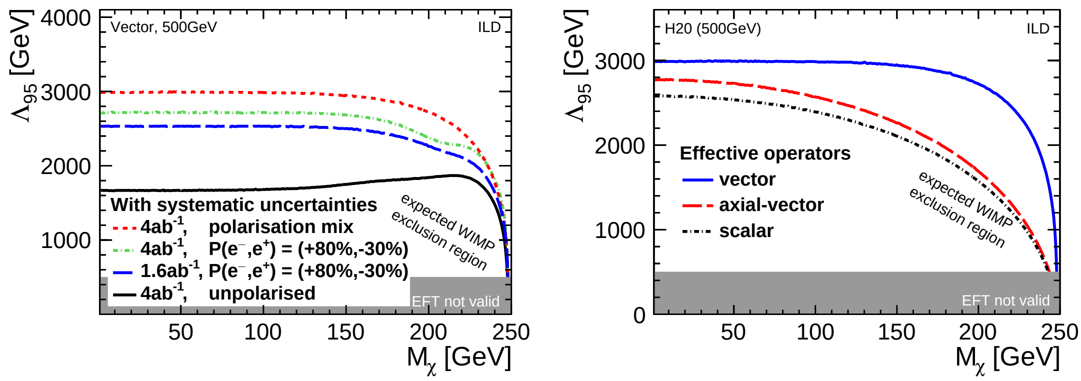


Figure 4: Expected 95% C.L. limits for the mediator mass scale, as a function of the assumed DM particle mass, from the full-simulation mono-photon study in the heavy mediator approximation for the ILD [2]. Left: for vector mediator and 4 ab^{-1} of data collected at 500 GeV with different beam polarisation combinations. Right: for combined analysis of data taken with different beam polarisation combinations, for different mediator hypotheses.

neutrino pair-production events. From comparison of the reconstructed photon energy distribution expected for signal and background events, limits on the mediator mass scale are extracted in the heavy mediator limit (operator mass scale in the EFT approach). Selected results of the study are presented in Fig. 4. Combined analysis of data collected with different electron and positron beam polarisations, as assumed in the H-20 running scenario, results in much stronger limits than data collected with unpolarised beams or with one polarisation combination only. This is mainly due to the fact that, by combining data collected with different polarisations, systematic uncertainties can be significantly constrained. Expected limits depend on the assumed mediator type. For light DM scenarios, mass scale limits range from about 2.6 TeV to 3.0 TeV, for scalar and vector mediator scenarios, respectively.

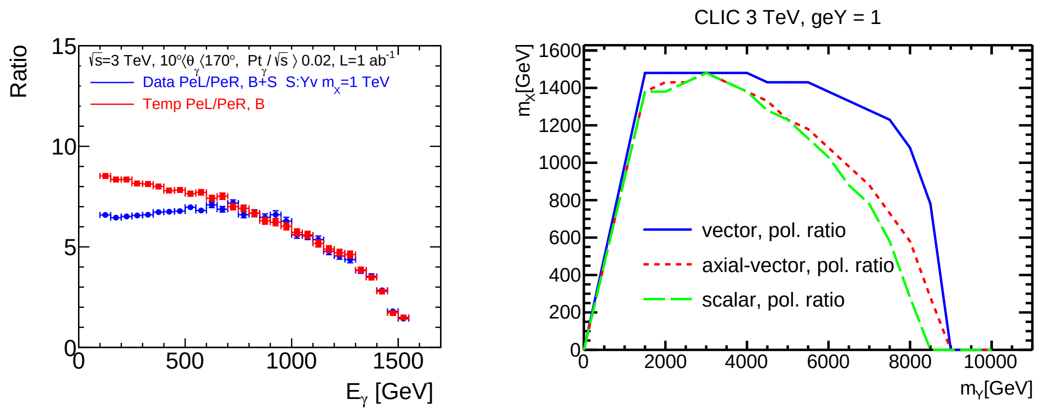


Figure 5: Results of the mono-photon study for CLIC at 3 TeV [3]. Left: ratio of photon energy distributions measured for left-handed and right-handed electron beam polarisations, for SM background (red) and after including DM production contribution with vector mediator exchange (blue points). Right: expected exclusion limits in the DM vs mediator mass plane (m_Y,m_χ) for mediator coupling to electrons, g_{eY} = 1.

Prospects for DM discovery at the 3 TeV CLIC were studied in [3], with simplified description of detector acceptance, efficiency and resolution on the generator level. Limits on different BSM scenarios were extracted from the ratio of photon energy distributions measured for left-handed and right-handed electron beam polarisations, as shown in Fig. 5. This distribution turned out to be most sensitive to new physics effects and least sensitive to systematic uncertainties. Fit to the measured cross section ratio was used to extract the expected exclusion limits on the radiative DM production in the DM vs mediator mass plane, see Fig. 5.

4. New analysis approach

The analysis procedure outlined below was developed in [4] to consider pair-production of DM particles at the ILC and CLIC for scenarios with both light and heavy mediators. As mentioned above, 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. Our 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 function of the mediator mass and width, assuming DM particles are light (the mass of fermionic DM is fixed to m_χ = 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. 6. The transverse momentum fraction, f^γ_T, 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 GeV ILC and 3 TeV CLIC, for vector mediator exchange scenario, are compared in Fig. 7. Combined

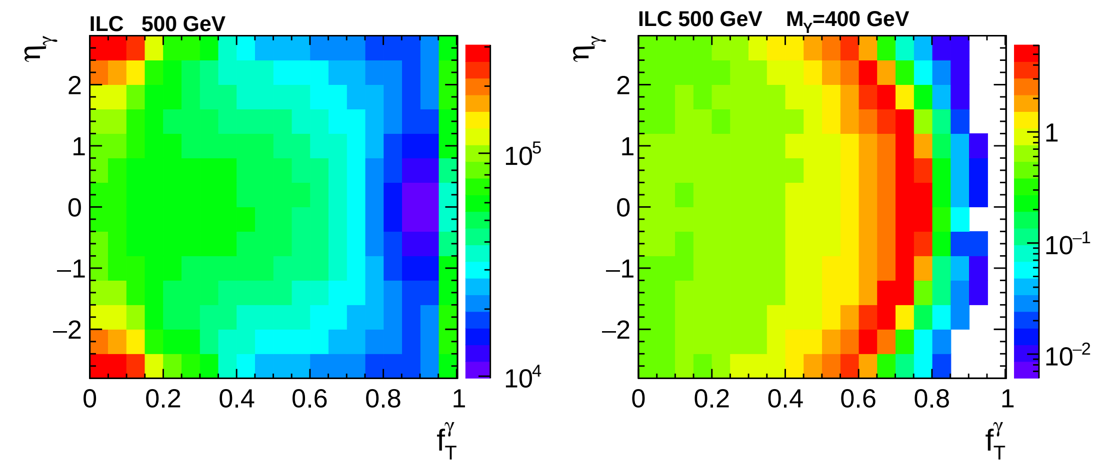


Figure 6: Pseudorapidity vs transverse momentum fraction for mono-photon events at 500 GeV ILC running with –80%/+30% electron/positron beam polarisation and integrated luminosity of 1.6 ab^{-1}. Left: for sum of considered SM backgrounds. Right: for pair-production of Dirac fermion DM particles with m_χ = 50 GeV and vector mediator mass of M_Y = 400 GeV, assuming total production cross section of 1 fb [4].

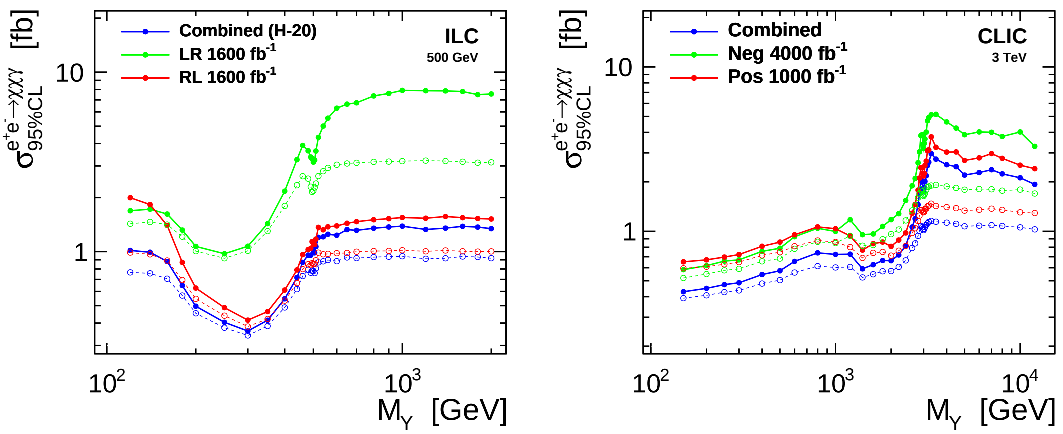


Figure 7: Limits on the cross section for the radiative light DM pair-production processes with vector mediator exchange at 500 GeV ILC (left) and 3 TeV CLIC (right), for mediator width Γ/M = 0.03, with (solid line) and without (dashed line) taking into account systematic uncertainties [4].

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 $\Gamma/M \ll 1$).

5. Results

After correcting for the hard photon tagging probability (refer Fig. 3), limits for the total DM pair-production cross section can be extracted. Presented in Fig. 8 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

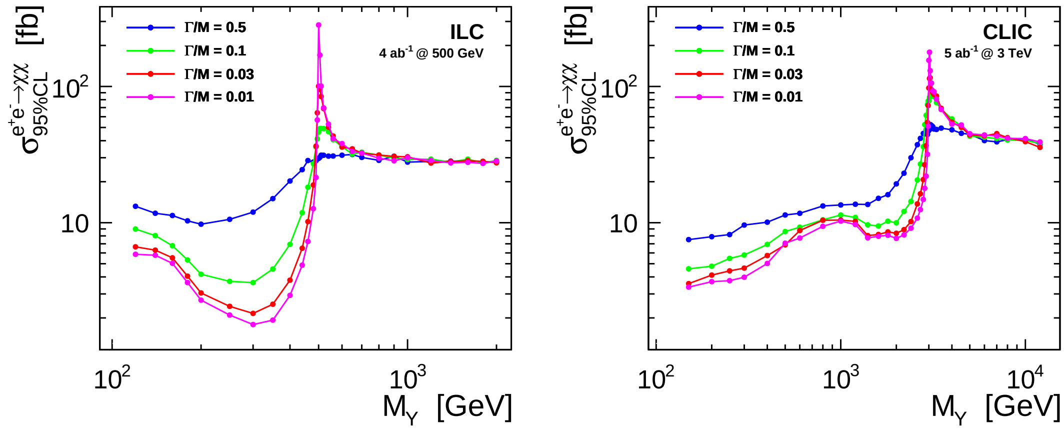


Figure 8: Limits on the cross section for light fermionic DM pair-production processes with s-channel mediator exchange for the ILC running at 500 GeV (left) and CLIC running at 3 TeV (right), for the vector mediator exchange and different fractional mediator widths. Combined limits corresponding to the assumed running scenarios are presented with systematic uncertainties taken into account [4].

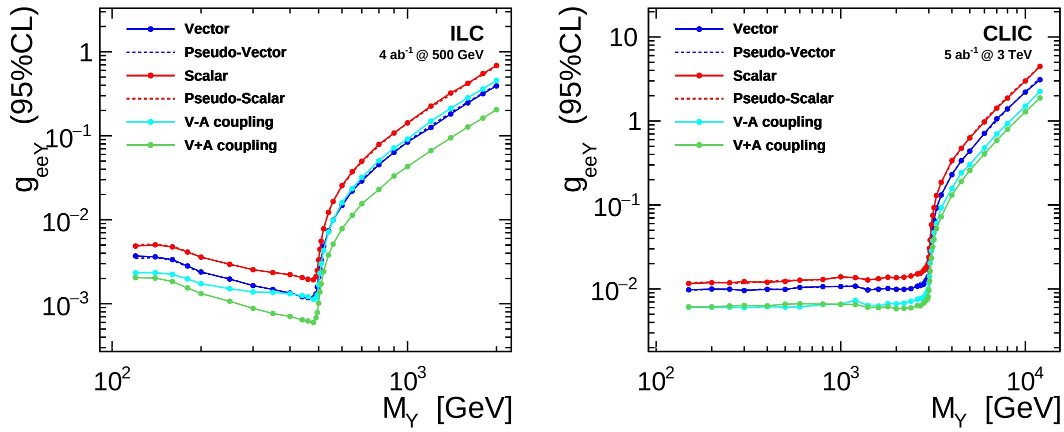


Figure 9: Limits on the mediator coupling to electrons for the ILC running at 500 GeV (left) and CLIC running at 3 TeV (right) for different mediator coupling scenarios and relative mediator width, $\Gamma/M = 0.03$. Combined limits corresponding to the assumed running scenarios are presented with systematic uncertainties taken into account [4].

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. Limits are significantly weaker for narrow mediator with $\mathrm{M_Y} \approx \sqrt{s}$, when photon radiation is significantly suppressed.

Shown in Fig. 9 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 EFT limit. Results of study [4] are in very good agreement with the limits resulting from the ILD analysis [2] based on the full detector simulation and EFT approach [19].

6. 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 [4]. Future experiments at 500 GeV ILC or 3 TeV CLIC will results in limits on the cross section for the radiative DM pair-production, $e^+e^- \to \chi\chi\gamma_{tag}$, 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, 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. If discovered, the new mediator can be precisely studied at e^+e^- colliders.

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