Sensitivity to dark matter production with light mediator exchange

Jan Kalinowski[a], Wojciech Kotlarski[b], Krzysztof Mekala[a], Pawel Sopicki[a], **Aleksander Filip Żarnecki**[a]

FACULTY OF PHYSICS UNIVERSITY OF WARSAW

[a] Faculty of Physics, University of Warsaw
[b] Institut für Kern- und Teilchenphysik, TU Dresden

Research supported by NATIONAL SCIENCE CENTRE POLAND

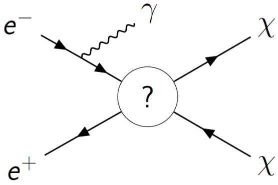
ILD Analysis/Software Meeting

February 10, 2021

Outline

Dark Matter production

The mono-photon signature is considered to be the most general way to look for DM particle production in future e^+e^- colliders.



DM can be pair produced in the e^+e^- collisions via exchange of a new mediator particle, which couples to both electrons (SM) and DM states

This process can be detected if additional hard photon radiation from the initial state is observed in the detector...

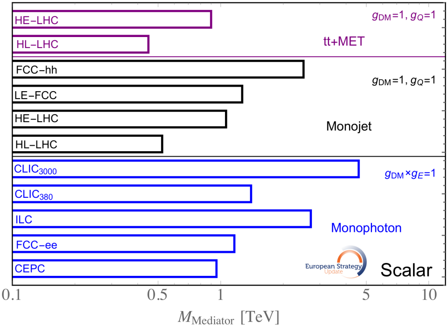
Motivation

New analysis approach

Most of the studies performed so far focused on heavy mediator exchange (EFT limit) and coupling values $\mathcal{O}(1)$
$\Rightarrow$ extracted were limits on DM or mediator masses

In our study:

- focus on light mediator exchange (DM even lighter)
- consider very small mediator coupling to SM, $\Gamma_{SM} \ll \Gamma_{tot}$



From arXiv:1910.11775
ESPP Physics Briefing Book

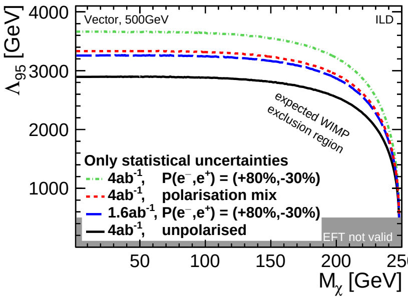
"Experimental-like" approach $\Rightarrow$ focus on cross section limits as a function of mediator mass and width

New analysis approach

Most of the studies performed so far focused on heavy mediator exchange (EFT limit) and coupling values $\mathcal{O}(1)$
$\Rightarrow$ extracted were limits on DM or mediator masses

In our study:

- focus on light mediator exchange (DM even lighter)
- consider very small mediator coupling to SM, $\Gamma_{SM} \ll \Gamma_{tot}$



ILD study: arXiv:2001.03011
Phys. Rev. D 101, 075053 (2020)

"Experimental-like" approach $\Rightarrow$ focus on cross section limits as a function of mediator mass and width

Simulating mono-photon events

Dedicated simulation procedure with Whizard

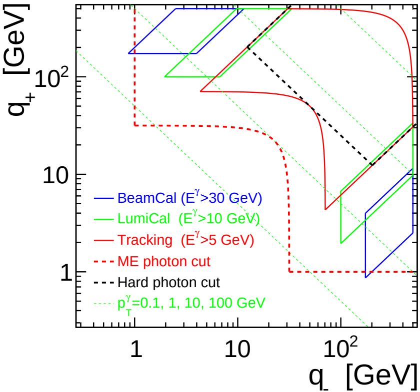
Two variables, calculated separately for each emitted photon:

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

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

are used to separate "soft ISR" emission region from the region described by ME calculations.

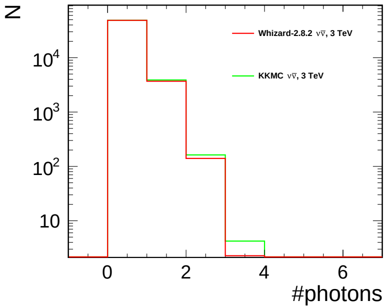
Detector acceptance $\sqrt{s} = 500$ GeV

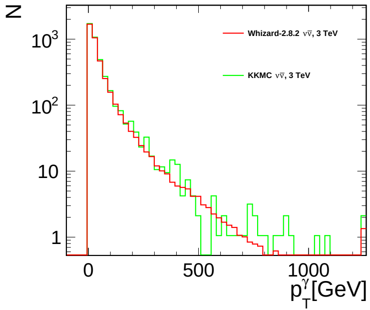


All "detectable" photons are simulated with Matrix Elements

Validation of the procedure

WHIZARD predictions were compared to the results from the KKMC code for $e^+e^- \to \nu\bar{\nu} + \mathrm{N}\gamma$





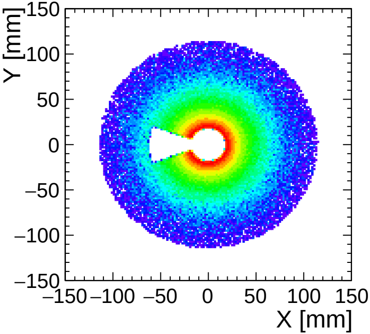
⇒ very good agreement observed (both for shape and normalisation)

For more details:
J. Kalinowski et al., Eur. Phys. J. C 80 (2020) 634, arXiv:2004.14486

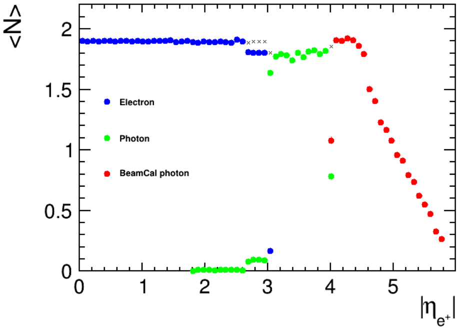
Detector simulation for ILC running at 500 GeV

ILCgen model for Delphes includes proper modelling of forward detectors

BeamCal



Reconstruction efficiency for $e^+e^- \rightarrow e^+e^-$



Included in the official Delphes repository as `delphes_card_ILCgen.tcl`

Event selection for ILC running at 500 GeV

On generator level:

- 1, 2 or 3 ME photons

  nonradiative events for signal only (for normalisation)

- all ME photons with

  $q_{\pm} > 1\,GeV \quad \& \quad E^{\gamma} > 1\,GeV$

  rejected are events with

  $q_{\pm} > 1\,GeV \quad \& \quad E^{\gamma} > 1\,GeV$

  for any of the ISR photons

- at least one ME photon with

  $p_T^{\gamma} > 2\,GeV \;\; \& \;\; 5^{\circ} < \theta^{\gamma} < 175^{\circ}$

On detector simulation level:

- single photon with

  $p_T^{\gamma} > 3\,GeV \;\; \& \;\; |\eta^{\gamma}| < 2.8$

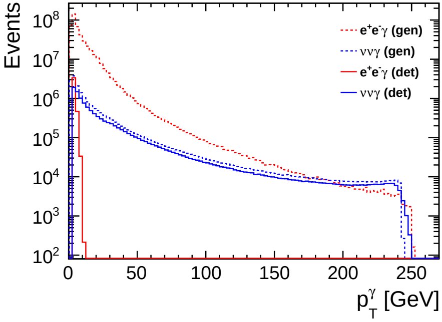
- no other activity in the detector

  other reconstructed objects

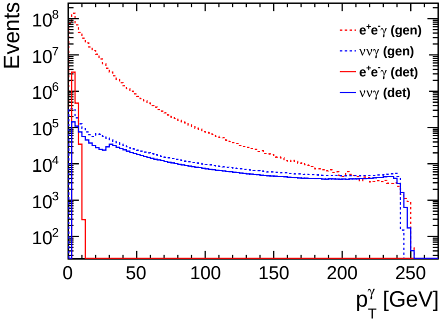
  - no electrons
  - no BeamCal photons
  - no jets ($p_T > 5\,GeV$)

Background distributions for ILC running at 500 GeV

Two SM backgrounds considered:
Bhabha scattering and (radiative) neutrino pair production



$e_L^- \; e_R^+$ (-80%/+30%)



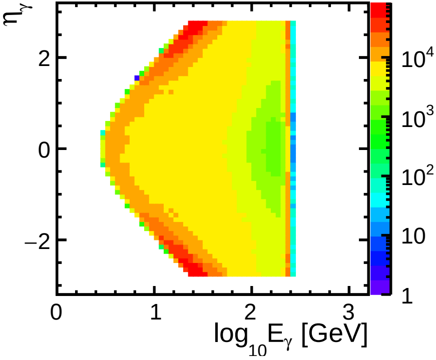
$e_R^- \; e_L^+$ (+80%/-30%)

$1600\,\mathrm{fb}^{-1}$ each

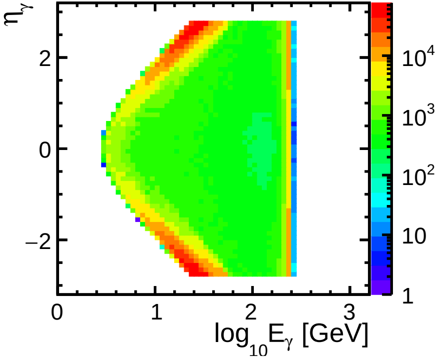
Simulating mono-photon events

Background distributions for ILC running at 500 GeV

For mono-photon events, two variables fully describe event kinematics
$\Rightarrow$ use 2D distribution of $(\log_{10} E_\gamma, \eta)$ to constrain DM production



$e^-_L \; e^+_R$ (-80%/+30%)



$e^-_R \; e^+_L$ (+80%/-30%)

$1600\,\text{fb}^{-1}$ each

Simplified DM model

Simplified model covering most popular scenarios of DM pair-production

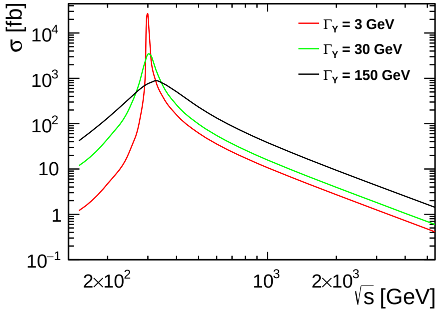
Possible DM candidates:

- real or complex scalar
- Majorana or Dirac fermion
- real vector

Possible mediators:

- scalar
- pseudo-scalar
- vector
- axial-vector

Cross section for $e^+e^- \to \chi\chi$ for $M_\chi = 50\ GeV$ and $M_Y = 300\ GeV$



(mixed couplings, eg. V-A or V+A, also possible)

Simulating mono-photon events

Simplified DM model

Simplified model covering most popular scenarios of DM pair-production

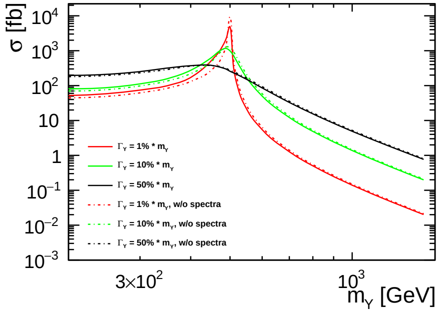
Possible DM candidates:

- real or complex scalar
- Majorana or Dirac fermion
- real vector

Possible mediators:

- scalar
- pseudo-scalar
- vector
- axial-vector

Cross section for $e^+e^- \to \chi\chi$ at 500 GeV ILC for $M_\chi = 50~GeV$



(mixed couplings, eg. V-A or V+A, also possible)

Simplified DM model

Simplified model covering most popular scenarios of DM pair-production

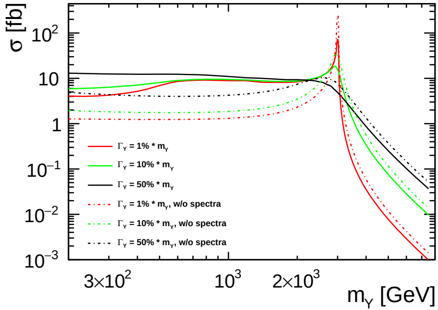
Possible DM candidates:

- real or complex scalar
- Majorana or Dirac fermion
- real vector

Possible mediators:

- scalar
- pseudo-scalar
- vector
- axial-vector

Cross section for $e^+e^- \rightarrow \chi\chi$ at 3 TeV CLIC for $M_\chi = 50\ GeV$



(mixed couplings, eg. V-A or V+A, also possible)

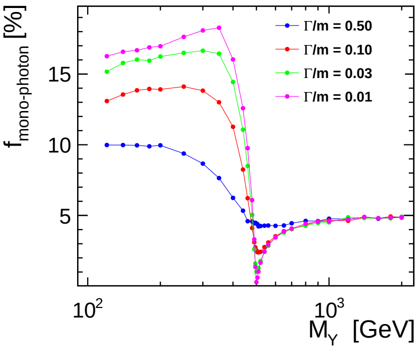
Tagging efficiency

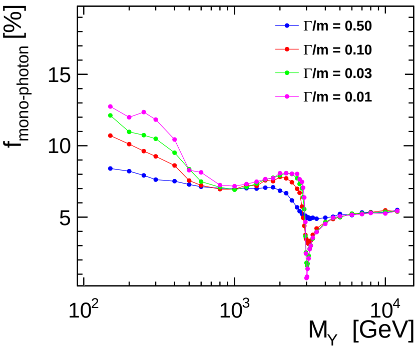
Detectable hard photon emitted only in a fraction of signal event

$$\sigma\left(e^{+}e^{-} \to \chi\,\chi\,\gamma_{\text{tag}}\right) \;=\; f_{\text{mono-photon}} \cdot \sigma\left(e^{+}e^{-} \to \chi\,\chi\,(\gamma)\,\right)$$

ILC @ 500 GeV

CLIC @ 3 TeV



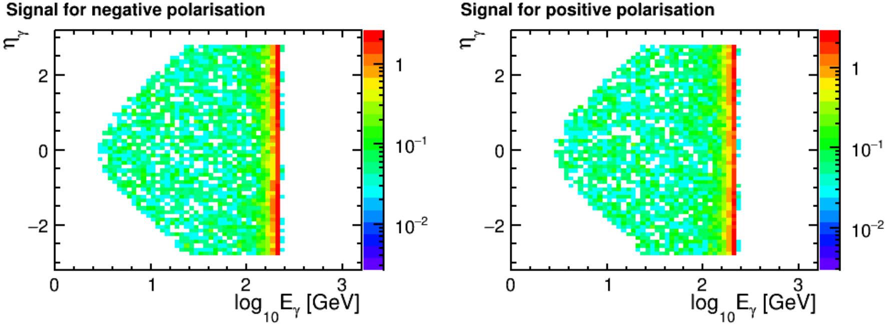


Emission strongly suppressed for narrow mediator with $M_Y \sim \sqrt{s}$

Signal distributions for ILC at 500 GeV

For fermion DM with $M_\chi = 50$ GeV and vector mediator with $\Gamma/M = 0.03$

Mediator mass: M_Y=200 GeV



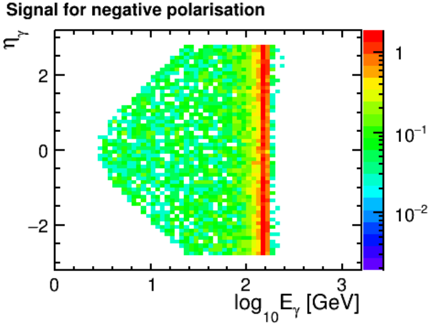
Signal normalised to the DM pair-production cross section of 1 fb

Simulating mono-photon events

Signal distributions for ILC at 500 GeV

For fermion DM with $M_\chi = 50\,\text{GeV}$ and vector mediator with $\Gamma/M = 0.03$

Mediator mass: M_Y=300 GeV



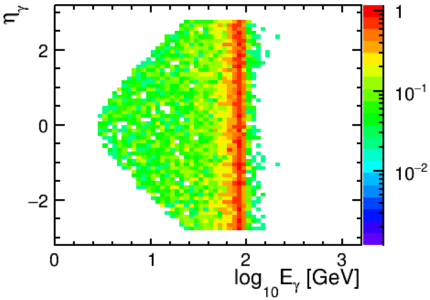
Signal normalised to the DM pair-production cross section of 1 fb

Signal distributions for ILC at 500 GeV

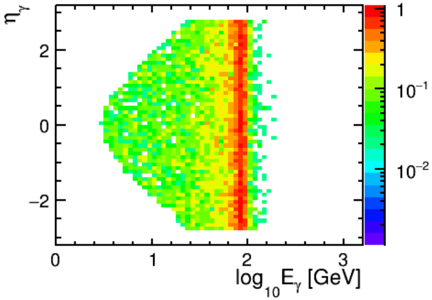
For fermion DM with $M_\chi = 50$ GeV and vector mediator with $\Gamma/M = 0.03$

Mediator mass: M_Y=400 GeV

Signal for negative polarisation



Signal for positive polarisation



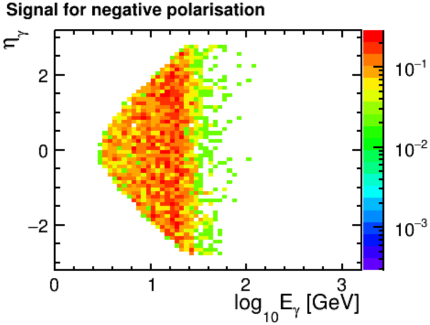
Signal normalised to the DM pair-production cross section of 1 fb

Simulating mono-photon events

Signal distributions for ILC at 500 GeV

For fermion DM with $M_\chi = 50$ GeV and vector mediator with $\Gamma/M = 0.03$

Mediator mass: M_Y=480 GeV

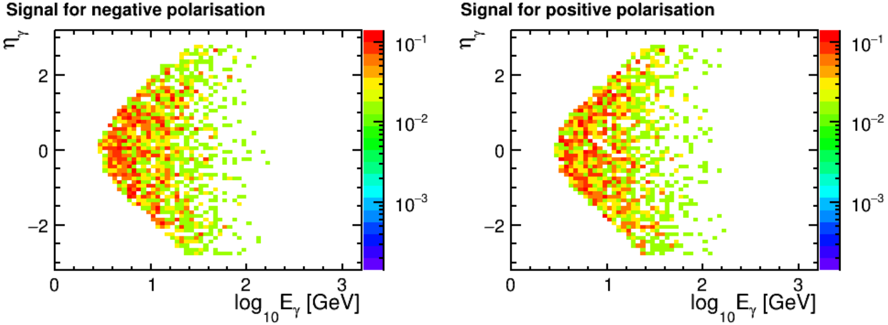


Signal normalised to the DM pair-production cross section of 1 fb

Signal distributions for ILC at 500 GeV

For fermion DM with $M_\chi = 50\,\text{GeV}$ and vector mediator with $\Gamma/M = 0.03$

Mediator mass: M_Y=520 GeV

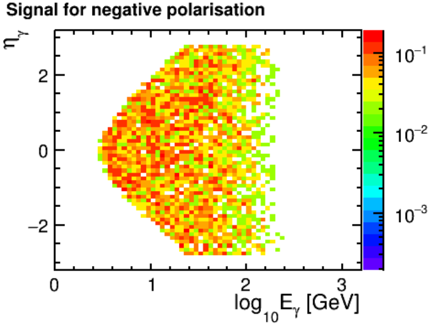


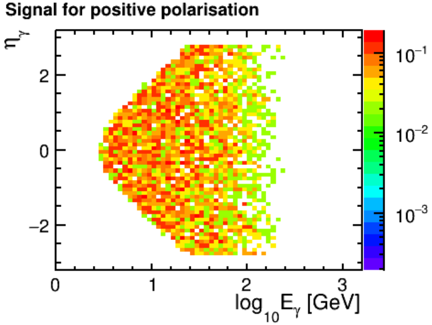
Signal normalised to the DM pair-production cross section of 1 fb

Signal distributions for ILC at 500 GeV

For fermion DM with $M_\chi = 50\,\text{GeV}$ and vector mediator with $\Gamma/M = 0.03$

Mediator mass: M_Y=2000 GeV



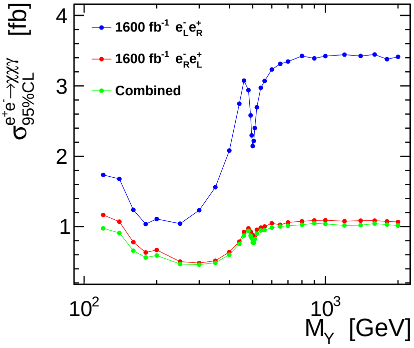


Signal normalised to the DM pair-production cross section of 1 fb

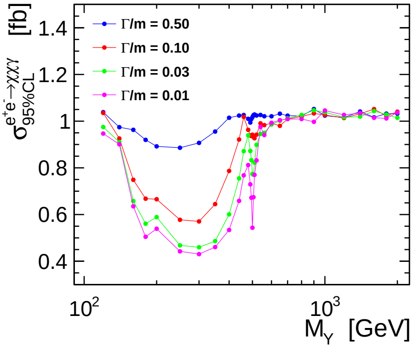
Results

Cross section limits for radiative events at ILC (tagged photon)

Vector mediator with $\Gamma/m = 3\%$



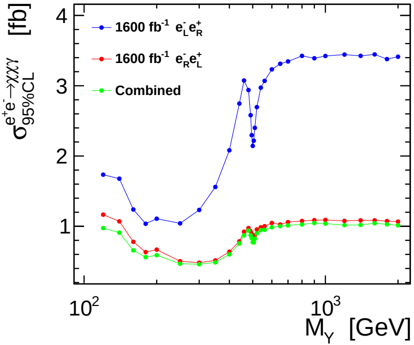
Combined limits for vector mediator



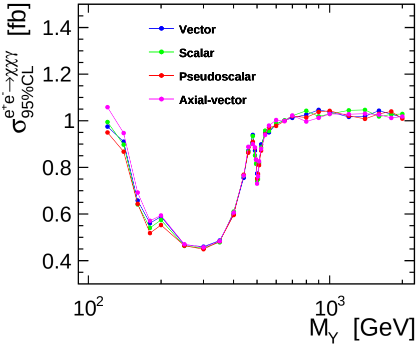
Limits calculated with CL_s approach using RooFit v3.60

Cross section limits for radiative events at ILC (tagged photon)

Vector mediator with $\Gamma/m = 3\%$



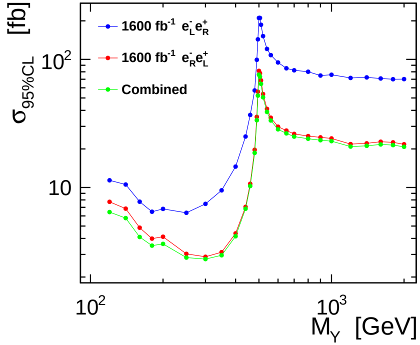
Combined limits for $\Gamma/m = 3\%$



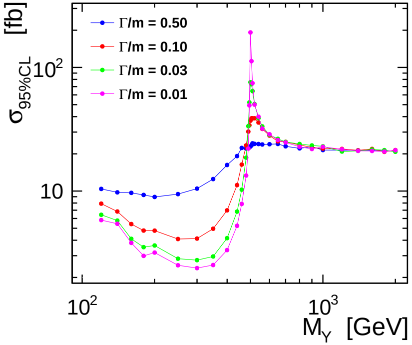
Limits calculated with CL_s approach using RooFit v3.60

Cross section limits for total DM production cross section at ILC

Vector mediator with $\Gamma/m = 3\%$



Combined limits for vector mediator

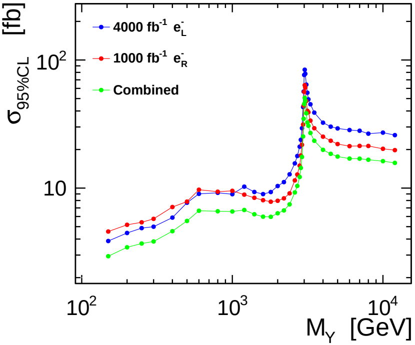


$1600\,\text{fb}^{-1}$ for $-80\%/+30\%$ + $1600\,\text{fb}^{-1}$ for $+80\%/-30\%$ e^-/e^+ polarisation

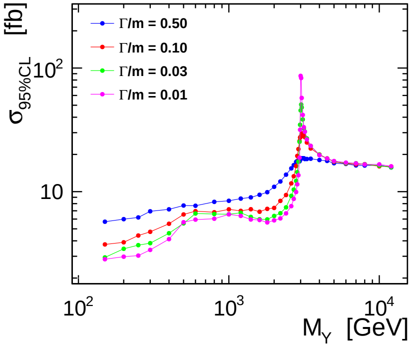
Results

Cross section limits for total DM production cross section at CLIC

Vector mediator with $\Gamma/m = 3\%$



Combined limits for vector mediator

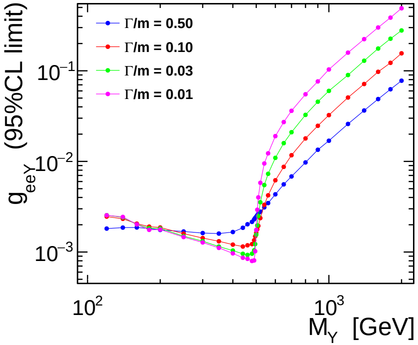


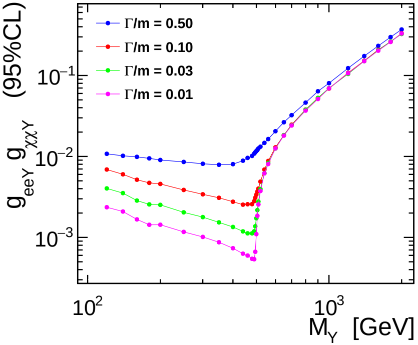
$4000\,\mathrm{fb}^{-1}$ for -80% e^- polarisation $+$ $1000\,\mathrm{fb}^{-1}$ for $+80\%$ e^- polarisation

Coupling limits at 500 GeV ILC

Combined coupling limits for assumed mass and width of the mediator.

For vector mediator



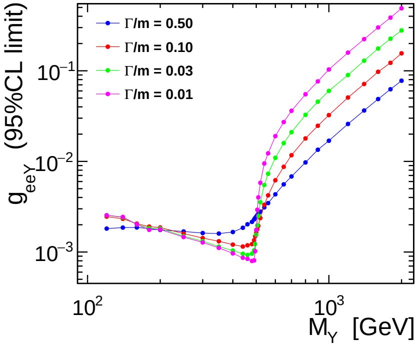


Almost uniform sensitivity to g_{eeY} up to kinematic limit.

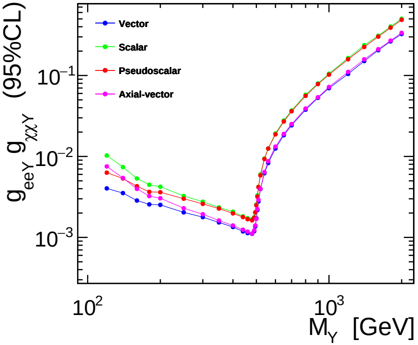
Coupling limits at 500 GeV ILC

Combined coupling limits for assumed mass and width of the mediator.

For vector mediator



Model comparison

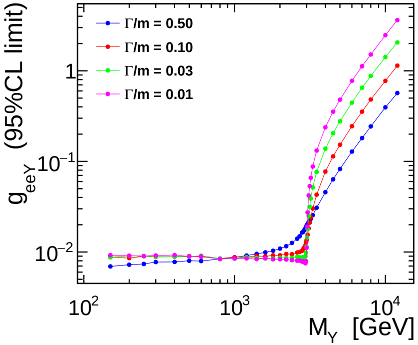


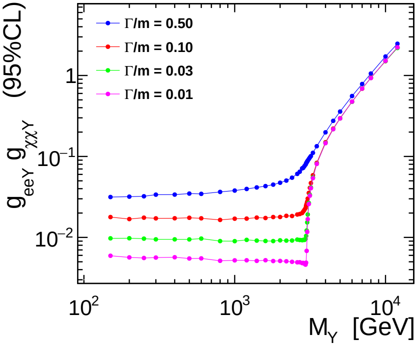
Coupling limits almost independent on the assumed coupling structure!

Coupling limits at 3 TeV CLIC

Combined coupling limits for assumed mass and width of the mediator.

For vector mediator



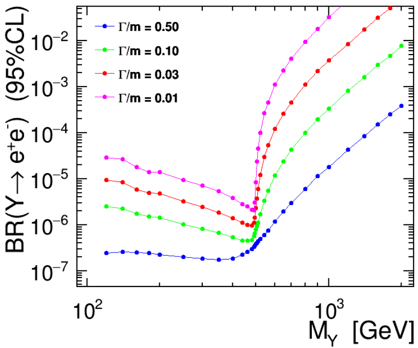


SM Branching Ratio limits

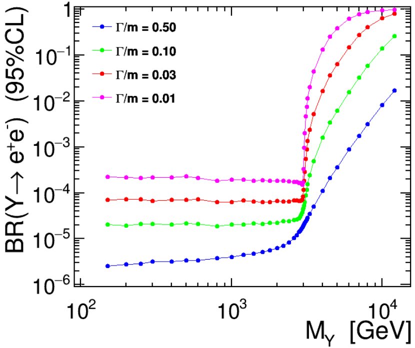
Branching Ratio for mediator decay to e^+e^-

corresponding to the extracted cross section and coupling limits

ILC @ 500 GeV



CLIC @ 3TeV



For $M_Y < \sqrt{s}$ numbers of expected events too small
to search for resonant mediator production in e^+e^- decay channel!

Results

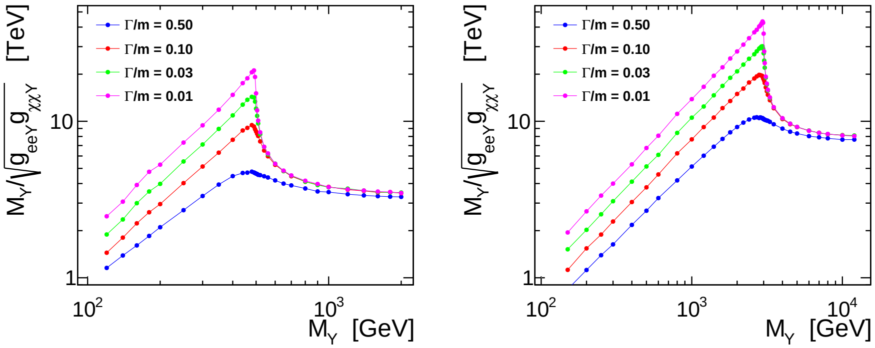
Effective mass scale limits

$$\Lambda^2 = \frac{M_Y^2}{|g_{eeY} g_{\chi\chi Y}|}$$

For $M_Y \gg \sqrt{s}$, limits on the effective mass scale of new interactions no longer depend on the assumed mediator mass or width

$\Rightarrow$ EFT approximation can be used

ILC @ 500 GeV $\Lambda^{lim} \sim 3.4$ TeV   CLIC @ 3TeV $\Lambda^{lim} \sim 8$ TeV



Summary

Analysis of mono-photon events at 500 GeV ILC sensitive to wide range of DM pair-production scenarios

- $\mathcal{O}(1\,\text{fb})$ limits on the radiative production cross section
  $e^+e^- \rightarrow \chi\chi\gamma_{\text{tag}}$
- $\mathcal{O}(10\,\text{fb})$ limits on the DM pair-production
  $e^+e^- \rightarrow \chi\chi(\gamma)$
  except for the resonance region $M_Y \sim \sqrt{s}$
- $\mathcal{O}(10^{-3} - 10^{-2})$ limits on the mediator coupling to electrons
  up to the kinematic limit $M_Y \leq \sqrt{s}$
- mono-photon analysis limits more stringent than the limits expected from direct resonance search in SM decay channels
- for heavy mediators, limits from EFT analysis can be reporoduced

Plans & Conclusions

Plans

For the next weeks:

- add $e_L^- e_L^+$ and $e_R^- e_R^+$ polarisation combinations
- include systematic uncertainties
- prepare results for LaThuile'2021 and LCWS'2021

Future options:

- compare more DM production scenarios
- estimate discovery range
- consider mediator mass and width determination
- estimate limits expected from Bhabha measurement

Conclusions

New framework for mono-photon analysis developed

- different scenarios possible with simplified DM model
- focus on light mediator exchange
- consider very small mediator coupling to SM, $\Gamma_{\mathrm{SM}} \ll \Gamma_{\mathrm{tot}}$

Mono-photon analysis at 500 GeV ILC sensitive to light mediators for SM coupling values down to $\mathcal{O}(10^{-3})$:

- sensitivity dominated by "positive" polarisation $(e^-_R e^+_L)$
- limits largely independent on the mediator type/coupling
- limits stronger than the estimated sensitivity from the direct resonance search

Thank you!

Simplified DM model

Dark matter particles, X_i, couple to the SM particles via an mediator, Y_j.

Each simplified scenario is characterized by one dark matter candidate and one mediator from the set listed below:

	particle	mass	spin	charge	self-conjugate	type
DM	X_R	m_{X_R}	0	0	yes	real scalar
	X_C	m_{X_C}	0	0	no	complex scalar
	X_M	m_{X_M}	$\frac{1}{2}$	0	yes	Majorana fermion
	X_D	m_{X_D}	$\frac{1}{2}$	0	no	Dirac fermion
	X_V	m_{X_V}	1	0	yes	real vector
mediator	Y_R	m_{Y_R}	0	0	yes	real scalar
	Y_V	m_{Y_C}	1	0	yes	real vector
	T_C	m_{T_C}	0	1	no	charged scalar

Simplified DM model

Lagrangian describing mediator coupling to electrons given by

$$\mathcal{L}_{eeY} \ni \bar{e}(g^1_{eY_R} + \imath\gamma^5 g^5_{eY_R}) e Y_R + \bar{e}\gamma_\mu (g^1_{eY_V} + \gamma^5 g^5_{eY_V}) e Y^\mu_V$$

The interaction of mediators with dark matter is described by

$$\begin{aligned}\mathcal{L}_{XXY} \ni\ & g_{X_R Y_R} X_R^2 Y_R + \imath g_{X_C Y_V} (X_C^*(\partial_\mu X_C) - (\partial_\mu X_C^*) X_C) Y_V^\mu + \\ & \bar{X}_D (g^1_{X_D Y_R} + \imath\gamma^5 g^5_{X_D Y_R}) X_D Y_R + \bar{X}_D \gamma_\mu (g^1_{X_D Y_V} + \gamma^5 g_{X_D Y_V}) X_D Y_V^\mu \\ & \bar{X}_M (g^1_{X_M Y_R} + \imath\gamma^5 g^5_{X_M Y_R}) X_M Y_R + g^5_{X_M Y_V} \bar{\psi}_M \gamma_\mu \gamma^5 \psi_M Y_V^\mu\end{aligned}$$

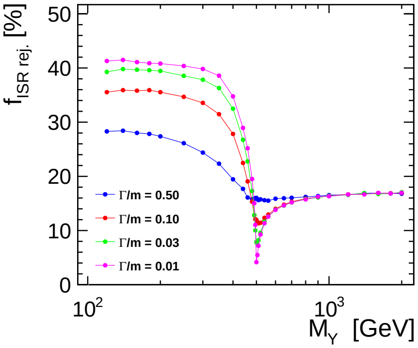
ILC vs CLIC comparison of simulation and analysis setup

	ILCgen	CLICdet
Detector acceptance (Delphes model)		
tracking	$\|\eta\| < 3$	$\|\eta\| < 2.54$
ECAL	$\|\eta\| < 3$	$\|\eta\| < 3$
LumiCal	$3 < \|\eta\| < 4$	$3 < \|\eta\| < 4$
BeamCal	$4 < \|\eta\| < 5.8$	$4 < \|\eta\| < 5.3$
Generator level cuts		
p_T^γ min.	2 GeV	5 GeV
Θ^γ min.	5°	7°
Detector level cuts		
p_T^γ min.	3 GeV	10 GeV
$\|\eta^\gamma\|$ max.	2.8 (7°)	2.6 (8.5°)

ISR rejection efficiency

Fraction of events generated by WHIZARD removed by ISR rejection procedure (ISR photons emitted in the phase-space region covered by ME)

ILC @ 500 GeV



CLIC @ 3 TeV