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

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

The 2021 International Workshop on Future Linear Colliders

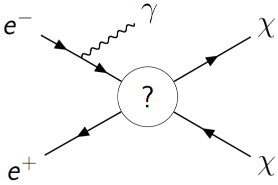
Theoretical Developments & Physics Analyses session

March 17, 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.

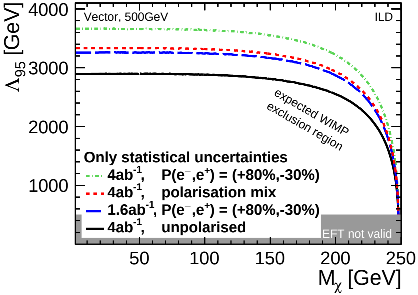


DM can be pair produced in the e^+e^- collisions via exchange of a new mediator particle, which couples to both electrons (SM) and DM states

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

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



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

CLIC study: arXiv:2103.06006

In our study:

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

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

Analysis framework

Running scenarios

ILC

Total of 4000 fb^{-1} assumed at 500 GeV (H-20 scenario)

- $2\times1600\,\mathrm{fb}^{-1}$ for LR and RL beam polarisation combinations
- $2\times400\,\mathrm{fb}^{-1}$ for RR and LL beam polarisation combinations

assuming polarisation of $\pm80\%$ for electrons and $\pm30\%$ for positrons

arXiv:1903.01629

CLIC

Total of 5000 fb^{-1} assumed at 3 TeV

- $4000\,\mathrm{fb}^{-1}$ for negative electron beam polarisation
- $1000\,\mathrm{fb}^{-1}$ for positive electron beam polarisation

assuming polarisation of $\pm80\%$ for electrons

arXiv:1812.06018

Analysis framework

Simulating mono-photon events

Dedicated simulation procedure for WHIZARD, with all "detectable" photons generated on Matrix Element level, matched with soft ISR.

For more details:
⇒ W.Kotlarski, *Simulating hard photon production with Whizard* (22:20 CET)
⇒ J. Kalinowski et al., Eur. Phys. J. C 80 (2020) 634, arXiv:2004.14486

Detector modeling

Detector response simulated in the Delphes framework.

Both ILCgen and (modified) CLICdet models include proper description of forward detectors: BeamCal and LumiCal

⇒ see backup slides for more details

Event selection

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
  $p_T^{\gamma} > 2\,GeV \;\; \& \;\; 5^\circ < \theta^{\gamma} < 175^\circ$ (ILC 500 GeV)
  $p_T^{\gamma} > 5\,GeV \;\; \& \;\; 7^\circ < \theta^{\gamma} < 173^\circ$ (CLIC 3 TeV)

On detector simulation level:

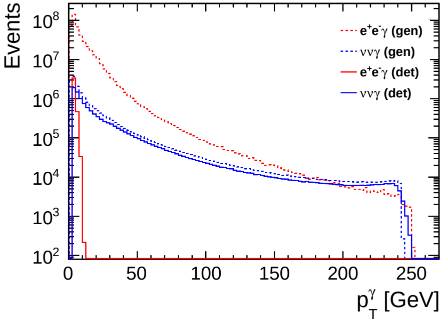
- single photon with
  $p_T^{\gamma} > 3\,GeV \;\; \& \;\; |\eta^{\gamma}| < 2.8$ (ILC)
  $p_T^{\gamma} > 10\,GeV \;\; \& \;\; |\eta^{\gamma}| < 2.6$ (CLIC)
- no other activity in the detector
  other reconstructed objects
  - no electrons
  - no LumiCal photons
  - no BeamCal photons
  - no jets

see backup slides for definition of $q_{\pm}$ variables

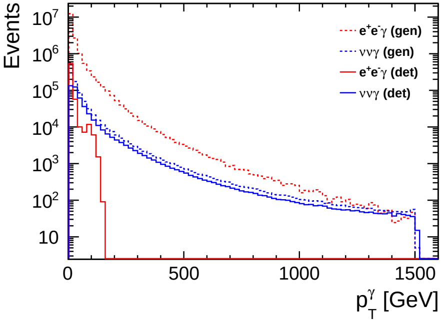
Analysis framework

Background distributions

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



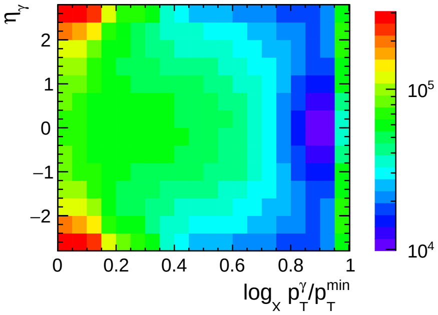
ILC 500 GeV
(-80%/+30%) 1600 fb^{-1}



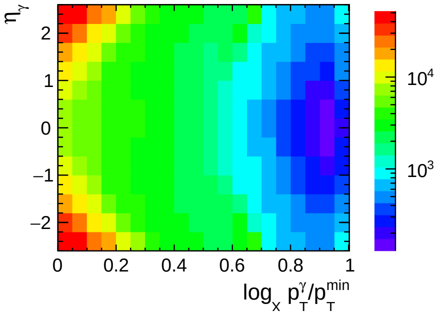
CLIC 3 TeV
(+80%) 1000 fb^{-1}

Background distributions

For mono-photon events, two variables fully describe event kinematics
⇒ use 2D distribution of (p_T^γ, η) to constrain DM production



ILC 500 GeV
(-80%/+30%) 1600 fb^{-1}



CLIC 3 TeV
(+80%) 1000 fb^{-1}

Simplified DM model

Simplified model covering most popular scenarios of DM pair-production

Possible DM candidates:

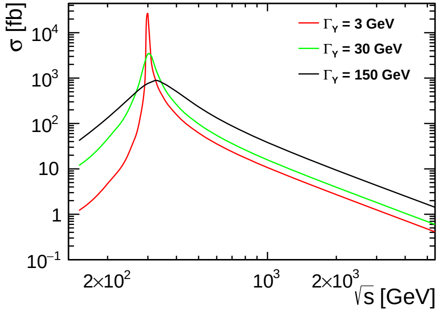
- real or complex scalar
- Majorana or Dirac fermion
- real vector

Possible mediators:

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

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

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

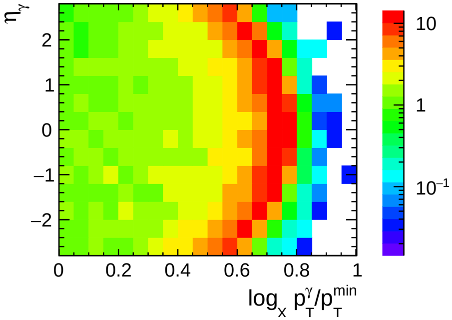


Signal distributions

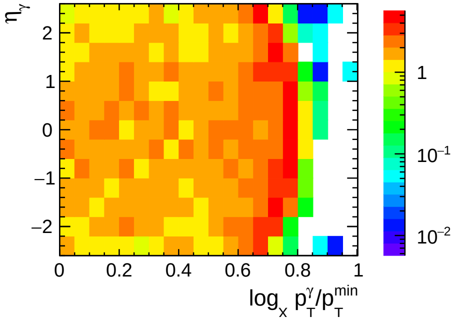
For fermion DM with $M_\chi = 50\,\mathrm{GeV}$ and vector mediator with $\Gamma/M = 0.03$

Mediator mass:

400 GeV @ ILC



2.4 TeV @ CLIC



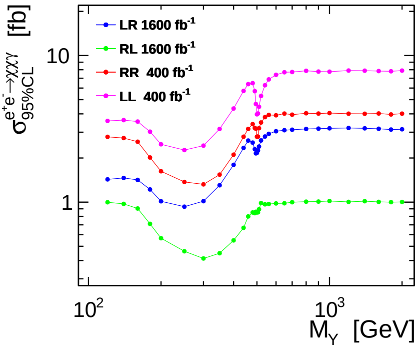
Signal normalised to unpolarised DM pair-production cross section of 1 fb

Results

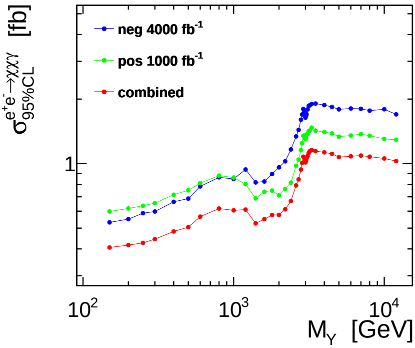
Cross section limits for radiative events (with tagged photon)

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

ILC @ 500 GeV



CLIC @ 3 TeV

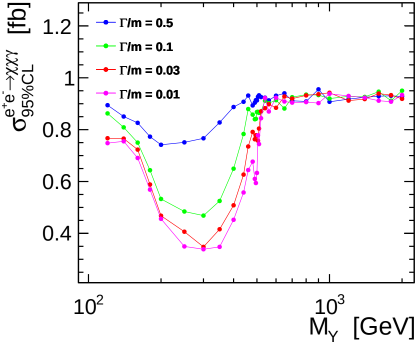


Limits calculated with CL_s approach using RooFit v3.60

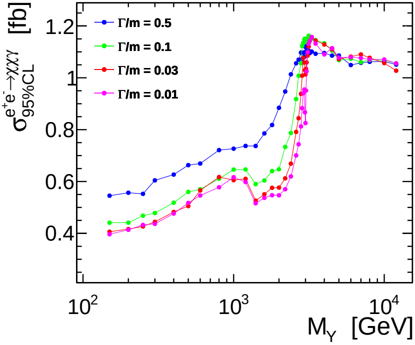
Cross section limits for radiative events (with tagged photon)

Vector mediator, combined limits

ILC @ 500 GeV



CLIC @ 3 TeV



Limits calculated with CL_s approach using RooFit v3.60

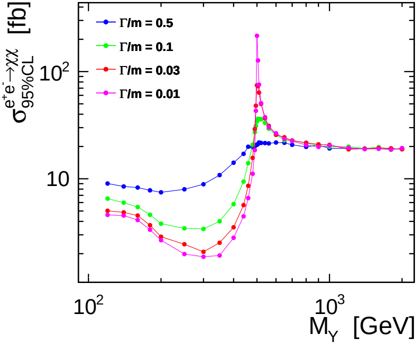
Results

Cross section limits for total DM production cross section

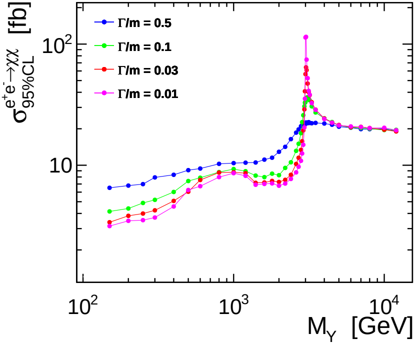
Corrected for probability of hard photon tagging! see backup slides

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

ILC @ 500 GeV



CLIC @ 3 TeV



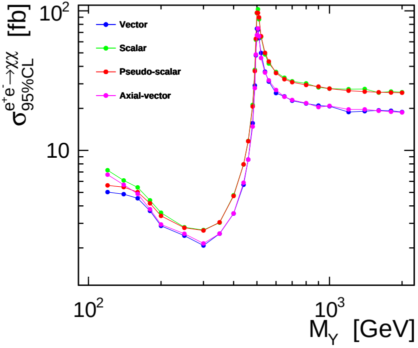
Radiation suppressed for narrow mediator with $M_Y \sim \sqrt{s} \Rightarrow$ weaker limits

Cross section limits for total DM production cross section

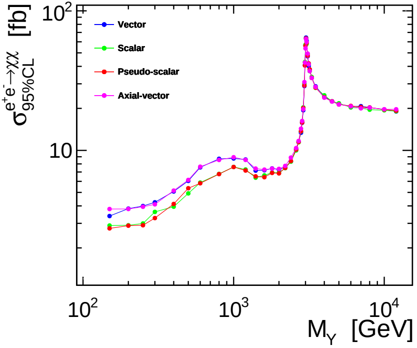
Corrected for probability of hard photon tagging! see backup slides

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

ILC @ 500 GeV



CLIC @ 3 TeV



Radiation suppressed for narrow mediator with $M_Y \sim \sqrt{s} \Rightarrow$ weaker limits

Systematic uncertainties PRELIMINARY

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

Considered sources of uncertainties:

- Integrated luminosity uncertainty of 0.26%
  uncorrelated between polarisations
- Luminosity spectra shape uncertainty
  correlated between polarisations
- Uncertainty in neutrino background normalisation of 0.2% (th+exp)
  correlated between polarisations
- Uncertainty in Bhabha background normalisation of 1% (th+exp)
  correlated between polarisations

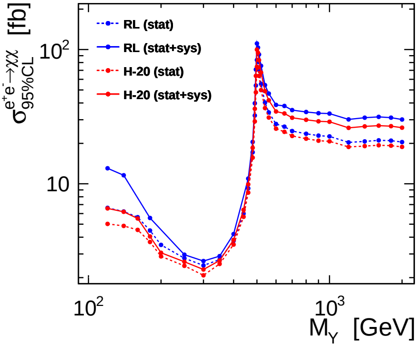
$\Rightarrow$ nuisance parameters in the model fit (7 for ILC, 5 for CLIC)

Results

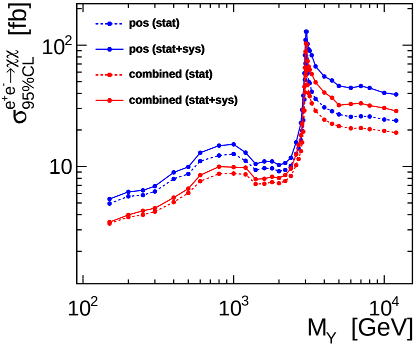
Systematic uncertainties PRELIMINARY

Limits for mediator with $\Gamma/m = 3\%$

ILC @ 500 GeV



CLIC @ 3 TeV

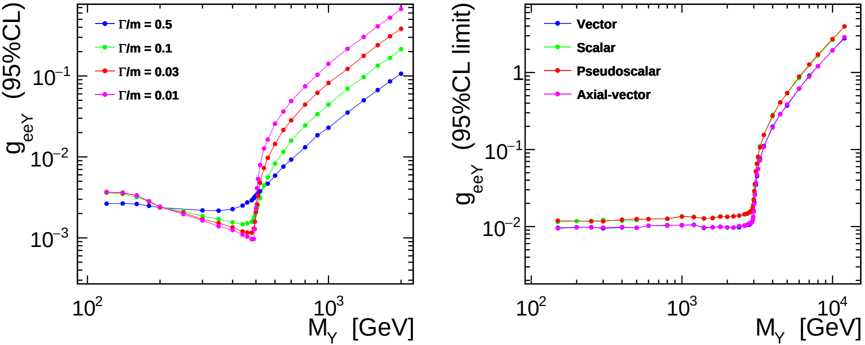


Influence of systematic effects reduced for light mediators, $M_Y < \sqrt{s}$

Coupling limits with systematic uncertainties

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

ILC @ 500 GeV   CLIC @ 3 TeV



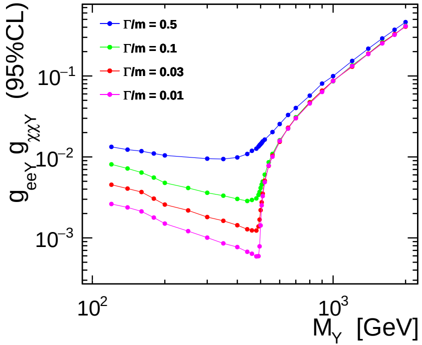
Almost uniform sensitivity to g_{eeY} up to kinematic limit.
Coupling limits weakly dependent on the assumed coupling structure!

Results

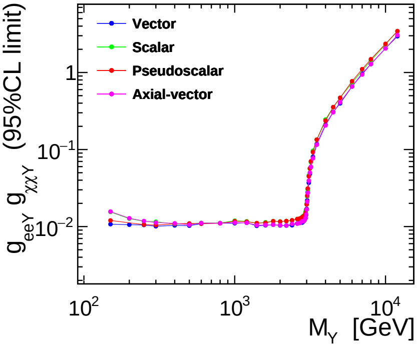
Coupling limits with systematic uncertainties

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

ILC @ 500 GeV



CLIC @ 3 TeV



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

Coupling limits weakly dependent on the assumed coupling structure!

Conclusions

New framework for mono-photon analysis developed
focus on light mediator exchange and very small mediator couplings to SM

Mono-photon production at e^+e^- colliders sensitive
to wide range of DM pair-production scenarios

- $\mathcal{O}(1\,\text{fb})$ limits on the radiative production $e^+e^- \rightarrow \chi\chi\gamma_{\text{tag}}$
- $\mathcal{O}(10\,\text{fb})$ 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 $M_Y \leq \sqrt{s}$

Limits largely independent on the mediator type/coupling

For for heavy mediators, limits from EFT analysis can be reproduced

For light mediators limits more stringent than those expected from direct resonance search in SM decay channels

Thank you!

Simulating mono-photon events

W.Kotlarski, *Simulating hard photon production with WHIZARD*,
PD1+PD4 session this evening (CET)

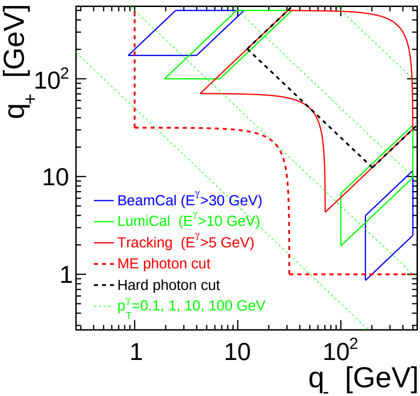
Two variables, calculated separately for each emitted photon:

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

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

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

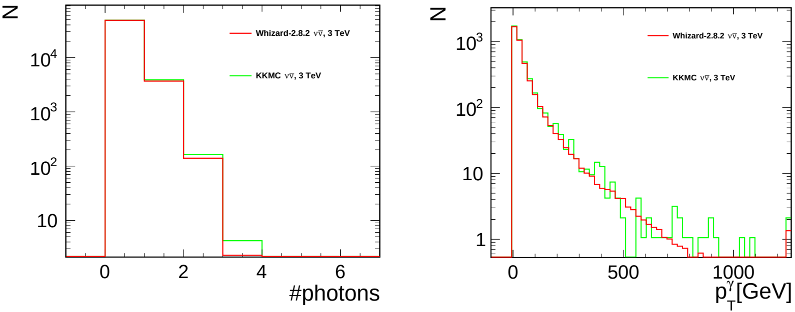
Detector acceptance $\sqrt{s} = 500$ GeV



All "detectable" photons are simulated with Matrix Elements

Simulating mono-photon events   Validation of the procedure

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



$\Rightarrow$ 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

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

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

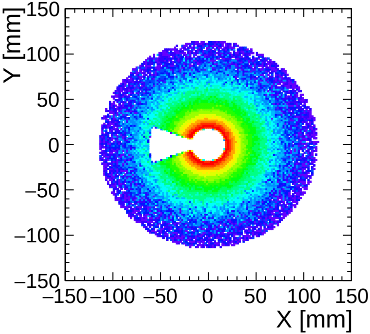
The interaction of mediators with dark matter is described by

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

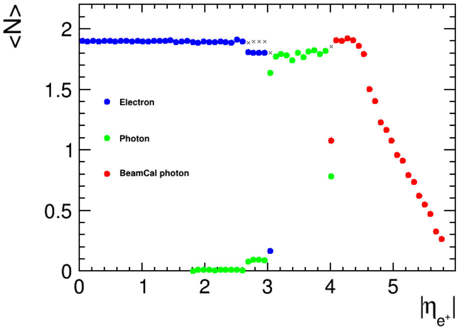
Detector simulation for ILC running at 500 GeV

ILCgen model for Delphes includes proper modelling of forward detectors

BeamCal



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

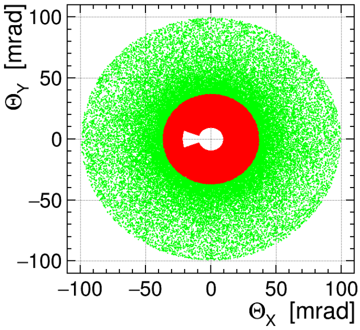


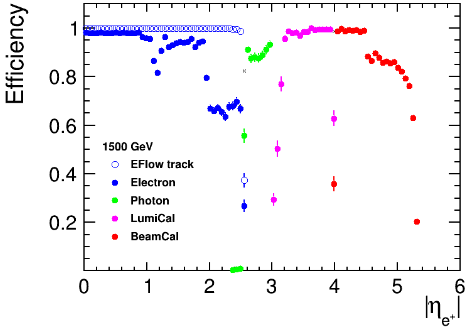
Included in the official Delphes repository as `delphes_card_ILCgen.tcl`

Detector simulation for CLIC running at 3 TeV

CLICdet model for Delphes also modified to include forward calorimeters

LumiCal + BeamCal Reconstruction efficiency for $e^+e^- \to e^+e^-$





Included in the repository as `delphes_card_CLICdet_Stage3_fcal.tcl`

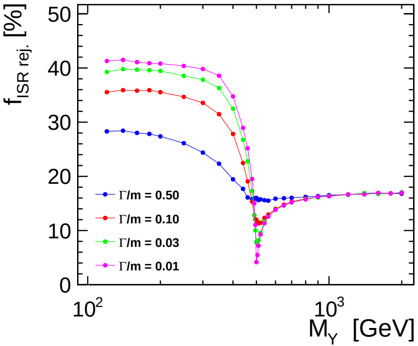
ILC vs CLIC comparison of simulation and analysis setup

	ILCgen @ 500 GeV	CLICdet @ 3 TeV
Generator level cuts		
p_T^γ min.	2 GeV	5 GeV
Θ^γ min.	5°	7°
Detector acceptance (Delphes model)		
tracking	$\lvert\eta\rvert < 3$	$\lvert\eta\rvert < 2.54$
ECAL	$\lvert\eta\rvert < 3$	$\lvert\eta\rvert < 3$
LumiCal	$3 < \lvert\eta\rvert < 4$	$3 < \lvert\eta\rvert < 4$
BeamCal	$4 < \lvert\eta\rvert < 5.8$	$4 < \lvert\eta\rvert < 5.3$
Detector level cuts		
p_T^γ min.	3 GeV	10 GeV
$\lvert\eta^\gamma\rvert$ max.	2.8 (7°)	2.6 (8.5°)

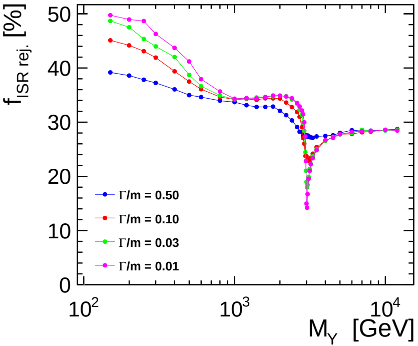
ISR rejection efficiency

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

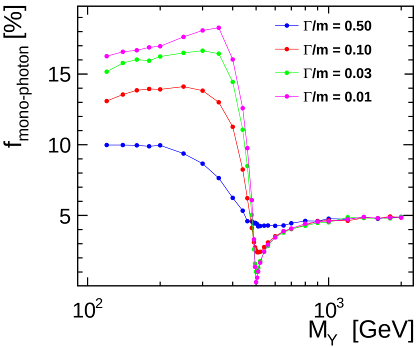


Tagging efficiency

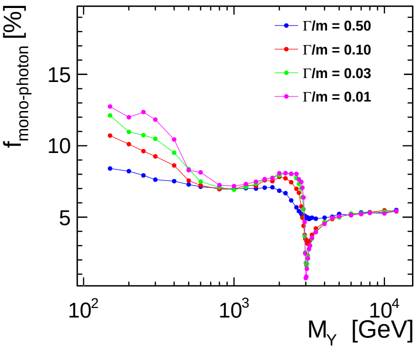
Detectable hard photon emitted only in a fraction of signal event

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

ILC @ 500 GeV



CLIC @ 3 TeV



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

Number of bins

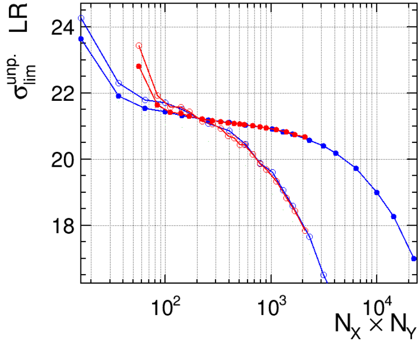
The higher number of bins in 2D (p_T^γ, η^γ) distribution,

the higher sensitivity to BSM scenarios...

but also to statistical fluctuations in MC samples (mainly for signal)

Expected limits vs number of bins

for 100k (open) and 1M (full circles) MC events in signal sample



$\Rightarrow N_{bin} \leq 300$

to avoid problems due to limited MC statistics

20×14 bins used for ILC

20×13 bins used for CLIC

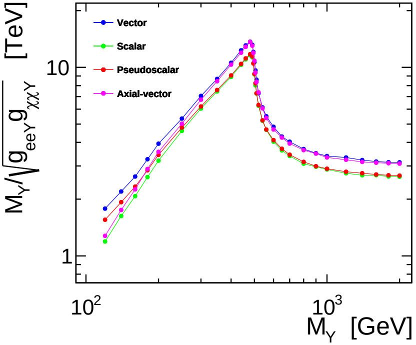
Effective mass scale limits

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

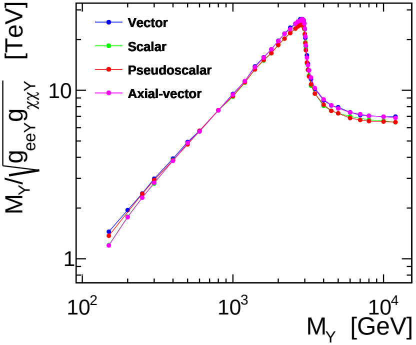
For $M_Y \gg \sqrt{s}$, limits on the effective mass scale of new interactions no longer depend on the assumed mediator mass or width

$\Rightarrow$ EFT approximation can be used

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



CLIC @ 3TeV $\Lambda^{lim} \sim 7$ TeV



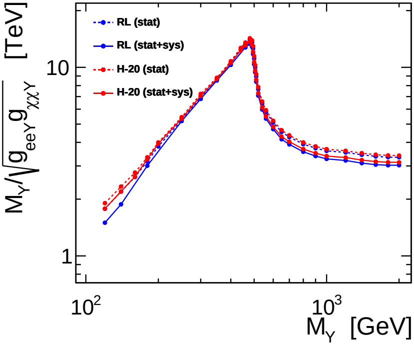
Effective mass scale limits

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

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 $\Lambda^{lim} \sim 3$ TeV



CLIC @ 3TeV $\Lambda^{lim} \sim 7$ TeV