Sensitivity of future e^+e^- colliders to processes of dark matter production with light mediator exchange

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Matter To The Deepest
Recent Developments In Physics Of Fundamental Interactions
XLIV International Conference of Theoretical Physics
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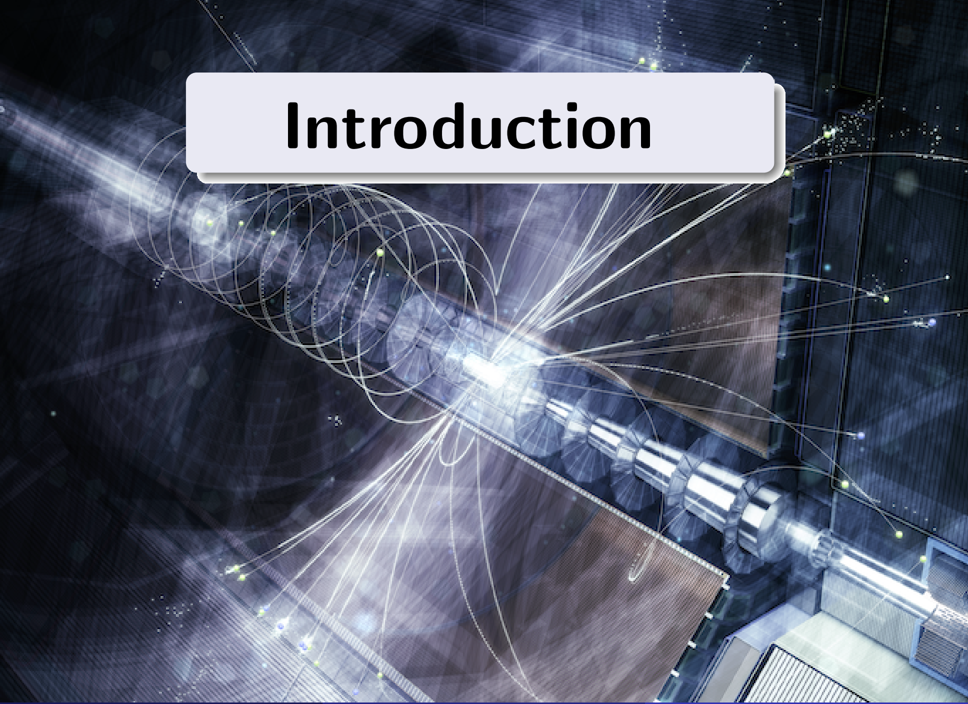
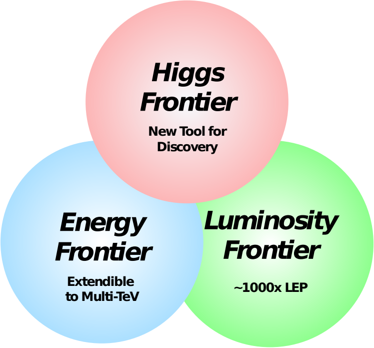
Introduction



Dark Matter

Many hints for existence of Dark Matter (DM), but its nature is unknown.
Many possible scenarios, wide range of masses and couplings to consider.

High energy e^+e^- machines offer many options for DM searches:



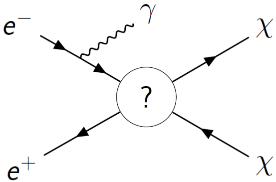
Tomohiko Tanabe @ LCWS'2021

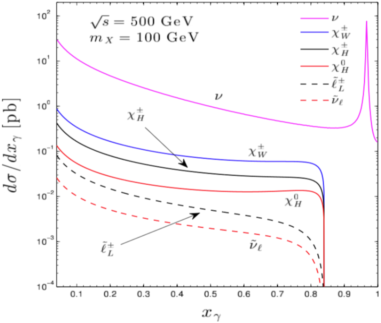
For more general picture see my presentation at SUSY'2021

Probing Dark Matter with e^+e^-

Mono-photon signature

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





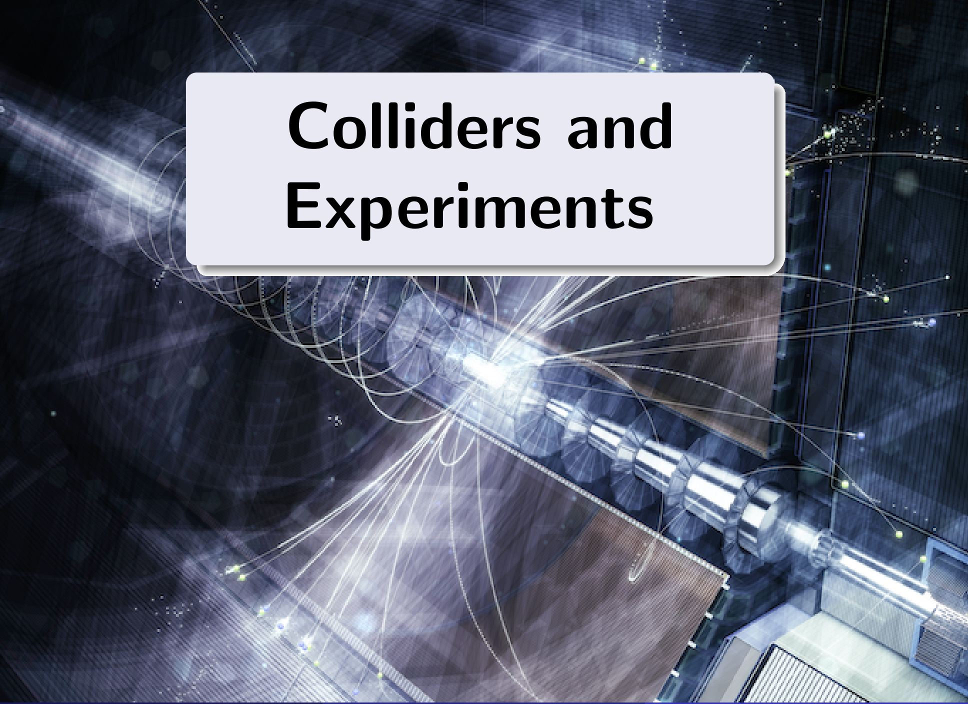
DM can be pair produced in the e^+e^- collisions via exchange of a new mediator particle, which couples to both electrons (SM) and DM states

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

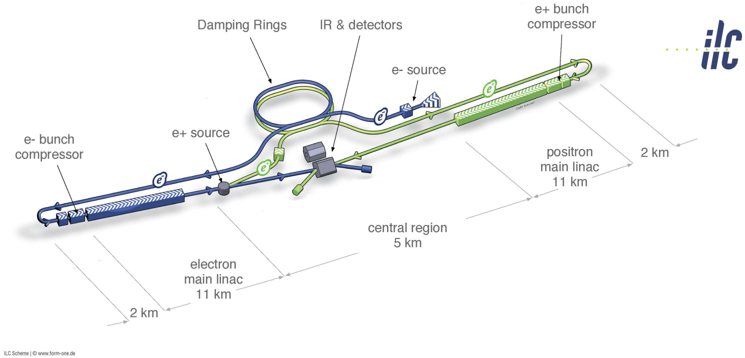
Outline

1. Introduction
2. Colliders and Experiments
3. Simulating mono-photon events
4. Mono-photon results
   - Heavy mediator approximation (ILD and CLICdp studies)
   - Light mediator exchange
5. Conclusions

Colliders and Experiments



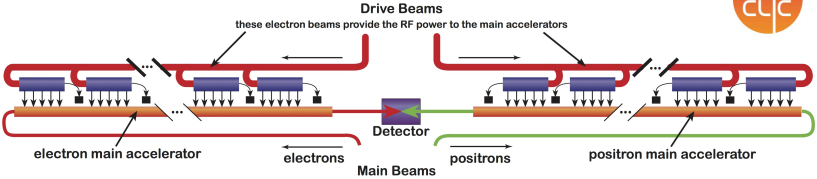
International Linear Collider



Technical Design (TDR) completed in 2013 arXiv:1306.6328

- superconducting accelerating cavities
- 250 – 500 GeV c.m.s. energy (baseline), 1 TeV upgrade possible
- footprint 31 km
- polarisation for both e^- and e^+ (80%/30%)

Compact LInear Collider



Conceptual Design (CDR) presented in 2012 CERN-2012-007

- high gradient, two-beam acceleration scheme
- staged implementation plan with energy from 380 GeV to 3 TeV
- footprint of 11 to 50 km
- e^- polarisation (80%)

For details refer to arXiv:1812.07987

Running scenarios

Staged construction assumed for both ILC and CLIC.
Results presented in this talk focus on the highest energy stages.

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 fb^{-1} for negative electron beam polarisation
- 1000 fb^{-1} for positive electron beam polarisation

assuming polarisation of $\pm80\%$ for electrons

arXiv:1812.06018

Detector Requirement

"Particle Flow" concept:

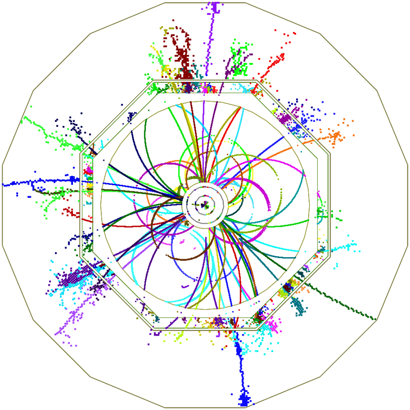
High calorimeter granularity
$\Rightarrow$ single particle reconstruction/ID

Precise momentum measurement
$\Rightarrow$ best energy for charged particles
$\Rightarrow$ dominates jet energy resolution

High precision vertex detector
$\Rightarrow$ very efficient flavour tagging

Instrumentation down to smallest angles
$\Rightarrow$ hermecity, missing energy tagging

Example event
$e^+e^- \rightarrow t\bar{t} \rightarrow 6j$

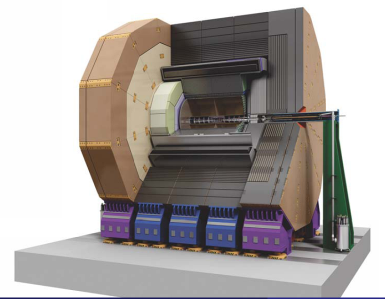


Detector Requirements same for ILC and CLIC

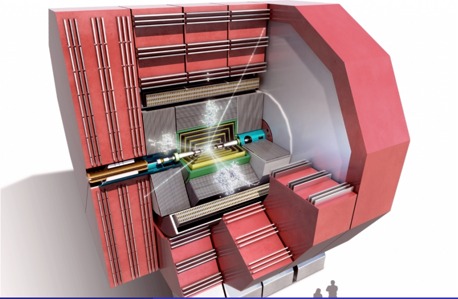
- Track momentum resolution: $\sigma_{1/p} < 5 \cdot 10^{-5}\ \mathrm{GeV}^{-1}$
- Impact parameter resolution: $\sigma_d < 5\mu m \oplus 10\mu m \frac{1\ \mathrm{GeV}}{p\ \sin^{3/2}\Theta}$
- Jet energy resolution: $\sigma_E/E = 3 - 4\%$ (for highest jet energies)
- Hermecity: $\Theta_{min} = 5$ mrad

Detailed detector concepts for ILC and CLIC:

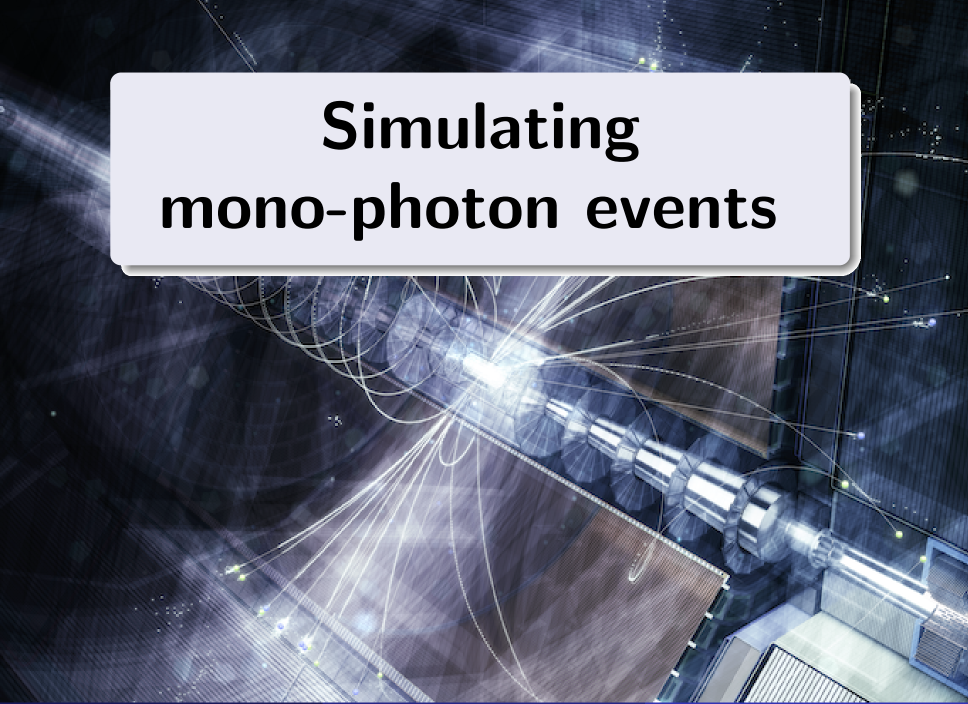
ILD



CLICdet



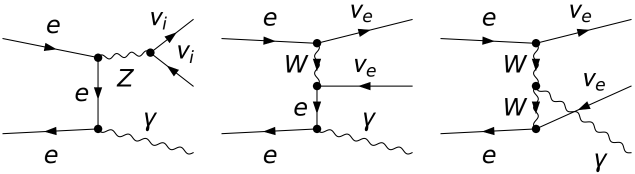
Simulating mono-photon events



Simulating mono-photon events in WHIZARD

For proper estimate of the mono-photon signature sensitivity consistent simulation of BSM processes and of the SM backgrounds is crucial.

"Irreducible" background comes from radiative neutrino pair-production



Detector acceptance & reconstruction efficiency

$\Rightarrow$ significant contribution from radiative Bhabha scattering

WHIZARD 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, WHIZARD ISR photons are not ordinary final state photons: they represent all photons radiated in the event from a given lepton line.

ISR structure function can not account for hard non-collinear photons
⇒ all "detectable" photons generated on Matrix Element level

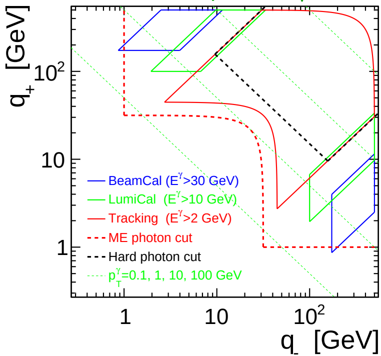
Dedicated procedure developed to avoid double-counting of ISR and ME
For details: J. Kalinowski et al., Eur. Phys. J. C 80 (2020) 634, arXiv:2004.14486

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.

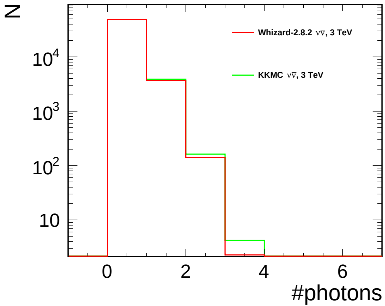
Detector acceptance $\sqrt{s} = 500\,\mathrm{GeV}$

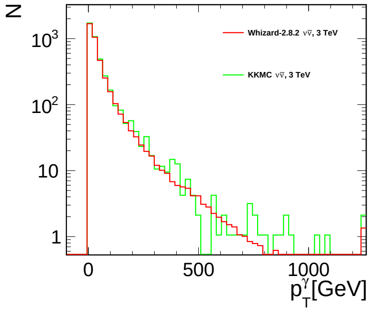


Validation of the procedure

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

3 TeV CLIC





$\Rightarrow$ 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

Simulating mono-photon events in WHIZARD

Simplified DM model

UFO model covering most popular scenarios of DM pair-production

⇒ Feynrules

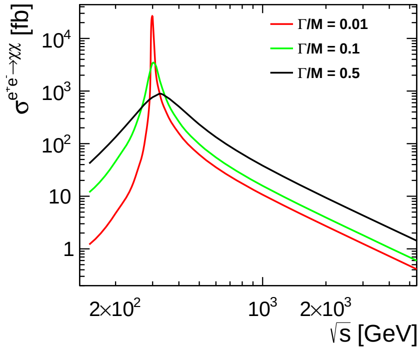
Possible mediators:

- scalar
- pseudo-scalar
- vector
- pseudo-vector
- V−A coupling
- V+A coupling

Possible DM candidates:

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

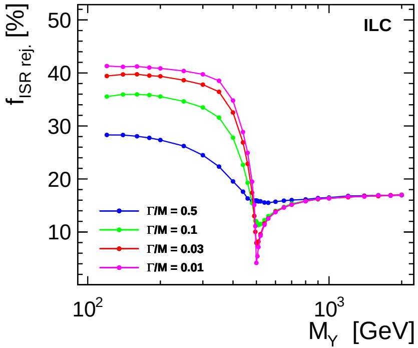
Cross section for $e^+e^- \rightarrow \chi\chi$ for $M_\chi = 50\ GeV$ and $M_Y = 300\ GeV$



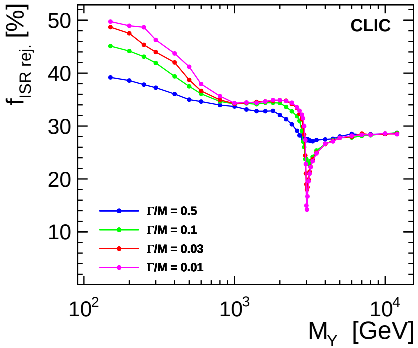
ISR rejection probability

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

ILC @ 500 GeV



CLIC @ 3 TeV



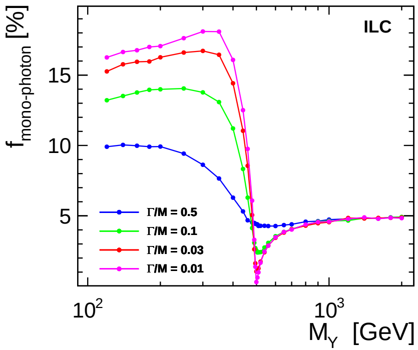
Tagging efficiency

based on DELPHES simulation

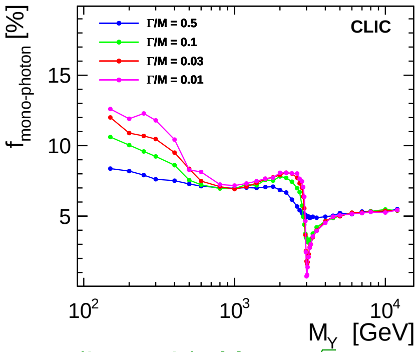
Mono-photons reconstructed only in a fraction of generated signal event

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

ILC @ 500 GeV

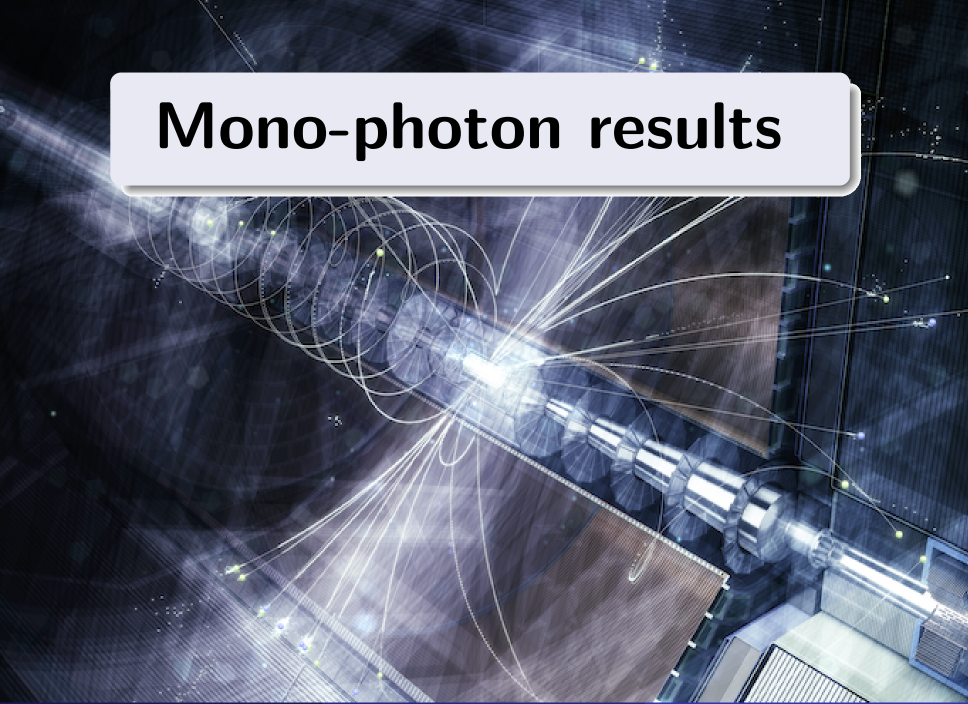


CLIC @ 3 TeV



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

Mono-photon results



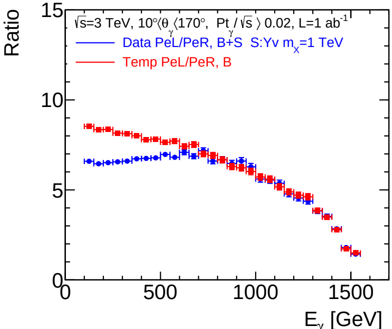
Heavy mediator approximation, generator level

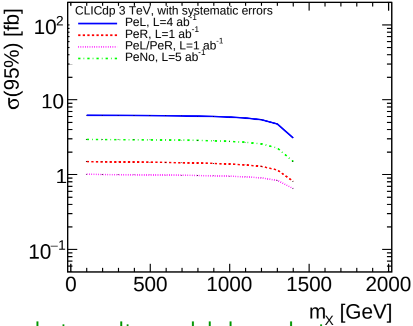
arXiv:2103.06006

Signature:

high energy, isolated photon no other “hard” activity in the detector

Highest sensitivity to DM production from the ratio of the photon energy distributions measured for the two electron beam polarisations





Ratio ⇒ cancelation of systematic uncertainties, but results model-dependent

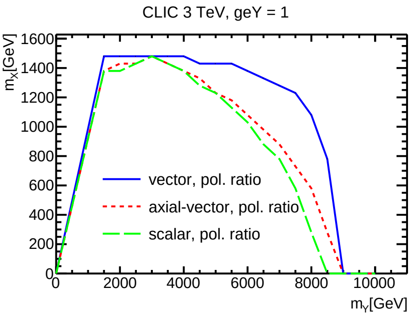
Heavy mediator approximation, generator level

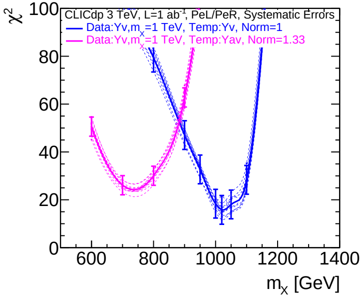
arXiv:2103.06006

Limits on the mono-photon cross section can be translated to the expected exclusion range in the DM-mediator mass space.

For a light WIMP mass the exclusion range extends up to 9 TeV

If significant excess of mono-photon events is observed,
WIMP mass in a TeV range can be extracted with a 1% accuracy.



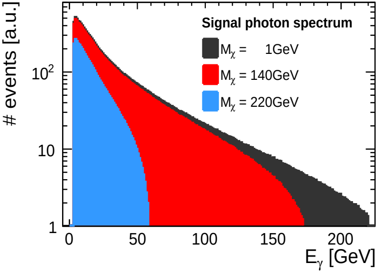


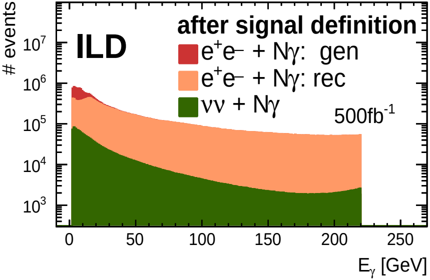
Heavy mediator (EFT limit), full simulation

arXiv:2001.03011

Signature:

- single photon in the central region (high tracking efficiency)





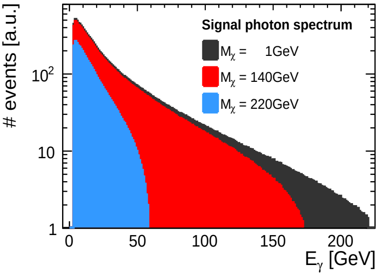
WIMP Dark Matter at the 500 GeV ILC

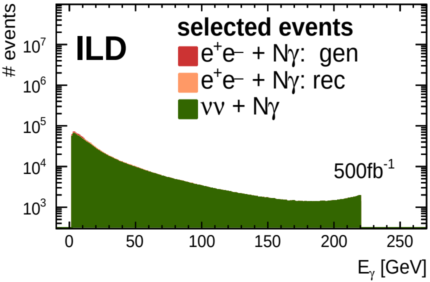
Heavy mediator (EFT limit), full simulation

arXiv:2001.03011

Signature:

- single photon in the central region (high tracking efficiency)
- no other activity in the detector
- veto in BeamCal (forward region)



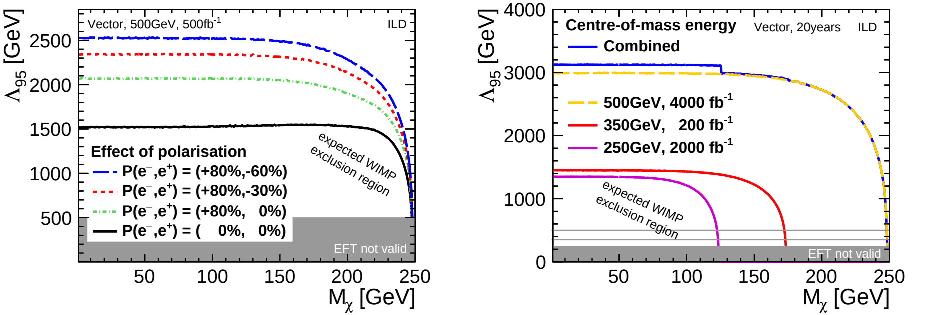


"Irreducible" background from radiative neutrino pair-production events $e^+e^- \to \nu\nu + N\gamma$ dominates after selection and bg suppression cuts

Heavy mediator (EFT limit), full simulation

arXiv:2001.03011

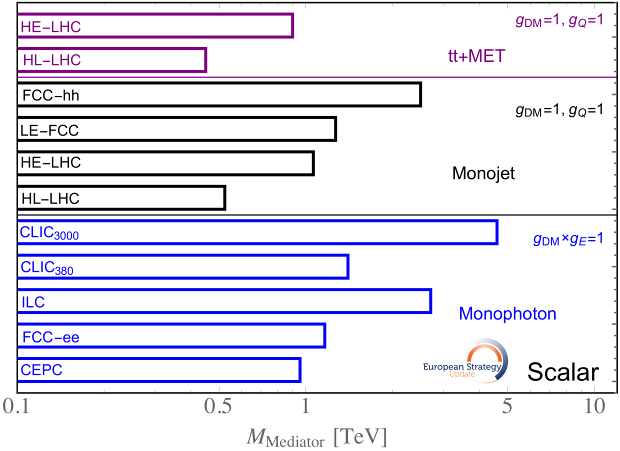
Different polarisation combinations help to reduce the systematics
$\Rightarrow$ significant improvement of mass scale limits



Sensitivity to the BSM mass scales up to $\Lambda \sim$3 TeV

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

Comparison of mass scale limits calculated in the EFT framework



e^+e^- mass reach comparable with that of FCC-hh !!!

New analysis approach

arXiv:2107.11194

DM production via light mediator exchange **still not excluded**
for scenarios with 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

Detector response simulated in the DELPHES framework (fast simulation).

WHIZARD level selection:

- 1, 2 or 3 ME 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)

DELPHES level selection:

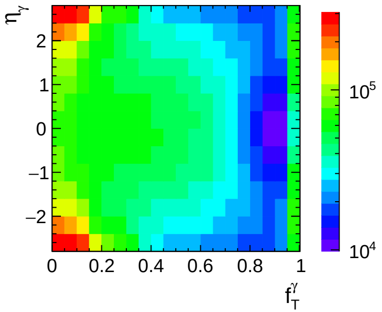
- single photon with
  $p_T^\gamma > 3\ GeV$ & $|\eta^\gamma| < 2.8$ (ILC)
  $p_T^\gamma > 10\ GeV$ & $|\eta^\gamma| < 2.6$ (CLIC)
- no other activity in the detector
  other reconstructed objects

Background vs Signal distributions

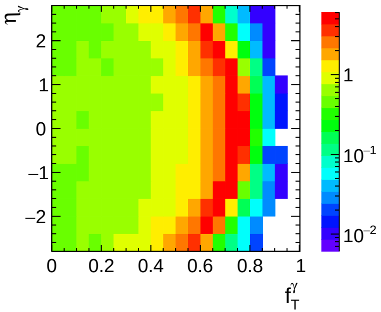
arXiv:2107.11194

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

Background



Signal



ILC 500 GeV (-80%/+30%) 1600 fb^{-1} $M_Y = 400$ GeV, $\Gamma/M = 0.03$

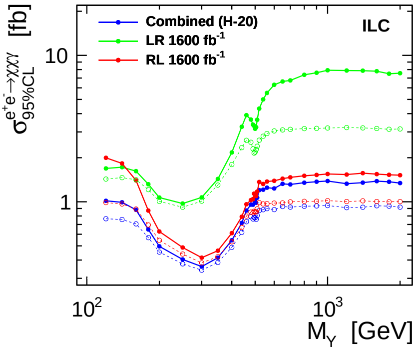
Signal normalised to unpolarised DM pair-production cross section of 1 fb

Light mediator exchange

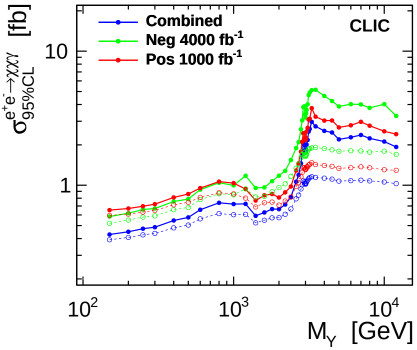
Cross section limits for radiative events (with tagged photon)

Vector Mediator $\Gamma/M = 0.03$ with and without systematics

ILC @ 500 GeV



CLIC @ 3 TeV

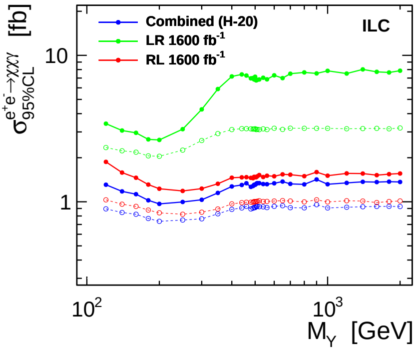


Systematic effects reduced for on-shell production of narrow mediator

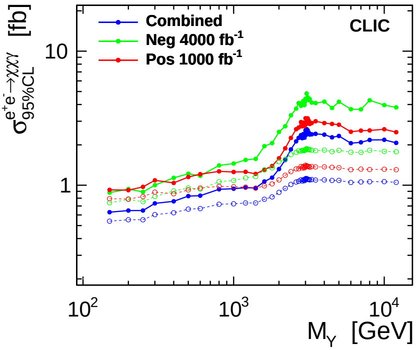
Cross section limits for radiative events (with tagged photon)

Vector Mediator $\Gamma/M = 0.5$ with and without systematics

ILC @ 500 GeV



CLIC @ 3 TeV



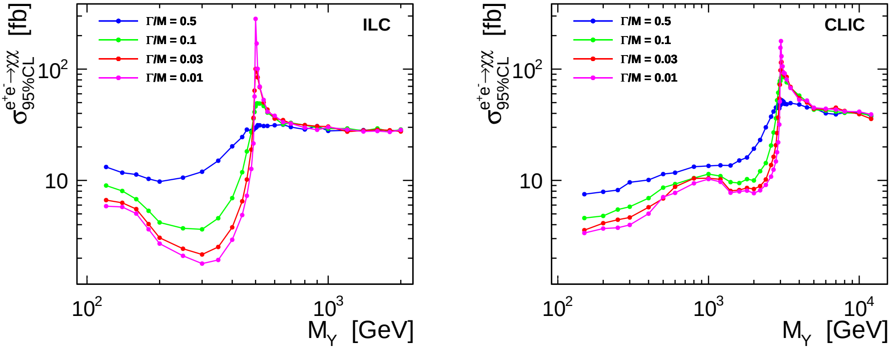
Systematic effects reduced for on-shell production of narrow mediator

Cross section limits for total DM production cross section

Corrected for probability of hard photon tagging!

Combined limits for Vector mediator

ILC @ 500 GeV CLIC @ 3 TeV



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

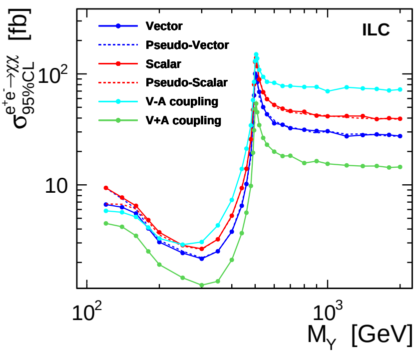
Light mediator exchange

Cross section limits for total DM production cross section

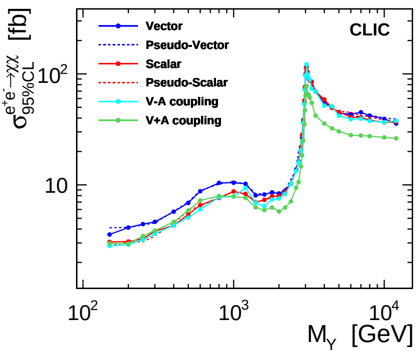
Corrected for probability of hard photon tagging!

Combined limits for mediators with $\Gamma/M = 0.03$

ILC @ 500 GeV



CLIC @ 3 TeV

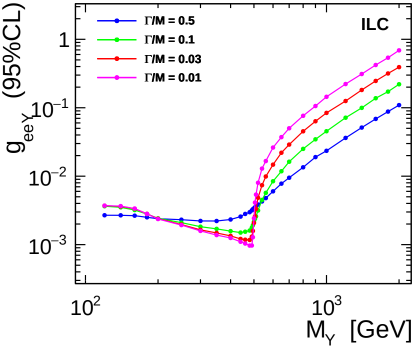


Radiation suppressed for narrow mediator with $M_Y \sim \sqrt{s} \Rightarrow$ weaker limits

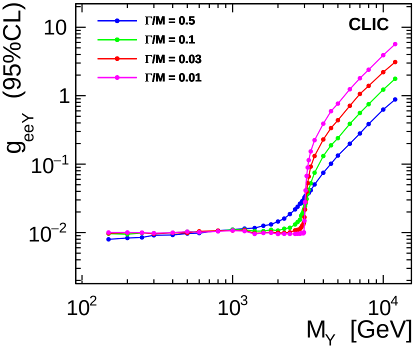
Coupling limits

Combined limits for Vector mediator

ILC @ 500 GeV



CLIC @ 3 TeV

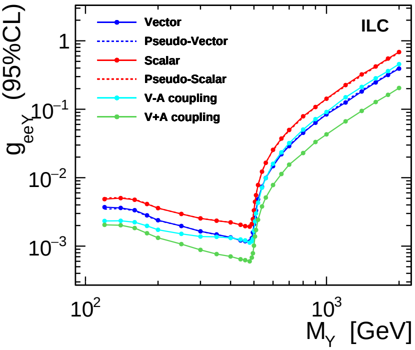


Almost uniform sensitivity to mediator coupling g_{eeY} up to kinematic limit.

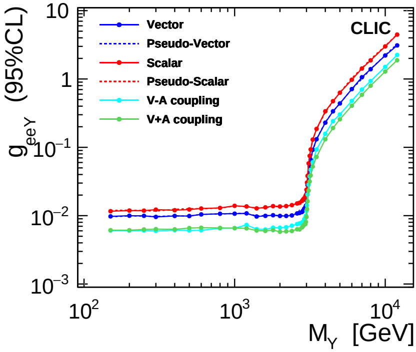
Coupling limits

Combined limits for mediators with $\Gamma/M = 0.03$

ILC @ 500 GeV



CLIC @ 3 TeV



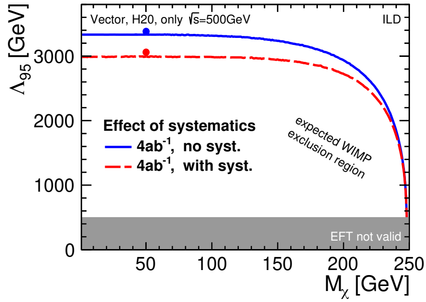
Almost uniform sensitivity to mediator coupling g_{eeY} up to kinematic limit.

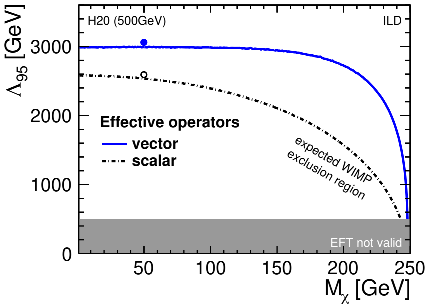
Comparison with ILD study

arXiv:2001.03011
arXiv:2107.11194

Effective mass scale limits: $$\Lambda^2 = \frac{M_Y^2}{|g_{eeY} g_{\chi\chi Y}|}$$

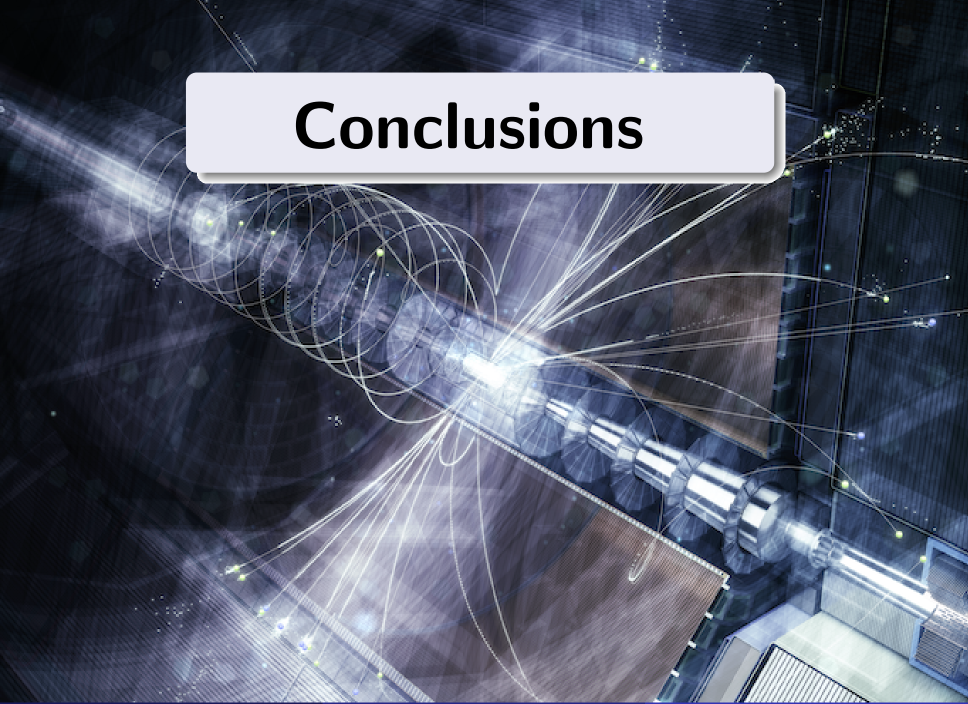
Limits from fast simulation (points) vs limits from full simulation (lines)





Very good agreement between full simulation and fast simulation results!
⇒ reliable extrapolation to low mediator mass domain...

Conclusions



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

Future e^+e^- colliders: many complementary options for DM searches.

Mono-photon signature: the most general way to look for DM production, EFT sensitivity extending to the $\mathcal{O}(10)$ TeV mass scales

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

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

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

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

Systematic uncertainties

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
- Uncertainty on beam polarisation of 0.02–0.08% (ILC)/0.2% (CLIC)
  correlated for runs with same beam polarisation at ILC

$\Rightarrow$ nuisance parameters in the model fit (11 for ILC, 7 for CLIC)