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

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Research supported by NATIONAL SCIENCE CENTRE POLAND

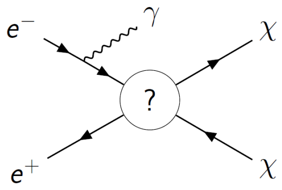
Snowmass 2021
EF10 DM@Colliders, topical meeting
October 27, 2021

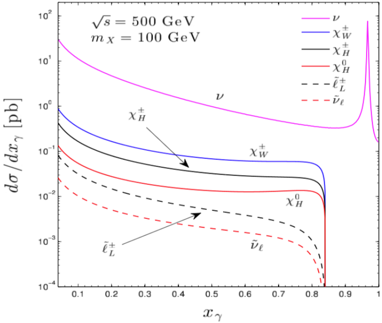
Motivation

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.



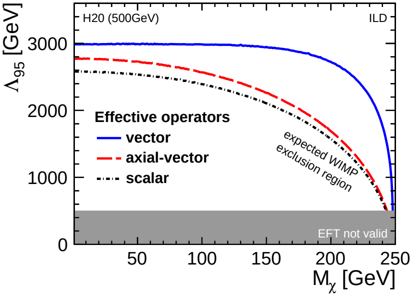


DM can be pair produced in the e^+e^- collisions via exchange of a new mediator particle, which couples to both electrons (SM) and DM states

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

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 couplings to SM, $\Gamma_{SM} \ll \Gamma_{tot}$

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

CLIC study: arXiv:2103.06006

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

Snowmass'2021 LoI

The proposal for this study was submitted in August 2020:

SNOWMASS21-EF10_EF9_Filip_Zarnecki-054.pdf

Final results have been just accepted for publication in EPJ C

arXiv:2107.11194

New approach to DM searches with mono-photon signature

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1. MOTIVATION

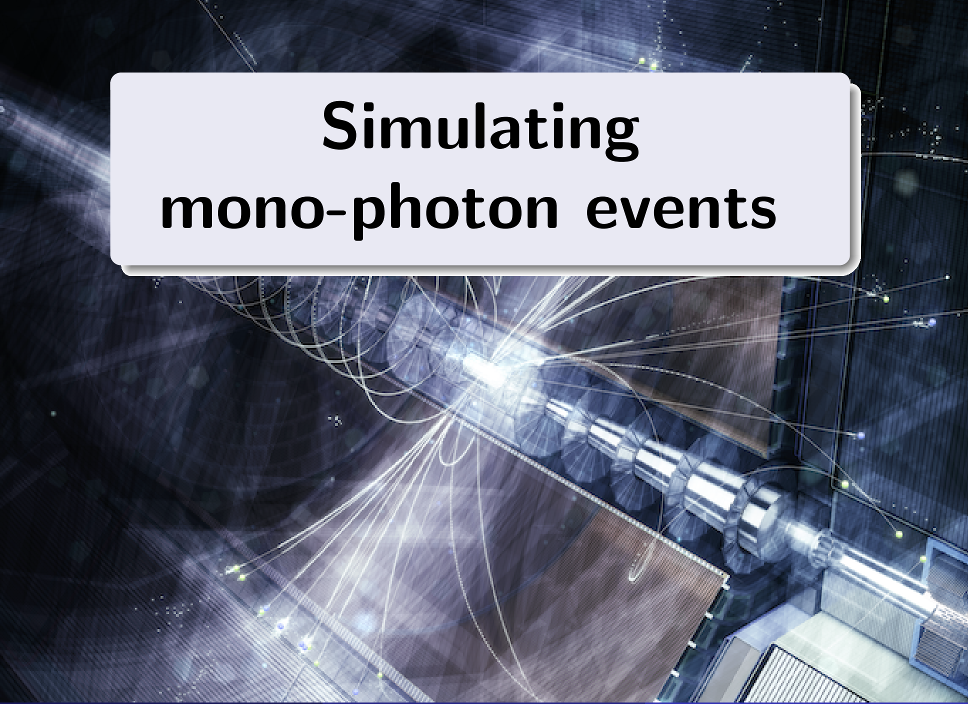
One of the important goals of the proposed future e^+e^- collider experiments is the search for dark matter particles using different experimental approaches. The most general one is based on the mono-photon signature, which is expected when production of the invisible final state is accompanied by a hard photon from initial state radiation. We proposed the procedure[1] which allows for consistent, reliable simulation of mono-photon events in WHIZARD,[2,3] for both BSM signal and SM background processes, based on merging the matrix element calculations with the lepton ISR structure function.

2. MERGING PROCEDURE

For precise kinematic description of photons entering the detector, we need to include hard photon emission directly in the process matrix element (ME) calculation. On the other hand, very soft and collinear photons should still be simulated with the parametric approach, taking into account proper summation of higher order corrections. A dedicated procedure for merging between the two regimes was proposed, exploiting variables[1]

Outline

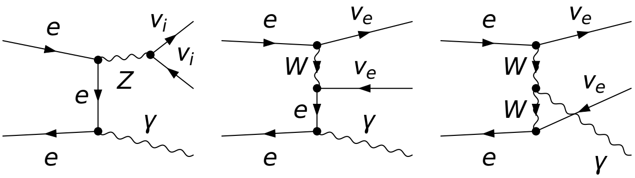
Simulating mono-photon events



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
⇒ 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.

Simulating mono-photon events in WHIZARD

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

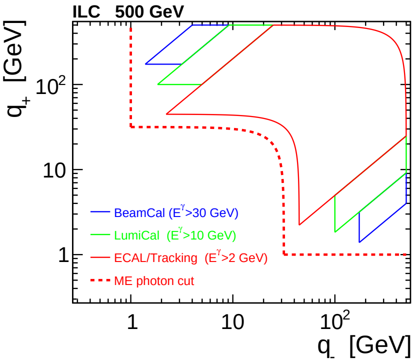
Dedicated procedure developed to avoid double-counting of ISR and ME
For details: J. Kalinowski et al., Eur. Phys. J. C 80 (2020) 634, arXiv:2004.14486

Two variables, calculated separately for each emitted photon:

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

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

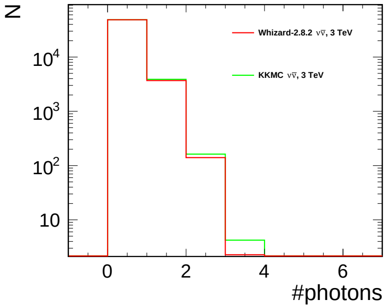
are used to separate "soft ISR" emission region from the region described by ME calculations.

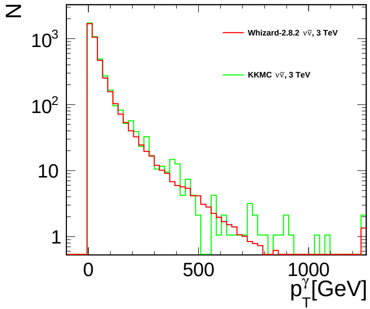


Validation of the procedure

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

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

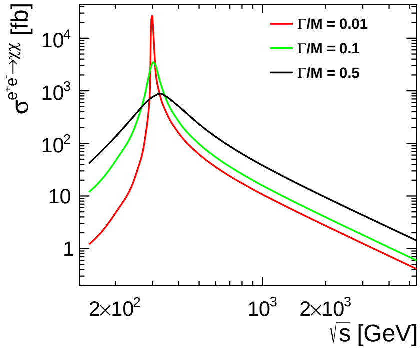
Possible mediators:

- 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

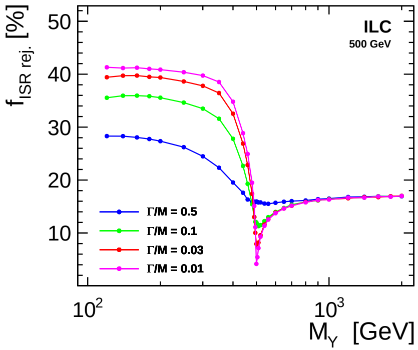
Cross section for $e^+e^- \rightarrow \chi\chi$ for $M_\chi = 50\ GeV$ and $M_Y = 300\ GeV$



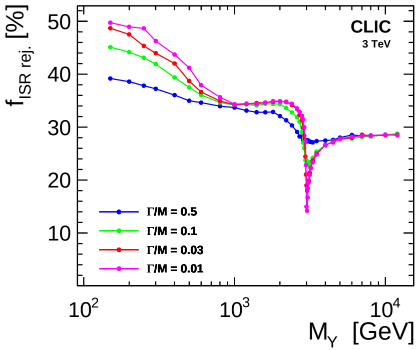
ISR rejection probability

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

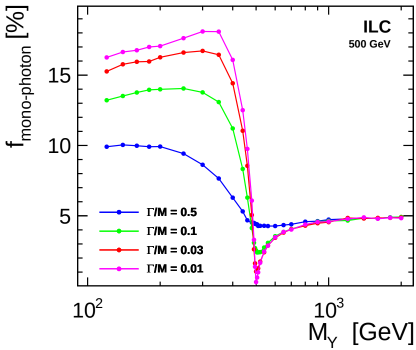
based on DELPHES simulation

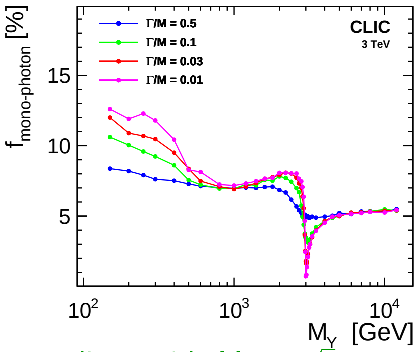
Mono-photons reconstructed only in a fraction of generated signal event

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

ILC @ 500 GeV

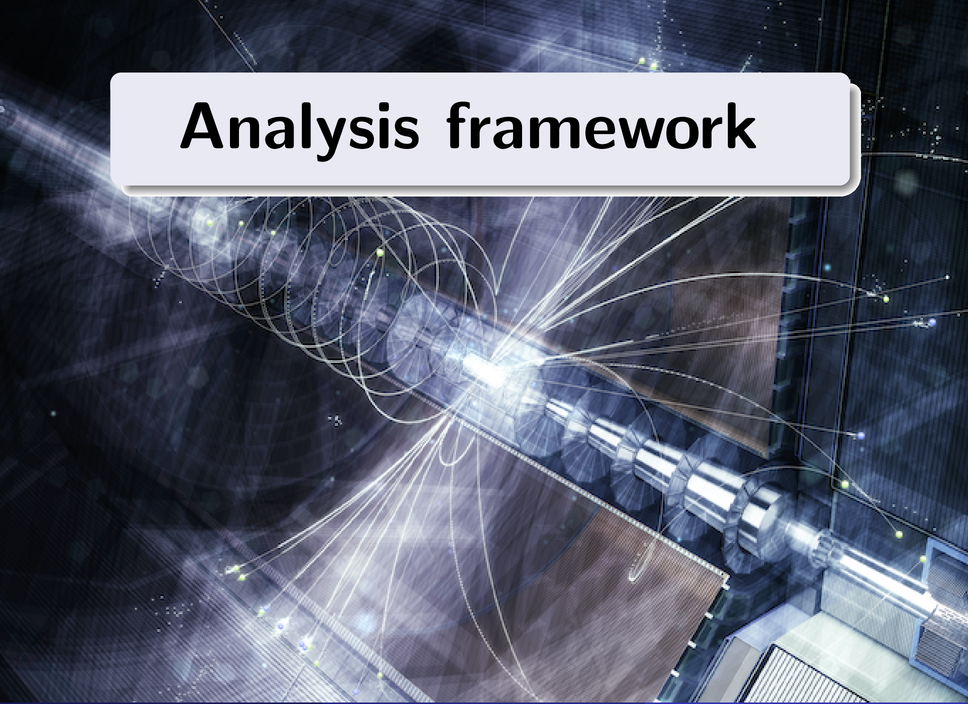
CLIC @ 3 TeV





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

Analysis framework



Analysis framework

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)

Delphes framework used for detector simulation and event reconstruction.

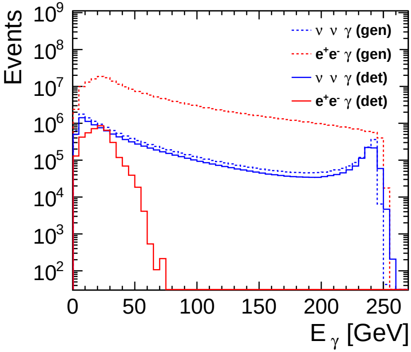
Require:

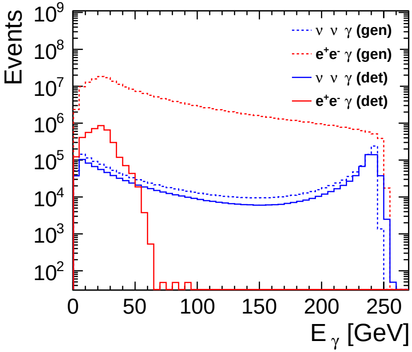
- single photon with
  $p_T^{\gamma} > 3\, GeV \;\&\; |\eta^{\gamma}| < 2.8$ (ILC)
  $p_T^{\gamma} > 10\, GeV \;\&\; |\eta^{\gamma}| < 2.6$ (CLIC)

- no other activity in the detector
  other reconstructed objects
  - no electrons
  - no LumiCal photons
  - no BeamCal photons
  - no jets

Background distributions

Two SM backgrounds considered: with up to 3 ME photons
Bhabha scattering and (radiative) neutrino pair production





ILC 500 GeV
(–80%/+30%) 1600 fb^{-1}

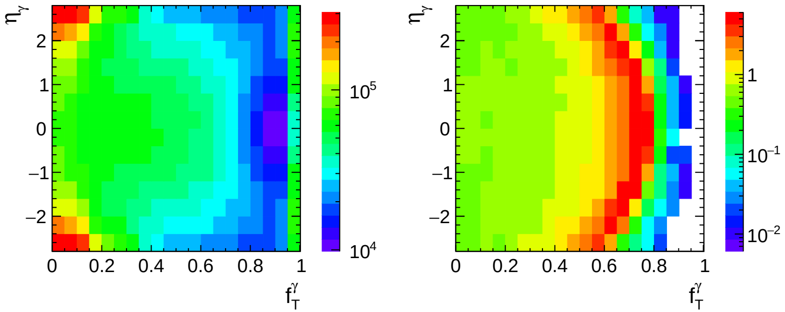
(+80%/–30%) 1600 fb^{-1}

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

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

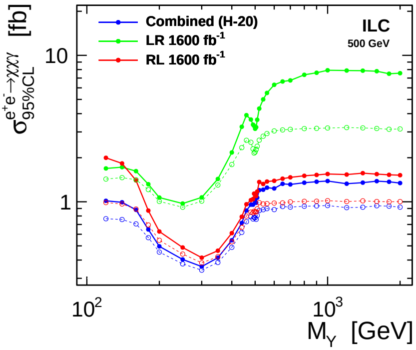
⇒ nuisance parameters in the model fit (11 for ILC, 7 for CLIC)

Results

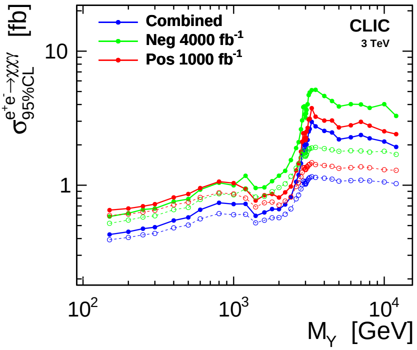
Cross section limits for radiative events (with tagged photon)

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

ILC @ 500 GeV



CLIC @ 3 TeV



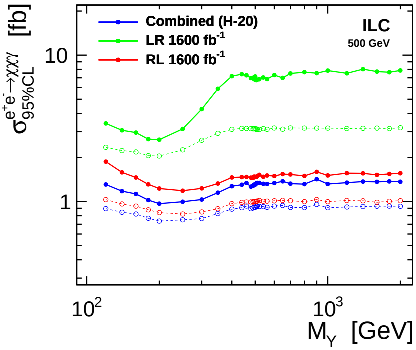
Systematic effects reduced for on-shell production of narrow mediator

Light mediator exchange

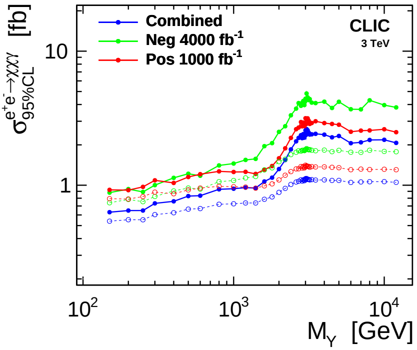
Cross section limits for radiative events (with tagged photon)

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

ILC @ 500 GeV



CLIC @ 3 TeV



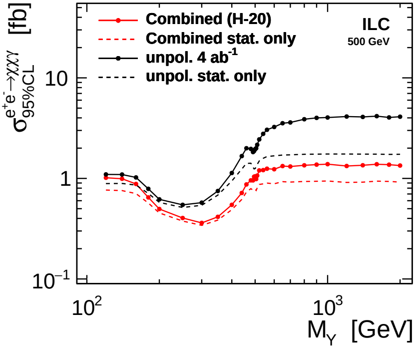
Systematic effects reduced for on-shell production of narrow mediator

Light mediator exchange

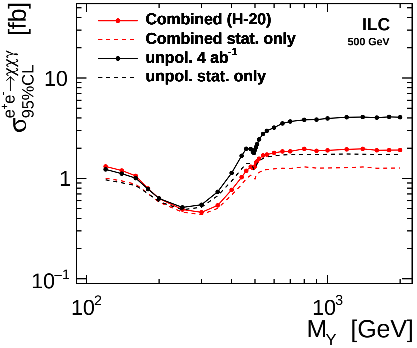
Cross section limits for radiative events (with tagged photon)

Impact of beam polarisation assuming 4 ab^{-1} for ILC @ 500 GeV

Vector mediator



Scalar mediator



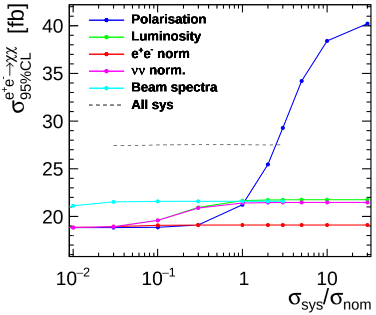
Combining four data sets taken with different beam polarisation settings significantly reduces impact of systematic uncertainties...

Impact of systematic uncertainties

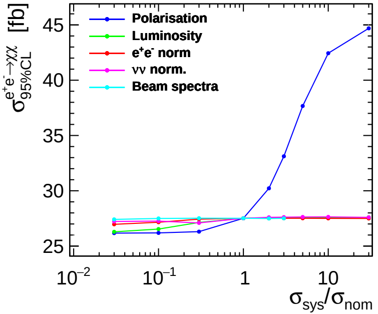
How important are the external constraints on the systematic effects?
Eg. precision of the lumionosity measurement or theoretical calculations...

Total cross section limits for Vector mediator with $M_Y = 2$ TeV, $\Gamma/M = 0.03$

Single uncertainty varied



All systematics (one varied)



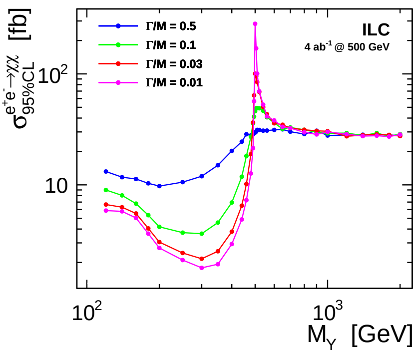
Most of the systemactic effects are constrained by the data itself!!!

Light mediator exchange

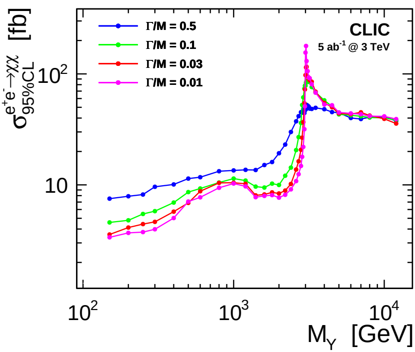
Cross section limits for total DM production cross section
Corrected for probability of hard photon tagging!

Combined limits for Vector mediator

ILC @ 500 GeV



CLIC @ 3 TeV



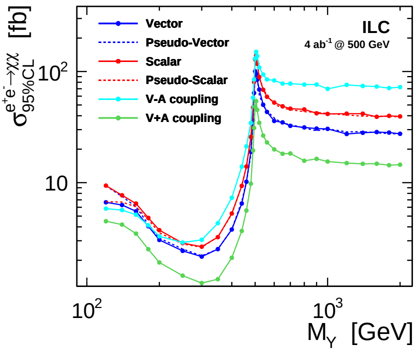
Radiation suppressed for narrow mediator with $M_Y \sim \sqrt{s} \Rightarrow$ weaker limits

Cross section limits for total DM production cross section

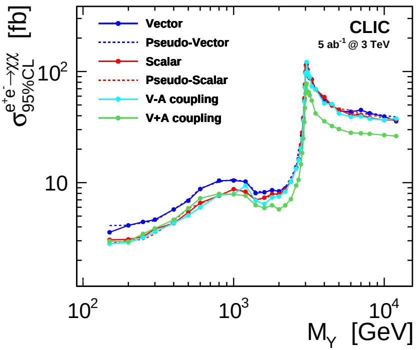
Corrected for probability of hard photon tagging!

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

ILC @ 500 GeV



CLIC @ 3 TeV



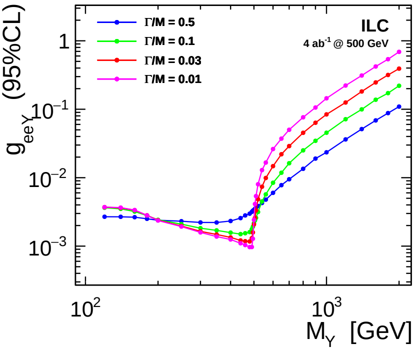
Radiation suppressed for narrow mediator with $M_Y \sim \sqrt{s} \Rightarrow$ weaker limits

Light mediator exchange

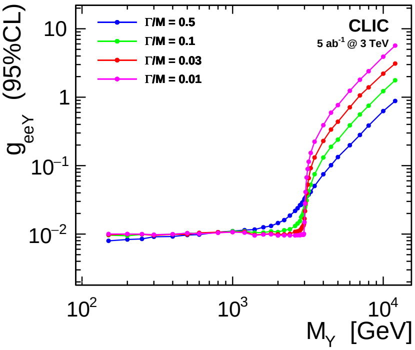
Coupling limits

Combined limits for Vector mediator

ILC @ 500 GeV



CLIC @ 3 TeV

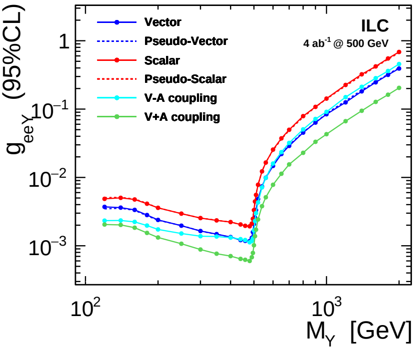


Almost uniform sensitivity to mediator coupling g_{eeY} up to kinematic limit.

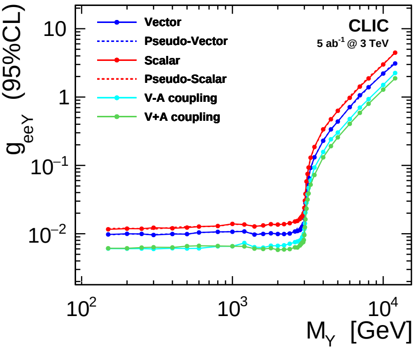
Coupling limits

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

ILC @ 500 GeV



CLIC @ 3 TeV

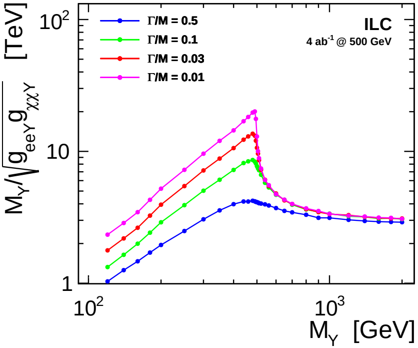


Almost uniform sensitivity to mediator coupling g_{eeY} up to kinematic limit.

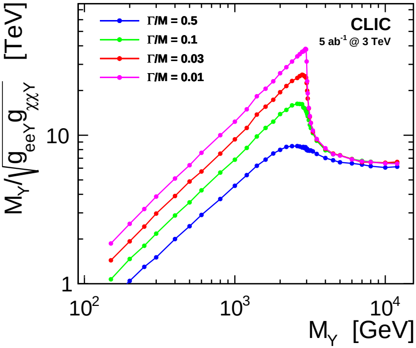
Effective mass scale limits
$$\Lambda^2 = \frac{M_Y^2}{|g_{eeY}\, g_{\chi\chi Y}|}$$

Combined limits for Vector mediator

ILC @ 500 GeV



CLIC @ 3 TeV



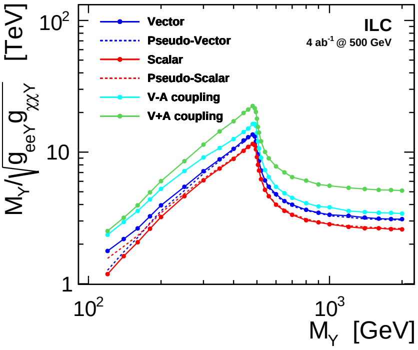
EFT approach valid only for $\sqrt{s} \gtrsim 3\,M_Y$!...

Light mediator exchange

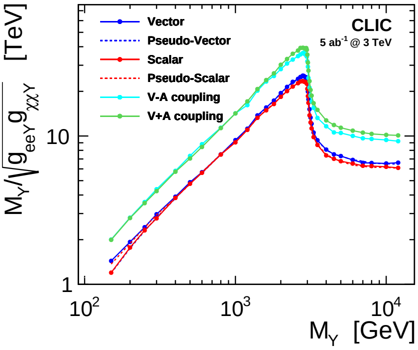
Effective mass scale limits $\Lambda^2 = \frac{M_Y^2}{|g_{eeY}\, g_{\chi\chi Y}|}$

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

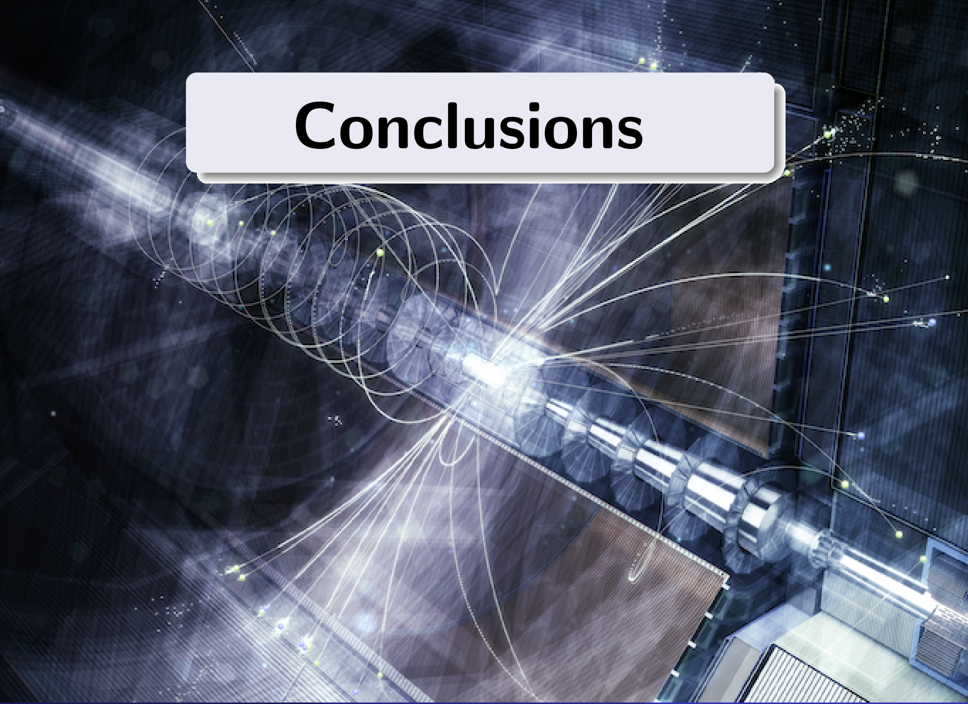
ILC @ 500 GeV



CLIC @ 3 TeV



EFT approach valid only for $\sqrt{s} \gtrsim 3\, M_Y$!...



Conclusions

Conclusions

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

arXiv:2107.11194, in print

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

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

Thank you!

Running scenarios

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

ILC

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

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

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

arXiv:1903.01629

CLIC

Total of $5000\,\text{fb}^{-1}$ assumed at $3\,\text{TeV}$

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

assuming polarisation of $\pm80\%$ for electrons

arXiv:1812.06018

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:

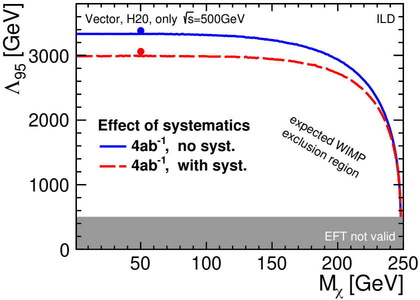
	particle	mass	spin	charge	self-conjugate	type
DM	X_R	m_{X_R}	0	0	yes	real scalar
	X_C	m_{X_C}	0	0	no	complex scalar
	X_M	m_{X_M}	$\frac{1}{2}$	0	yes	Majorana fermion
	X_D	m_{X_D}	$\frac{1}{2}$	0	no	Dirac fermion
	X_V	m_{X_V}	1	0	yes	real vector
mediator	Y_R	m_{Y_R}	0	0	yes	real scalar
	Y_V	m_{Y_C}	1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

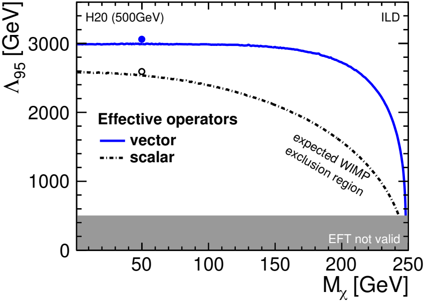
Comparison with ILD study

arXiv:2001.03011

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!
$\Rightarrow$ reliable extrapolation to low mediator mass domain...