Light mediator searches with mono-photon signature

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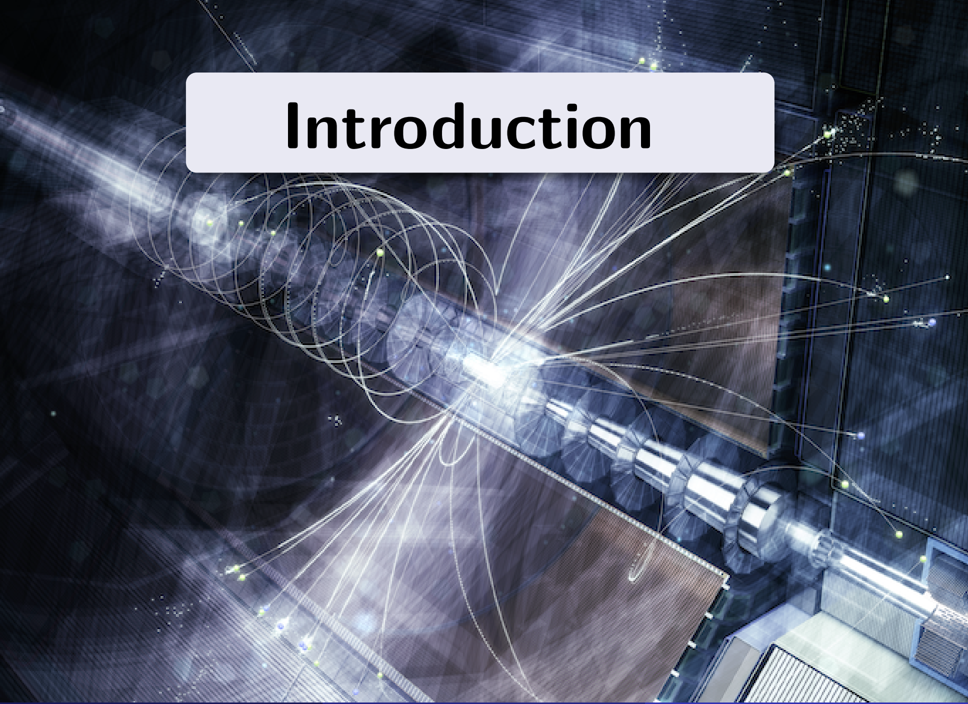
WG1-SRCH parallel session, October 6, 2022

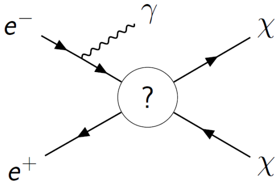
Outline

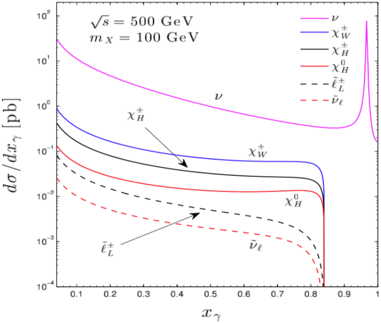
Introduction



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...

Introduction

Mono-photon signature

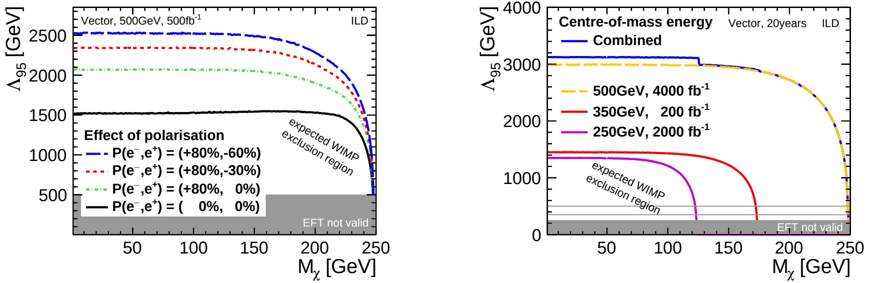
Most studies assumed heavy mediator and coupling $\mathcal{O}(1)$ (EFT limit)

Only DM particle assumed to be light...

Example: results from full simulation study for ILD @ ILC arXiv:2001.03011

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

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



Different polarisation combinations help to reduce the systematics

⇒ significant improvement of mass scale limits

Light mediator searches

DM production via light mediator exchange still not excluded
for scenarios with very small mediator couplings to SM, $\Gamma_{SM} \ll \Gamma_{tot}$

Light mediators still allowed for couplings $\mathcal{O}(10^{-2})$ and below

Dedicated simulation procedure for WHIZARD, with all "detectable" photons generated on Matrix Element level, matched with soft ISR.
⇒ J. Kalinowski et al., Eur. Phys. J. C 80 (2020) 634, arXiv:2004.14486

Sensitivity to processes with light mediator exchange
studied for 500 GeV ILC and 3 TeV CLIC.
⇒ J. Kalinowski et al., Eur. Phys. J. C 81, 955 (2021), arXiv:2107.11194

Presented in this contribution: new results for 250 GeV ILC

H-20 running scenario for the ILC
is assumed for the results presented in this talk:

ILC @ 250 GeV
Total of $2000\,\mathrm{fb}^{-1}$:

- $2\times 900\,\mathrm{fb}^{-1}$ for LR and RL beam polarisation combinations
- $2\times 100\,\mathrm{fb}^{-1}$ for RR and LL beam polarisation combinations

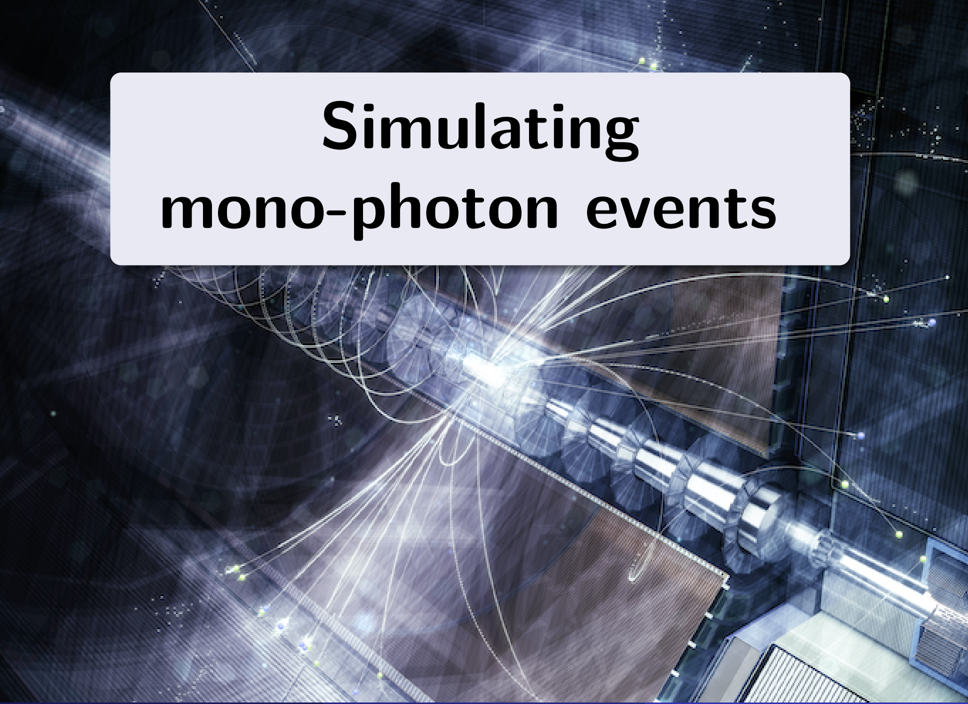
ILC @ 500 GeV included for comparison
Total of $4000\,\mathrm{fb}^{-1}$:

- $2\times 1600\,\mathrm{fb}^{-1}$ for LR and RL beam polarisation combinations
- $2\times 400\,\mathrm{fb}^{-1}$ for RR and LL beam polarisation combinations

assuming polarisation of $\pm 80\%$ for electrons and $\pm 30\%$ for positrons

arXiv:1903.01629

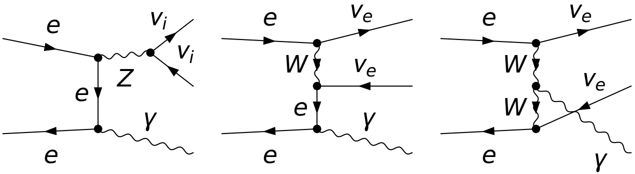
Simulating mono-photon events



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.

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

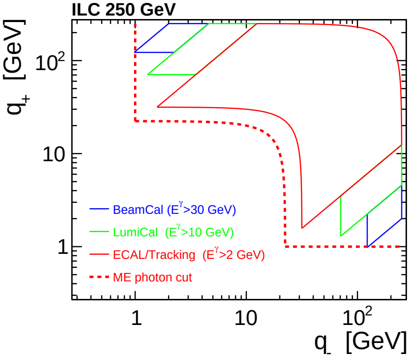
Dedicated procedure developed to avoid double-counting of ISR and ME
For details: J. Kalinowski et al., Eur. Phys. J. C 80 (2020) 634, arXiv:2004.14486

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.



Simplified DM model

UFO model covering most popular scenarios of DM pair-production

⇒ FeynRules wiki

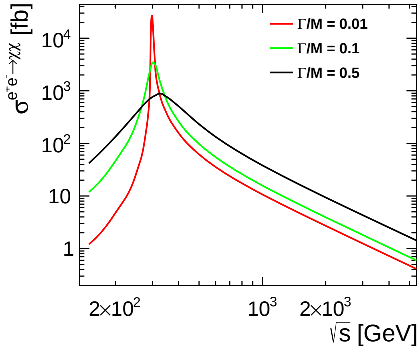
Possible mediators:

- 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 $M_Y = 300\ GeV$



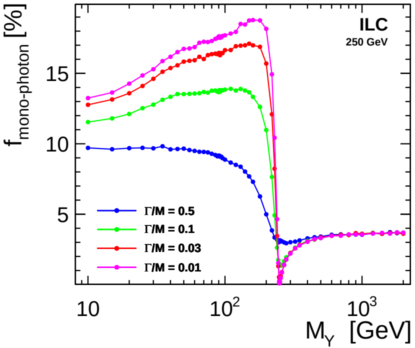
Simulating mono-photon events in WHIZARD

Tagging efficiency based on DELPHES simulation

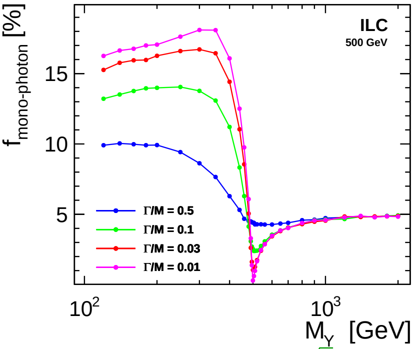
Mono-photons reconstructed only in a fraction of generated signal event

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

ILC @ 250 GeV ($M_\chi = 1$ GeV)

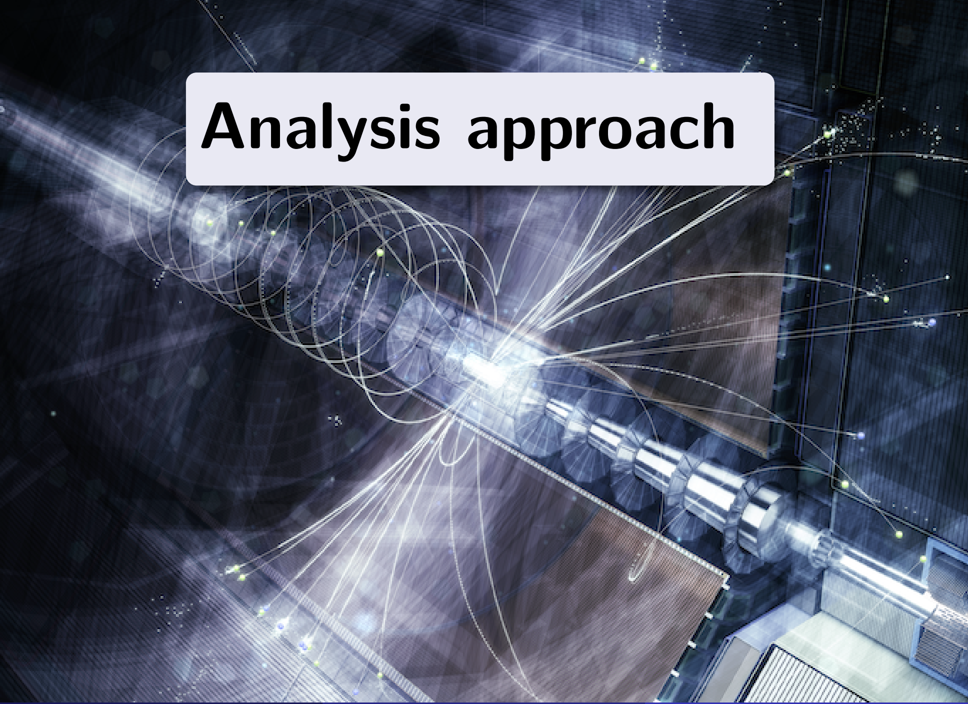


ILC @ 500 GeV ($M_\chi = 50$ GeV)



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

Analysis approach



Analysis approach

Event simulation

as in Eur. Phys. J. C 81 (2021) 955 [arXiv:2107.11194]

Light mediator exchange for scenarios with very small mediator couplings to SM, $\Gamma_{SM} \ll \Gamma_{tot}$ ⇒ only invisible mediator decays considered here

"Experimental-like" approach
⇒ focus on cross section limits as a function of mediator mass and width
⇒ reduced dependence on the dark sector details

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

WHIZARD level selection:

- 1, 2 or 3 ME photons
- at least one ME photon with

$$p_T^\gamma > 2\ GeV$$

$$5^\circ < \theta^\gamma < 175^\circ$$

DELPHES level selection:

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

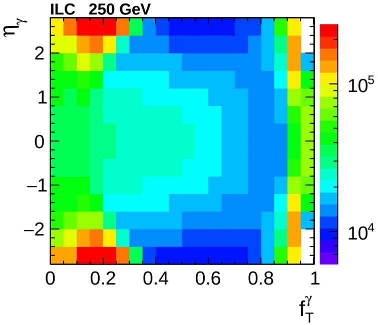
Analysis approach

Background vs Signal distributions

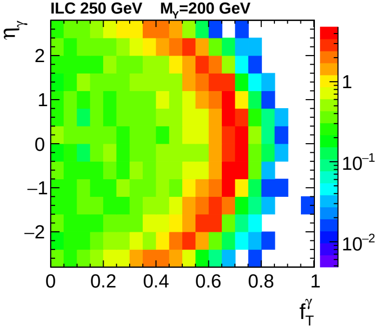
arXiv:2107.11194

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

Background



Signal



ILC 250 GeV (-80%/+30%) 900 fb^{-1}

$M_Y = 200$ 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% correlated for runs with same beam polarisation

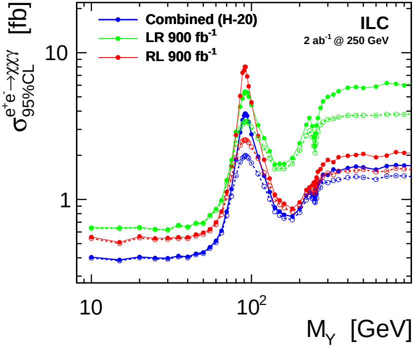
⇒ 11 nuisance parameters in the model fit

Analysis approach

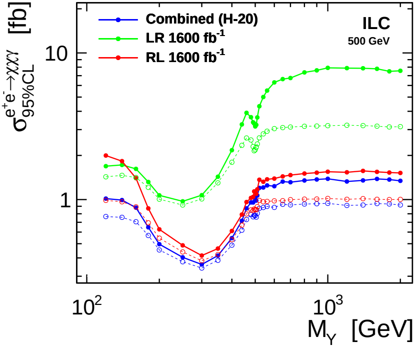
Cross section limits for radiative events (with tagged photon)

Vector Mediator $\Gamma/M = 0.03$ with (•) and without (◦) systematics

ILC @ 250 GeV



ILC @ 500 GeV



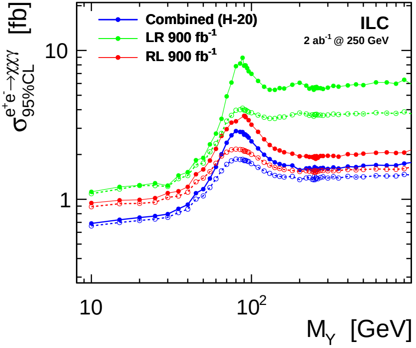
As expected, systematic effects largest for $M_Y \sim M_Z$

Analysis approach

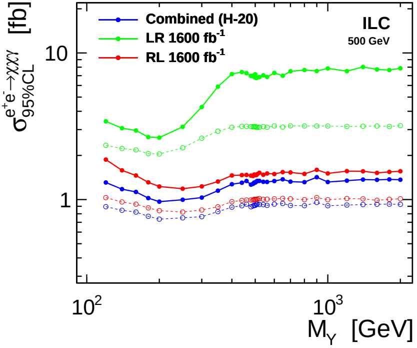
Cross section limits for radiative events (with tagged photon)

Vector Mediator $\Gamma/M = 0.5$ with (•) and without (◦) systematics

ILC @ 250 GeV



ILC @ 500 GeV



As expected, systematic effects largest for $M_Y \sim M_Z$

Results

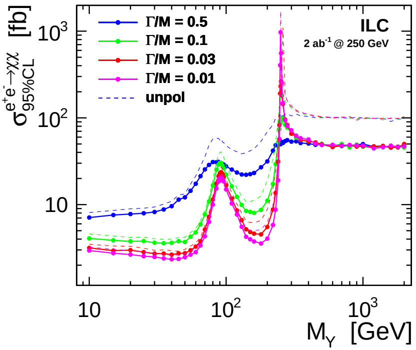
Results

Cross section limits for total DM production cross section

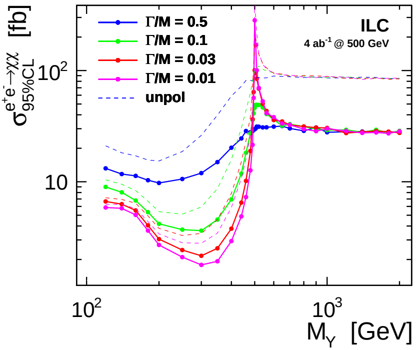
Corrected for probability of hard photon tagging!

Combined limits for Vector mediator

ILC @ 250 GeV



ILC @ 500 GeV



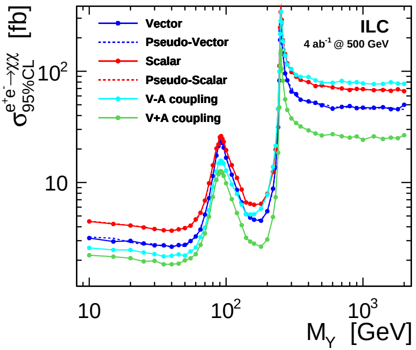
Use of beam polarisation significantly improves sensitivity

Cross section limits for total DM production cross section

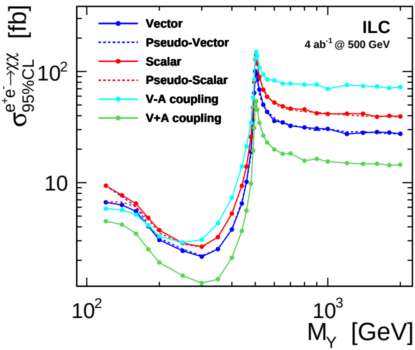
Corrected for probability of hard photon tagging!

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

ILC @ 250 GeV



ILC @ 500 GeV

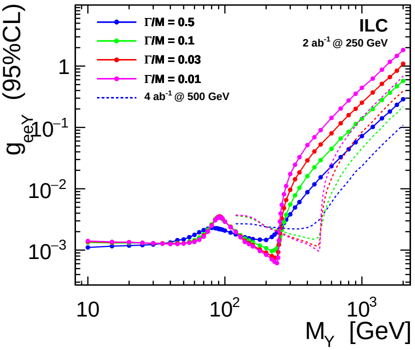


Radiation suppressed for narrow mediator with $M_Y \sim \sqrt{s} \Rightarrow$ weaker limits

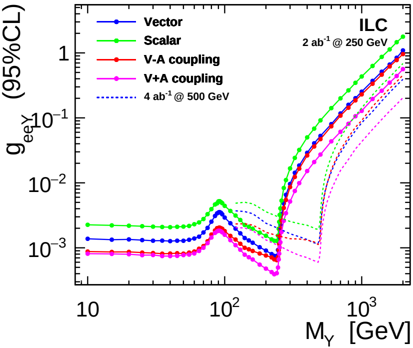
Coupling limits for mediator coupling to SM fermions
$\mathcal{O}(1)$ mediator coupling to DM, fixed by mediator width

Combined limits for ILC @ 250 GeV (compared to ILC @ 500 GeV)

Vector mediator



Mediators with $\Gamma/M = 0.03$

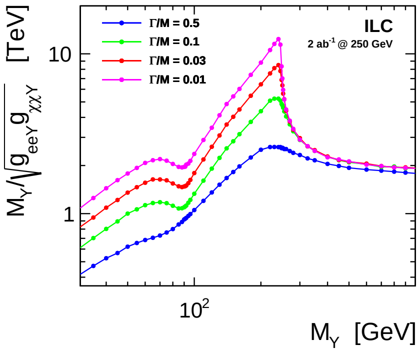


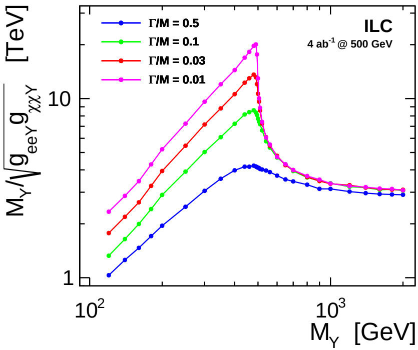
Almost uniform sensitivity to mediator coupling g_{eeY} up to kinematic limit

Applicability of EFT approach

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

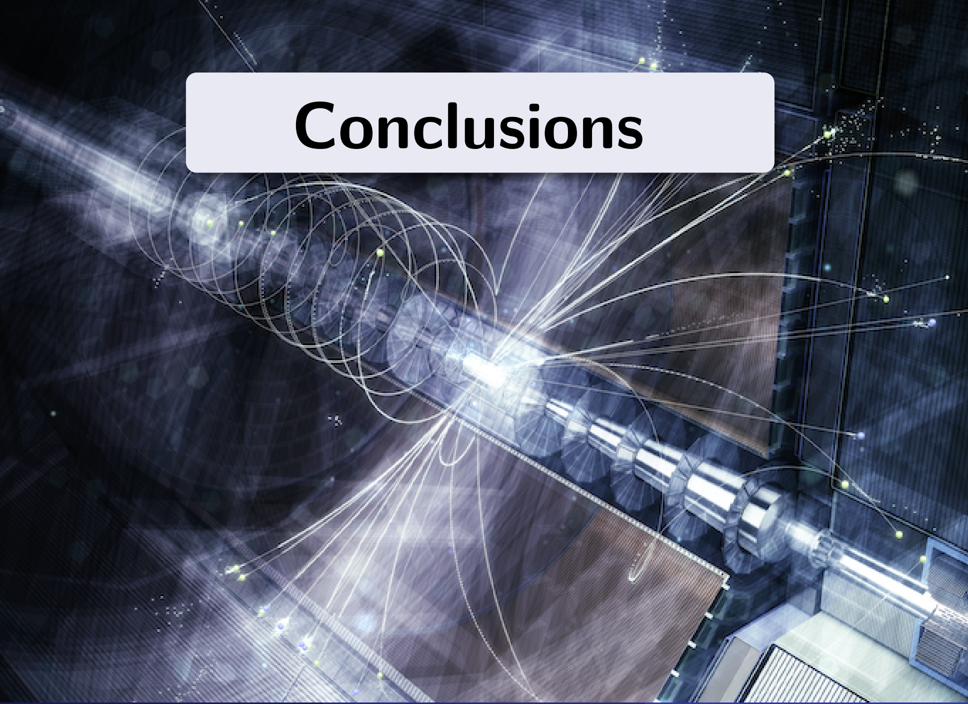
Combined limits for vector mediator





$\Rightarrow$ EFT approximation valid only above $M_Y \sim 3 - 4\, \sqrt{s}$!!!

Conclusions



Conclusions

Light mediator searches with mono-photon signature

e^+e^- Higgs/EW/Top factories - complementary option for BSM searches

Mono-photon signature: most general way to look for DM production

EFT sensitivity extending to the $\mathcal{O}(10)$ TeV mass scales

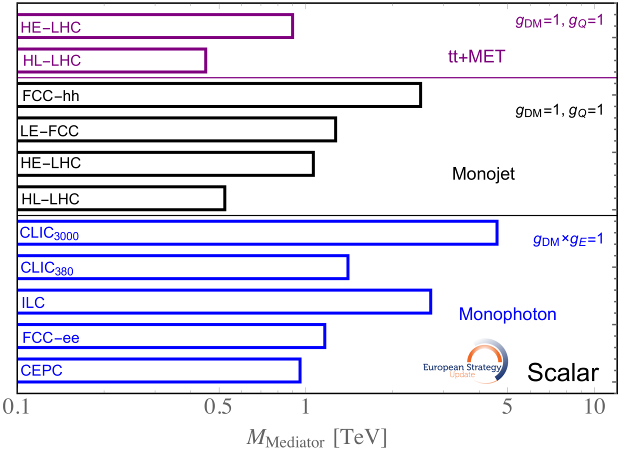
New framework developed for scenarios with light mediator exchange
previous study extended to 250 GeV ILC and mediator masses below M_Z:

- $\mathcal{O}(2-5\,\text{fb})$ limits on the DM pair-production $e^+e^- \to \chi\chi(\gamma)$
  except for the resonance region $M_Y \sim M_Z$ and $M_Y \sim \sqrt{s}$
- $\mathcal{O}(10^{-3})$ limits on the mediator coupling to electrons
  up to the kinematic limit $M_Y \leq \sqrt{s}$
- expected limits for 250 GeV stronger than for 500 GeV
  for on-shell light mediator production
- significant impact of beam polarisation
  mediator coupling structure determination possible

Thank you!

Dark Matter searches

Comparison of extracted mediator mass limits (EFT based)



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

Simplified DM model

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

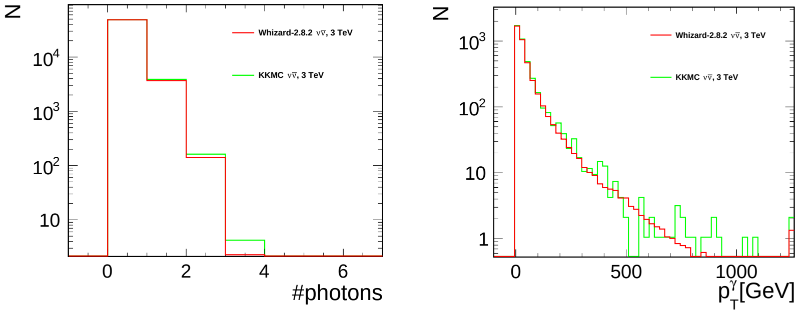
Each simplified scenario is characterized by one dark matter candidate and one mediator from the set listed below:

	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

Validation of the simulation procedure

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

3 TeV CLIC



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

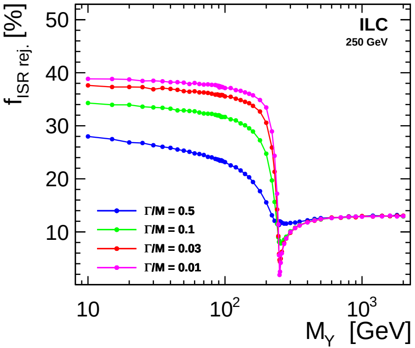
For more details:

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

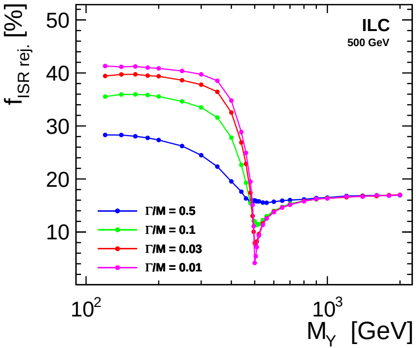
ISR rejection probability

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

ILC @ 250 GeV



ILC @ 500 GeV

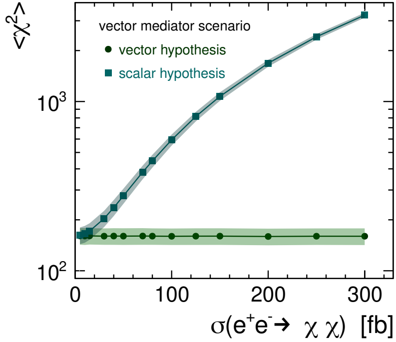


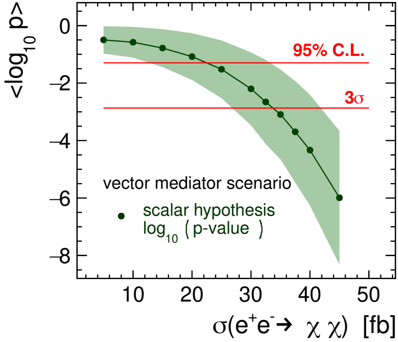
Mediator studies

If light mediator scenario discovered at future e^+e^- collider
(possible already for DM production cross sections of $\mathcal{O}(10\text{ fb})$)
its coupling structure can be easily identified using beam polarisation

Vector mediator at 500 GeV ILC M=300 GeV, Γ=30 GeV

Signal scenario fit to mono-photon energy spectra for four polarisation settings



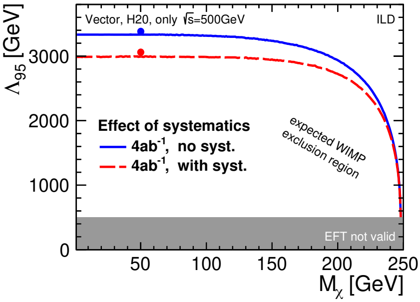


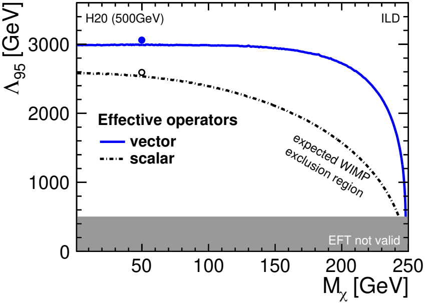
Comparison with full simulation study

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...