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

Jan Kalinowski[a], Wojciech Kotlarski[b], Krzysztof Mekala[a],
Aleksander Filip Żarnecki[a], Kamil Zembaczynski[a]

FACULTY OF PHYSICS UNIVERSITY OF WARSAW

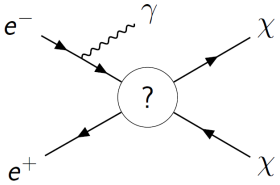
[a] Faculty of Physics, University of Warsaw
[b] National Centre for Nuclear Research, Warsaw

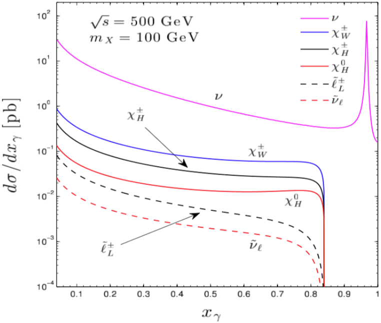
Research supported by NATIONAL SCIENCE CENTRE POLAND

mini-workshop on BSM-related aspects at ILC
February 28, 2022

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

As this workshop is devoted to BSM at ILC,
only ILC results on light mediator exchange are included
see arXiv:2107.11194 for corresponding results for CLIC at 3 TeV

Simplified DM model

UFO model covering most popular scenarios of DM pair-production

$\Rightarrow$ Feynrules

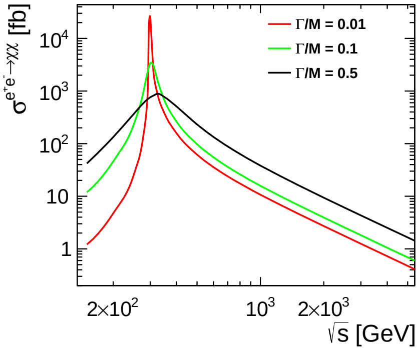
Possible mediators:

- 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

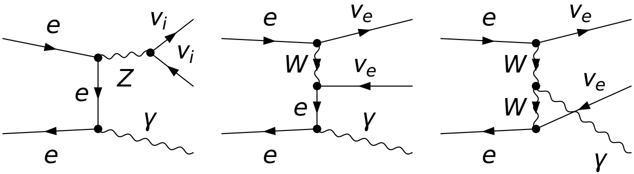
Cross section for $e^+e^- \to \chi\chi$ for $M_\chi = 50\ GeV$ and $M_Y = 300\ GeV$



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

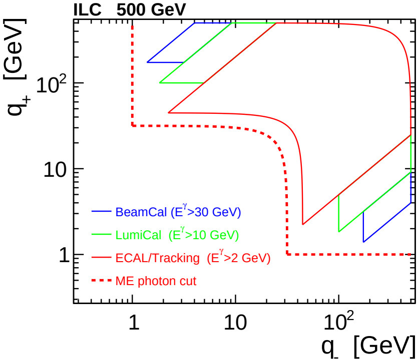
Two variables, calculated separately for each emitted photon:

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

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

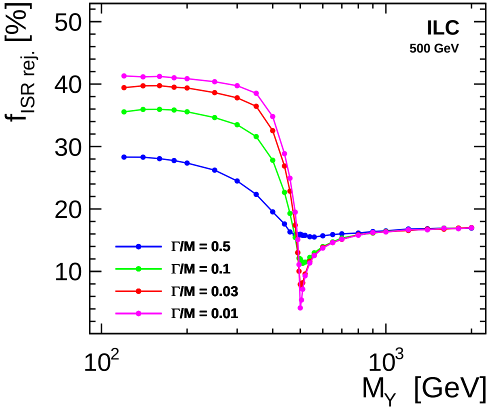
are used to separate "soft ISR" emission region from the region described by ME calculations.

Expected detector acceptance



ISR rejection probability for signal events

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

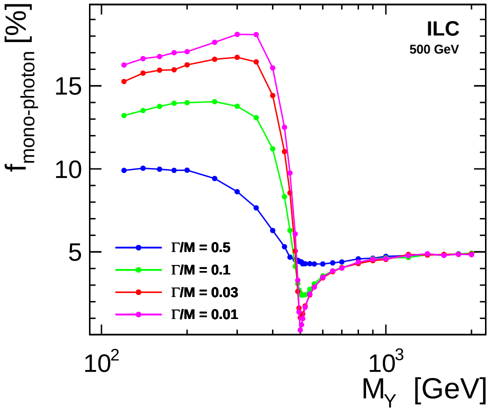


Proper merging of ME and ISR crucial for light mediator scenarios!

Tagging efficiency for signal events, based on DELPHES simulation

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

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



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

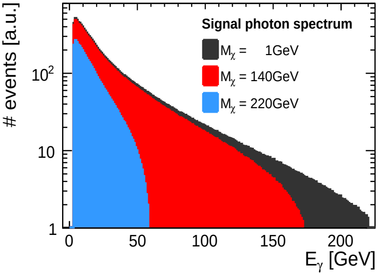
Heavy mediator case (EFT limit), full simulation

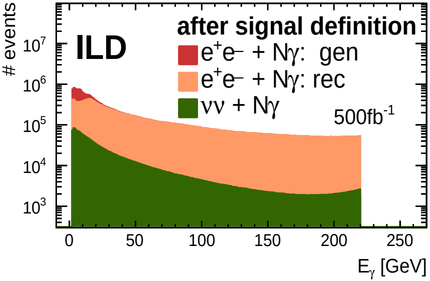
arXiv:2001.03011

Moritz Habermehl, Mikael Berggren, Jenny List

Signature:

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





WIMP Dark Matter at the 500 GeV ILC

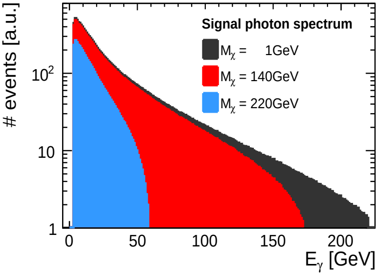
Heavy mediator case (EFT limit), full simulation

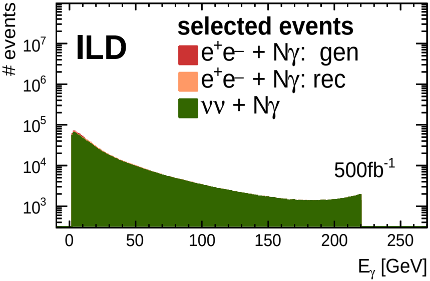
arXiv:2001.03011

Moritz Habermehl, Mikael Berggren, Jenny List

Signature:

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



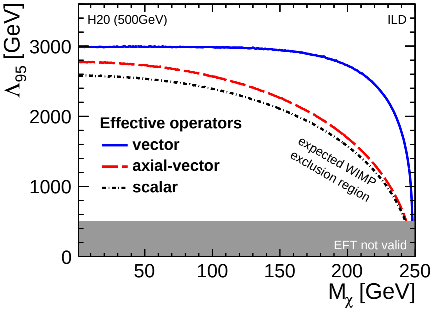


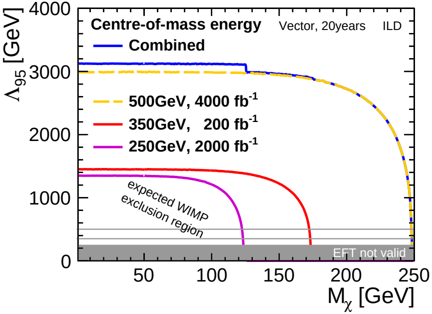
"Irreducible" background from radiative neutrino pair-production events $e^+e^- \to \nu\nu + \mathrm{N}\gamma$ dominates after selection and bg suppression cuts

WIMP Dark Matter at the 500 GeV ILC

Heavy mediator case (EFT limit), full simulation arXiv:2001.03011

Combined limits for H20 scenario at 500 GeV, with systematics included
(significantly reduced when combining different polarisation combinations)





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

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

e^+e^- mass reach comparable with that of FCC-hh in mono-jet channel !!!

Light mediator exchange

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

$\Gamma_{SM} \ll \Gamma_{tot} \Rightarrow$ limits hardly depend on the mediator coupling to DM !

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:

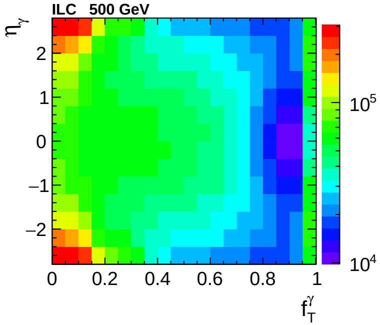
- single photon with
  $p_T^\gamma > 3\,GeV$ & $|\eta^\gamma| < 2.8$
- no other activity in the detector
  other reconstructed objects

Background vs Signal distributions

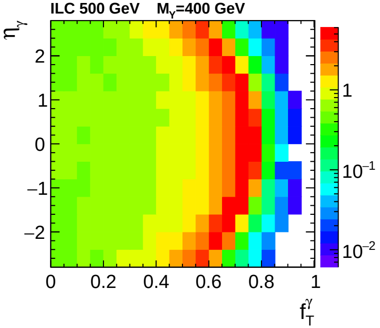
arXiv:2107.11194

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, $\Gamma/M = 0.03$

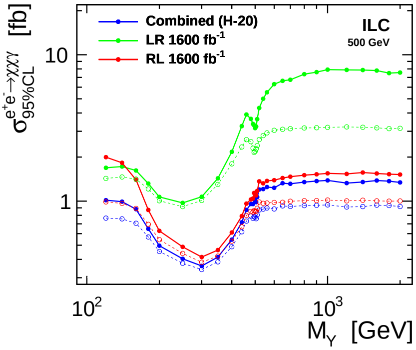
Signal normalised to unpolarised DM pair-production cross section of 1 fb

Light mediator exchange

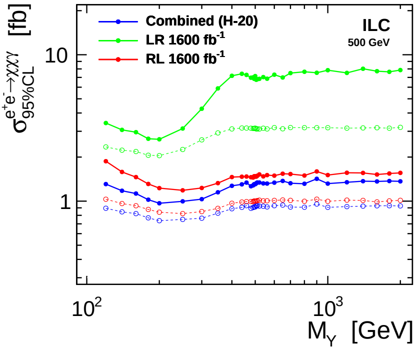
Cross section limits for radiative events (with tagged photon)

Vector Mediator with (——) and without (- - -) systematics

$\Gamma/M = 0.03$



$\Gamma/M = 0.5$



Systematic effects reduced for on-shell production of narrow mediator

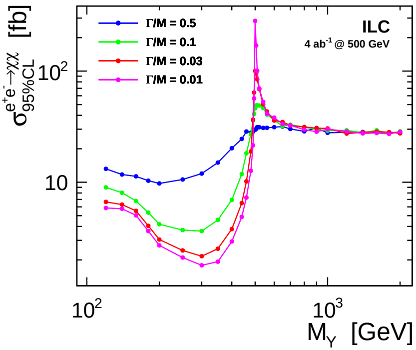
Light mediator exchange

Cross section limits for total DM production cross section

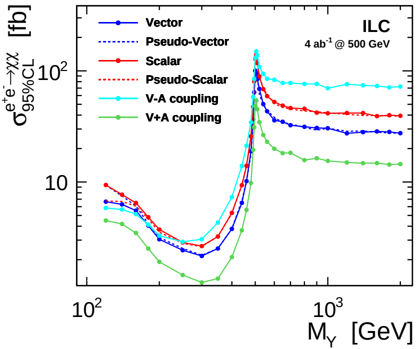
Corrected for probability of hard photon tagging!

Combined limits (H20 scenario for 500 GeV) with systematic uncertainties

Vector mediator



Mediators with $\Gamma/M = 0.03$



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

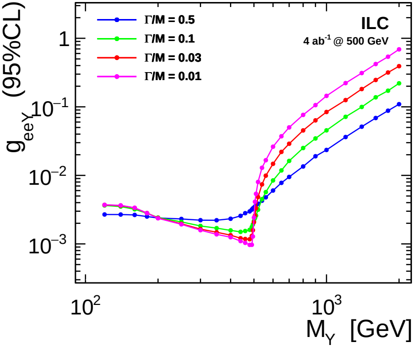
Light mediator exchange

Coupling limits

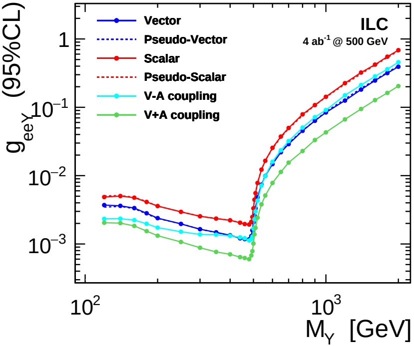
for mediator coupling to electrons

Combined limits (H20 scenario for 500 GeV) with systematic uncertainties

Vector mediator



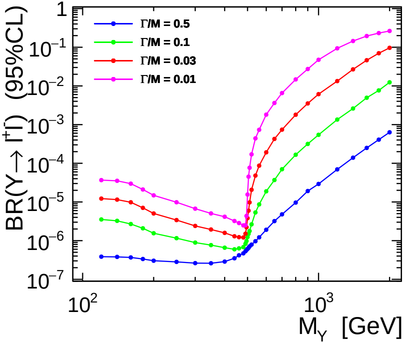
Mediators with $\Gamma/M = 0.03$

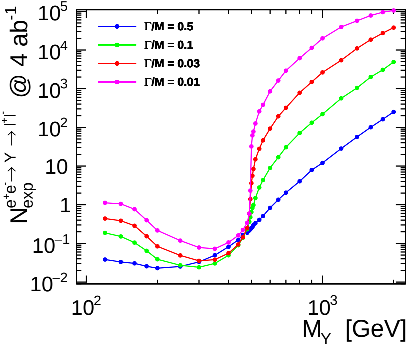


Almost uniform sensitivity to mediator coupling g_{eeY} up to kinematic limit.

Prospects for SM decay observation

Limits on the SM-mediator couplings can be translated into limits on the mediator branching ratio to charged leptons and expected numbers of produced lepton pairs





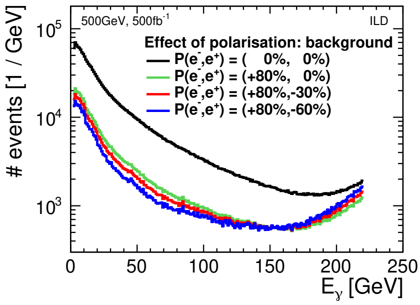
Limits from mono-photon analysis more stringent than those expected from direct resonance search in SM decay channels

Impact of polarisation

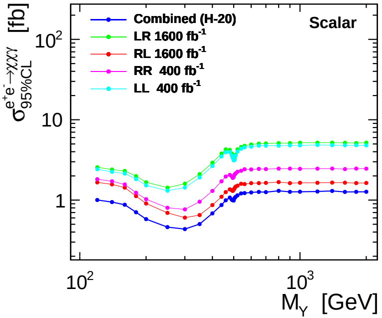
Sensitivity to radiative DM production limited by the "irreducible" background from radiative neutrino pair-production events $e^+e^- \rightarrow \nu\nu + \gamma$

Beam polarisation can be used to suppress/control background levels.
It can also enhance mono-photon signal (depending on the scenario).

arXiv:2001.03011



arXiv:2107.11194



Impact of polarisation

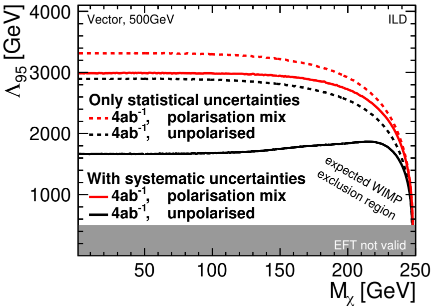
Mediator coupling structure unknown

⇒ need to combine data taken with different polarisation combinations

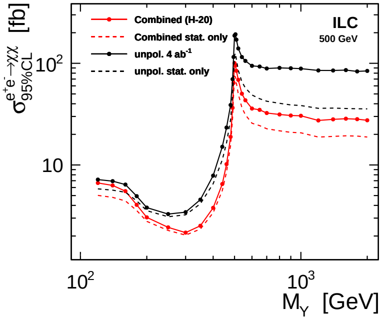
Combination results in best sensitivity to all scenarios

but also significantly reduces the impact of systematic uncertainties

Heavy mediator exchange



Light mediator exchange



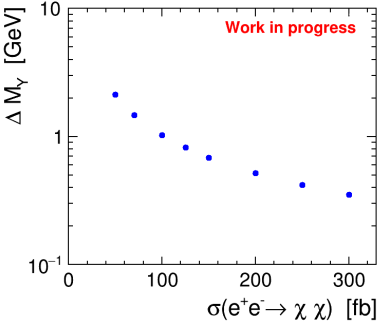
Signal measurement precision

We are currently working on estimating mediator mass and width measurement precision and coupling structure determination.

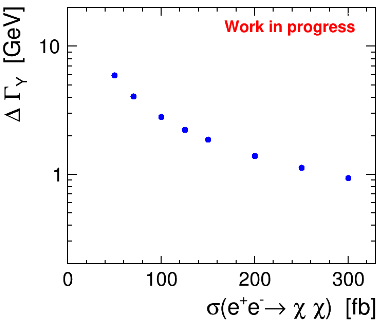
Combined analysis (H20 scenario for 500 GeV), statistical errors only

Vector mediator with $M_Y = 300$ GeV, $\Gamma/M = 0.1$

Mass determination



Width determination



Conclusions

Dark matter production with light mediator exchange

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

- $\mathcal{O}(1\,\mathrm{fb})$ limits on the radiative production $e^+e^- \to \chi\chi\gamma_{\mathrm{tag}}$
- $\mathcal{O}(10\,\mathrm{fb})$ 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 $M_Y \leq \sqrt{s}$
- light mediator limits more stringent than direct search estimates

Running with different beam polarisation crucial for optimal sensitivity and suppression of systematic uncertainties

Conclusions

Snowmass contribution

Analysis described in our LoI #054

"New approach to DM searches with mono-photon signature"

was completed and results were published in:

J. Kalinowski et al., Eur. Phys. J. C 81, 955 (2021), arXiv:2107.11194

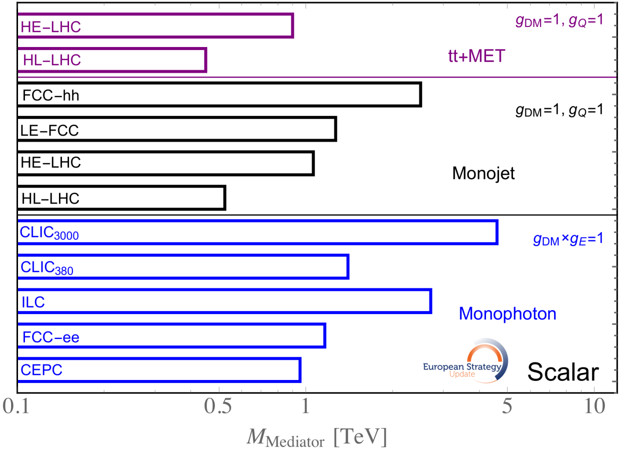
as well as in numerous proceedings...

Unfortunately, we are not supposed to submit published works to Snowmass!

We can try to prepare a (short) dedicated contribution,
but it will rather be difficult (taking into account all other obligations)

Thank you!

Comparison of mass scale limits calculated in the EFT framework



e^+e^- mass 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.

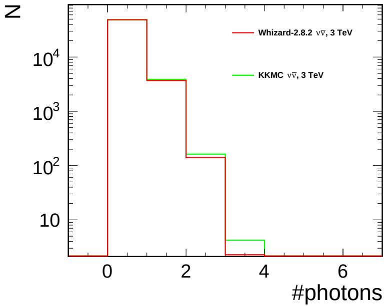
Each simplified scenario is characterized by one dark matter candidate and one mediator from the set listed below:

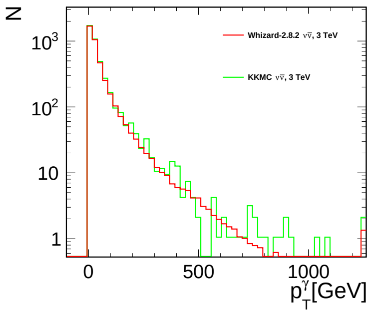
	particle	mass	spin	charge	self-conjugate	type
DM	X_R	m_{X_R}	0	0	yes	real scalar
	X_C	m_{X_C}	0	0	no	complex scalar
	X_M	m_{X_M}	$\frac{1}{2}$	0	yes	Majorana fermion
	X_D	m_{X_D}	$\frac{1}{2}$	0	no	Dirac fermion
	X_V	m_{X_V}	1	0	yes	real vector
mediator	Y_R	m_{Y_R}	0	0	yes	real scalar
	Y_V	m_{Y_C}	1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

Validation of Whizard simulation 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

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

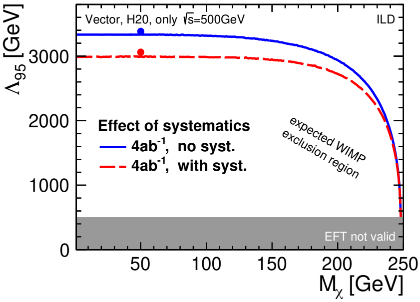
$\Rightarrow$ 11 nuisance parameters in the model fit

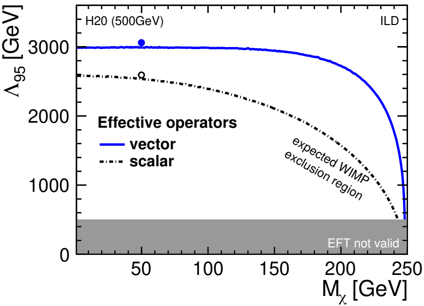
Comparison of fast and full simulation results

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...