The XXVIII International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY 2021)

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

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Motivation

Great expectations for New Physics at the LHC, but no direct evidence (yet?)

Outstanding questions remain + various BSM hints (DM, neutrinos,...)

A plausible scenario with dark matter candidate(s):

- all colored particles very heavy
- a few light EW particles, nearly mass-degenerate
- even charged states difficult to detect due to soft decay products
- dark matter cannot be seen directly

A future e+e- collider with:

- clean environment
- fixed CM frame
- polarized beams

can cope with such a difficult scenario via processes with a photon

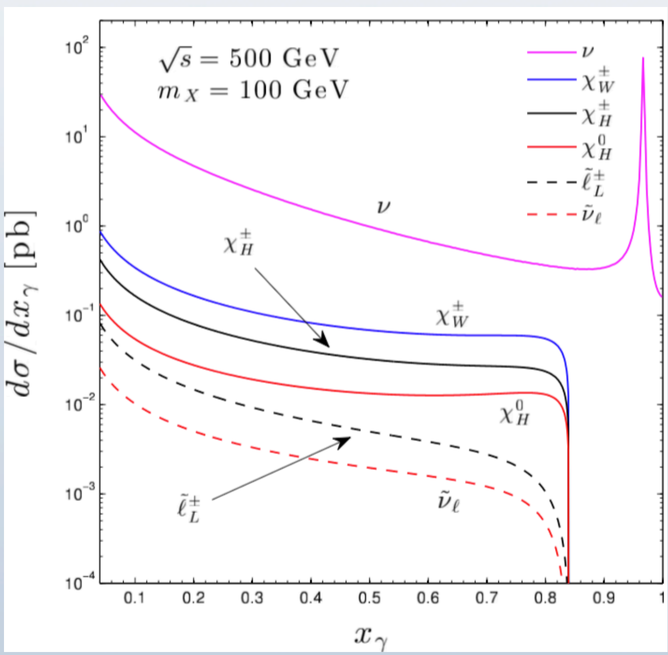
$$e^+e^- \to \chi\,\chi\,\gamma \to \gamma + E^{miss}$$

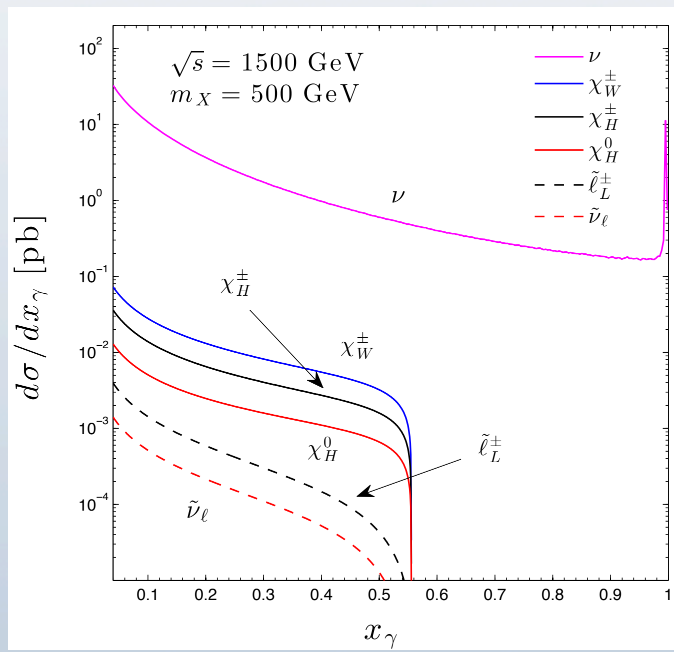
Motivation

Processes $e^+e^- \to \gamma + E^{miss}$ have been exploited in the past:

- counting neutrino families
- anomalous gauge couplings
- search for invisible states like lightest neutralino

e.g. previous studies: DM signal vs. neutrino background



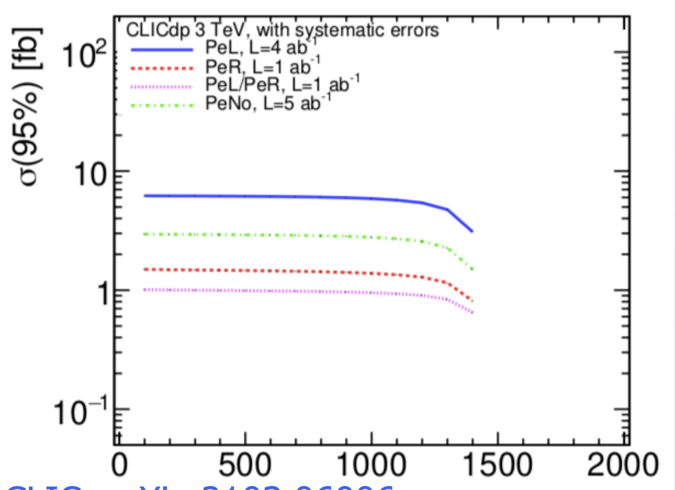


S.Y. Choi, T. Han, JK., K. Rolbiecki and X. Wang, PRD 92(2015)095006

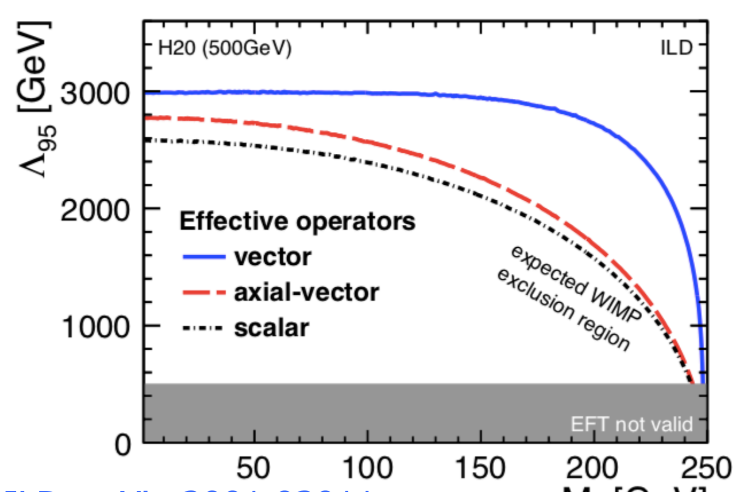
Motivation

The mono-photon signature: most general way to look for DM

- DM can be pair produced via exchange of a mediator that couples to electrons and DM states
- Most studies performed so far focused on heavy mediator (EFT) and couplings O(1) => limits on DM production cross section or mediator mass



CLIC: arXiv:2103.06006



ILD: arXiv:2001.03011

Our study: focus on light mediator with very small couplings to SM particles and derive limits as a function of mediator mass and width

Outline

- Simulating mono-photons events with Whizard
- Analysis framework
- Results
- Conclusions

based on

JK, W. Kotlarski, P. Sopicki, A.F. Zarnecki, EPJC80(2020)634

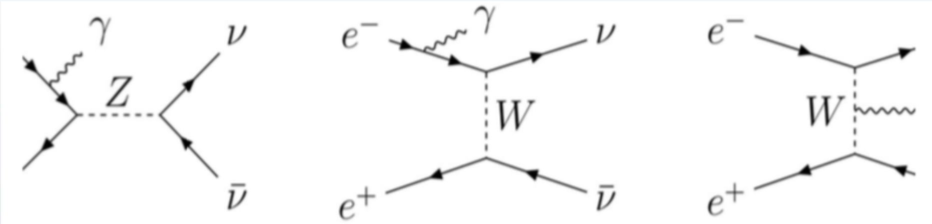
JK, W. Kotlarski, K. Mękała, P. Sopicki, A.F. Żarnecki, arXiv:2107.11194

Simulating photons in WHIZARD

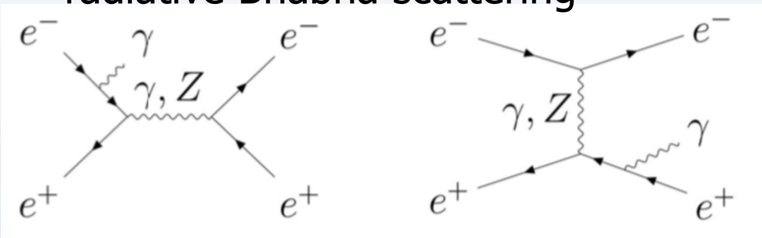
- Before assessing the discovery potential of the mono-photon processes the SM background must be carefully studied

main SM background processes

radiative neutrino pair-production



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.
- 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 does not account for hard non-collinear photons.

→ Must avoid double-counting of ISR and hard photons emitted in the same region of phase space

Merging procedure for ISR and ME photons

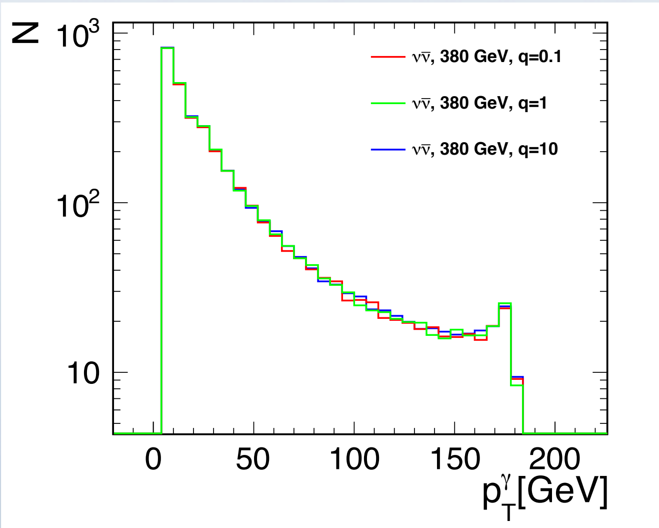
- Define for <u>each</u> photon $$q_- = \sqrt{4E_0E_\gamma}\ \sin\frac{\theta_\gamma}{2}, \quad q_+ = \sqrt{4E_0E_\gamma}\ \cos\frac{\theta_\gamma}{2}$$

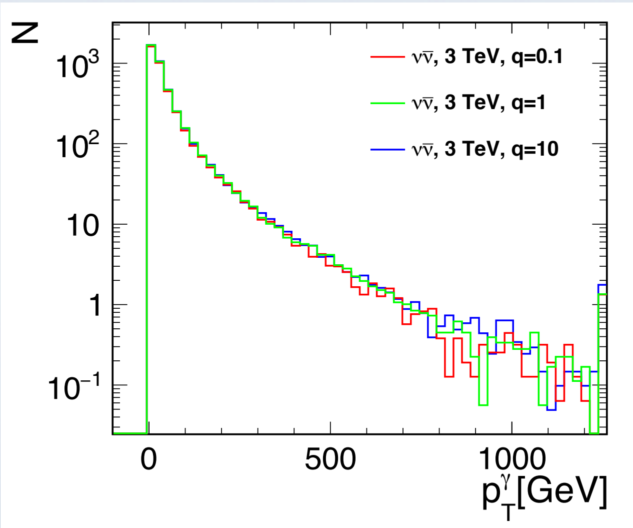
  for events with only one photon these variables would correspond to virtualities of electron and/or positron after photon emision

- Only photons with large enough $q_-,\ q_+$ can be measured in the detector

- Merging of ISR and ME photons at E_{min} and/or $q_-,\ q_+ = q_{min}$

- ISR photons are rejected above E_{min} and q_{min}





results not sensitive to the choice of merging scale q_{min}

JK, W. Kotlarski, P. Sopicki, A.F. Zarnecki, EPJC80(2020)634

Analysis framework

JK, W. Kotlarski, K. Mękała, P. Sopicki, A.F. Żarnecki, arXiv:2107.11194

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

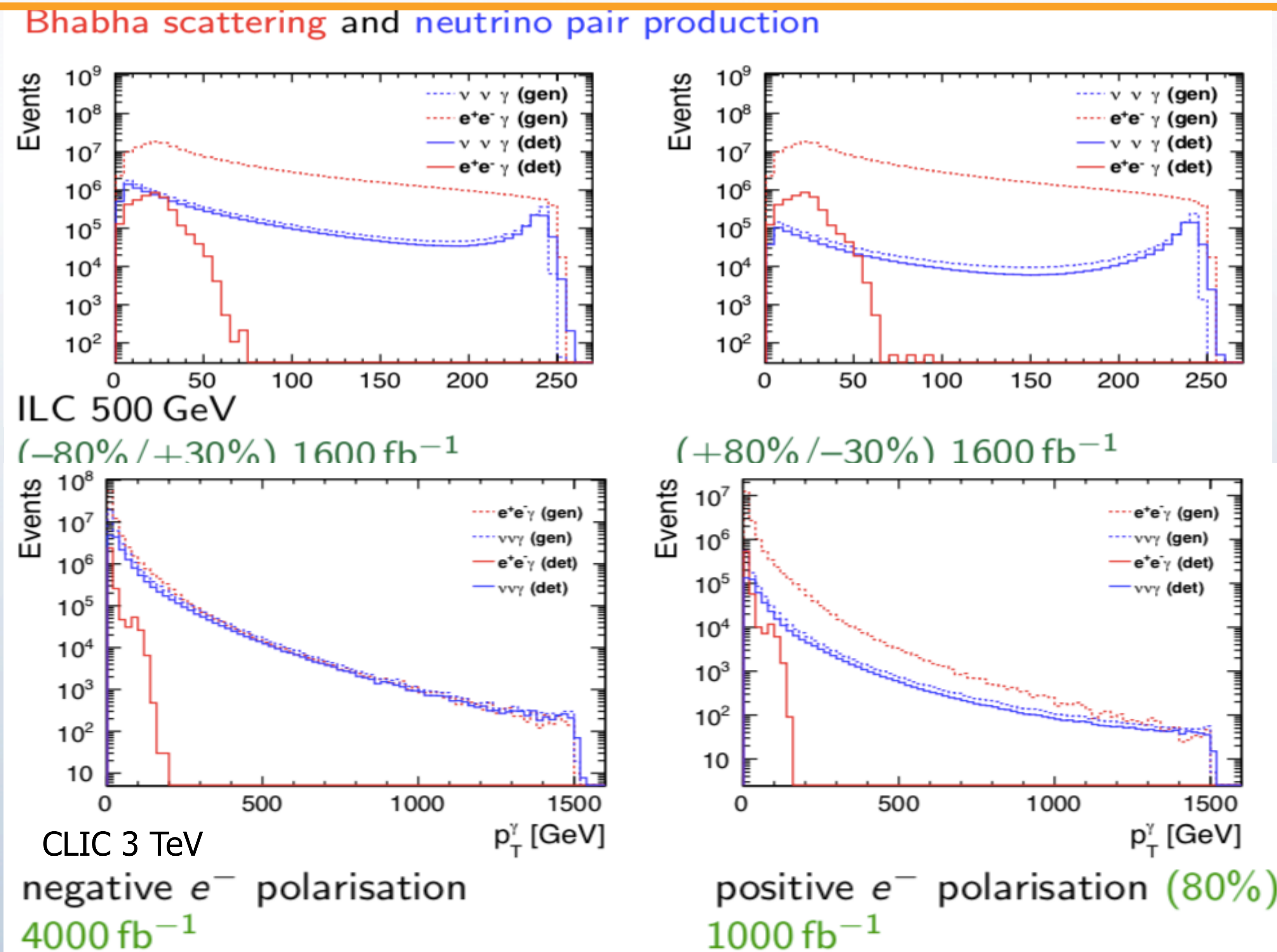
  other reconstructed objects

  - no electrons
  - no LumiCal photons
  - no BeamCal photons
  - no jets

Detector response simulated in the Delphes framework:

ILCgen for ILC, CLICdet extended to include BeamCal and LumiCal

Analysis framework: SM background



Analysis framework: simplified DM model

UFO model covering most popular DM scenarios

Possible mediators: Y

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

Possible DM candidates: χ

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

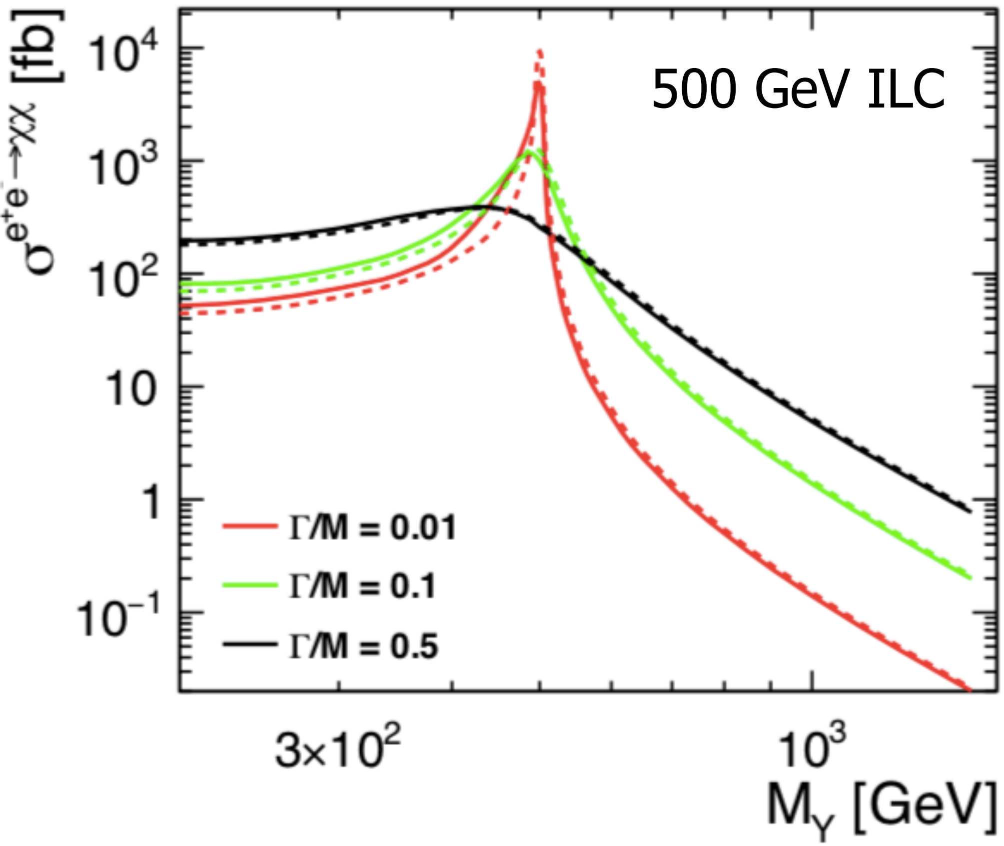
$$\mathcal{L}_{eeY} \ni \bar{e}(g^1_{eY_R} + \imath\gamma^5 g^5_{eY_r})eY_R + \bar{e}\gamma_\mu(g^1_{eY_V} + \gamma^5 g^5_{eY_V})eY^\mu_V$$

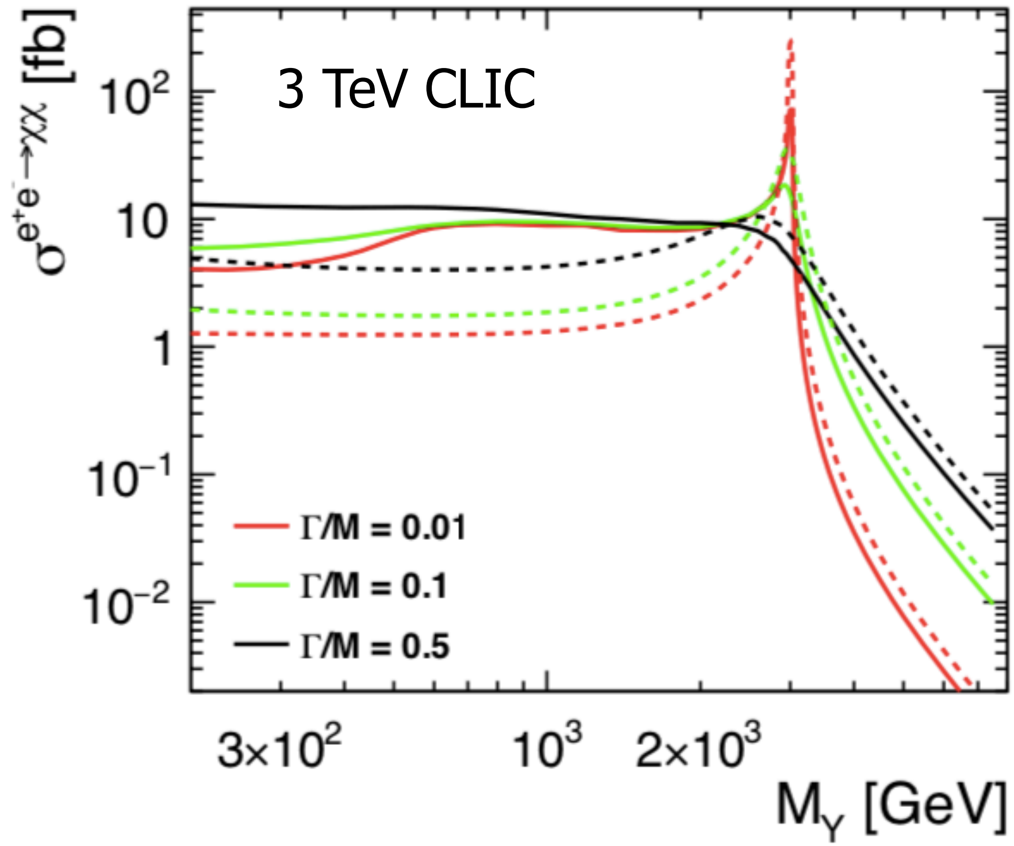
$$\mathcal{L}_{\chi\chi Y} \ni \bar{\chi}_D(g^1_{\chi_D Y_R} + \imath\gamma^5 g^5_{\chi_D Y_R})\chi_D Y_R + \bar{\chi}_D\gamma_\mu(g^1_{\chi_D Y_V} + \gamma^5 g_{\chi_D Y_V})\chi_D Y^\mu_V$$

in simulations we take DM mass = 50 GeV

Analysis framework: simplified DM model

Expected cross sections for $e^+e^- \rightarrow \chi\chi$ as a function of mediator mass





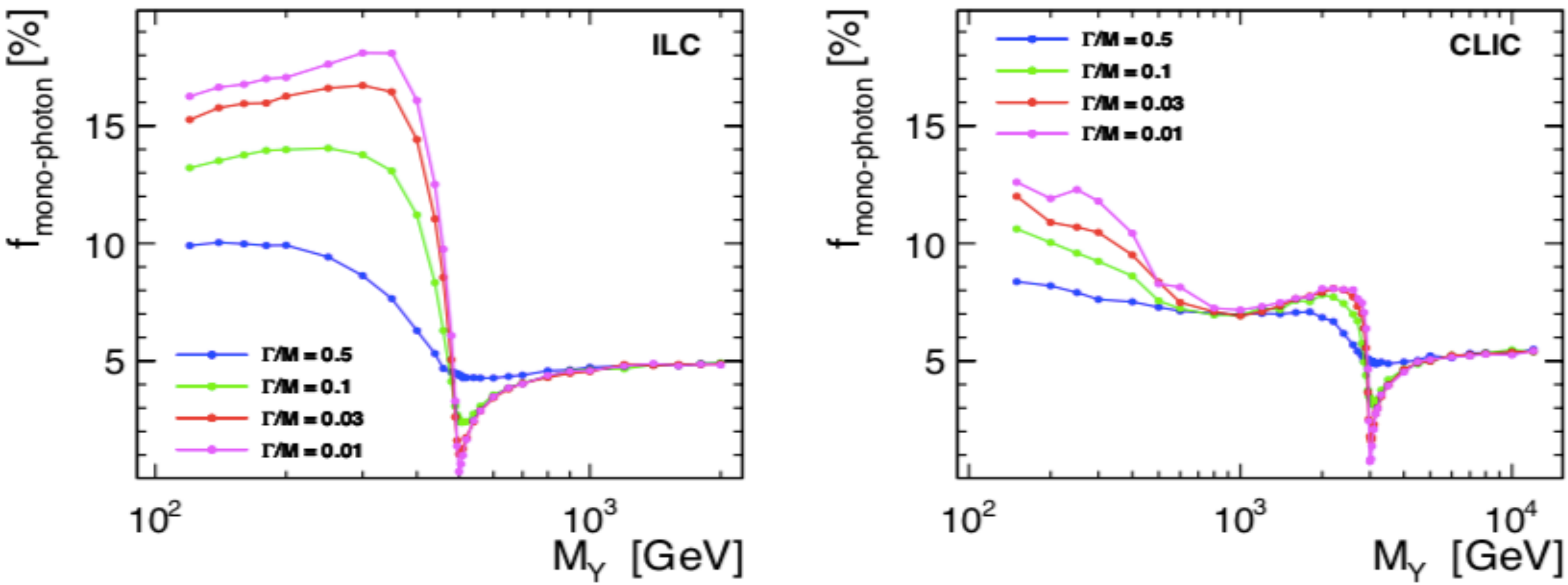
solid - luminosity spectra

dashed - monochromatic beams

Analysis framework:

Detectable hard photon emitted only in a fraction of signal events

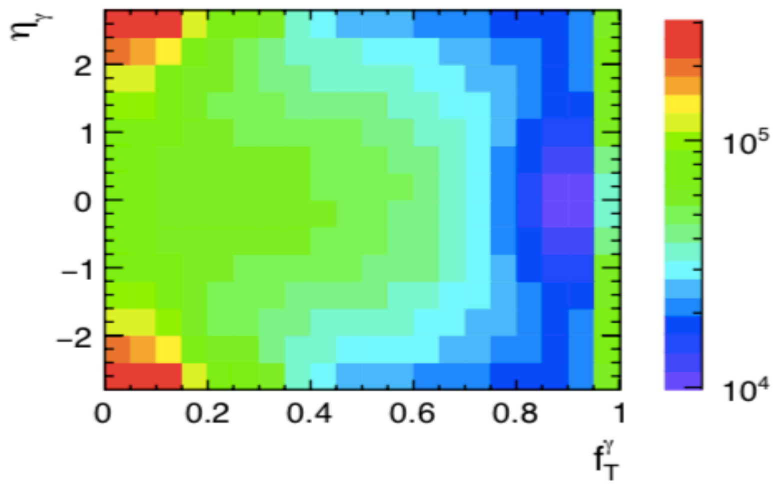
$$\sigma\left(e^+e^- \rightarrow \chi\,\chi\,\gamma_{tag}\right) \;=\; f_{\text{mono-photon}} \cdot \sigma\left(e^+e^- \rightarrow \chi\,\chi\,(\gamma)\,\right)$$

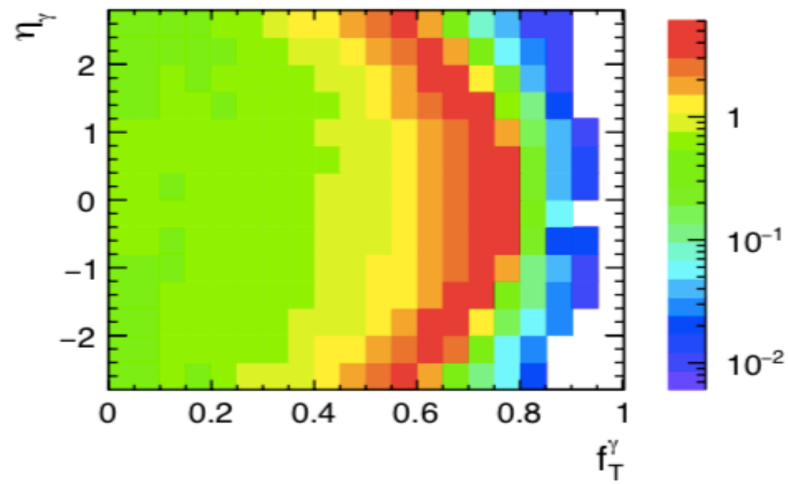


efficiency: for light mediators ~ 10-15%
for heavy ones only ~ 5% events can be tagged

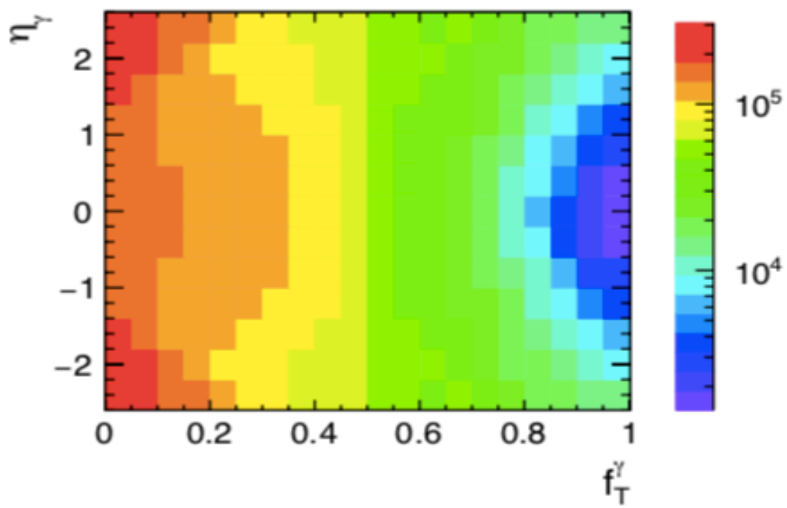
Analysis framework: background vs signal

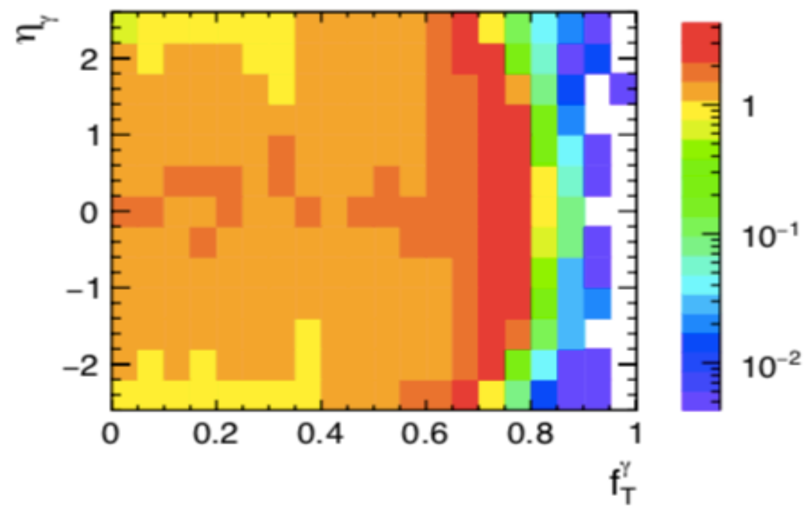
Background | Signal





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



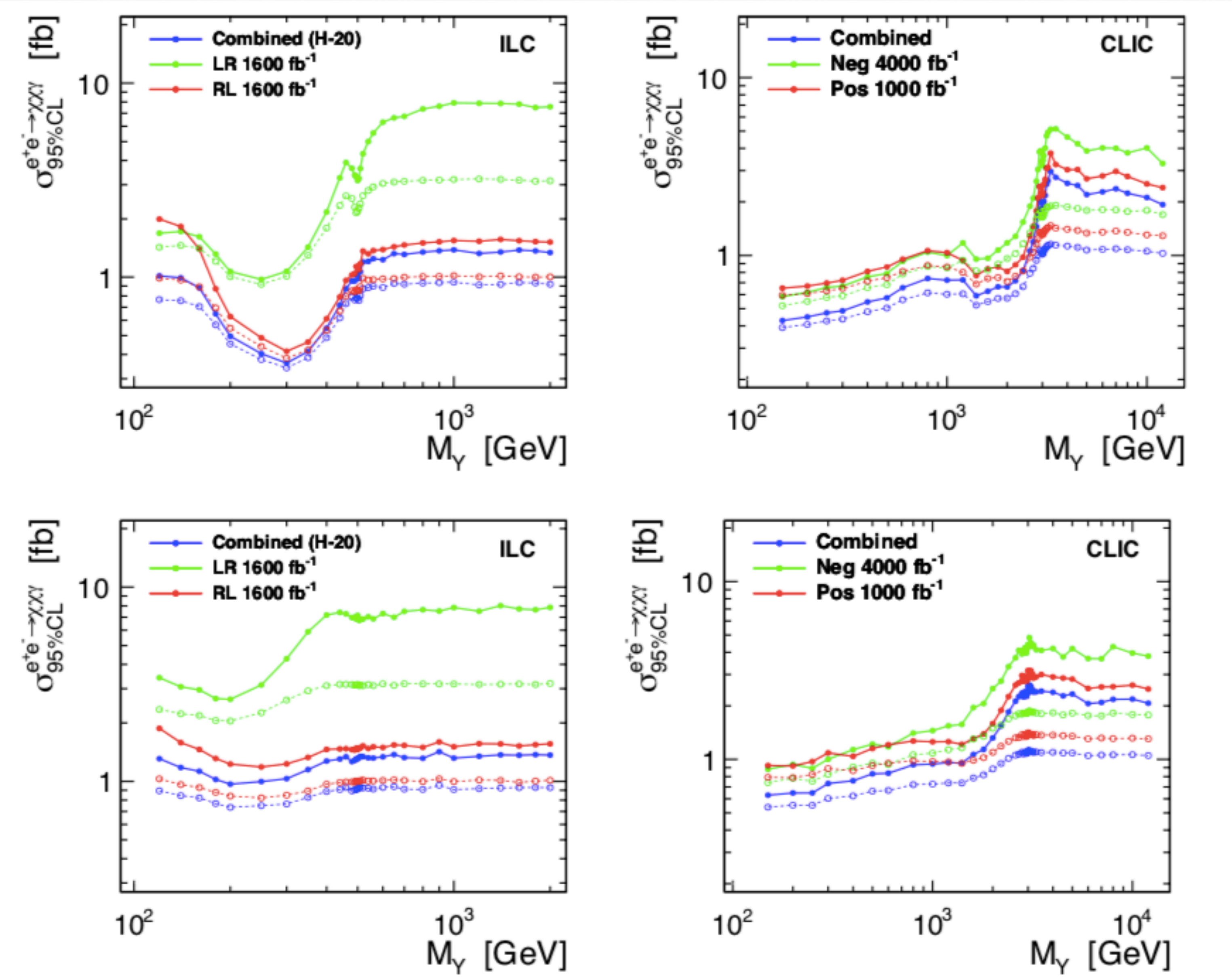


CLIC 3 TeV -80% e^- 4000 fb^{-1} | $M_Y = 2.4$ TeV, $\Gamma/M = 0.03$

$$f_T^\gamma = \frac{\log\left(\frac{p_T^\gamma}{p_T^{min}}\right)}{\log\left(\frac{p_T^{max}}{p_T^{min}}\right)}$$

$$p_T^{max} = \frac{\sqrt{s}}{2}\sin\theta_\gamma$$

Results: limits on radiative cross section



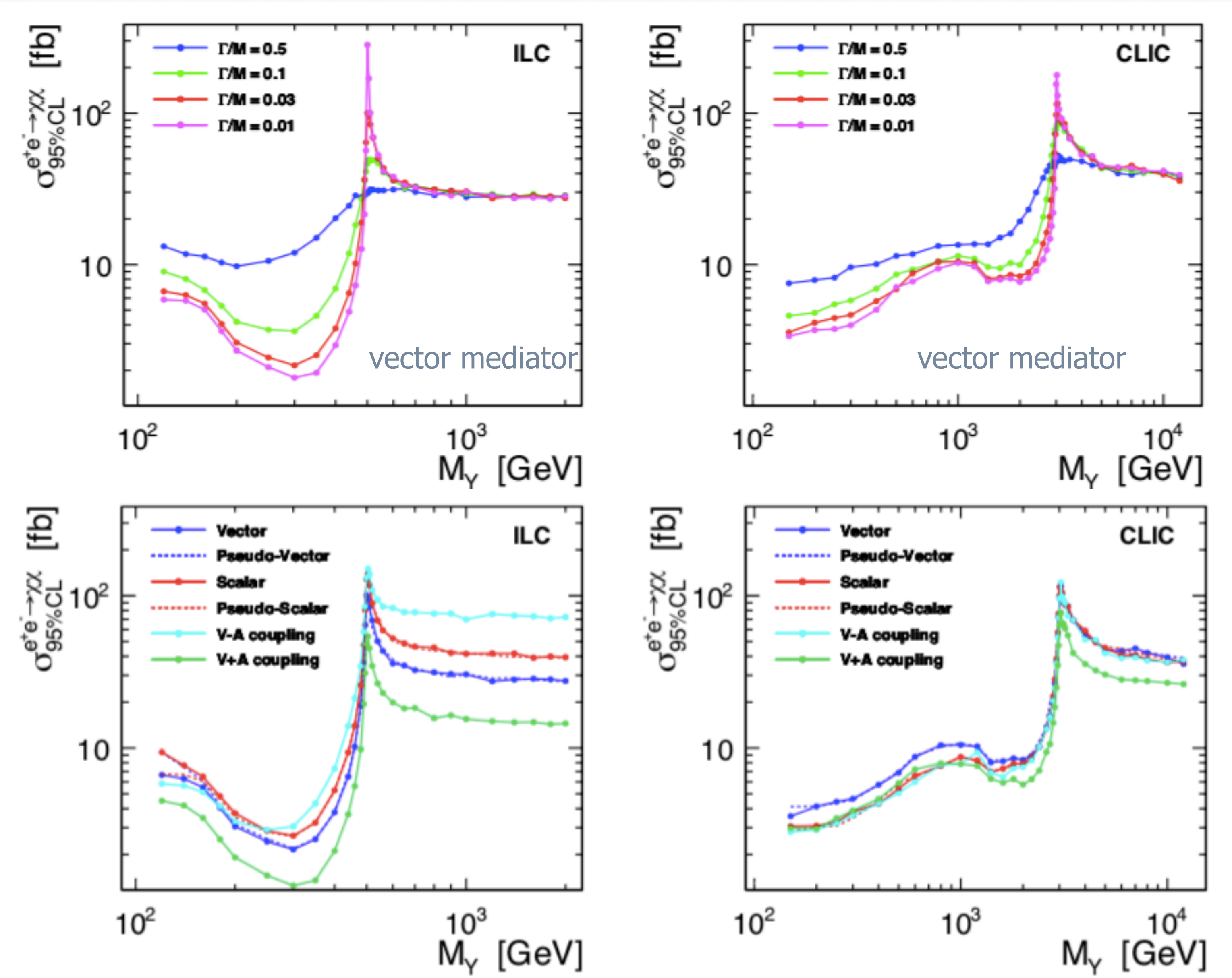
Cross section limits on radiative light DM pair-production with vector mediator

solid lines – with systematic uncert.
dashes - without

systematic effects reduced for on-shell mediator production

top row $\Gamma/M=0.03$
bottom row $\Gamma/M=0.5$

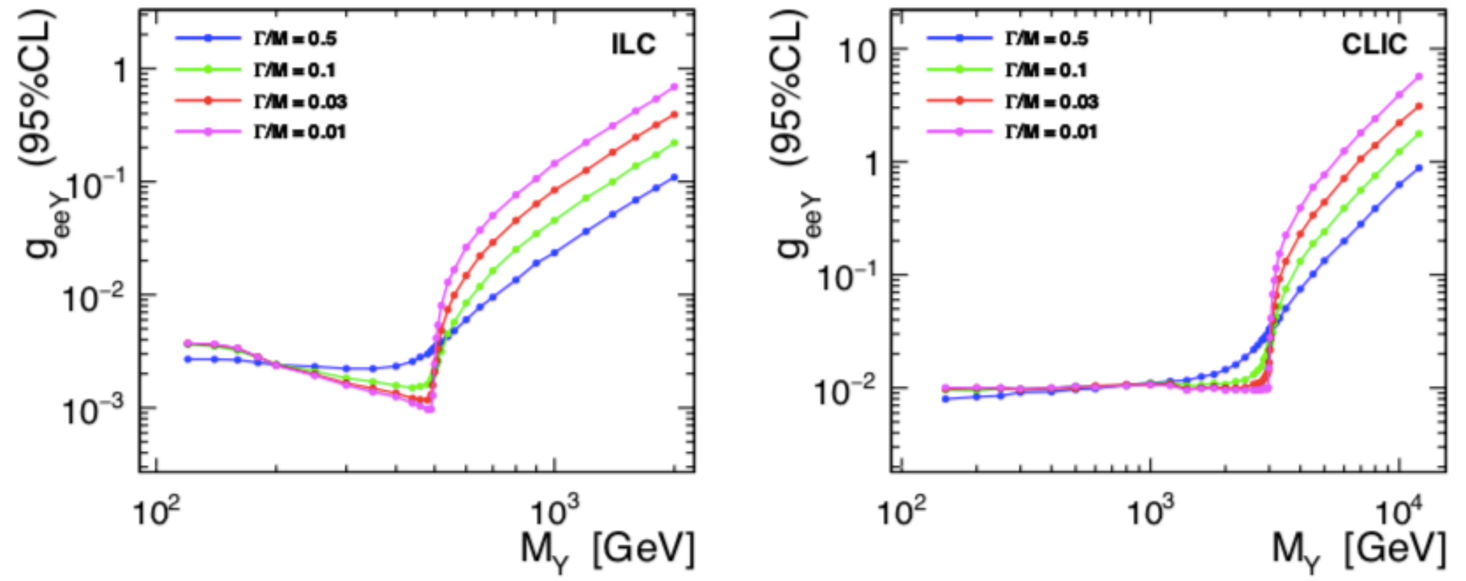
Results: limits on cross section



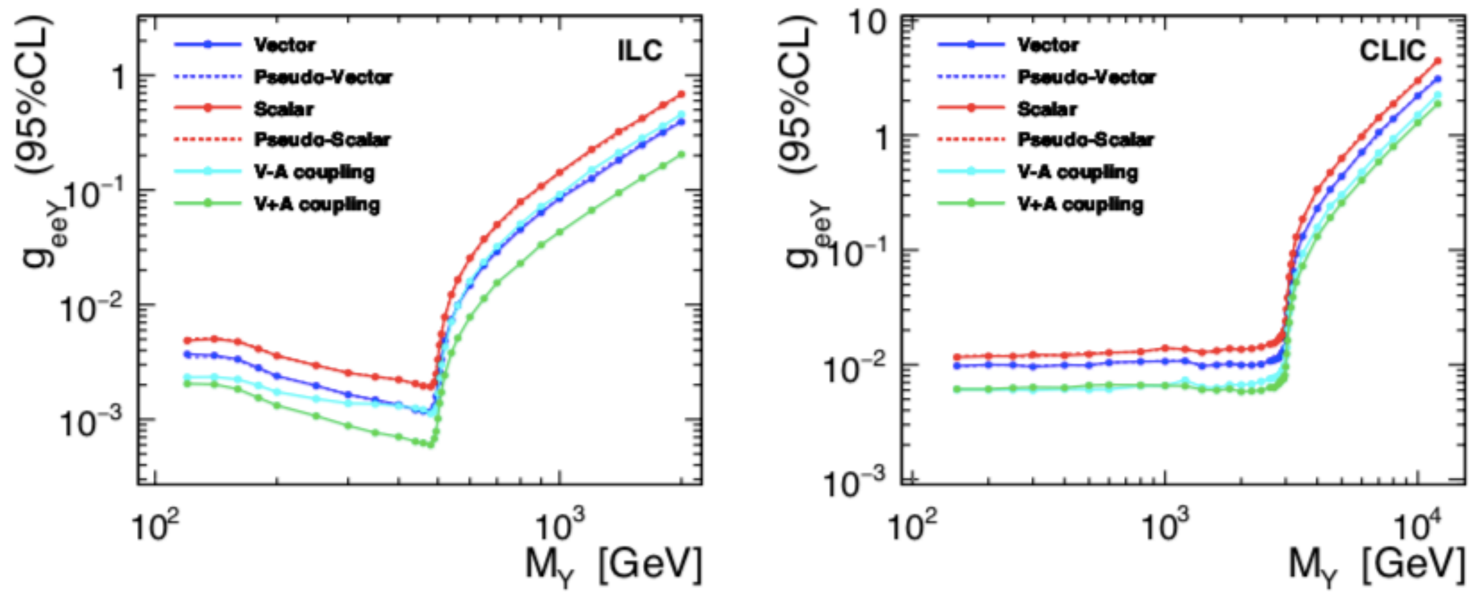
combined limits including photon tagging efficiency

$\Gamma/M=0.03$

Results: limits on electron-mediator couplings



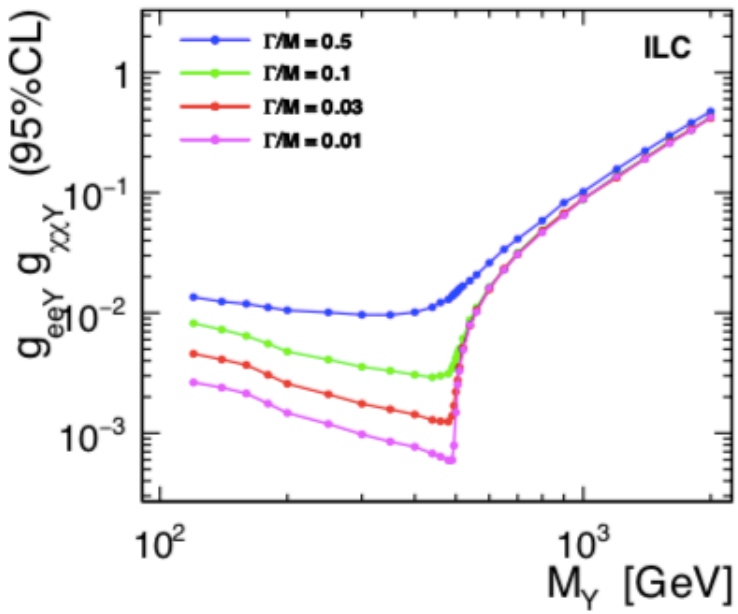
vector mediator

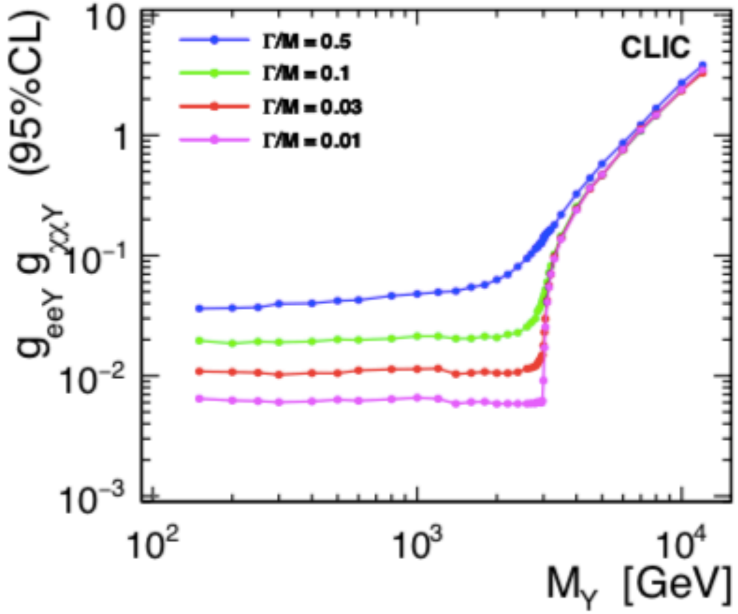


$\Gamma/M=0.03$

Results: limits on (electron-mediator)x(mediator-DM) couplings

For heavy mediator exchange the DM production should not depend on mediator width. This is seen when limits on the product of mediator couplings to electrons and DM is considered.





for heavy mediator EFT approach

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

The scale Λ for ILC ~2.6 TeV (scalar) to 5.1 TeV (V+A)
for CLIC ~ 6.1 TeV (scalar) to 10.1 TeV (V+A)

Conclusions

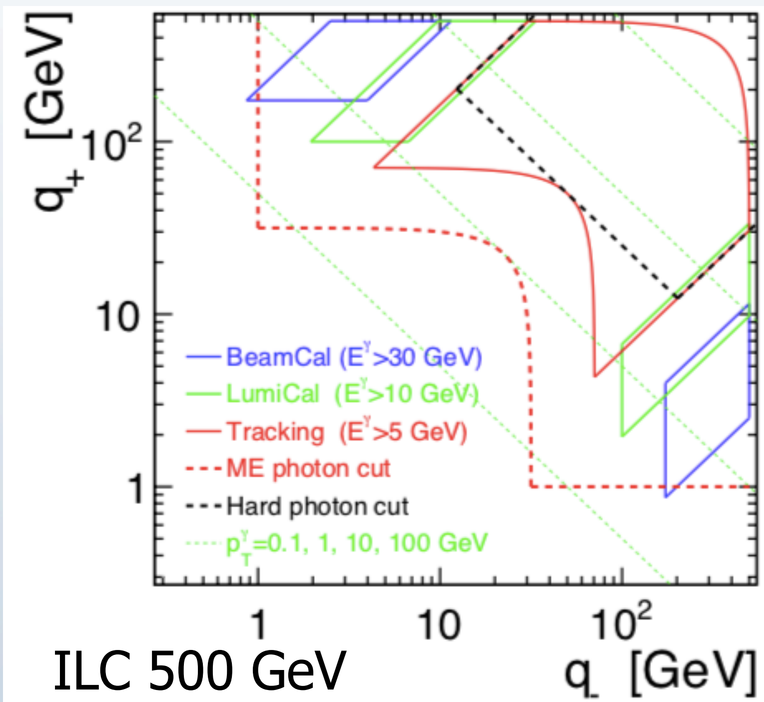
- New framework for mono-photon analysis developed
  focus on light mediator with very small couplings to SM
- Systematic uncertainties taken into account following full simulation studies
- Mono-photon production sensitive to wide range of DM pair-production scenarios
  - $\mathcal{O}$(1 fb) limits on the radiative production $e^+e^- \rightarrow \chi\chi\gamma_{tag}$
  - $\mathcal{O}$(10 fb) limits on the DM pair-production $e^+e^- \rightarrow \chi\chi(\gamma)$
  - $\mathcal{O}(10^{-3} - 10^{-2})$ limits on the mediator couplings to electrons up to kinematic limit
- For heavy mediators limits from EFT analysis reproduced
- For light mediators limits more stringent than from direct searches
  in SM decay channels

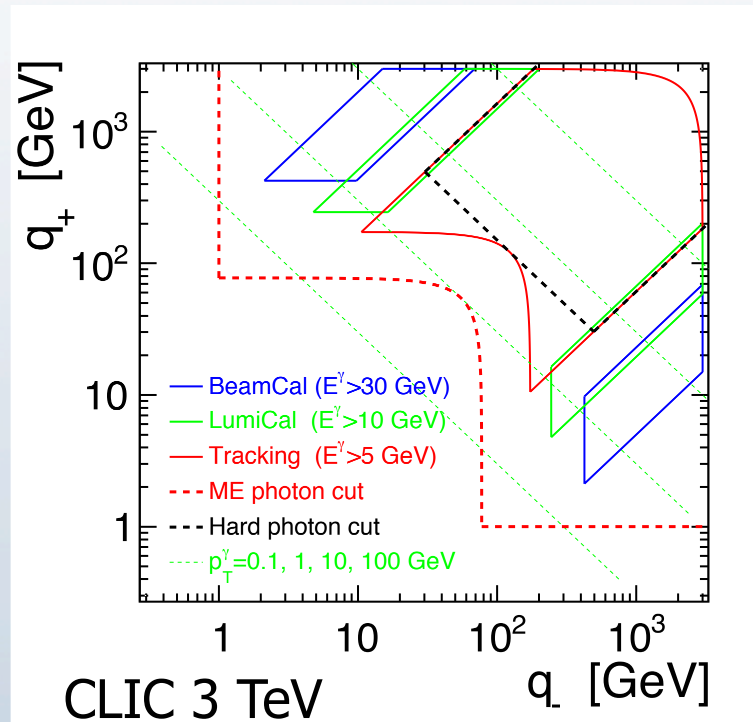
see also talk by A.F. Zarnecki: Probing DM with ILC
tomorrow in the parallel session on Linear Colliders at 10:30

Backup slides

Merging ISR and ME photons

detector coverage in q_-, q_+ plane

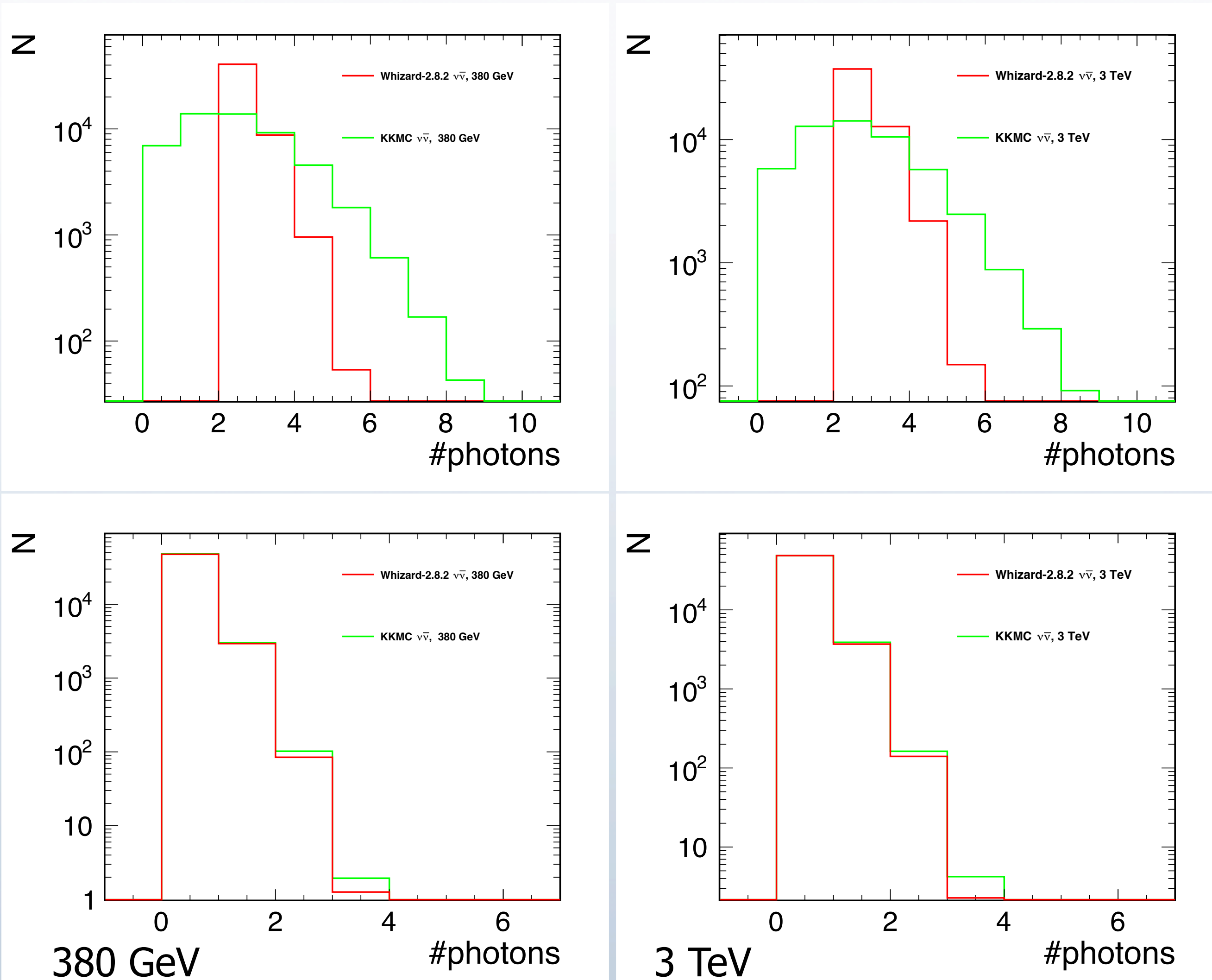




$$E_{min} = 1 \text{ GeV}, \quad q_{min} = 1 \text{ GeV}$$

Comparison with *KK* MC: photon multiplicity

*KK*MC: soft photon resummation in CEEX + exact O(Born + $\alpha^{3/2}$)

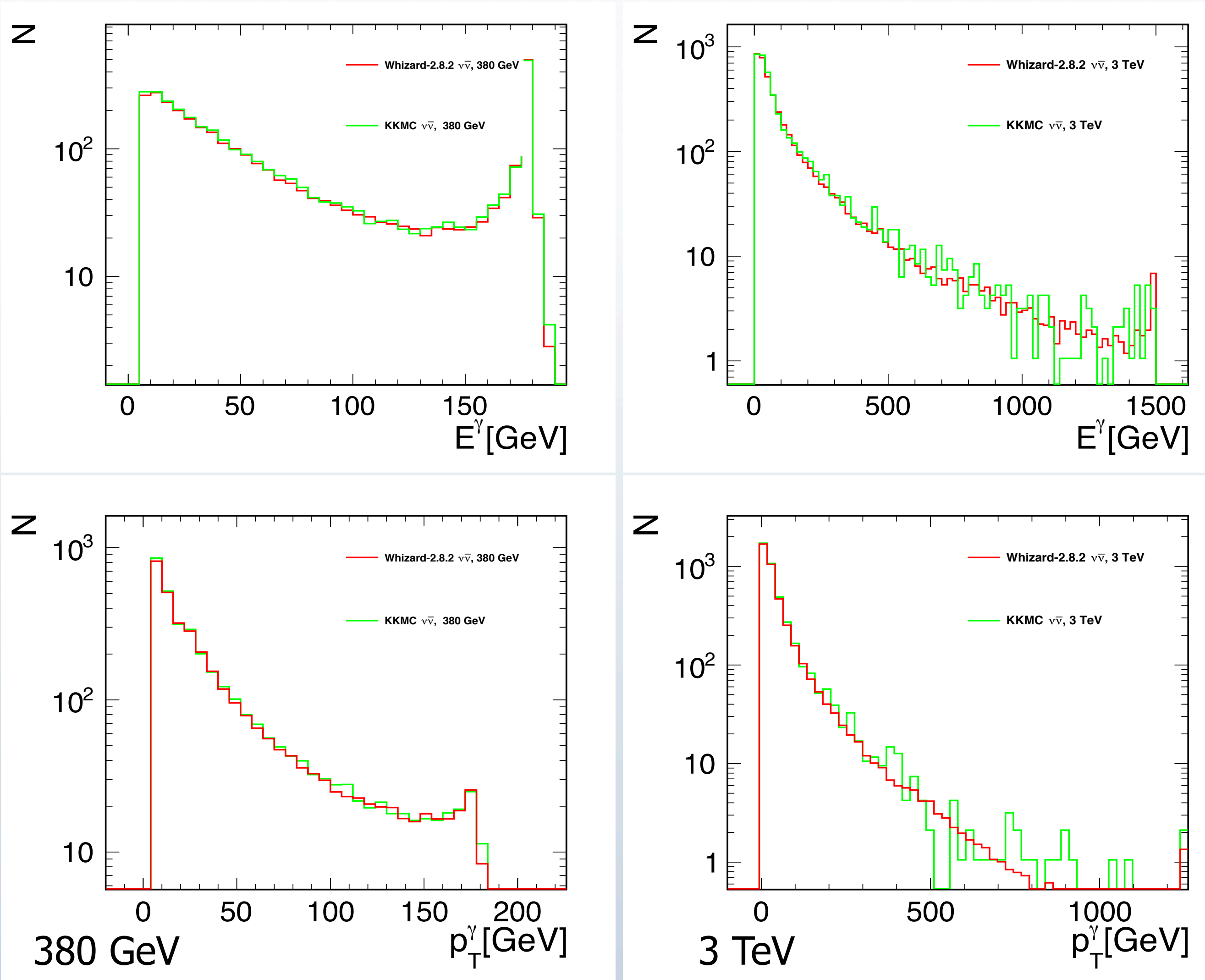


all photons

after hard photon selection

distributions normalised to # events expected for 1/fb

Comparison with *KK* MC: photon p_T



after hard photon selection

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

Results

systematic uncertainties: following ILD study arXiv:2001.03011
CLIC mono-photon study arXiv:2103.06006

- integrated luminosity uncertainty 0.26% (ILD), 0.2% (CLIC)
- neutrino background normalisation 0.2% (th+exp)
- Bhabha background normailsation 1% (th+exp)
- uncertainty on beam polarisation 0.02-0.08% (ILD), 0.2% (CLIC)
- luminosity spectra shape uncertainty

nuisance parameters in the model fit: 11 (ILD H-20 secnario), 7 (CLIC)

Limits on production cross sections calculated with CL_s using RooFit v3.60

Simplified DM model

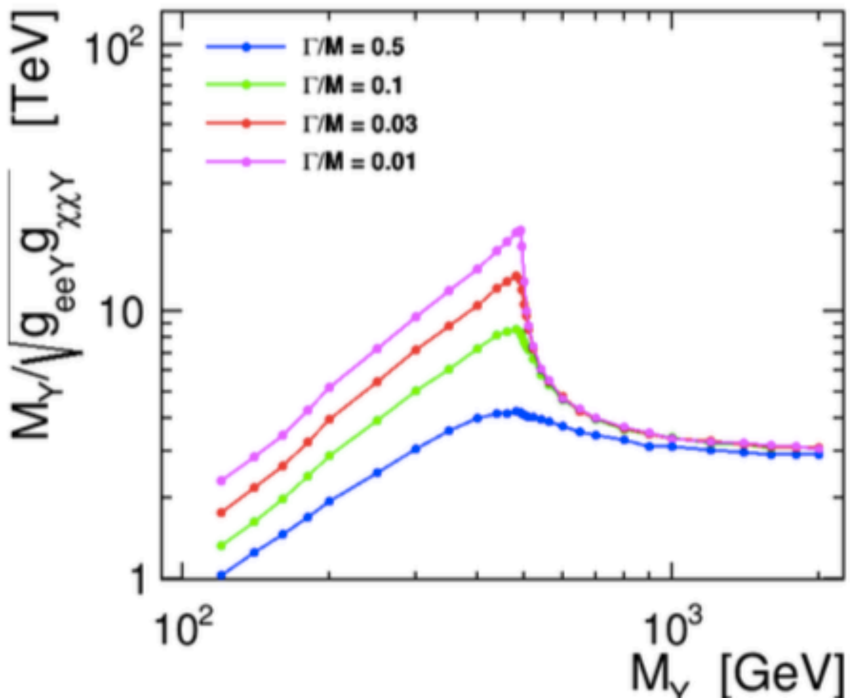
Effective mass scale limits

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

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

Vector mediator



$\Gamma/M = 0.03$