Limits on dark matter production with light mediator exchange

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CLICdp WG Analysis Meeting

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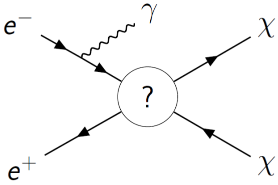
Outline

1. Motivation
2. Analysis framework
3. Results
4. Conclusions

Dark Matter production

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



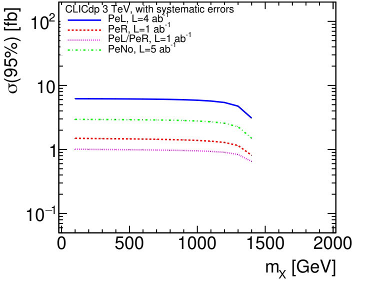
DM can be pair produced in the $\mathrm{e^+e^-}$ collisions via exchange of a new mediator particle, which couples to both electrons (SM) and DM states

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

Motivation

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

CLIC study: arXiv:2103.06006

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

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

Analysis framework

Simulating mono-photon events

Dedicated simulation procedure for WHIZARD, with all "detectable" photons generated on Matrix Element level, matched with soft ISR.

For more details:
⇒ J. Kalinowski et al., Eur. Phys. J. C 80 (2020) 634, arXiv:2004.14486
⇒ A.F.Zarnecki, presentation at WG Analysis meeting on February 8.

Detector modeling

Detector response simulated in the Delphes framework.

CLICdet model extended to include proper description of forward detectors: BeamCal and LumiCal, which is crucial for this analysis

⇒ see backup slides for more details

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

  $p_T^{\gamma} > 5\,GeV \;\; \& \;\; 7^{\circ} < \theta^{\gamma} < 173^{\circ}$

On detector simulation level:

- single photon with

  $p_T^{\gamma} > 10\,GeV \;\; \& \;\; |\eta^{\gamma}| < 2.6$

- no other activity in the detector

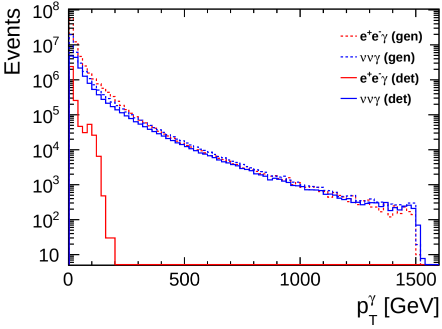
  other reconstructed objects

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

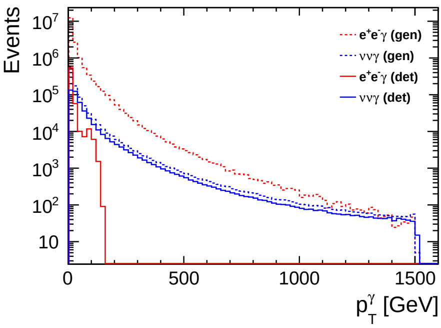
see backup slides for definition of $q_{\pm}$ variables

Background distributions

Two SM backgrounds considered:
Bhabha scattering and (radiative) neutrino pair production



negative e^- polarisation
4000 fb^{-1}



positive e^- polarisation (80%)
1000 fb^{-1}

Simplified DM model

UFO model covering most popular scenarios of DM pair-production

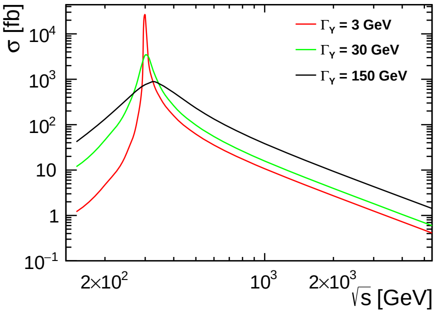
Possible mediators:

- 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

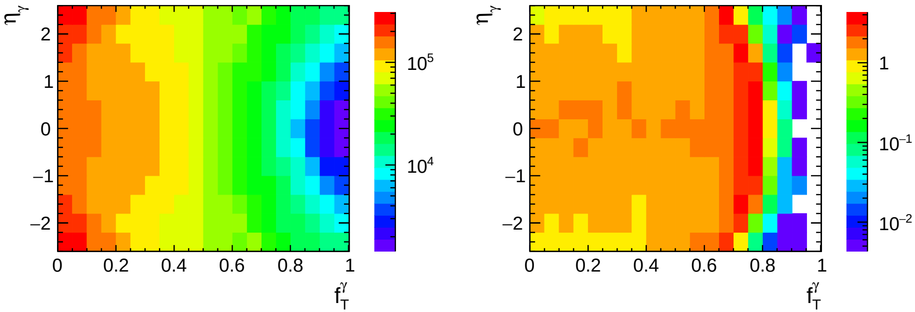
Cross section for $e^+e^- \to \chi\chi$ for $M_\chi = 50\ GeV$ and $M_Y = 300\ GeV$



Background vs Signal distributions

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

Background   Signal



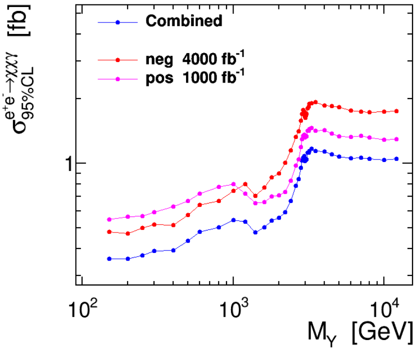
CLIC 3 TeV   −80% e^- 4000 fb^{-1} $M_Y = 2.4\,\text{TeV},\ \Gamma/M = 0.03$

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

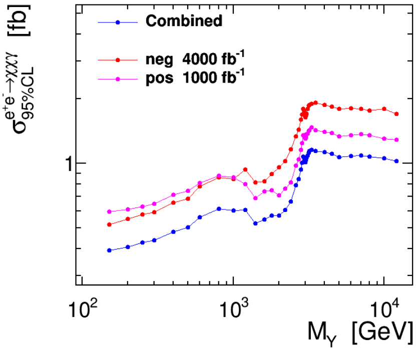
Cross section limits for radiative events (with tagged photon)

CLIC @ 3 TeV   Mediator with $\Gamma/m = 3\%$ no systematics

Scalar



Vector



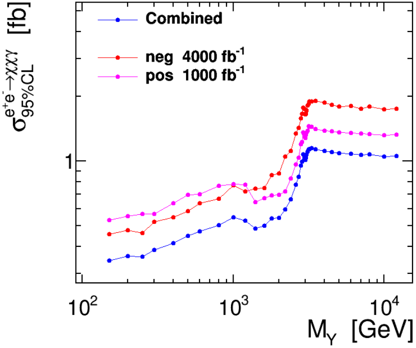
Limits calculated with CL_s approach using RooFit v3.60

Results

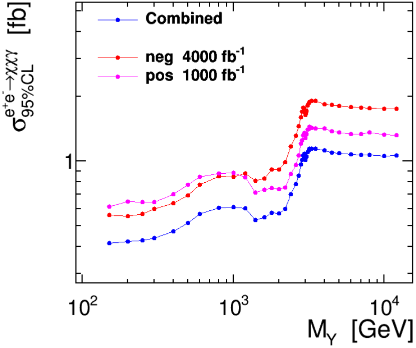
Cross section limits for radiative events (with tagged photon)

CLIC @ 3 TeV Mediator with $\Gamma/m = 3\%$ no systematics

Pseudo-scalar



Pseudo-vector

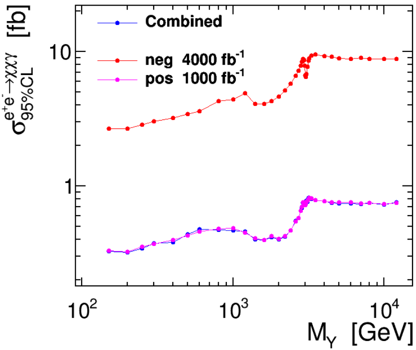


Limits calculated with CL_s approach using RooFit v3.60

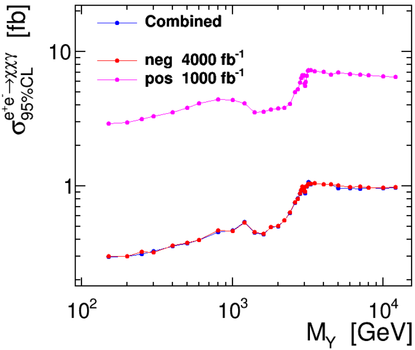
Cross section limits for radiative events (with tagged photon)

CLIC @ 3 TeV   Mediator with $\Gamma/m = 3\%$ no systematics

V+A coupling



V-A coupling



Limits calculated with CL_s approach using RooFit v3.60

Systematic uncertainties for CLIC

following CLICdp mono-photon study: arXiv:2103.06006

- Integrated luminosity uncertainty of 0.2%
  uncorrelated 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 the beam polarisation of 0.2%
  uncorrelated between polarisations
- Luminosity spectra shape uncertainty NEW!
  correlated between polarisations

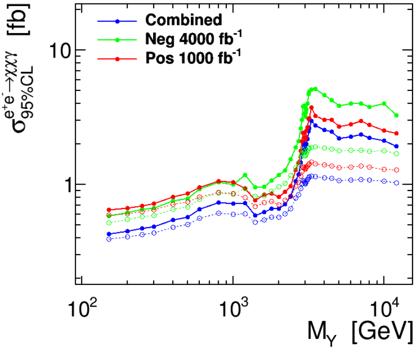
⇒ 7 nuisance parameters in the model fit to combined data

Results

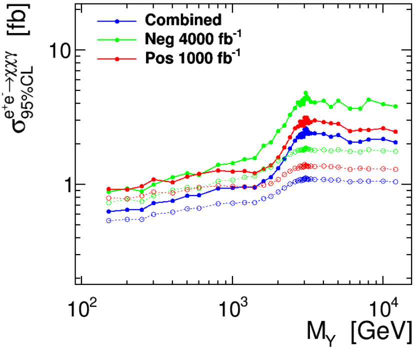
Cross section limits for radiative events (with tagged photon)

CLIC @ 3 TeV Vector Mediator with and without systematics

$\Gamma/M = 0.03$



$\Gamma/M = 0.5$

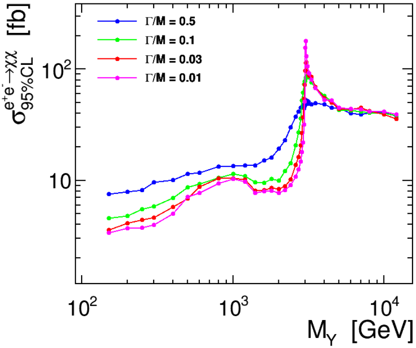


Systematic effects reduced for on-shell production of narrow mediator

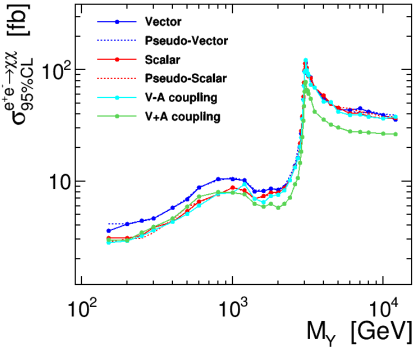
Cross section limits for total DM production cross section
Corrected for probability of hard photon tagging! see backup slides

Combined limits for CLIC @ 3 TeV

Vector mediator



Mediator with $\Gamma/m = 3\%$

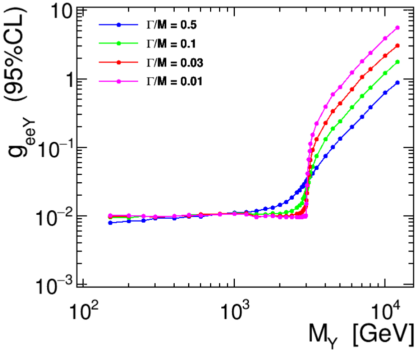


Radiation suppressed for narrow mediator with $M_Y \sim \sqrt{s} \Rightarrow$ weaker limits

Coupling limits with systematic uncertainties

Combined coupling limits for assumed mass and width of the mediator.

Vector mediator



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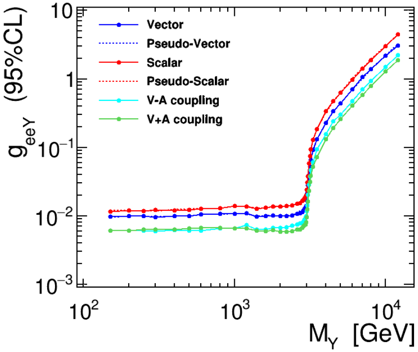

Almost uniform sensitivity to g_{eeY} up to kinematic limit.

Coupling limits with systematic uncertainties

Combined coupling limits for assumed mass and width of the mediator.

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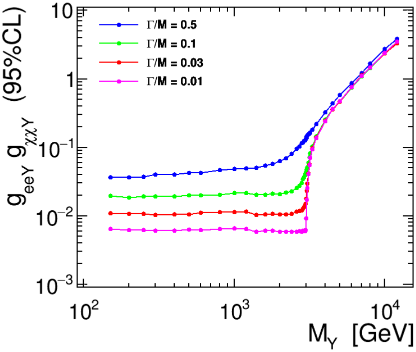
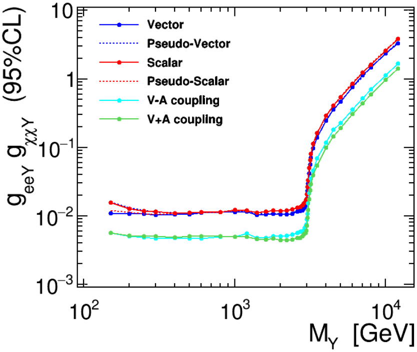


$\Gamma/M = 0.03$

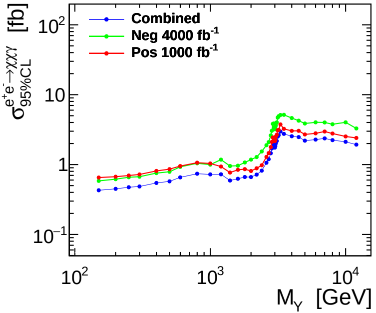


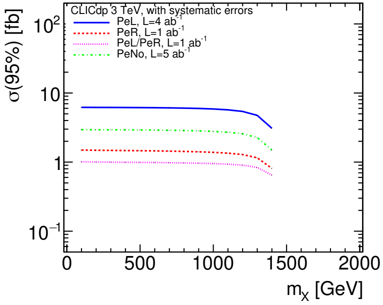
No width dependence for heavy mediators ⇒ EFT limit

Cross section limits for radiative events

Comparison of radiative cross section limits with results of the mono-photon analysis by J-J. Blaising et al. (arXiv:2103.06006)

Results should be consistent for $M_Y \gg \sqrt{s}$ (EFT limit)





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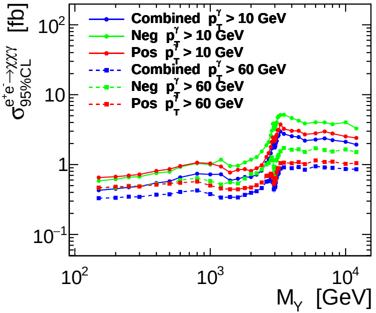
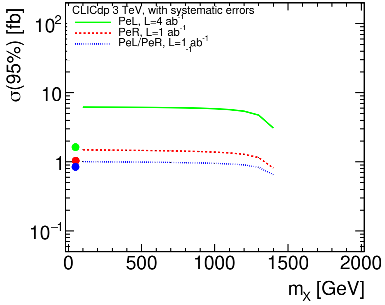




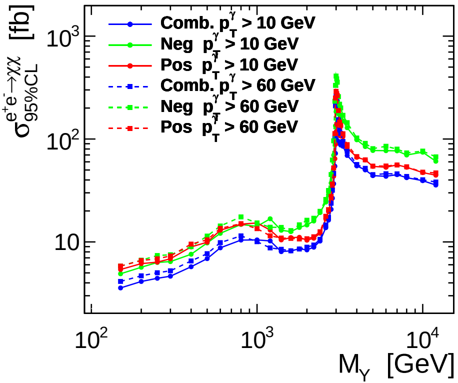
Radiative cross section limits depend on the phase space considered!

Combined limits in qualitative agreement...

taking into account remaining differences in the analysis

Cross section limits

Comparison of radiative cross section limits with results of the mono-photon analysis by J-J. Blaising et al. (arXiv:2103.06006)



High mass limits hardly depend on the p_T^γ selection cut, after correcting for the photon tagging efficiency

Conclusions

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

Systematic uncertainties taken into account following full simulation study

Mono-photon production at 3 TeV CLIC sensitive
to wide range of DM pair-production scenarios

- $\mathcal{O}(1\,\text{fb})$ 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 $M_Y \sim \sqrt{s}$
- $\mathcal{O}(10^{-2})$ 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!

Simulating mono-photon events

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

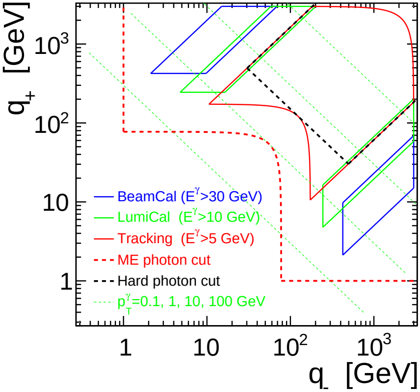
Two variables, calculated separately for each emitted photon:

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

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

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

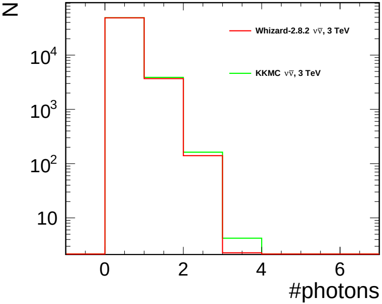
Detector acceptance $\sqrt{s} = 3\,\text{TeV}$

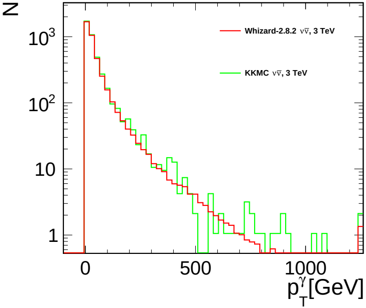


All "detectable" photons are simulated with Matrix Elements

Simulating mono-photon events Validation of the procedure

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





$\Rightarrow$ 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

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

Simplified DM model

Lagrangian describing mediator coupling to electrons given by

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

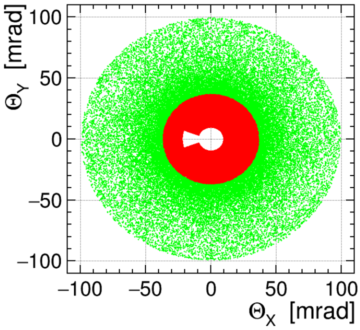
The interaction of mediators with dark matter is described by

$$\begin{aligned}\mathcal{L}_{XXY} \ni\ & g_{X_R Y_R} X_R^2 Y_R + \imath g_{X_C Y_V}(X^*_C(\partial_\mu X_C) - (\partial_\mu X^*_C)X_C)Y^\mu_V + \\ & \bar{X}_D(g^1_{X_D Y_R} + \imath\gamma^5 g^5_{X_D Y_R})X_D Y_R + \bar{X}_D\gamma_\mu(g^1_{X_D Y_V} + \gamma^5 g_{X_D Y_V})X_D Y^\mu_V \\ & \bar{X}_M(g^1_{X_M Y_R} + \imath\gamma^5 g^5_{X_M Y_R})X_M Y_R + g^5_{X_M Y_V}\bar{\psi}_M\gamma_\mu\gamma^5\psi_M Y^\mu_V\end{aligned}$$

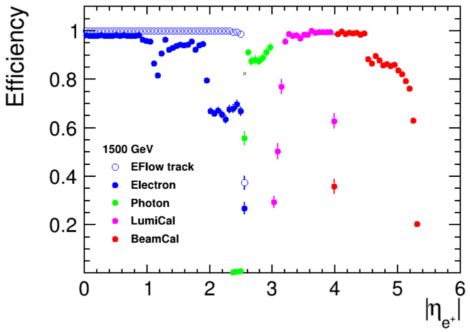
Detector simulation for CLIC running at 3 TeV

CLICdet model for Delphes also modified to include forward calorimeters

LumiCal + BeamCal



Reconstruction efficiency for $e^+e^- \to e^+e^-$

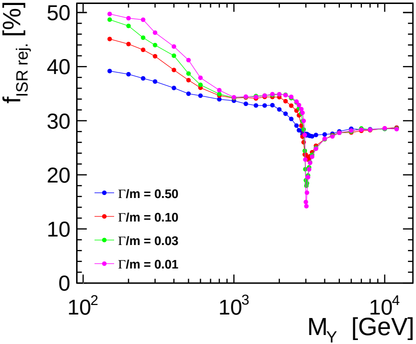


Included in the repository as `delphes_card_CLICdet_Stage3_fcal.tcl`

ISR rejection efficiency

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

CLIC @ 3 TeV



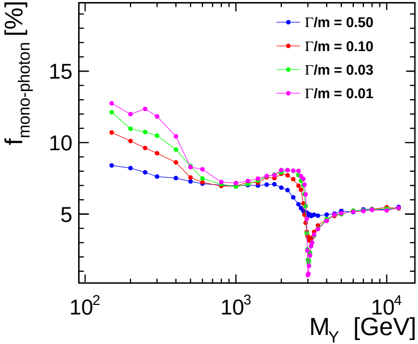
ISR emission enhanced for $M_Y < \sqrt{s}$, suppressed for $M_Y \sim \sqrt{s}$

Tagging efficiency

Detectable hard photon emitted only in a fraction of signal event

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

CLIC @ 3 TeV



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

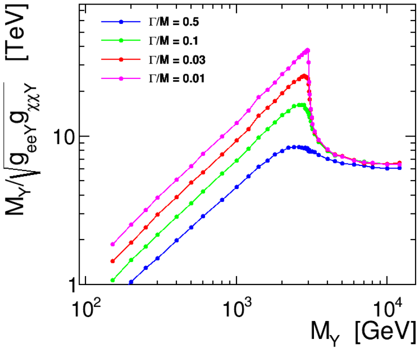
Effective mass scale limits

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

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



$\Gamma/M = 0.03$