The use of beam polarization in the search for dark matter at the ILC

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on behalf of the ILC International Development Team Physics and Detector Working Group

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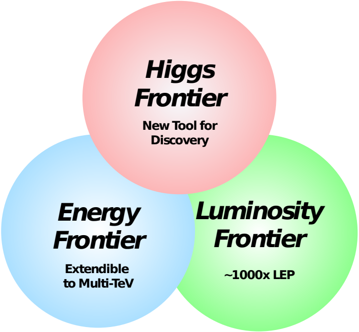
Dark Matter

Many hints for existence of Dark Matter (DM), but its nature is unknown.
Many possible scenarios, wide range of masses and couplings to consider.

ILC is a unique machine offering many options for DM searches.

This talk will focus on ILC sensitivity to DM particle pair-production with the mono-photon signature, $e^+e^- \rightarrow \chi\chi + \gamma$.

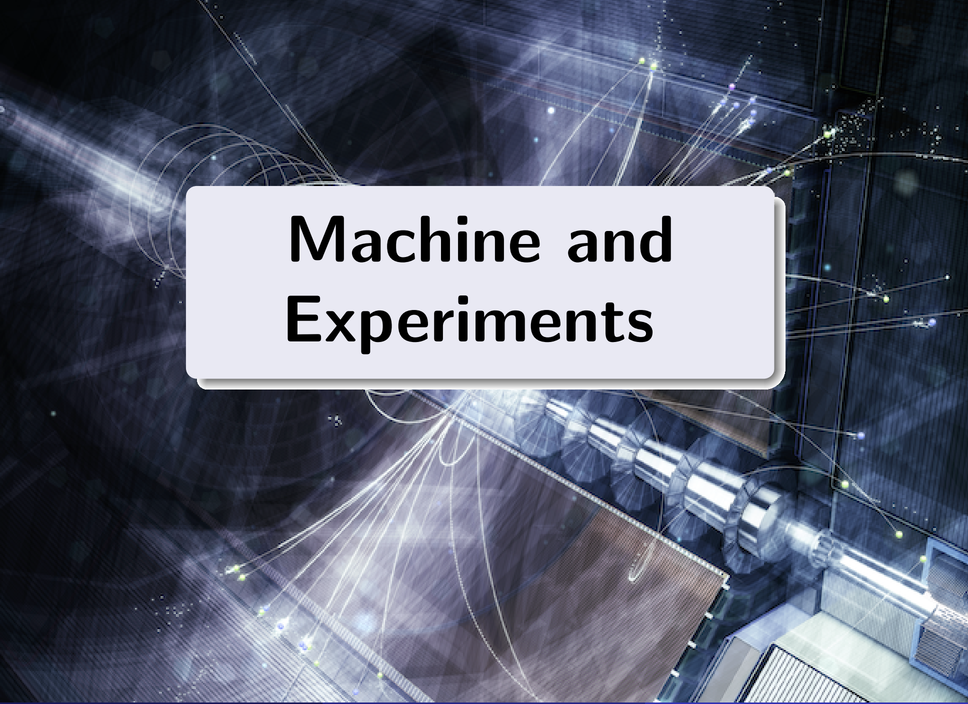
For overview of ILC capabilities in probing DM see my presentation at SUSY'2021



Tomohiko Tanabe @ LCWS'2021

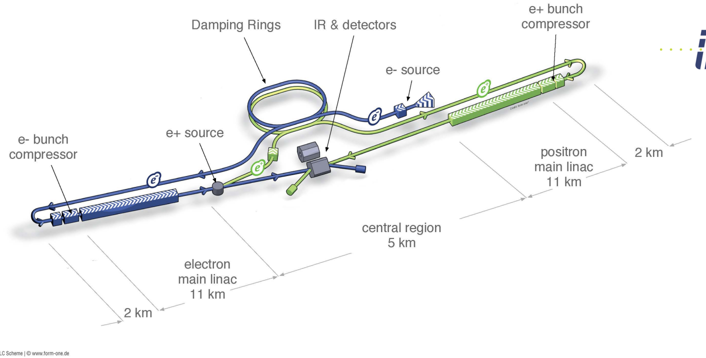
Cover image: Rey.Hori (copied from ILC Newsline)

Outline



Machine and Experiments

International Linear Collider



Technical Design (TDR) completed in 2013 arXiv:1306.6328

- superconducting accelerating cavities
- 250 – 500 GeV c.m.s. energy (baseline), 1 TeV upgrade possible
- polarisation for both e^- and e^+ (80%/30%)
- staged construction, starting as 250 GeV Higgs factory arXiv:1903.01629

Polarisation

The unique feature of the ILC is the possibility of having both electron and positron beams polarised! This is crucial for many precision measurements as well as BSM searches. Four independent measurements instead of one:

- increase accuracy of precision measurements
- more input to global fits and analyses
- remove ambiguity in many BSM studies
- reduce sensitivity to systematic effects

Integrated luminosity planned with different polarisation settings [fb^{-1}]

H-20 $\sqrt{s}$	sgn($P(e^-)$, $P(e^+)$) $(-,+)$	$(+,-)$	$(-,-)$	$(+,+)$	Total
250 GeV	900	900	100	100	2000
350 GeV	135	45	10	10	200
500 GeV	1600	1600	400	400	4000

arXiv:1903.01629

Detector Requirement

"Particle Flow" concept:

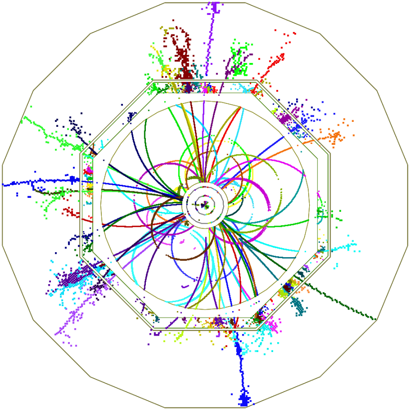
High calorimeter granularity
⇒ single particle reconstruction/ID

Precise momentum measurement
⇒ best energy for charged particles
⇒ dominates jet energy resolution

High precision vertex detector
⇒ very efficient flavour tagging

Instrumentation down to smallest angles
⇒ hermecity, missing energy tagging

Example event
$e^+e^- \to t\bar{t} \to 6j$

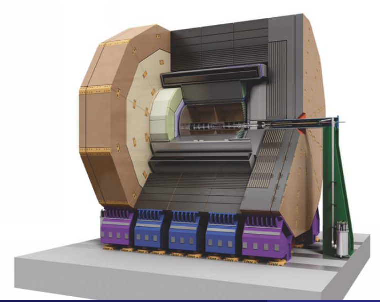


Detector Requirements

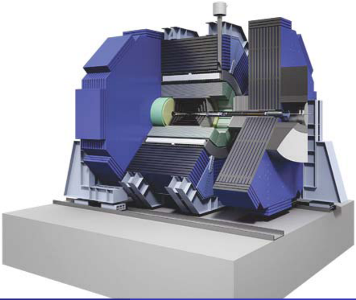
- Track momentum resolution: $\sigma_{1/p} < 5 \cdot 10^{-5}$ GeV^{-1}
- Impact parameter resolution: $\sigma_d < 5\mu m \oplus 10\mu m \frac{1\,\mathrm{GeV}}{p\ \sin^{3/2}\Theta}$
- Jet energy resolution: $\sigma_E/E = 3 - 4\%$ (for highest jet energies)
- Hermecity: $\Theta_{min} = 5$ mrad

Two detailed ILC detector concepts:

ILD



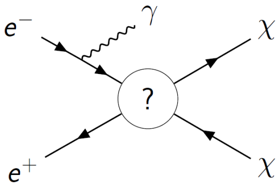
SiD

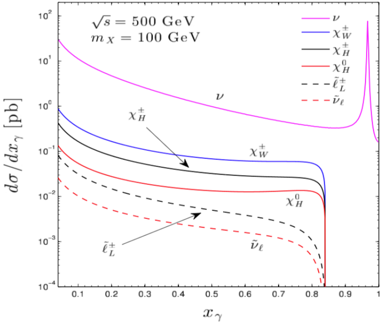


Mono-photon events

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...

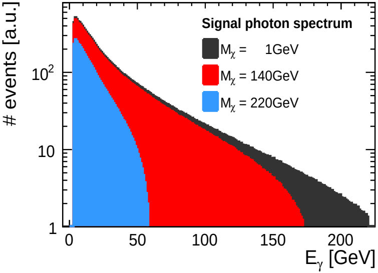
Mono-photon events

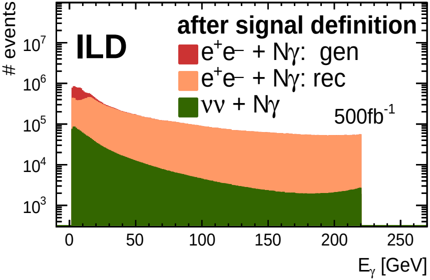
Heavy mediator study (full simulation) arXiv:2001.03011

Scenarios with heavy mediator and coupling values $\mathcal{O}(1)$ (EFT limit)

Signature: single photon in an "empty" detector

Main backgrounds: radiative Bhabha and neutrino pair-production





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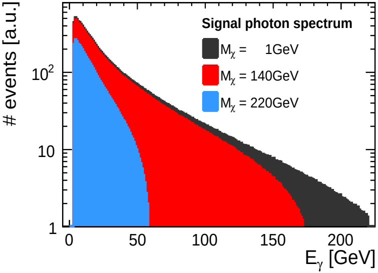
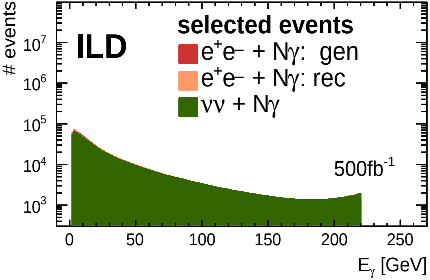


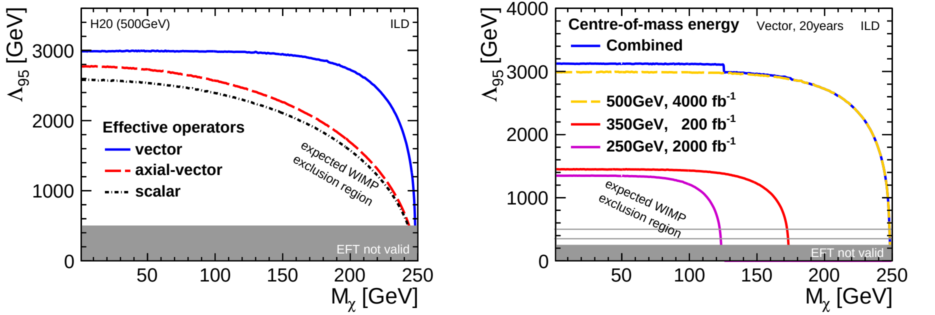


"Irreducible" background from radiative neutrino pair-production events $e^+e^- \rightarrow \nu\nu + N\gamma$ dominates after selection and bg suppression cuts

Heavy mediator study (full simulation) arXiv:2001.03011

Scenarios with heavy mediator and coupling values $\mathcal{O}(1)$ (EFT limit)

Mass scale limits based on combined analysis of data taken with different electron and positron beam polarisation combinations.



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

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

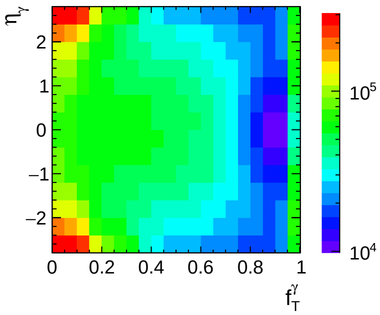
Light mediator scenarios (fast simulation)

arXiv:2107.11194

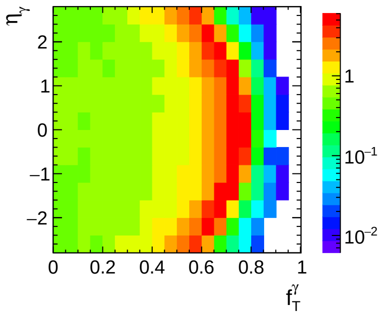
Still not excluded for very small mediator couplings to SM, $\Gamma_{SM} \ll \Gamma_{tot}$

Measured 2D distribution of $(p_T^\gamma, \eta^\gamma)$ used to constrain DM production cross section as a function of mediator mass and width

Background



Signal



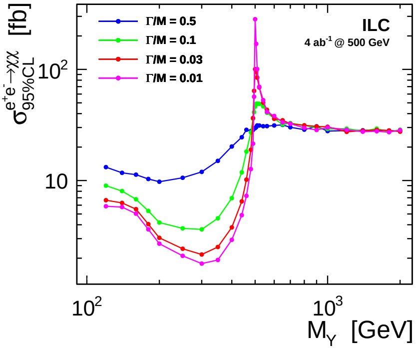
ILC 500 GeV (-80%/+30%) 1600 fb^{-1} $M_Y = 400$ GeV, $\Gamma/M = 0.03$

Mono-photon events

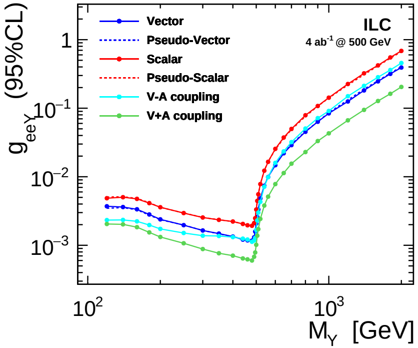
Light mediator scenarios (fast simulation) arXiv:2107.11194

Combined limits for ILC @ 500 GeV

Limits on total DM production cross section for Vector mediator



SM coupling limits for different mediator types, $\Gamma/M = 0.03$



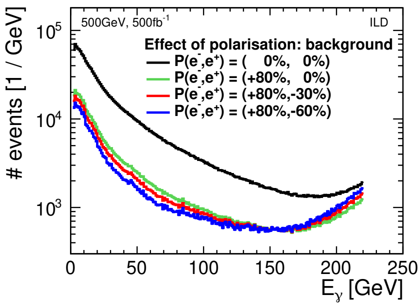
Impact of polarisation

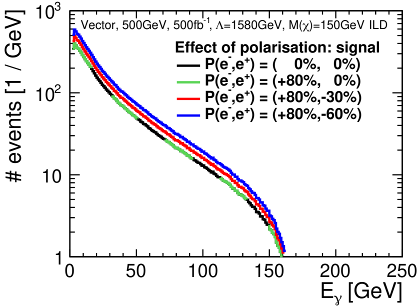
Impact of polarisation

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

arXiv:2001.03011





It can also enhance mono-photon signal (depending on the scenario).

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

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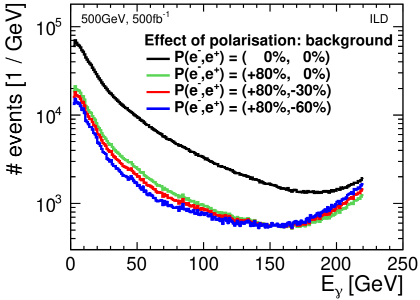
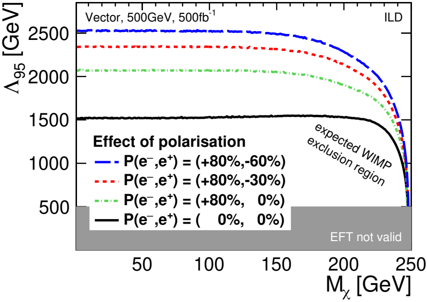




Mass scale limits improve significantly with proper choice of polarisation.

Impact of polarisation

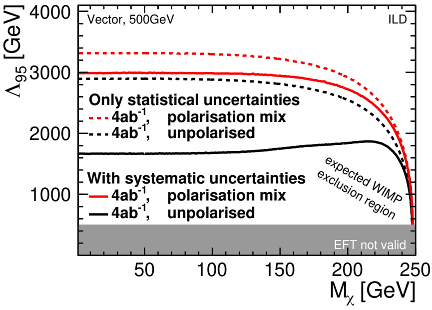
Mediator coupling structure unknown

⇒ need to combine data taken with different polarisation combinations

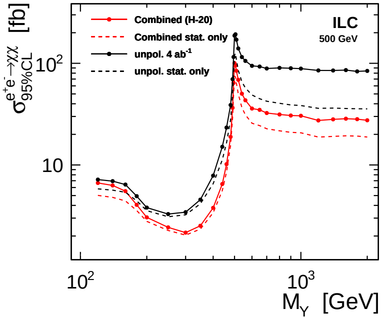
Combination results in best sensitivity to all scenarios

but also significantly reduces the impact of systematic uncertainties

Heavy mediator exchange



Light mediator exchange

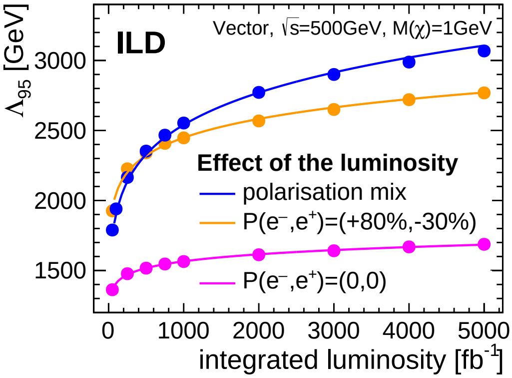


Impact of polarisation

By combining four independent data sets taken with different polarisation combinations systematic uncertainties can be significantly reduced

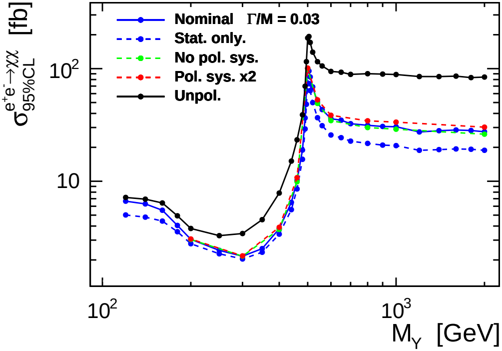
We profit from precision of polarisation dependence predictions for SM bg

Combined limits statistics limited up to the highest integrated luminosities

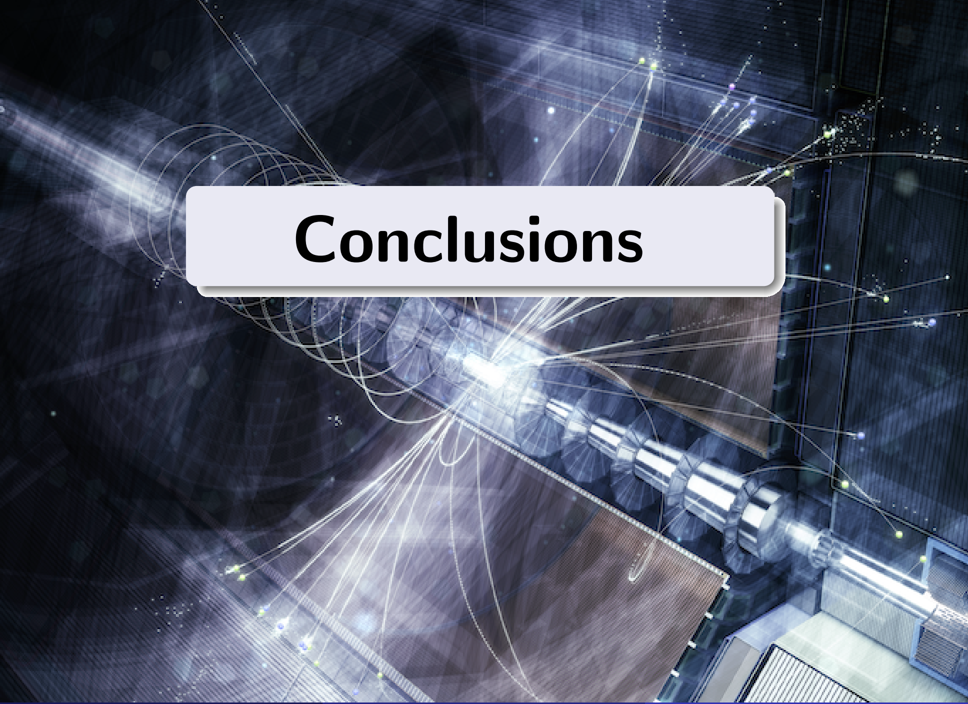


By combining the polarimeter measurements with precision SM measurements beam polarisation can be extracted with precision down to 0.2 per mille

Impact of polarisation uncertainty on DM sensitivity is much smaller than that of other systematic uncertainties.



Conclusions



Conclusions

Beam polarization in dark matter searches at the ILC

ILC will offer many complementary options for DM searches.

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

EFT sensitivity extending up to the $\mathcal{O}(10)$ TeV mass scales
order of magnitude higher than the collision energy

Sensitivity to the mediator coupling to electrons down to $\mathcal{O}(10^{-3})$
up to the kinematic limit $M_Y \leq \sqrt{s}$

Beam polarisation can be used to control background levels and significantly increases sensitivity to DM production

By combining data collected with different polarisation impact of systematic uncertainties can be significantly reduced

Thank you!

References

Recent documents

- Proposal for the ILC Preparatory Laboratory (Pre-lab) arXiv:2106.00602
- ILC Study Questions for Snowmass 2021 arXiv:2007.03650
- International Large Detector: Interim Design Report arXiv:2003.01116
- Tests of the Standard Model at the International Linear Collider arXiv:1908.11299

European Strategy submissions

- The International Collider. A Global Project submission, arXiv:1903.01629
- The International Collider. An European perspective submission
- The ILD Detector at the ILC submission, arXiv:1912.04601

Other reports

- The role of positron polarization for the inital 250 GeV stage of the International Linear Collider arXiv:1801.02840
- The International Linear Collider Machine Staging Report 2017 arXiv:1711.00568
- Physics Case for the 250 GeV Stage of the International Linear Collider arXiv:1710.07621
- The Potential of the ILC for Discovering New Particles arXiv:1702.05333
- The International Linear Collider Technical Design Report Volume 3.II: Accelerator Baseline Design arXiv:1306.6328
- The International Linear Collider Technical Design Report Volume 4: Detectors arXiv:1306.6329

Links

General

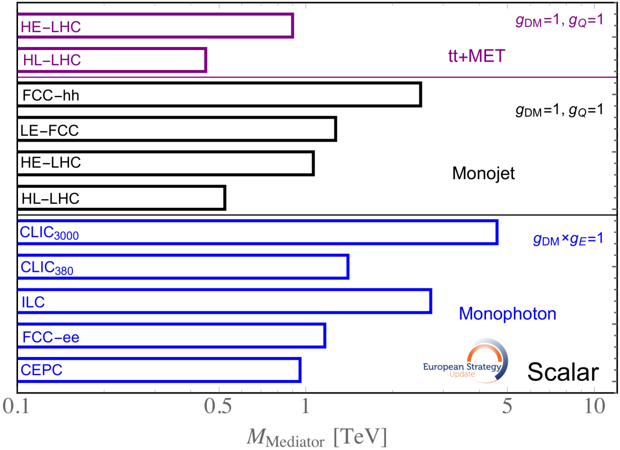
- ILC International Development Team https://linearcollider.org/
- ILC Newsline http://newsline.linearcollider.org/
- ILC IDT Working Group 3 (Physics and Detectors) https://linearcollider.org/team/wg3/ also including many links to subgroups, indico sites etc.
- ILC Simulation Resources for Snowmass 2021 http://ilcsnowmass.org/ including links to past tutorials and large sets of generated events samples
- SiD detector concept for ILC http://silicondetector.org
- ILD detector concept for ILC https://www.ilcild.org/ https://confluence.desy.de/display/ILD/ILD

Software tools

- repository https://whizard.hepforge.org/
- ILC beam spectra files for https://whizard.hepforge.org/circe_files/ILC/
- repository https://github.com/delphes/delphes
- wiki https://cp3.irmp.ucl.ac.be/projects/delphes
- ILCgen model documentation https://github.com/iLCSoft/ILCDelphes
- LCIO package at github https://github.com/iLCSoft/LCIO
- Delphes2LCIO documentation https://github.com/iLCSoft/LCIO/tree/master/examples/cpp/delphes2lcio

Prospects for Dark Matter searches

Comparison of extracted mediator mass limits



ILC 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.

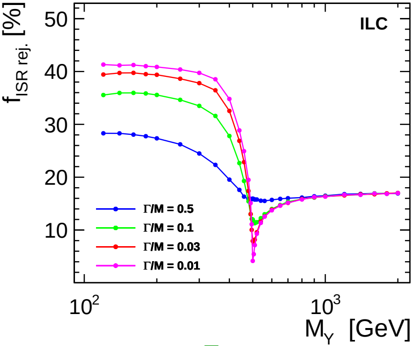
Each simplified scenario is characterized by one dark matter candidate and one mediator from the set listed below:

	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

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)

ILC @ 500 GeV



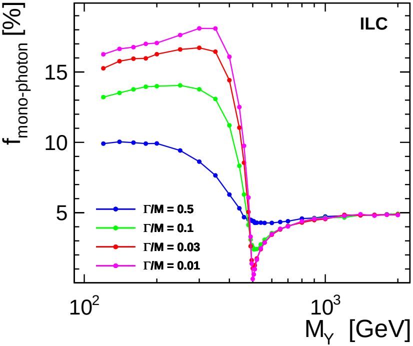
ISR emission enhanced for $M_Y < \sqrt{s}$, suppressed for $M_Y \sim \sqrt{s}$

Tagging efficiency

Detectable hard photon emitted only in a fraction of signal event

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

ILC @ 500 GeV



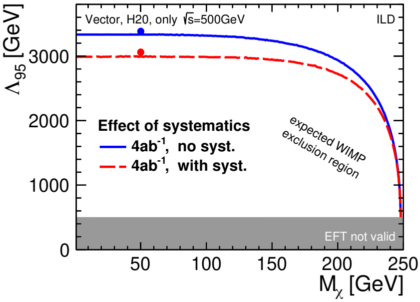
Emission strongly suppressed for narrow mediator with $M_Y \sim \sqrt{s}$

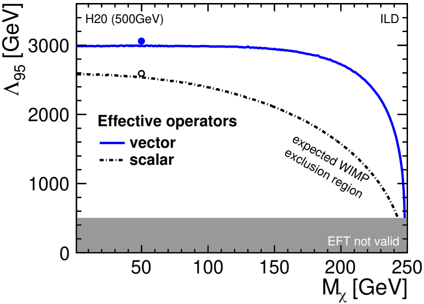
Mono-photon events

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...