Probing Dark Matter with ILC

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

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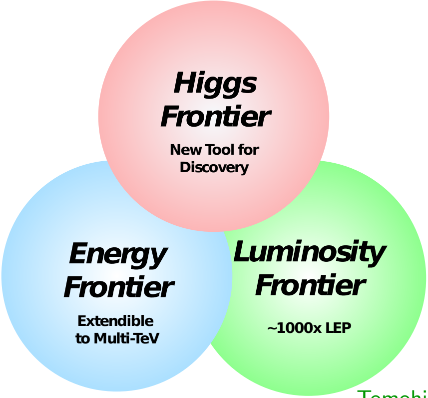
Dark Matter

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 an unique machine offering many options for DM searches:

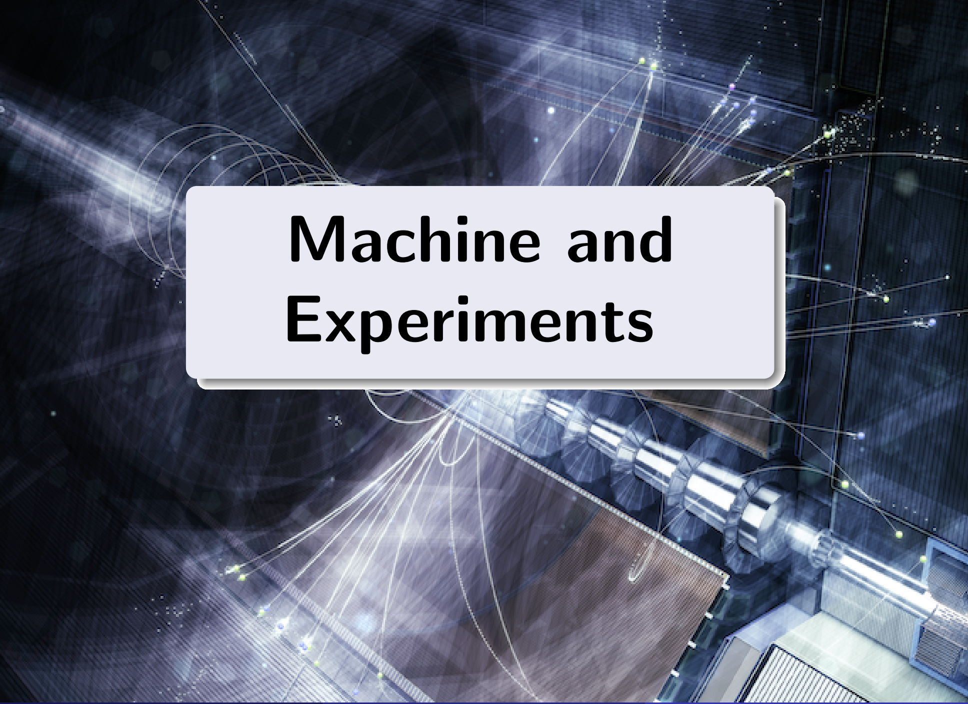


Tomohiko Tanabe @ LCWS'2021

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

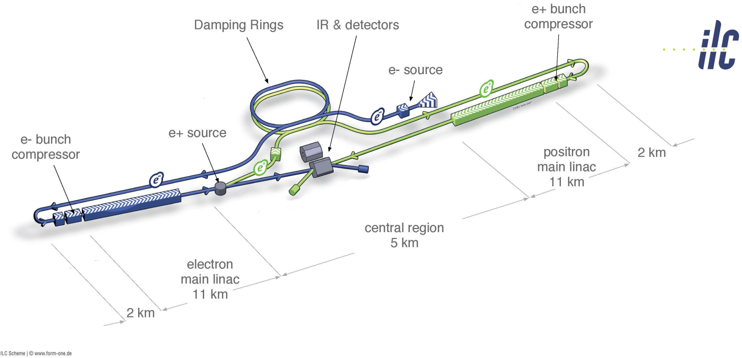
Outline

1. Machine and Experiments
2. Collider searches
   - Higgs measurements
   - Mono-photon events
3. Non-collider experiments
4. Conclusions
   - References and links



Machine and Experiments

International Linear Collider

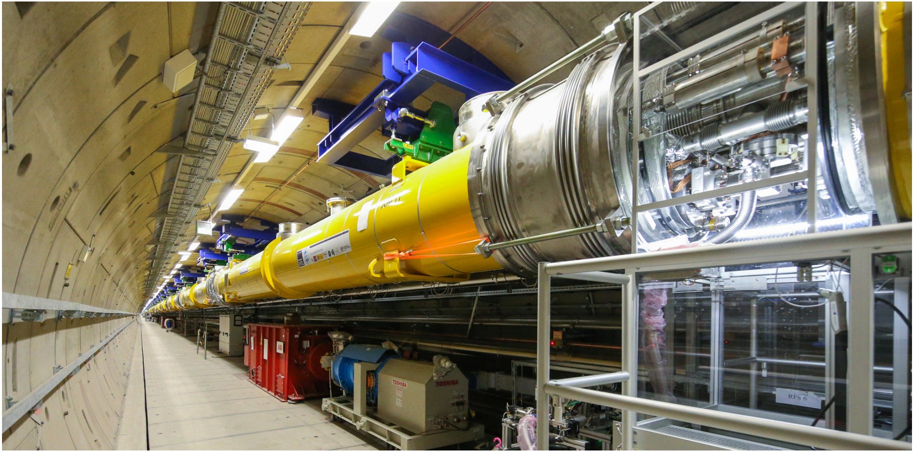


Technical Design (TDR) completed in 2013 arXiv:1306.6328

- superconducting accelerating cavities
- 250 – 500 GeV c.m.s. energy (baseline), 1 TeV upgrade possible
- footprint 31 km
- polarisation for both e^- and e^+ (80%/30%)

E-XFEL first X-ray laser flashes in May 2017

Largest ever accelerator prototype: ILC-250 arm in 1:7 scale (17.5 GeV)



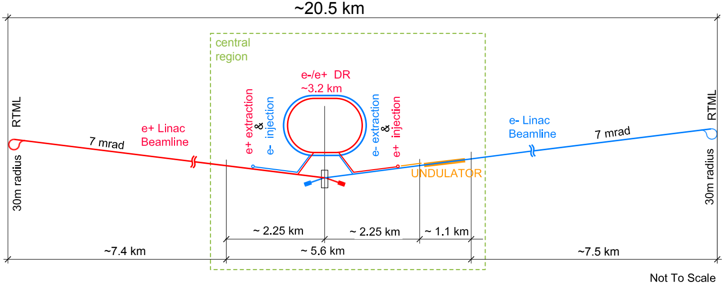
All construction issues verified. Full industrialization of cavity production.

ILC-250

The discovery of a Higgs Boson with a mass of 125 GeV opened the possibility of reducing ILC cost by starting at a centre-of-mass energy of 250 GeV with the possibility of future upgrades to 500 GeV or even 1 TeV.

arXiv:1711.00568

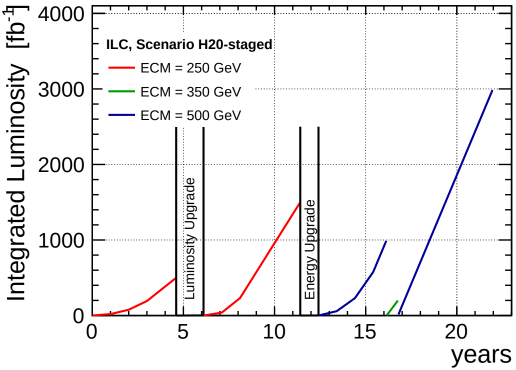
“Higgs-factory” layout 250 GeV optimal for Higgs production



arXiv:1903.01629

International Linear Collider

Baseline running scenario for staged ILC construction



arXiv:1903.01629

Total integrated luminosities same as in original H-20 proposal for ILC-500!

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
- remove ambiguity in many BSM studies
- reduce sensitivity to systematic effects

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

$\sqrt{s}$	$\text{sgn}(P(e^-), P(e^+))$			
	(−,+)	(+,−)	(−,−)	(+,+)
250 GeV	900	900	100	100
350 GeV	135	45	10	10
500 GeV	1600	1600	400	400

arXiv:1903.01629

ILC Preparatory Laboratory (Pre-Lab) proposal

In August 2020 the International Committee for Future Accelerators (ICFA) setup the ILC International Development Team (IDT).

The Team is hosted by the High Energy Accelerator Research Organization (KEK) in Japan and its mandate is to make preparations for the ILC Preparatory Laboratory (Pre-Lab) in Japan, as the first step of the preparation phase of the ILC to be constructed as an international project.

In June 2021 the Pre-lab proposal was submitted to the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan.

The proposal and the supporting documents are now under review by the MEXT advisory panel.

$\Rightarrow$ we do hope for the positive response...

Pre-Lab will allow to finalise the machine design, clarify all formal and organisational issues and prepare for the final decision on the ILC construction

Detector Requirement

"Particle Flow" concept:

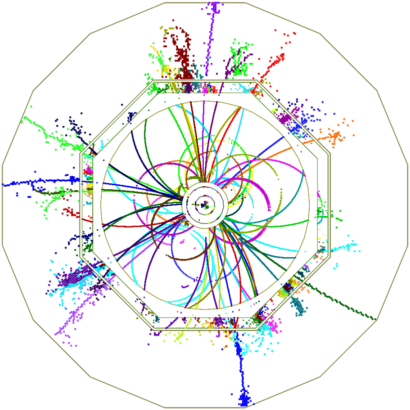
High calorimeter granularity
⇒ single particle reconstruction/ID

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

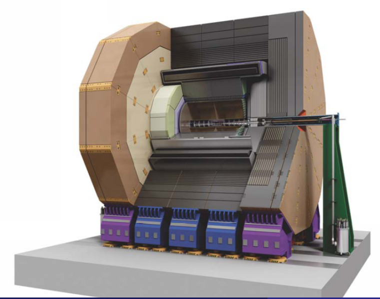


Detector Requirements

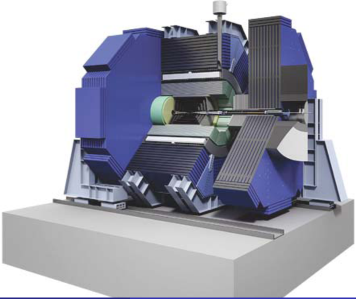
- Track momentum resolution: $\sigma_{1/p} < 5 \cdot 10^{-5}\ \mathrm{GeV}^{-1}$
- Impact parameter resolution: $\sigma_d < 5\mu m \oplus 10\mu m \frac{1\ \mathrm{GeV}}{p\ \sin^{3/2}\Theta}$
- Jet energy resolution: $\sigma_E/E = 3 - 4\%$ (for highest jet energies)
- Hermecity: $\Theta_{min} = 5$ mrad

Two detailed ILC detector concepts:

ILD



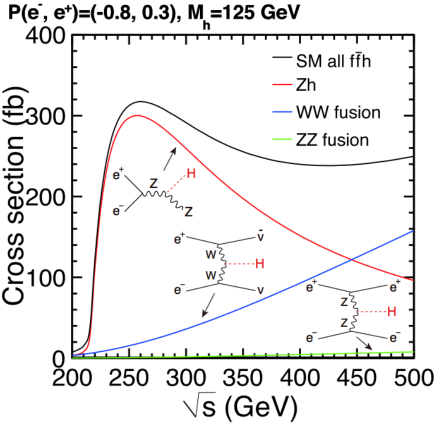
SiD



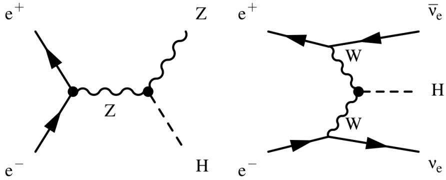
Collider searches

First ILC running stage will clearly be focused on Higgs measurements

Production cross section



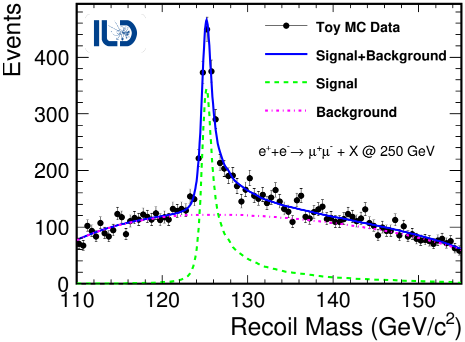
At 250 GeV dominated by Higgs-strahlung (ZH production)



but we still profit from combining two production channels
$\Rightarrow$ model independent analysis

Event reconstruction

In the ZH production channel (dominating below 450 GeV) we can use "Z-tagging" for unbiased selection of Higgs production events

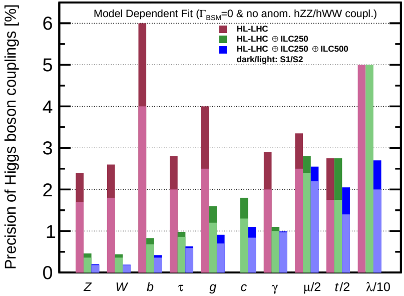


We avoid any dependence on the Higgs decay channel!

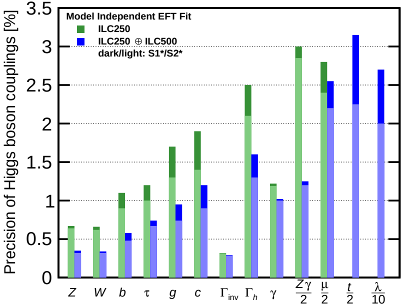
Higgs couplings

ILC sensitivity to the different Higgs boson couplings
compared with the HL-LHC projections

Model-dependent analysis



Model-independent analysis



arXiv:1903.01629

Sub-percent level precision already at the first energy stage

Invisible decays

In Higgs-portal models, new scalars fields ϕ coupling to dark matter particles can mix with the SM Higgs field h resulting in two mass eigenstates:

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ \phi \end{pmatrix}$$

If $\alpha \ll 1$, h_1 is SM-like (the observed 125 GeV state),
but it can also decay invisibly via ϕ component (BR $\sim \sin^2\alpha$)

$\Rightarrow$ search for invisible Higgs decays

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$\Rightarrow$ search for invisible Higgs decays

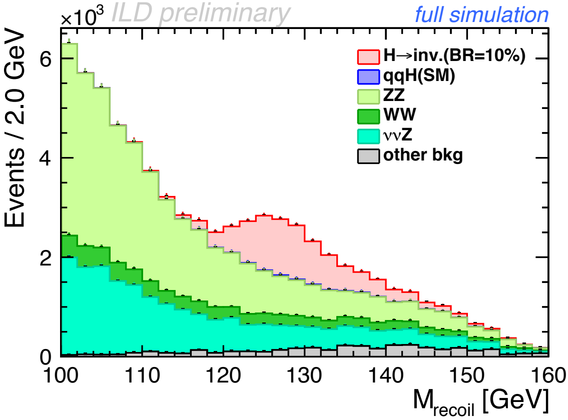
If h_2 is also light, it can be produced in e^+e^- collisions in the same way as the SM-like Higgs boson.

$\Rightarrow$ search for additional scalar states

Visible in recoil mass distribution even, if invisible decays dominate.

Invisible decays

High sensitivity to invisible Higgs boson decays with recoil mass technique



Expected 95% C.L. limit for 2 ab^{-1} collected at 250 GeV ILC: 0.23%

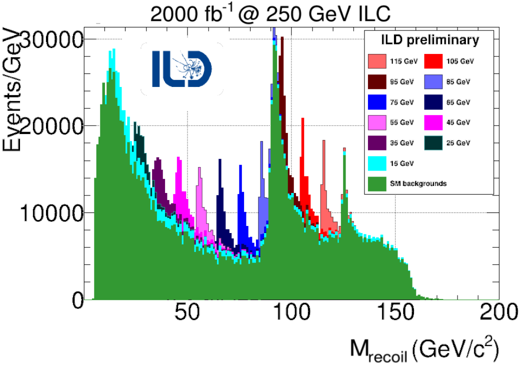
a factor of 10 better than the HL-LHC prospect. arXiv:2002.12048

Search for new scalars

Many BSM models introduce extended Higgs sectors.

New scalars could be light, if their couplings to SM particles are small.

Search for production of new scalars: arXiv:1903.01629 arXiv:2005.06265



Search independent on the scalar decay: $e^+e^- \to Z\ S^0 \to \mu^+\mu^- + X$

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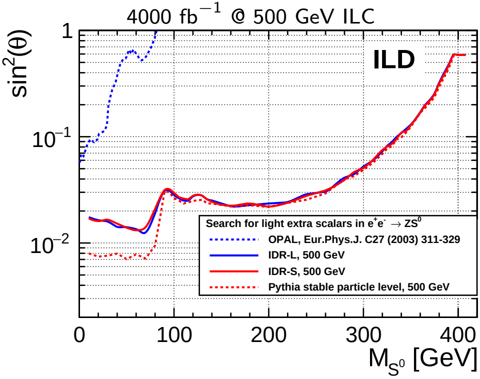
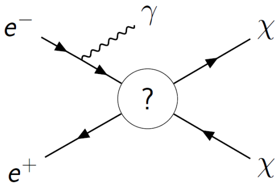
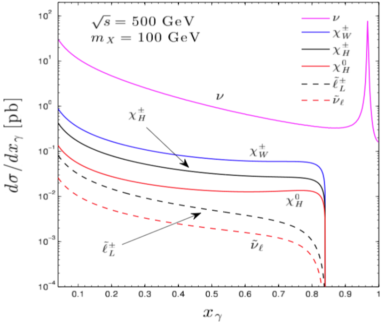


Search independent on the scalar decay: $e^+e^- \to Z\, S^0 \to \mu^+\mu^- + X$

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

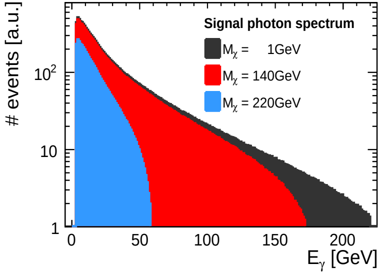
This process can be detected, if additional hard photon radiation from the initial state is observed in the detector...

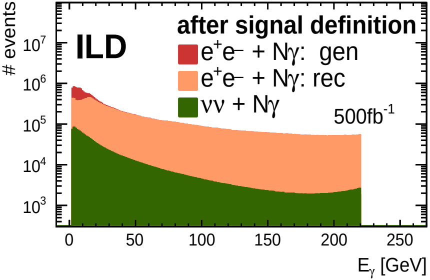
Heavy mediator study (full simulation) arXiv:2001.03011

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





Mono-photon events

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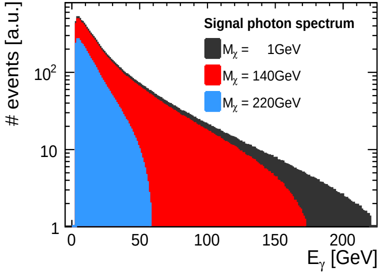
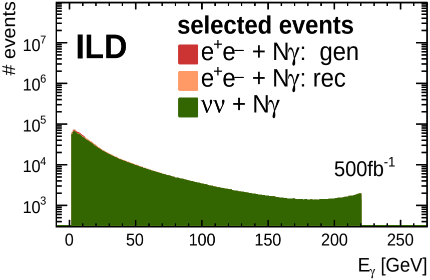




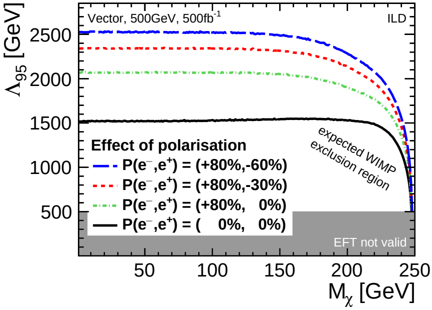
"Irreducible" background from radiative neutrino pair-production events $e^+e^- \to \nu\nu + \mathrm{N}\gamma$ dominates after selection and bg suppression cuts

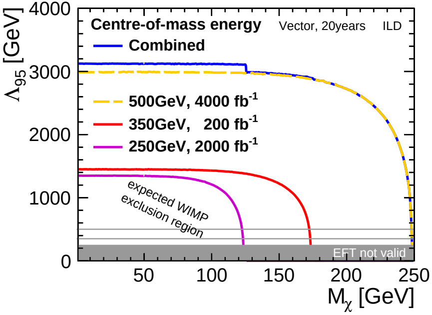
Mono-photon events

Heavy mediator study (full simulation) arXiv:2001.03011

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

Different polarisation combinations help to reduce the systematics
⇒ significant improvement of mass scale limits



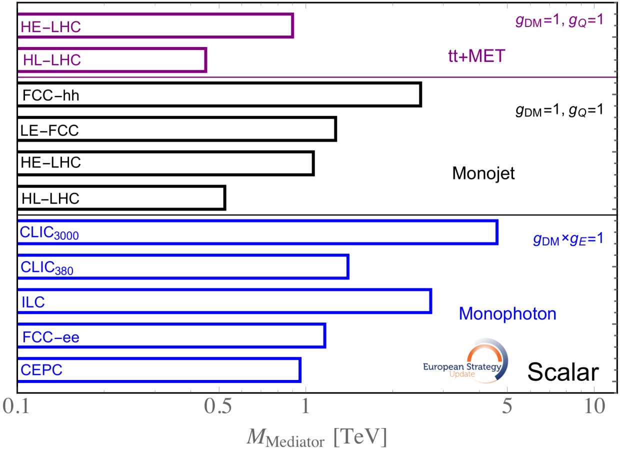


Sensitivity to the BSM mass scales up to $\Lambda \sim$3 TeV

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

Dark Matter searches

Comparison of extracted mediator mass limits



ILC mass reach comparable with that of FCC-hh !!!

Light mediator study

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
⇒ focus on cross section limits as a function of mediator mass and width

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

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

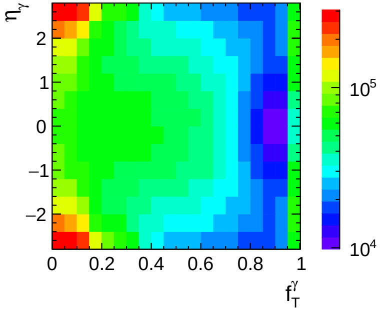
More details given yesterday in Dark Matter and Astroparticle Physics session: "Sensitivity of future e^+e^- colliders to processes of dark matter production with light mediator exchange", presented by Jan Kalinowski, contribution #280

Background vs Signal distributions

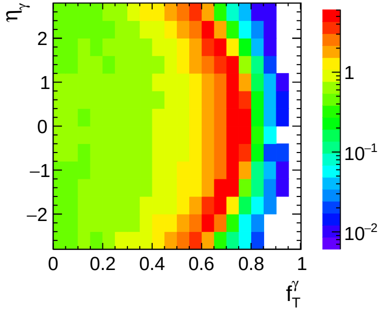
arXiv:2107.11194

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, $\Gamma/M = 0.03$

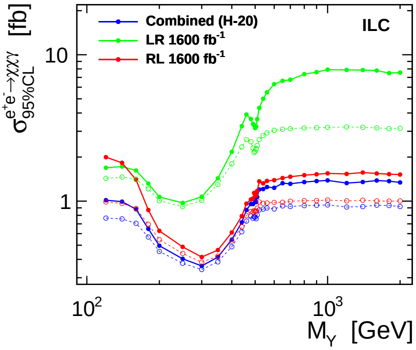
Signal normalised to unpolarised DM pair-production cross section of 1 fb

Mono-photon events

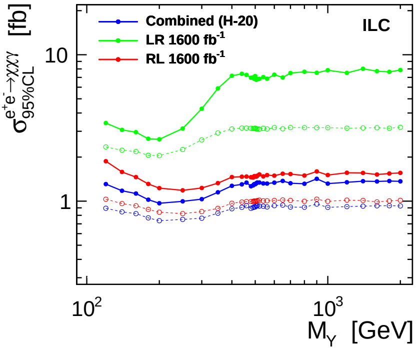
Cross section limits for radiative events (with tagged photon)

ILC @ 500 GeV Vector Mediator with and without systematics

$\Gamma/M = 0.03$



$\Gamma/M = 0.5$



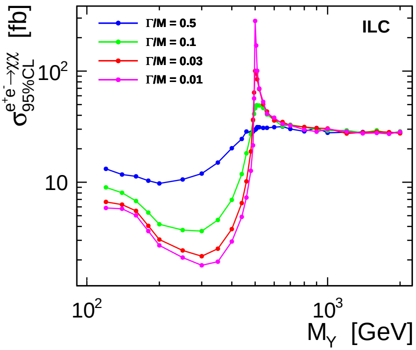
Systematic effects reduced for on-shell production of narrow mediator

Cross section limits for total DM production cross section

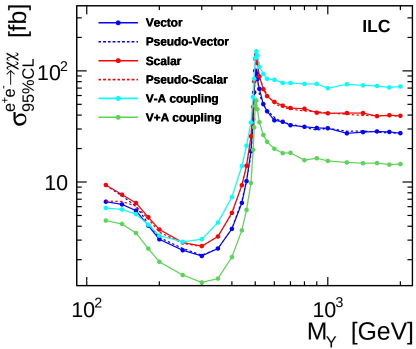
Corrected for probability of hard photon tagging! see backup slides

Combined limits for ILC @ 500 GeV, H-20 scenario

Vector mediator



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

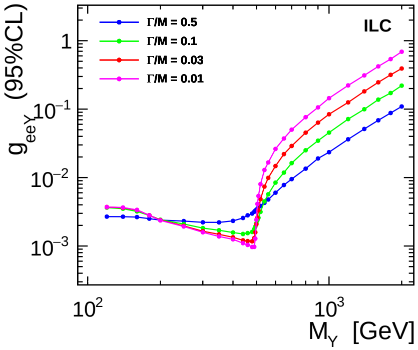


Radiation suppressed for narrow mediator with $M_Y \sim \sqrt{s} \Rightarrow$ weaker limits

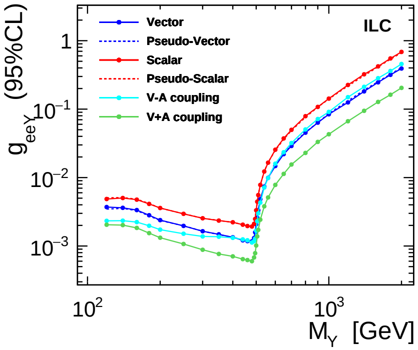
Coupling limits with systematic uncertainties

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

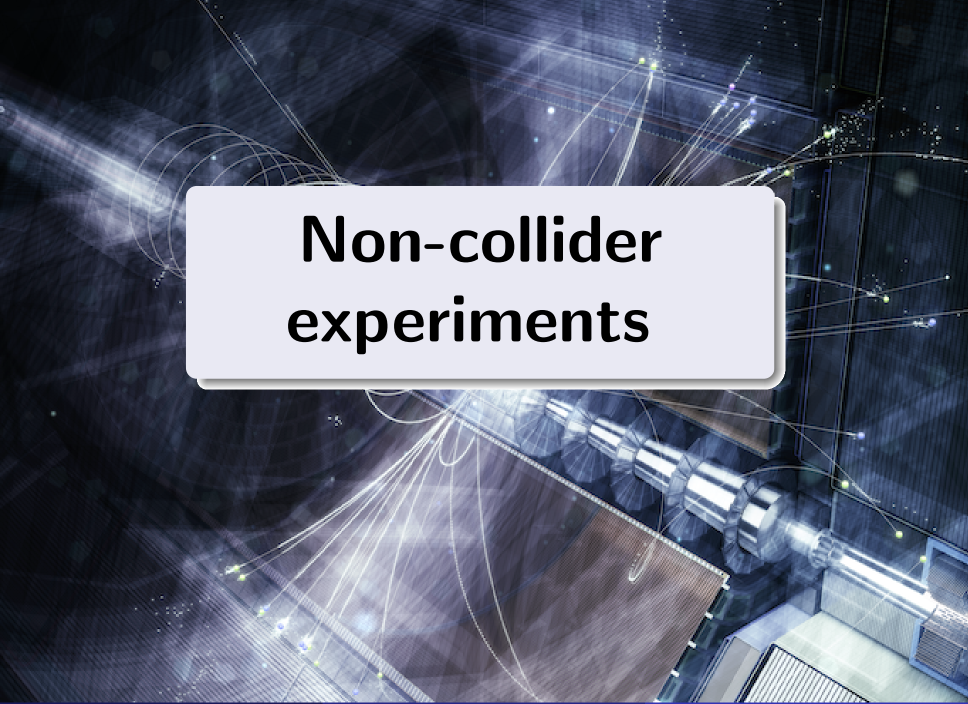
Vector mediator



$\Gamma/M = 0.03$



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

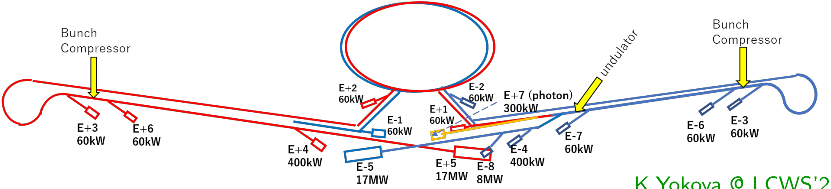


Non-collider experiments

ILC beam dumps

Electron and positron beams, with extreme intensities ($\sim 10^{22} e^{\pm}/y$)

Many beam dump points planned around the ILC facility



K.Yokoya @ LCWS'2021

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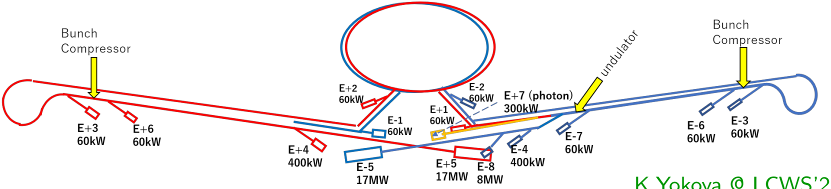
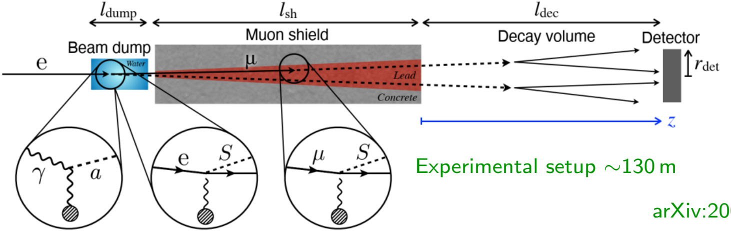


K.Yokoya @ LCWS'2021

Concept of main beam dump experiments searching for axion-like particles or new scalars:

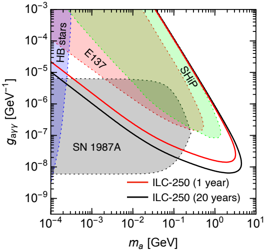


Experimental setup ~130 m

arXiv:2009.13790

Main beam dump experiments

Looking for SM decays of new exotic particles produced in the beam dump
arXiv:2009.13790



Axion-like particle model   looking for $a \to \gamma\gamma$

$$\mathcal{L} \ni -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2} m_a^2 a^2$$

An order of magnitude better sensitivity than other experiments

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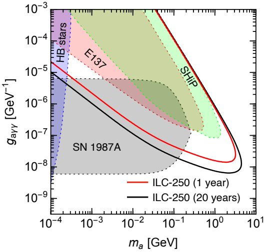

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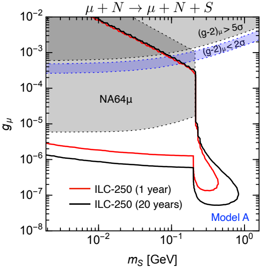


Light scalar coupled to charged leptons

$$\mathcal{L} \ni \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2} m_S^2 S^2 - \sum_{l=e,\mu,\tau} g_l S \bar{l} l$$

Model A: $g_l \propto m_l$

Sensitivity down to very small couplings

Main beam dump experiments

M.Perelstein @ LCWS'2021

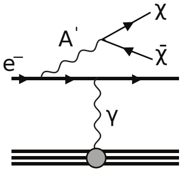
Scenarios with Dark Photon (A') and Dirac fermion DM (χ)

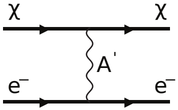
$$\mathcal{L} \ni -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m^2_{A'} A'_\mu A'^\mu - \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} + \bar{\chi}(\imath D - m_\chi)\chi$$

Resonant ($e^+e^- \to A'$), associated prod. ($e^+e^- \to A' \gamma$) or radiation ($e^\pm N \to e^\pm N A'$)

$\Rightarrow$ collimated stream of DM particles from A' decay ($A' \to \chi\chi$)

$\Rightarrow$ looking for elastic χ interactions in the detector





Approach used in SLAC Beam Dump Experiment E137

arXiv:1406.2698

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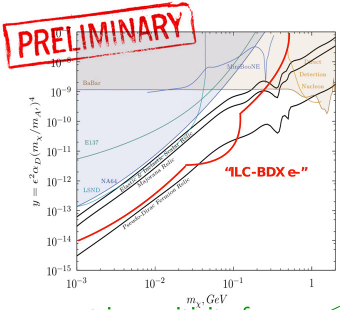
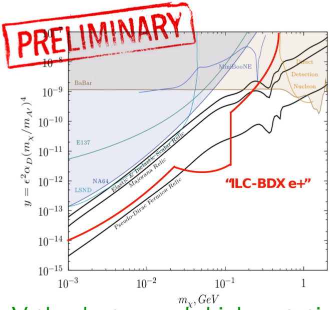
Scenarios with Dark Photon (A') and Dirac fermion DM (χ)

$$\mathcal{L} \ni -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'_\mu A'^\mu - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \bar{\chi}(\imath D - m_\chi)\chi$$

Resonant ($e^+e^- \to A'$), associated prod. ($e^+e^- \to A'\,\gamma$) or radiation ($e^\pm\, N \to e^\pm\, N\, A'$)
$\Rightarrow$ collimated stream of DM particles from A' decay ($A' \to \chi\chi$)
$\Rightarrow$ looking for elastic χ interactions in the detector





Huge improvement in sensitivity for $m_{A'} \lesssim 1$ GeV thanks to much higher statistics

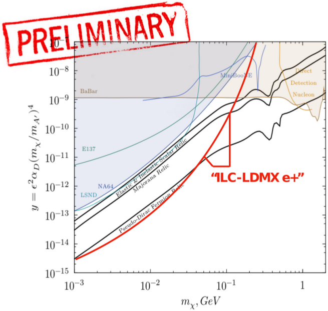
Experiments with extracted beams

M.Perelstein @ LCWS'2021

Searching for Dark Photons with extracted positron beams

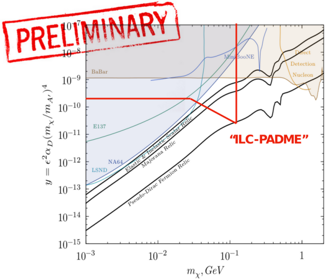
$$e^+e^- \rightarrow A'\gamma$$

Missing energy reconstruction in thick active target



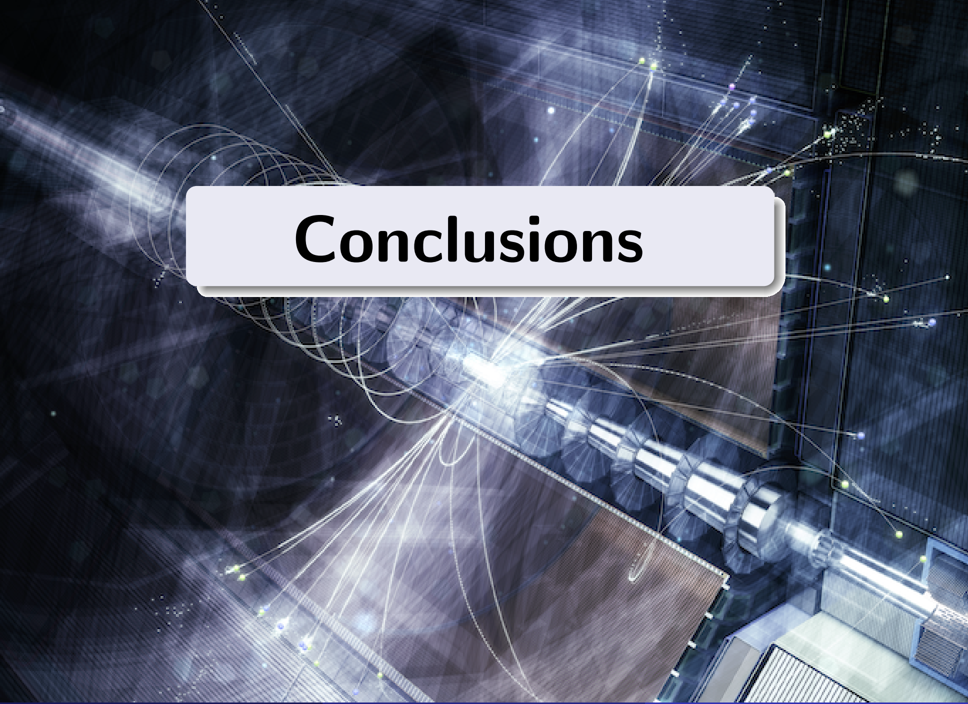
LDMX for SLAC: arXiv:1807.05884

Thin target, missing mass reconstruction in dedicated detector



PADME @ Frascati: arXiv:1910.00764

Sensitivity extending down to the minimum couplings allowed by relic density bounds



Conclusions

Probing Dark Matter with ILC

ILC will offer many complementary options for DM searches.

- Different scenarios can be constrained via precision Higgs studies.
- Clean environment and kinematic constraints of e^+e^- collisions result in high sensitivity to different DM production scenarios.
- Sensitivity extends to the TeV mass scales,
  order of magnitude higher than the collision energy.

The ILC will also offer highest energy electron and positron beams, with unprecedented intensities, for beam dump and extracted beam exp.

Fixed-target experiments offer many interesting opportunities for dark sector searches in the low mass domain and other science goals.

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

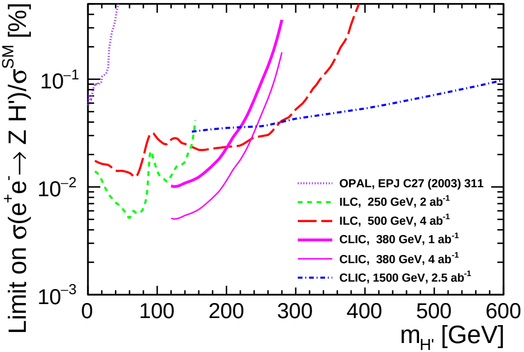
- repository https://whizard.hepforge.org/
- ILC beam spectra files for https://whizard.hepforge.org/circe_files/ILC/
- repository https://github.com/delphes/delphes
- wiki https://cp3.irmp.ucl.ac.be/projects/delphes
- ILCgen model documentation https://github.com/iLCSoft/ILCDelphes
- LCIO package at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

Higgs measurements

Many BSM models introduce extended Higgs sectors.

New scalars could be light, if their couplings to SM particles are small.

Search for production of new scalars (independent on the scalar decay):



Comparison with CLIC limits assuming 100% invisible scalar decays EPJP 136 (2021) 2, 160

Simplified DM model

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

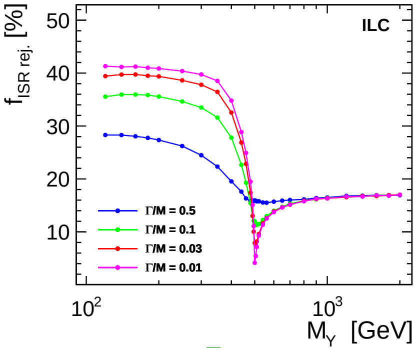
Each simplified scenario is characterized by one dark matter candidate and one mediator from the set listed below:

	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



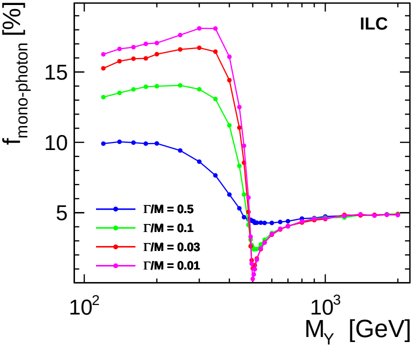
ISR emission enhanced for $M_Y < \sqrt{s}$, suppressed for $M_Y \sim \sqrt{s}$

Tagging efficiency

Detectable hard photon emitted only in a fraction of signal event

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

ILC @ 500 GeV



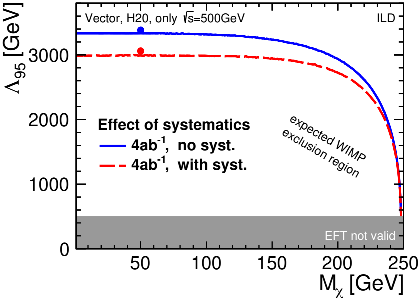
Emission strongly suppressed for narrow mediator with $M_Y \sim \sqrt{s}$

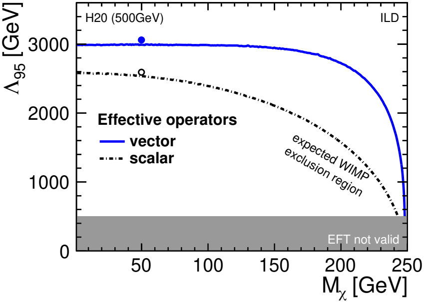
Mono-photon events

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...