Probing Dark Matter with ILC

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

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

- 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.

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

arXiv:1711.00568

arXiv:1903.01629
International Linear Collider

Baseline running scenario for **staged ILC construction**

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$^{-1}$]

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (GeV)</th>
<th>sgn($P(e^-)$, $P(e^+)$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>($-,+$)</td>
</tr>
</tbody>
</table>
| 250             | 900     | 900     | 100     | 100
| 350             | 135     | 45      | 10      | 10
| 500             | 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.

⇒ 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.
**Experiments**

**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:

\[ e^+ e^- \rightarrow t\bar{t} \rightarrow 6j \]
Detector Requirements

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

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

⇒ 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 measurements

Higgs couplings

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

Model-dependent analysis

Model-independent analysis

Sub-percent level precision already at the first energy stage

arXiv:1903.01629
In Higgs-portal models, new scalars fields $\phi$ 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 $\phi$ component ($\text{BR} \sim \sin^2 \alpha$) ⇒ search for invisible Higgs decays
In Higgs-portal models, new scalars fields $\phi$ coupling to dark matter particles can mix with the SM Higgs field $h$ resulting in two mass eigenstates:

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    \phi
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\]

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

$\Rightarrow$ 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 $2 \text{ ab}^{-1}$ collected at 250 GeV ILC: 0.23%

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

**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 independent on the scalar decay: $e^+ e^- \rightarrow Z S^0 \rightarrow \mu^+ \mu^- + X$
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 independent on the scalar decay: $e^+e^- \rightarrow Z S^0 \rightarrow \mu^+\mu^- + X$
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) \( \text{arXiv:2001.03011} \)

Scenarios with heavy mediator and coupling values \( O(1) \) (EFT limit)

Signature: single photon in an “empty” detector

Main backgrounds: radiative Bhabha and neutrino pair-production

---

**Signal photon spectrum**

\[
\begin{align*}
\text{Signal photon spectrum} & \\
M_\chi &= 1 \text{GeV} \\
M_\chi &= 140 \text{GeV} \\
M_\chi &= 220 \text{GeV}
\end{align*}
\]

---

**ILD**

\[
\begin{align*}
\text{after signal definition} & \\
e^+e^- + N\gamma: \text{gen} & \\
e^+e^- + N\gamma: \text{rec} & \\
\nu\nu + N\gamma & \\
\text{500fb}^{-1}
\end{align*}
\]
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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**Signal photon spectrum**

- $M_x = 1$ GeV
- $M_x = 140$ GeV
- $M_x = 220$ GeV

---

**ILD selected events**

- $e^+e^- + N\gamma$: gen
- $e^+e^- + N\gamma$: rec
- $\nu\nu + N\gamma$

---

“Irreducible” background from radiative neutrino pair-production events $e^+e^- \rightarrow \nu\nu + N\gamma$ 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

![Effect of polarisation graph]

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

$$\Lambda^2 = \frac{M_Y^2}{|g_{eeY}g_{XXY}|}$$
Mono-photon events

Dark Matter searches

Comparison of extracted mediator mass limits

ILC mass reach comparable with that of FCC-hh !!!
Light mediator study

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.


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

**Background**

**Signal**

\[
0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1
\]
\[
T^{γ}
\]

\[
0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1
\]
\[
f_{T}^{γ}
\]

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

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
Mono-photon events

**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**

![Graph showing cross section limits for Vector mediator](image)

**Mediator with \( \Gamma/m = 3\% \)**

![Graph showing cross section limits for Mediator with \( \Gamma/m = 3\% \)](image)

Radiation suppressed for narrow mediator with \( M_\gamma \sim \sqrt{s} \Rightarrow \) weaker limits
Mono-photon events

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
**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
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

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

Experimental setup $\sim 130$ m

K. Yokoya @ LCWS'2021

Non-collider experiments

Main beam dump experiments
Looking for SM decays of new exotic particles produced in the beam dump

Axion-like particle model looking for \( a \to \gamma\gamma \)

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

An order of magnitude better sensitivity than other experiments
Main beam dump experiments
Looking for SM decays of new exotic particles produced in the beam dump

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

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

An order of magnitude better sensitivity than other experiments

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
Non-collider experiments

Main beam dump experiments

Scenarios with Dark Photon ($A'$) and Dirac fermion DM ($\chi$)

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

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

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

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

Approach used in SLAC Beam Dump Experiment E137

arXiv:1406.2698
Non-collider experiments

Main beam dump experiments

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

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

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

\[ \Rightarrow \text{collimated stream of DM particles from } A' \text{ decay } (A' \rightarrow \chi\chi) \]

\[ \Rightarrow \text{looking for elastic } \chi \text{ interactions in the detector} \]

Huge improvement in sensitivity for \( m_{A'} \lesssim 1 \text{ GeV} \) thanks to much higher statistics
Experiments with extracted beams
Searching for Dark Photons with extracted positron beams

\[ e^+ e^- \rightarrow A' \gamma \]

Missing energy reconstruction in thick active target

Thin target, missing mass reconstruction in dedicated detector

LDMX for SLAC: arXiv:1807.05884

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  
- International Large Detector: Interim Design Report  
- 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 initial 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, $X_j$, 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:

<table>
<thead>
<tr>
<th>particle</th>
<th>mass</th>
<th>spin</th>
<th>charge</th>
<th>self-conjugate</th>
<th>type</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_R$</td>
<td>$m_{X_R}$</td>
<td>0</td>
<td>0</td>
<td>yes</td>
<td>real scalar</td>
</tr>
<tr>
<td>$X_C$</td>
<td>$m_{X_C}$</td>
<td>0</td>
<td>0</td>
<td>no</td>
<td>complex scalar</td>
</tr>
<tr>
<td>$X_M$</td>
<td>$m_{X_M}$</td>
<td>$\frac{1}{2}$</td>
<td>0</td>
<td>yes</td>
<td>Majorana fermion</td>
</tr>
<tr>
<td>$X_D$</td>
<td>$m_{X_D}$</td>
<td>$\frac{1}{2}$</td>
<td>0</td>
<td>no</td>
<td>Dirac fermion</td>
</tr>
<tr>
<td>$X_V$</td>
<td>$m_{X_V}$</td>
<td>1</td>
<td>0</td>
<td>yes</td>
<td>real vector</td>
</tr>
<tr>
<td>$Y_R$</td>
<td>$m_{Y_R}$</td>
<td>0</td>
<td>0</td>
<td>yes</td>
<td>real scalar</td>
</tr>
<tr>
<td>$Y_V$</td>
<td>$m_{Y_V}$</td>
<td>1</td>
<td>0</td>
<td>yes</td>
<td>real vector</td>
</tr>
<tr>
<td>$T_C$</td>
<td>$m_{T_C}$</td>
<td>0</td>
<td>1</td>
<td>no</td>
<td>charged scalar</td>
</tr>
</tbody>
</table>
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

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

ILC @ 500 GeV

Emission strongly suppressed for narrow mediator with \( M_Y \sim \sqrt{s} \)
Effective mass scale limits: \( \Lambda^2 = \frac{M_Y^2}{|g_{eeY}g_{\chi\chi\gamma}|} \)

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...