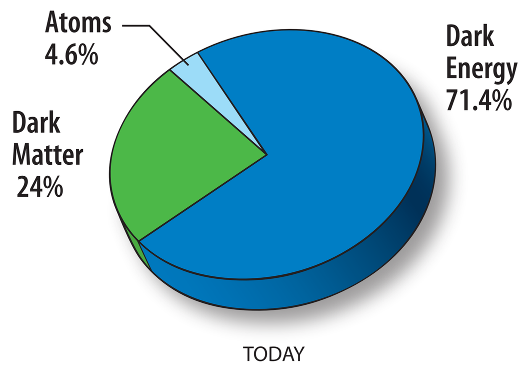
Model-independent WIMP Characterisation at the International Linear Collider.

J.List on behalf of the ILD Detector Concept Study.

Closing in on WIMP Dark Matter

According to cosmological observations, about 25% of the energy content of today's universe consists of Dark Matter. One of the most popular candidates for this yet unknown type of matter are *Weakly Interacting Massive Particles*, WIMPs. These can be searched for in three complementary ways:

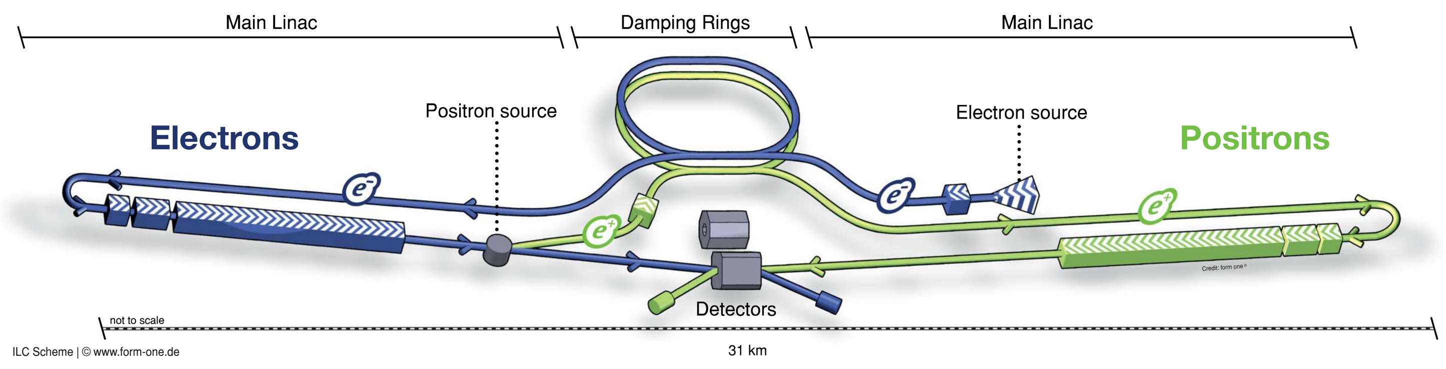
- Direct Detection of primordial WIMPs when they hit the earth and scatter off nuclei
- Indirection Detection via annihilation products of primordial WIMPs
- Production of WIMPs in the laboratory at colliders, eg. in proton-proton collisions at the LHC



Direct Detection and the LHC are very powerful to probe the interaction of WIMPs with quarks (and gluons). Indirect detection could find signals of WIMP annihilations into photons or leptons as well as to hadrons. However the interpretation of signals is challenging due to astrophysical sources and uncertainties in the signal propagation.

WIMP searches at a future e^+e^- Linear Collider like the ILC allow to test the WIMP-lepton coupling under laboratory conditions, analoguously to the LHC exploring the WIMP-quark couplings. Indepently of a future discovery or further exclusions from the above type of experiments, the ILC would add fully complementary information, since a priori WIMP-quark and WIMP-lepton interactions could be governed by different operators at different scales.

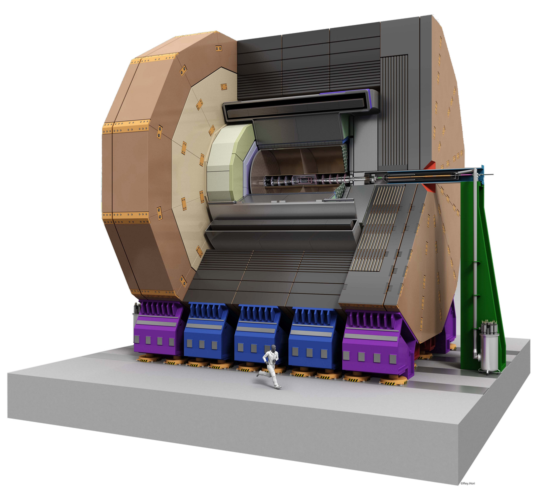
The International Linear Collider and ILD



The baseline design of the ILC forsees:

- tunable center-of-mass energy between 200 and 500 GeV, upgradable to 1 TeV
- an integrated luminosity of $500\,\text{fb}^{-1}$ in the *first* 4 years, and then every 2 years (at 500 GeV)
- beam polarisations of $|P(e^-)| \geq 80\%$ and $|P(e^+)| \geq 30\%$

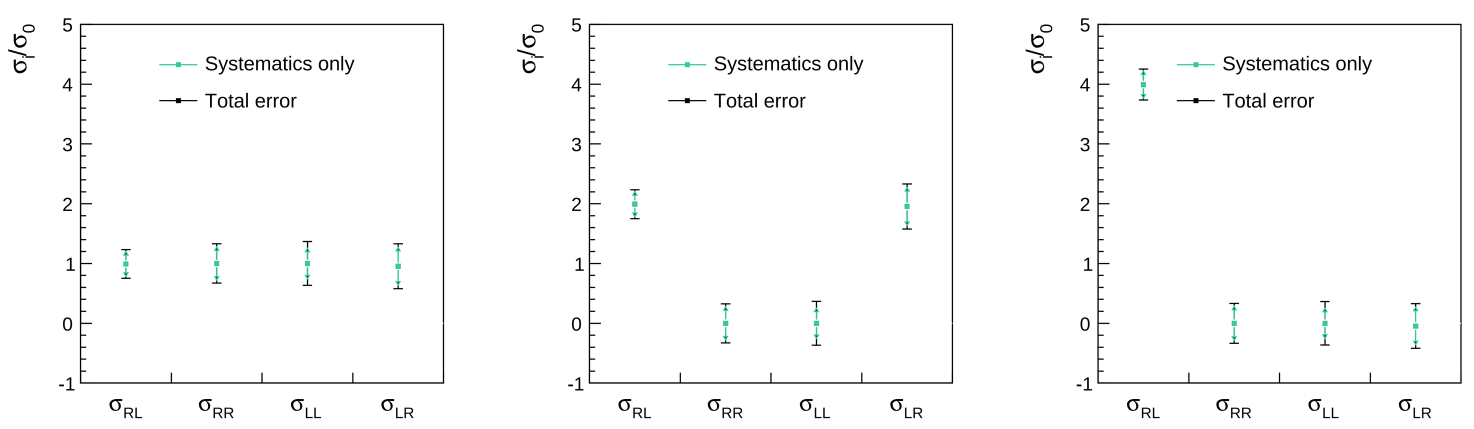
The results presented here are based on full simulation of the ILD detector concept for the ILC for signal and all relevant background processes.



The tracking system of ILD is based a Time Projection Chamber augmented by Silicon Strip and Pixel detectors and allows to detect charged particles efficiently down to polar angles of $\theta = 7°$.
The electromagnetic calorimeter (ECal) is a highly granular SiW sampling calorimeter with a transverse cell size of 5 mm $\times$ 5 mm and 20 layers. In test-beam measurements with a prototype detector a resolution of $(16.6 \pm 0.1)/\sqrt{E(\text{GeV})} \oplus (1.1 \pm 0.1)\%$ has been achieved.
The only region not in the acceptance of the calorimetric system are the holes in the very foward calorimeters for the beam-pipes.

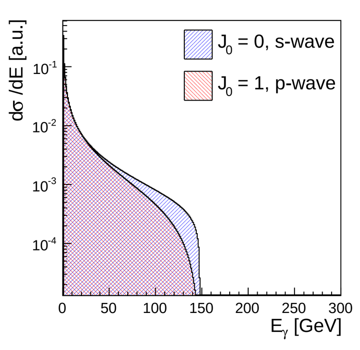
Helicity Structure of WIMP-fermion Interaction

The measurement of the polarised cross-sections gives access to the helicity structure of the WIMP-fermion couplings. The achievable precision and separation power has been evaluated for three benchmark cases, assuming that the total luminosity of $500\,\text{fb}^{-1}$ is split such that $200\,\text{fb}^{-1}$ are accumulated for each of the opposite sign configurations and $50\,\text{fb}^{-1}$ for each of the like-sign configurations, which are less interesting eg. for Standard Model physics. The result is dominant by the assumed precision of the polarisation measurement, where the conservative case of $\delta P/P = 0.25\%$ is shown below. In a χ^2 test between these three benchmarks, the wrong hypotheses obtain p-values of less than 10^{-8}.

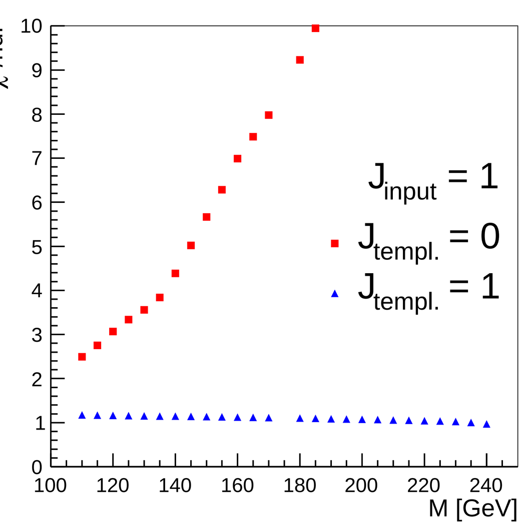


Dominant Partial-Wave of WIMP Annihilation

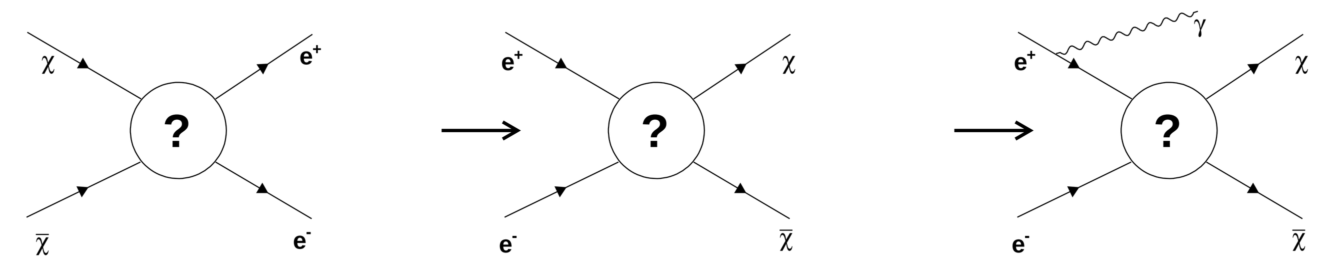
The dominant partial wave of the WIMP-WIMP annihilation process can eg. indicate whether the WIMP is a majorana fermion or a scalar. It is observable through it's influence on the ISR photon energy spectrum near the endpoint:



In a template fit to the photon energy spectrum after detector simulation, the correct hypothesis yields the lower χ^2/ndf. The discrimination becomes less significant at lower WIMP mass far from threshold.
If a WIMP signal is observed in a mass range where the distinction is not significant, dedicated data-taking near the production threshold can overcome this issue.



From Cosmology to Colliders [Phys. Rev. D70 (2004) 077701 [hep-ph/0403004]]



Assuming that today's relic density value is determined by WIMP pair annihilation, the cross-section for this annihilation, σ_{an}, sets the scale for the reverse process: WIMP pair production at colliders. The cross-section for $e^+e^- \to \chi\chi$ is completely determined by the following parameters:

- the WIMP mass M_χ and spin S_χ
- the spin-averaged fraction of annihilations to e^+e^-, κ_e, and the corresponding fractions for the four possible chiral combinations $e^+_R e^-_L$, $e^+_L e^-_R$, $e^+_L e^-_L$, $e^+_R e^-_R$
- the dominant partial wave J_0 of the annihilation process

While the WIMPs themselves don't leave signals in collider detectors, initial-state photon radiation (emitted under polar angle θ and with energy $x = \frac{2E_\gamma}{\sqrt{s}}$ can be used to detect these events. This results in the following cross-section parametrisation:

$$\frac{d\sigma}{dx\,d\cos\theta} \approx \frac{\alpha\kappa_e\sigma_{an}}{16\pi}\frac{1+(1-x)^2}{x\sin^2\theta}2^{2J_0}(2S_\chi+1)^2\left(1-\frac{4M_\chi^2}{(1-x)s}\right)^{1/2+J_0} \quad (1)$$

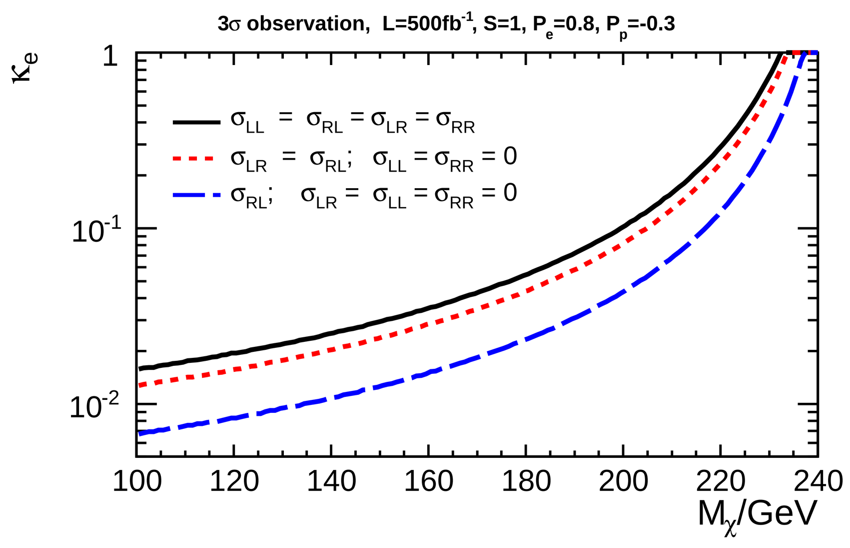
The photon energy spectrum allows – as will be shown here – to reconstruct the following observables:

- the WIMP mass
- the polarised and unpolarised production cross-section
- the dominant partial-wave of the annihilation process

Can the ILC see Dark Matter?

Assuming the cosmologically required total WIMP-WIMP annihilation cross-section, the observability of WIMP production in e^+e^- collisions depends on the fraction, κ_e of these annihilations which results in electron-positron pairs.

The lower limit on κ_e, for which an observation at a level of 3σ is still possible for a Spin-1 WIMP and a dataset with $P(e^-,e^+) = (+80\%, -30\%)$ and an integrated luminosity of $500\,\text{fb}^{-1}$ is shown here as a function of the WIMP mass for three different assumptions on the helicity structure of the WIMP-fermion coupling.
This clearly shows that the annihilation into e^+e^- does not have to be dominant, but that percent-level fractions are sufficient for not too heavy WIMPs. Even for WIMP masses 30 GeV below the kinematic limit, a κ_e of about 10% would still be sufficient.

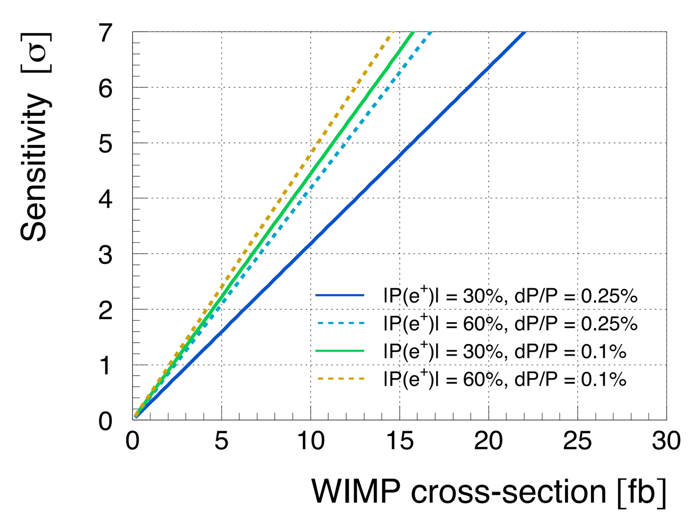


Total Cross-section and Discovery Reach

The measurements of the polarised cross-sections can be combined to determine the total unpolarised cross-section σ_0. With $|P(e^+)| = 30\%$, σ_0 can be determined to precisions between 3 and 5%, depending on the helicity structure of the WIMP-fermion coupling. This is limited systematically by the assumed uncertainty on the beam polarisation of $\delta P/P = 0.25\%$, due to its impact on the background prediction and due to the correction for possible deviation from identical absolute values for both beam helicities.

If $\delta P/P = 0.1\%$ can be achieved, the systematic uncertainty shrinks by 50%. For a total integrated luminosity of $500\,\text{fb}^{-1}$, which corresponds to two years of ILC operation at design parameters, the total uncertainty is then between 2 and 3%.

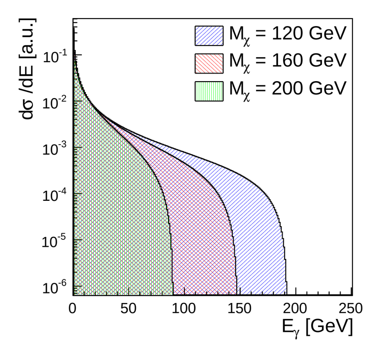
These precisions can be turned into a signal significance σ as a function of the unpolarised cross-section for $e^+e^- \to \chi\chi\gamma$ ($E_\gamma > 8$ GeV and $|\cos\theta_\gamma| < 0.995$).
This is shown here for $\sigma_{RL} = 4\sigma_0$ and $\sigma_{LR} = \sigma_{RR} = \sigma_{LL} = 0$ under different assumptions on the positron polarisation and on the precision to which the beam polarisations are known.



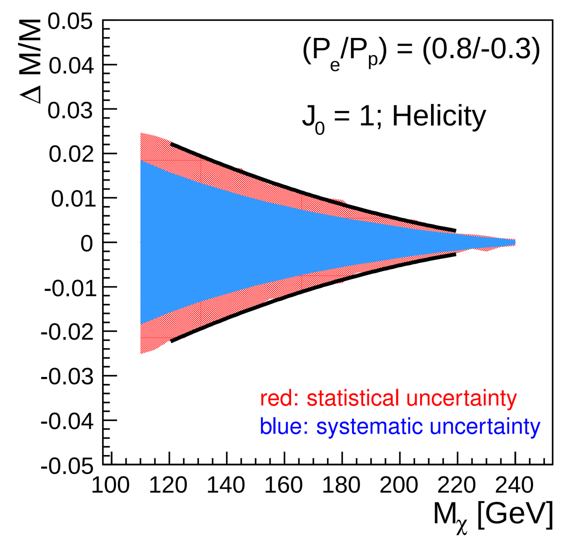
In this case, radiative WIMP production can be discovered at a 5σ-level for cross-sections between 10 and 16 fb based on a counting experiment-type of analysis.

WIMP Mass Measurement

WIMP mass M_χ can be determined from the endpoint of the photon energy spectrum - or by a template fit to the whole spectrum once the dominant partial wave has been determined.



The right plot shows $\Delta M_\chi/M_\chi$ vs M_χ for the case of $\sigma_{RL} = \sigma_{RL}$, $\sigma_{LL} = \sigma_{RR} = 0$. The relative uncertainty ranges from 2.5% to 0.4% and is limited by systematic uncertainties. The dominant source is the knowledge of the shape of the beam energy spectrum, which has been estimated in a very conservative way in this study.



Curious?

C. Bartels, M. Berggren, J. List, Eur. Phys. J. C **72** (2012) 2213 [arXiv:1206.6639 [hep-ex]].
Y. J. Chae and M. Perelstein, JHEP **1305** (2013) 138 [arXiv:1211.4008 [hep-ph]].
A. Birkedal, K. Matchev and M. Perelstein, Phys. Rev. D **70** (2004) 077701 [hep-ph/0403004].

The International Linear Collider Technical Design Report (2013)
`http://www.linearcollider.org/ILC/Publications/Technical-Design-Report`

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