SEARCHES FOR DARK MATTER AT FUTURE HIGH ENERGY LEPTON COLLIDERS

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Abstract

Several future lepton colliders are proposed with energies ranging from a few hundred GeV to a few TeV. The well known intial state and their clean environment make them precision machines for Standard Model phyics and suitable to look for beyond the Standard Model signals. Searches for dark matter at electron-positron colliders are complementary to searches at the LHC because they directly probe the coupling to leptons rather than couplings to quarks and gluons. Two approaches to search for dark matter are presented.

The first one is a highly model-independent search for Weakly Interacting Massive Particles (WIMPs, χ). Like at hadron colliders, WIMP pair production can be observed via an additional tag particle, in particular a photon from initial state radiation ($e^+e^- \to \chi\chi\gamma$). WIMP masses to nearly half the centre-of-mass energy can be probed. Polarised beams are essential to reduce Standard Model backgrounds and to characterise the properties of the new particles in case a signal is discovered.

In the second approach the nature of dark matter is explored by looking at a UV-complete theory. In supersymmetric (SUSY) scenarios the lightest supersymmetric particle (LSP) is a candidate for dark matter. Two scenarios are investigated by fitting SUSY parameters to the observables a lepton collider would provide. In this way the dark matter relic density can be determined with percent precision.

1 Introduction

1.1 Future lepton colliders

Several electron-positron colliders at the energy frontier are proposed, two linear accelerators with energies up to a few TeV and two circular machines with more moderate energies.

The Circular Electron Positron Collider (CEPC)[1] is a Chinese project with energies around 240-250 GeV and a circumference of 50-70 km. At CERN an initial electron-positron phase at the Future Circular Collider (FCC-ee)[2] is studied. The proposed 100 km ring which could provide energies from 90 to 350 GeV.

The International Linear Collider (ILC)[3] is currently under consideration to be built in Japan. The energy can be tuned between 250 GeV and 500 GeV and is upgradeable to 1 TeV. At the baseline design of 500 GeV the length is 34 km. The Compact Linear Collider (CLIC)[4], a second future CERN project, is supposed to be extended in several steps to provide energies of 380 GeV, 1.4 and 3 TeV at a final length of 50 km.

1.2 The International Linear Collider

As most physics studies exist for the ILC, all dark matter searches discussed in this document are performed for the ILC. But everything shown applies to all lepton colliders with sufficient

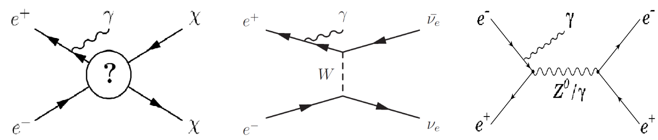

Figure 1 – Visualisation of the signal process and example Feynman diagrams for the two main background processes: radiative neutrino pair production and Bhabha scattering.

centre-of-mass energy and beam polarisation.

The ILC is based on the mature superconducting TESLA technology. The instantaneous luminosity at 500 GeV is $1.8 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for the baseline design and $3.6 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ after a luminosity upgrade. Both beams are polarised, the electron beam at a level of 80% and the positron beam 30%, which is suppposed to reach 60% after an upgrade. Two detectors share the same interaction region and are operated alternatively in a push-pull approach. The results shown are based on detector simulations of the International Large Detector (ILD) concept.

2 General search: mono-photon

Weakly Interacting Massive Particles (WIMPs, χ) are candidates for dark matter. In a collider search the assumption is that in the collision of Standard Model particles via some unknown process WIMPs can be produced in pairs. The dark matter particles do not interact with the detector material and escape detection. The process can be observed via an additional "tag" particle, for example a photon from initial state radiation (ISR). We look for the signal process $e^+e^- \to \chi\chi\gamma$ whose signature is a single photon in an "empty" detector. This approach is quasi model-independent. Due to the known initial state, the missing four-momentum can be calculated using two observables, namely the photon energy E_γ and the photon polar angle θ_γ.

The two main background processes are neutrino pair production and Bhabha scattering, both with an associated photon from initial state radiation, or in the latter case also from final state radiation (see fig.1). The neutrino background is irreducible, but can be enhanced or suppressed by changing the polarisation combination. Bhabha scattering has a huge cross section and mimics the signal if both leptons escape undetected. For their suppression the best possible hermeticity in the forward region of the detector is required.

2.1 Modelling of signal and background

The events are generated using WHIZARD 2.4.0[5] at a centre-of-mass energy of 500 GeV. Beam polarisation and the luminosity spectrum according to the ILC technical design report[6] are taken into account. For the background processes different channels with several photons are produced: $\nu\bar{\nu}$+nγ and for Bhabha scattering $\mathrm{e}^+\mathrm{e}^-$+nγ. The signal events $\chi\chi\gamma$ are obtained by reweighting the neutrino events according to WIMP parameters like mass and spin. For the detector simulation the Geant4 based programme Mokka, version 08-00-03 is used and a full detector simulation of the International Large Detector (ILD) concept[7] is performed.

2.2 Event selection

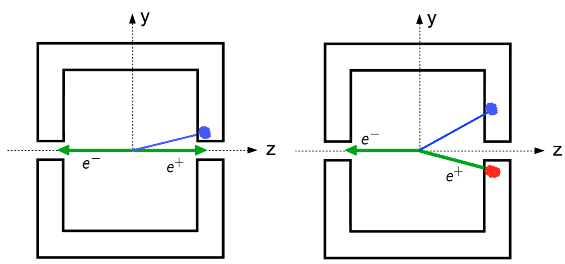

Figure 2 – Sketch of Bhabha scattering events in the detector. With a low p_T photon the leptons tend to go down the beam pipe (left) and the events is indistinguishable from a mono-photon WIMP signal. With the signal requirement of a minimum p_T one of the leptons can be reconstructed in the detector (right).

An event is considered signal-like if it contains a photon with $2\,\text{GeV} < E_\gamma < 220\,\text{GeV}$, $\theta_\gamma > 7°$ and a minimum transverse momentum which is ϕ-dependent and, for convenience, expressed in a coordinate system centred around the outgoing beam which is tilted by 7° with respect to the detector axis: $p_{T,\gamma} > 1.97\,\text{GeV}$ for $\phi_\gamma > 35°$ and $p_{T,\gamma} > 5.71\,\text{GeV}$ for $\phi_\gamma \leq 35°$.

The minimum energy is required to distinguish the photon from noise. The maximum energy cut is applied to avoid the high background rates around the radiative return to the Z boson. The minimum polar angle ensures that the photon hits the detector region where tracking instruments are installed which is mandatory to distinguish it from electrons. The minimum transverse momentum ensures that a lepton from the Bhabha scattering background hits the detector (see figure 2).

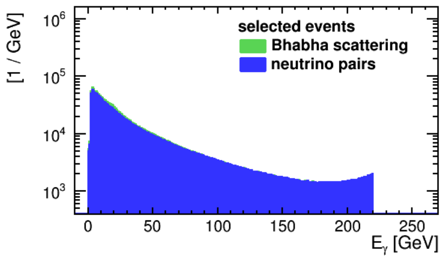

Figure 3 – Selected background events for unpolarised beams and $500\,\text{fb}^{-1}$. 83.58% of the irreducible neutrino background are kept and the Bhabha background suppression efficiency is 0.37%.

After several cuts that ensure a low detector activity the Bhabha background can be heavily suppressed while most of the signal-like neutrino events are kept (see figure 3).

2.3 Theoretical framework: effective operators

The theoretical framework used in this analysis is of effective operators, where the underlying idea is to classify the WIMP based on its quantum numbers (spin and weak isospin) and the mediator by its spin and construct the minimal effective Lagrangian. The only parameter that remains, Λ, can be called the energy scale of new physics and is a function of the mediator mass and the coupling to the fermions g_f and the coupling to the WIMPs g_χ: $\Lambda = M_{mediator}/\sqrt{g_f g_\chi}$.

In such a framework, considering the full Lagrangian, a likelihood analysis of data of existing experiments, together with extrapolations of expected exclusion limits at the time the ILC is running is being performed. In figure 4 the surviving region is shown for the example of a singlet-like fermion WIMP, assuming that no WIMP signal is detected[8]. Data from the following experiments are considered: from the Planck satellite, from the direct detection experiments PICO-2L, LUX and XENON100, from collider searches at LEP and LHC and from future experiments like LZ and PICO250. Here, the couplings are tested in the range [-1,1]. Above the grey area this simplified model reproduces the results of effective operators. The yellow region shows the parameter space which will not be explored by other experiments before the ILC starts operation.

At the energies of future lepton colliders a sizeable fraction of the parameter space can be tested with the sensitivities shown in the following sections.

2.4 Sensitivity for effective operators

The 3 σ exclusion limits for different effective operators are shown in figure 5 (left). At a centre-of-mass energy of 500 GeV and an integrated luminosity of $500\,\text{fb}^{-1}$ and for unpolarised beams the exclusion limits are in the range of $\Lambda = 1.8 - 2\,\text{TeV}$. WIMP masses up to almost half the centre-of-mass energy can be tested. For low WIMP masses the sensitivity for a vector and axial-vector operator is the same and higher than for a scalar operator, for higher WIMP masses the testable energy scales are highest for a vector operator. The cross-sections are taken from ref.[9] and the different operators are defined as shown in table 1.

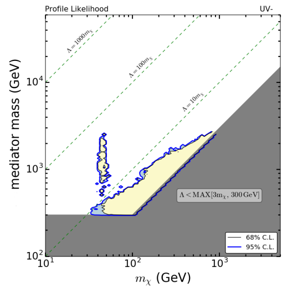

Figure 4 – The parameter space which will not be covered by dark matter experiments by the time the ILC will be running is shown in yellow (68% confidence level) and blue (95% C.L.). The grey area reflects the parameter space in which the approach of effective operators is not valid: Λ has to be larger than three times the WIMP mass and above 300 GeV.[8]

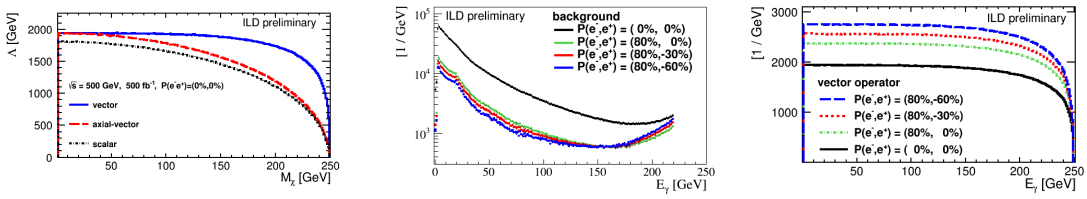

Figure 5 – Exclusion limit on the energy scale Λ as a function of the WIMP mass for different effective operators (left). Number of background events for 500 fb^{-1} (centre) and sensitivity (right) for different beam polarisations.

Role of polarisation

The role of beam polarisation is twofold, the neutrino background can be suppressed and the WIMP production can be enhanced. In case of a signal, it can also help to identify the chirality of the coupling, see section 4.2.

For unpolarised beams the number of neutrino background events surviving all selection criteria is 3761. For 80% right-handed electrons and 30% left-handed positrons it can be reduced by a factor 5 to 820 events. Taking the Bhabha scattering events into account, which are 187 for both cases, the number of background events can be reduced by a factor 4. In figure 5 (centre) it is shown that the electron beam polarisation helps to reduce the background considerably and polarisation of the positron beam helps to further reduce the number of background events at the dominating lower energies.

As shown in figure 5 (right) the sensitivity for a vector operator increases significantly for polarised beams. Here, the role of the polarisation of both beams is more pronounced because the signal increases at the same time as the background drops, as can be seen from the polarised cross-section in the last two columns of table 1.

Sensitivities for different operation scenarios

With an extrapolation of the sensitivity from the full simulation at 500 GeV to different centre-of-mass energies and integrated luminosities estimates can be given for the reachable Λ for different time scales and different running scenarios. The approach is valid for WIMP masses where the sensitivity is independent of the mass, up to $\sim$100 GeV for a vector operator.

The extrapolated sensitivity is shown in figure 2.4 for unpolarised beams (left) and a relative sharing of 40% $sgn(P_{e^-}, P_{e^+}) = (-,+)$, 40% $(+,-)$, 10% $(-,-)$ and 10% $(+,+)$ (right). In one considered running scenario for a 20 years programme the ILC is starting operation at 500 GeV[10]. After four years the integrated luminosity would be 500 fb^{-1} and

vector	$(\overline{f}\gamma^\mu f)(\overline{\chi}\gamma_\mu\chi)$	$\sigma_{LR} = \sigma_{RL}$	$\sigma_{LL} = \sigma_{RR} = 0$
axial-vector	$(\overline{f}\gamma^\mu\gamma^5 f)(\overline{\chi}\gamma_\mu\gamma_5\chi)$	$\sigma_{LL} = \sigma_{RR}$	$\sigma_{LR} = \sigma_{RL} = 0$
scalar (s-channel)	$(\overline{f}f)(\overline{\chi}\chi)$	$\sigma_{LL} = \sigma_{RR}$	$\sigma_{LR} = \sigma_{RL} = 0$

Table 1: Effective operators.

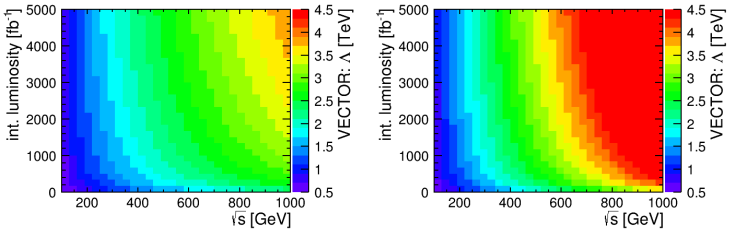

Figure 6 – Testable energy scale Λ as a function of the centre-of-mass energy and the integrated luminosity, left (right) without (with) beam polarisation.

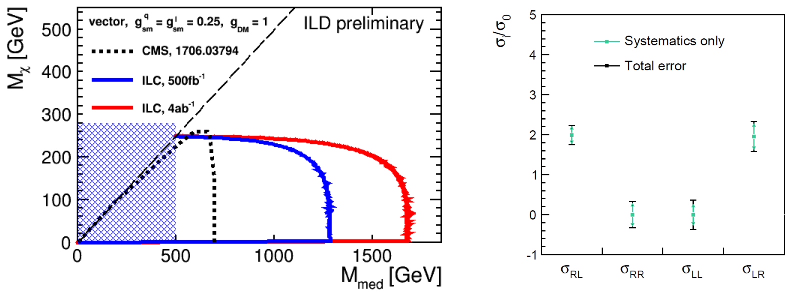

Figure 7 – Left: Comparison of CMS and ILC exclusion limits for a vector operator. Right: Determination of the fully polarised cross-sections for 500 fb^{-1}. The chirality of the vector-like operator can be tested.

the corresponding sensitivity $\Lambda = 1.9$ TeV. Only considering the time when the machine runs at 500 GeV the sensitivity would rise to $\Lambda = 3.1$ TeV once the 3500 fb^{-1} after the luminosity upgrade are reached. For polarised beams the result can be improved to 2.6 TeV (500 fb^{-1}) and 3.3 TeV (3500 fb^{-1}).

This study shows that already at 240 or 250 GeV a future lepton collider would explore new phase space. With a centre-of-mass energy, which is only slightly higher than at LEP, the clear improvements are the higher luminosity and beam polarisation of future machines.

3 Lepton colliders vs. LHC

Analogously to the mono-photon channel at lepton colliders, mono-jet WIMP searches are performed at the LHC. The tested parameter space is complementary because the LHC tests couplings to quarks and gluons rather than direct couplings to leptons. This also means that assumptions have to be made when results are compared.

At the LHC the testable parameter space is not suitable for effective operators. Instead simplified models are used with the three parameters mediator mass M_{med}, coupling to the Standard Model g_{SM} and coupling to dark matter g_{DM}. A common presentation of results are limits for M_{med} and for fixed couplings, e.g. $g_{SM} = 0.25$ and $g_{DM} = 1$.

In figure 7 (left) CMS results for a vector operator[11] are compared to ILC results for different integrated luminosities. With the assumptions that the coupling to the corresponding incoming particles is the same, the limits on Λ can be converted according to $M_{med} = \sqrt{g_{SM} \cdot g_{DM}} \cdot \Lambda = 0.5 \cdot \Lambda$ and the ILC can test significantly higher energy levels.

4 Measurement of WIMP parameters in case of a signal

In case of a WIMP-like signal, parameters of the new interaction and the new particle can be determined with high precision at a lepton collider.

4.1 WIMP mass measurement

As shown in figure 8 (left) the photon energy spectrum depends on the WIMP mass. With the initial state being known at a lepton collider, the spectrum has a clear endpoint which is at higher photon energies for smaller WIMP masses. The endpoint is buried in the fluctuations of the background and cannot be determined. Instead, template photon energy spectra

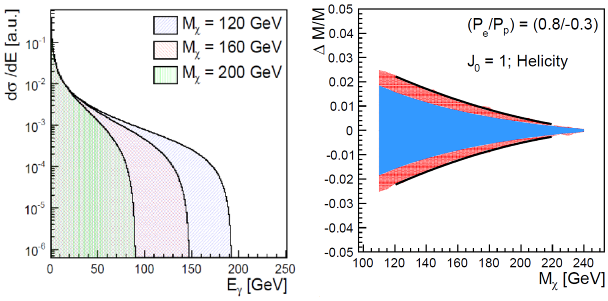

Figure 8 – Left: Photon energy spectrum for different WIMP masses. Right: Uncertainty of the fitted WIMP mass as a function of WIMP mass in the framework of a vector effective operator. The systematic uncertainties (blue) dominate in this conservative approach where it is assumed that no information on the beam spectrum is available.

for different WIMP masses are compared to the data and the WIMP mass is fitted with a χ^2-minimisation. With 500 fb^{-1} and polarised beams the precision ranges from a few GeV to sub-GeV[12] (see figure 8, right). The uncertainty is dominated by systematic effects with conservative assumptions on the influence of the beam spectrum. With a realistic assessment the uncertainty will decrease significantly.

4.2 Measurement of polarised cross-sections

Beam polarisation does not only help to suppress the neutrino background and enhance the WIMP production, but can also be used to test the chirality of the interaction.

From the measured polarised cross-sections with different polarisation combinations the fully polarised cross-sections can be deduced. In an experiment the polarisation is below 100% and the measured cross-section is always a combination of all four fully polarised cross sections: $\sigma_{measured}$ = A·σ_{LL} + B·σ_{LR} + C·σ_{RL} + D·σ_{RR}, e.g.: $\sigma_{-+} = (1+|P_{e-}|)(1-|P_{e^+}|)\sigma_{LL} + (1+|P_{e-}|)(1+|P_{e^+}|)\sigma_{LR} + (1-|P_{e-}|)(1-|P_{e^+}|)\sigma_{RL} + (1-|P_{e-}|)(1+|P_{e^+}|)\sigma_{RR}$.

In figure **??** (right) it is shown that the determination of the fully polarised cross-sections gives strong constraints on the chirality[12].

5 Identifying the nature of dark matter

The discovery of a WIMP at a collider alone can not answer the question whether it explains the dark matter observed in the Universe. If the relic density can be determined from collider measurements it can be compared with cosmological observations of the cosmic microwave background. For such a prediction a UV-complete theory is needed. In this section two supersymmetry (SUSY) models are presented. The lightest supersymmetric particle (LSP) is a candidate for dark matter, if R-parity is conserved.

5.1 Scenario 1: natural SUSY models

Naturalness and a small fine-tuning require the supersymmetric higgsino mass μ parameter at the electroweak scale and with μ being small the higginos are light. In this kind of model the LSP does not generally fill the relic density.

In the natural supersymmetric benchmark points ILC1 and ILC2[13] only the four higgsinos $\widetilde{\chi}_1^0$, $\widetilde{\chi}_2^0$, $\widetilde{\chi}_1^\pm$ can be observed at a centre-of-mass energy of 500 GeV. The production cross-section at an e$^+$e$^-$ collider is in the order of a few hundred femtobarn.

The masses can be extracted from the muon (electron) pair which is created in the process $e^+e^- \to \widetilde{\chi}_1^0\widetilde{\chi}_2^0 \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0\mu^+\mu^-$ $(\widetilde{\chi}_1^0\widetilde{\chi}_1^0 e^+e^-)$. As the initial state at a lepton collider is known the maximum of the invariant mass of the di-muon system (figure 9, centre) gives the mass splitting directly and together with the maximum of the di-muon energy (figure 9, right) this gives the masses of $\widetilde{\chi}_2^0$ and $\widetilde{\chi}_1^0$. With 4 ab^{-1} sub-percent mass precisions can be obtained[14].

With the higgsino masses as input fittino[15] is used to fit the SUSY parameters[16] which are used to calculate the dark matter relic density Ω with MicrOMEGAs[17]. With $\Omega_{fit}/\Omega_{Planck}$ = 0.054 ± 0.001 the density is far too small to explain dark matter, as expected in higgsino models with m=$\mathcal{O}$(100 GeV). With the high precision measurements of lepton colliders, it can be clearly seen that natural SUSY models do not provide a good dark matter candidate. If such a scenario was discovered it would imply that a large component of dark matter is non-supersymmetric or higgsinos would be produced in a non-thermal way.

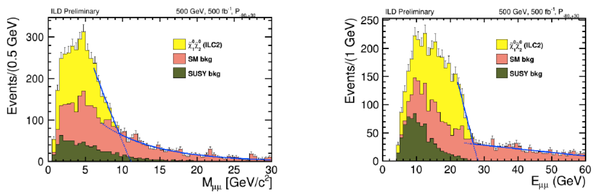

Figure 9 – Left: Excluded parameter space for natural SUSY with the studied scenarios ILC1 and ILC2. The di-muon invariant mass (centre) and di-muon energy (right) distributions for ILC2 and 500 fb^{-1}.

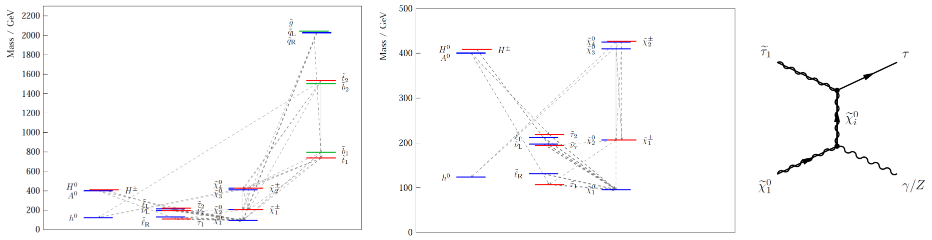

Figure 10 – With a small mass splitting of the bino-like LSP ($m_{\tilde{\chi}_1^0} = 96$ GeV) and the right-handed stau ($m_{\tilde{\tau}_1} =$ 107 GeV) the two particles can coannihilate to τ and γ or Z.

5.2 *Scenario 2: SUSY model with LSP as dark matter*

The second scenario studied at the ILC is designed to have an LSP that matches the observed dark matter relic density[18]. As visualised in the spectrum of supersymmetric particles shown in figure 10, the mass splitting of the LSP and the next-to-lightest SUSY particle $\tilde{\tau}_1$ is small which gives rise to stau coannihilation. Lepton colliders are suitable to discover coannihilation scenarios because the clean environment allows to see also small mass differences.

In this scenario called STC8 all sleptons, sneutrinos, $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ can be discovered at 500 GeV and the masses are measured at permille precision[19]. For example the stau mass can be determined with a precision of 0.15% from the endpoint of the τ produced in $\tilde{\tau}_1 \to \tau\tilde{\chi}_1^0$.

A study[20] shows that a discovery of an incomplete SUSY spectrum is sufficient to fit the correct dark matter relic density. In order to quantify the influence of the individual observables on the fit a number of assumptions was tested.

By including different combinations of particles in the fit it can be found out that the LSP and $\tilde{\tau}_1$ are crucial for the relic density determination. The observation of the electroweakino and Higgs sector (TeV scale) helps to improve the fit and particles with higher masses (squarks) are irrelevant.

As shown in figure 11 the precision of a fit for infinitely well known neutralino mixing varies significantly from a fit assuming knowledge of the mixing with 1% precision. The red curve in the figure shows the result of a fit where the neutralino mixing matrix element N11 ("binoness") is fixed to the model value.

The requirements to reach the precision of Planck (2%)[21] are tested by varying the precisions on observables. The ILC precisions on the SUSY masses are sufficient. Both the LSP mixing and the stau mixing would have to be known with 1% precision. The discovery of such a scenario would be a strong hint that the discovered LSP is *the* dark matter particle.

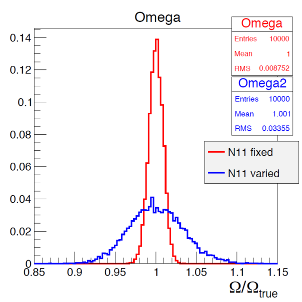

Figure 11 – The fitted dark matter relic density Ω reproduces the model value Ω_{true}. The better the knowledge of the neutralino mixing the smaller the uncertainty.

6 Conclusions

Future high energy lepton colliders can explore new phase space in the search for dark matter. Already at the lowest centre-of-mass energies of the suggested accelerators, higher luminosity and beam polarisation will improve the limits made by LEP or could lead to the discovery of a new particle. Searches for WIMPs are complementary to searches at the LHC because e^+e^- colliders directly probe the coupling to leptons rather than couplings to quarks and gluons. With polarised beams the neutrino background can be suppressed and the WIMP production enhanced. Additionaly, the chirality of the new process can be tested.

In the case of the discovery of a new particle, parameters like its mass, the production cross-section and the chirality of the interaction can be determined with high precision. In the framework of a UV-complete theory, like supersymmetry, model fits allow the determination of the dark matter relic density with percent precision. In this way, lepton colliders can contribute to the verification or falsification of a WIMP as thermal dark matter, if a new particle is discovered.

Acknowledgements

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