WIMP Searches at the ILC using a model-independent Approach

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In this note the ILC’s capabilities for detecting WIMPs and measuring their properties are studied. The expected signal cross section is derived in a model-independent way from the observed relic density of Dark Matter. Signal events are detected by means of initial state radiation (ISR). The study is performed with a full simulation of the ILD detector. The results show that WIMPs are observable at the ILC if their coupling to electrons is not too small ($\mathcal{O}(0.1)$). Their masses can be measured with a precision of 1 to 2 GeV. The accessible phase space can be increased significantly using polarised beams, especially if the positrons are polarised as well.

1 Introduction

Due to its clean experimental environment the International Linear Collider (ILC) offers the possibility to look for Weakly Interacting Massive Particles (WIMPs) in a model-independent way. This has been pointed out in [2, 3]. In this study the expected sensitivity to such a WIMP signal, the achievable mass resolution and the influence of beam polarisation are investigated using a full detector simulation of the International Large Detector (ILD) of the ILC.

2 Model-independent WIMP production cross section

It is assumed that the cosmic Dark Matter (DM) component is only due to one new type of particle, and that the relic density is determined by pair annihilation of WIMPs into SM particles. These annihilations may produce an $e^+e^-$ pair ($\chi\chi \rightarrow e^+e^-$) with an unknown branching fraction $\kappa_e$, where $\kappa_e \geq 0.3$ is strongly motivated by recent PAMELA results [4, 5]. The total annihilation cross section $\sigma_{\text{an}}$ is then determined by the observed DM density $\Omega_{DM}$. The annihilation cross section required to match the observed relic density is in the order of a few pb [3]. Using crossing relations one can derive the expected cross section for the reverse process, i.e. $e^+e^- \rightarrow \chi\chi$, which could be observable at the ILC. The resulting cross section contains as free parameters:

- the $e^+e^-$ branching fraction $\kappa_e$
- the mass of the WIMP $M_\chi$ and its spin $S_\chi$
- the angular momentum $J_0$ of the dominant partial wave ($J_0$ corresponds to the spin of the exchange particle in the annihilation (production) process).

*The authors acknowledge the support by DFG grant Li 1560/1-1.

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Since the produced WIMPs leave the detector without any further interaction an additional photon from ISR is required \( (e^+e^- \rightarrow \chi\chi\gamma) \). The main background is the radiative neutrino pair production \( e^+e^- \rightarrow \nu\nu\gamma \). This reaction is mediated dominantly by t-channel \( W \)-exchange if the center of mass energy is significantly above the \( Z^0 \)-pole. Therefore the \( \nu\nu\gamma \) background is strongly reducible depending on the polarisation state of the initial electrons and positrons.

In this model-independent approach no constraints are imposed on the helicity structure of the WIMP couplings to electrons, which therefore enter the production cross section as a new free parameter. We consider three different scenarios for the helicity structure of the WIMP couplings:

- the same as the SM charged current interaction, i.e. only \( \kappa(e_L^- e_R^+) \) is nonzero
- parity and helicity are conserved: \( \kappa(e_L^- e_R^+) = \kappa(e_R^- e_L^+) \)
- opposite to the SM charged current interaction, only \( \kappa(e_R^- e_L^+) \) is nonzero.

In the last two cases a significant enhancement of the signal to background ratio is expected if electrons (and positrons) beams are appropriately polarised.

3 Software and reconstruction tools

For the SM \( \nu\nu\gamma \) background the SLAC SM Whizard event sample [6] is used. This sample is generated with the Whizard event generator including beamstrahlung and beam energy spread from Guinea Pig for nominal ILC beam parameters. Each \( e^+e^- \rightarrow \nu\nu\gamma \) event contains up to two additional ISR photons. The sample size corresponds to 10 fb\(^{-1}\) of luminosity at \( \sqrt{s} = 500 \) GeV. The background sample is reweighted with respect to the energy and polar angle of the detected photon according to the WIMP production and background cross sections. The benefit of this method is that a full signal sample can be obtained for all investigated combinations of cross section parameters with only one simulation and reconstruction cycle, reducing the amount of processing time significantly. Since the predicted signal cross section assumes only one photon to be radiated, the center of mass energy of the hard subprocess is used for the application of weights.

The event sample is then fed into the full Mokka 06-06-p03 ILD detector simulation (detector model LDCPrime_02Sc) with a 3.5 Tesla magnetic field, and reconstructed with MarlinReco using the Pandora Particle Flow algorithm (PFlow) [7].

The event simulation and reconstruction process introduces a smearing of the reconstructed photon candidate energies due to the intrinsic energy resolution of the detector and the performance of the Particle Flow algorithm. Figure 1(a) shows the energy distribution of the most energetic photon candidate identified by the Pandora algorithm. The radiative return to the \( Z^0 \) at \( \approx 240 \) GeV is with a width of about 6.4 GeV significantly broadened compared to the spectrum on generator level (Fig. 1(b)).

4 Cluster splitting

The full reconstruction yields less photons at high energies resulting in a shift of the \( Z^0 \) return from the expected central value of 241 GeV to 237.7 GeV (Fig. 1(a)). This behaviour is quantified in Figure 2(a) showing the average ratio \( E_{\text{rec}}/E_{\text{gen}} \) of the reconstructed photon...
Figure 1: Energy spectrum of the most energetic photon of the $\nu\nu\gamma$ background (a) after reconstruction using Pandora PFlow and (b) on generator level.

Figure 2: (a) Average ratio of reconstructed photon energy to generated photon energy before and after merging. (b) Energy spectra before and after merging procedure.

candidate’s energy to the photon energy on generator level. The Pandora PFlow algorithm tends to split photon clusters stemming from one generated photon into several photon candidates. This lowers the ratio $E_{\text{rec}}/E_{\text{gen}}$ especially at high energies (black triangles). This effect can be compensated by applying a simple merging procedure. Neighbouring photon candidates are combined to form a new set of photon candidates, with which an average ratio of $E_{\text{rec}}/E_{\text{gen}} \approx 1$ is recovered (red squares). The $Z^0$ return is also shifted back to its expected value (see Figure 2(b)).

5 Preliminary analysis results

So far the following scenarios have been investigated:

- WIMP spin: p-wave annihilation ($J_0 = 1$) for $S_\chi = 1$ and $S_\chi = 1/2$
- WIMP couplings: $\kappa(e^+_Le^-_R) > 0$, $\kappa(e^+_Re^-_L) > 0$ and $\kappa(e^-_Le^+_R) = \kappa(e^-_Re^+_L) > 0$
- Polarisation: unpolarised beams, $e^-$ polarisation only ($P_{e^-} = 0.8$) and additional $e^+$ polarisation ($P_{e^+} = 0.8$ and $P_{e^+} = 0.6$).

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Figure 3: Observational reach (3σ) of the ILC for a Spin-1 WIMP in terms of WIMP mass and \( \kappa_e \) for three different chirality and coupling scenarios. Full line: \( P_{e^-} = P_{e^+} = 0 \), dotted line: \( P_{e^-} = 0.8, P_{e^+} = 0 \), dashed line: \( P_{e^-} = 0.8, P_{e^+} = 0.6 \).

5.1 Observational reach

For each combination of these parameters the ILC reach for a 3σ observation has been determined as a function of the WIMP mass \( M_\chi \). The reach has been evaluated for an integrated luminosity of 500 fb\(^{-1}\) at \( \sqrt{s} = 500 \) GeV using a larger event sample from a previous detector simulation [2]. Due to the high SM neutrino production background, the sensitivity has been obtained statistically by using fractional event counting [8] as implemented in the ROOT class TLimit. Figure 3 shows the expected ILC sensitivity for Spin-1 WIMPs in terms of the minimal observable branching fraction to electrons \( \kappa_e \) as a function of the WIMP mass. The regions above the curves are accessible, where the full line gives the result for unpolarised beams, the dotted line for \( P_{e^-} = 0 \) and the dashed line for \( P_{e^-} = 0.8 \) and \( P_{e^+} = 0 \) and \( P_{e^-} = 0.8, P_{e^+} = 0.6 \). Figure 3(a) shows the case where the WIMPs couple only to left-handed electrons and right-handed positrons, \( \kappa(e^-_L e^+_R) \), Fig 3(b) shows the parity and helicity conserving case, \( \kappa(e^-_L e^+_R) = \kappa(e^+_R e^-_L) \), while Fig 3(c) right plot is dedicated to the case that the WIMPs couple to right-handed electrons and left-handed positrons (\( \kappa(e^-_R e^+_L) \)).

For the latter two scenarios polarised beams increase the reach significantly, especially the additional positron polarisation increases the accessible range in \( \kappa_e \) by about a factor of two. In case of a Spin-\( \frac{3}{2} \) WIMP the sensitivity is somewhat worse, but again beam polarisation extends the observable part of the parameter space significantly [1]. In all presented cases the ILC is sensitive to the branching fraction \( \kappa_e \) over a large range of possible WIMP masses and down to values below 0.3 indicated by the PAMELA results.

5.2 Mass resolution

If WIMPs are observed at the ILC, their mass can be determined from the recoil mass distribution of the photons:

\[
M^2_{\text{recoil}} = s - 2\sqrt{s}E_\gamma
\]  

Figure 4 shows an example for the recoil mass distribution for a 180 GeV Spin-1 WIMP with both beams polarised. The WIMP signal shown in red (dark grey) on top of the SM neutrino...
background kicks in at $M_{\text{recoil}} = 360$ GeV. From this distribution the WIMP mass can be reconstructed e. g. with a template method. For this procedure, only 200 fb$^{-1}$ of the available MC sample have been analysed as dataset, the rest is used for the templates. Figure 5 shows the obtained $\Delta \chi^2$ as function of the reconstructed WIMP mass for a 150 GeV Spin-1 WIMP for $\kappa_e = 0.3$. Fig. 5(a) shows the helicity and parity conserving case, while (b) illustrates the case that the WIMPs couple to righthanded electrons and lefthanded positrons, $\kappa(e_R e_L^+)$. Again the full line gives the result for unpolarised beams, the dotted line for $P_{e^-} = 0.8$, and the dashed line for $P_{e^-} = 0.8$ and $P_{e^+} = 0.6$. Without any beam polarisation, the mass resolution is about 4 GeV, which is reduced to about 1.2 GeV by switching on the electron polarisation. Additional positron polarisation improves the resolution by another factor of two to about 0.6 GeV.

Similar results are obtained for Spin-$\frac{1}{2}$ WIMPs [1]. As for the observation reach, the situation is slightly worse than in the Spin-1 case, but again the use of beam polarisation leads to a significant gain in resolution.

6 Conclusions and outlook

This study is one example of a physics analysis using the full simulation of the ILD detector concept. It is part of the optimisation effort for the ILD detector, and is further improved in parallel to the ongoing optimisation of the detector model. It demonstrates that there is a good chance of detecting WIMPs at the ILC in a model-independent way, and to measure their mass with a precision of about 1 GeV. The preliminary results show that the reach of the ILC on the branching fraction $\kappa_e$ of WIMP pair annihilation to electrons covers values of $\kappa_e$ down to $\approx 0.01$, which is well below the $\kappa_e \geq 0.3$ indicated by the recent PAMELA data. Both the range in phase space, as well as the mass resolution improve significantly when polarised beams are assumed. Typically the use of 80% electron polarisation gives improvements of a factor of two over unpolarised beams, whereas an additional positron polarisation of 60% yields another factor of two.

The results will be updated using different Particle Flow algorithms and Photon finders. Reducible backgrounds as well as beamstrahlung will be included. The obtained results will also be compared to specific SUSY scenarios in which the only open SUSY channel at the ILC’s center of mass energy is radiative neutralino production [9].
References

[1] Presentation: http://ilcagenda.linearcollider.org/contributionDisplay.py?contribId=200&sessionId=20&confId=2628

[2] C. Bartels and J. List, In the Proceedings of 2007 International Linear Collider Workshop (LCWS07 and ILC07), Hamburg, Germany, 30 May - 3 Jun 2007, pp COS02 [arXiv:0709.2629 [hep-ex]].

[3] A. Birkedal, K. Matchev and M. Perelstein, Phys. Rev. D70 (2004) 077701 [arXiv:hep-ph/0403004].

[4] G. Shaughnessy: http://ilcagenda.linearcollider.org/contributionDisplay.py?contribId=198&sessionId=20&confId=2628

[5] O. Adriani et al., [arXiv:0810.4995 [astro-ph]].

[6] http://confluence.slac.stanford.edu/display/ilc/Standard+Model+Data+Samples

[7] M. Thomson, J. Phys. Conf. Ser. 110, 092032 (2008).

[8] T. Junk, Nucl. Instrum. Meth. A 434, 435 (1999) [arXiv:hep-ex/9902001].

[9] H. K. Dreiner, O. Kittel and U. Langenfeld, Eur. Phys. J. C 54, 277 (2008) [arXiv:hep-ph/0703009].