Pinning Down the Invisible Sneutrino at the ILC

J. Kalinowski, 1 W. Kilian, 2 J. Reuter, 3 T. Robens, 4 and K. Rolbiecki 5

1- Physics Department, University of Warsaw, 00-681 Warsaw, Poland
2- University of Siegen, Faculty of Physics, D–57068 Siegen, Germany
3- University of Freiburg, Institute of Physics, D–79104 Freiburg, Germany
4- RWTH Aachen, Institute for Theoretical Physics E, D–52056 Aachen, Germany
5- University of Durham, IPPP, Durham, DH1 3LE, UK

Using the event generator WHIZARD we study in a realistic ILC environment the prospects of measuring properties of sneutrinos that decay invisibly into the lightest neutralino and the neutrino.

1 Introduction

If sneutrinos of the MSSM are lighter than the lightest chargino and next-to-lightest neutralino, their decays to charged particles are of higher order and strongly suppressed. Therefore sneutrinos decay completely invisibly into a neutrino and the lightest supersymmetric particle (LSP, the lightest neutralino in the considered case). As a result, they cannot be directly detected in cascade decays at the LHC and a threshold scan at the ILC is precluded for the very same reason. In such a case, the only possibility to discover sneutrinos is to select a well-reconstructible process where the sneutrino is exchanged or shows up as part of a cascade decay, and in which the precise determination of kinematic distributions gives an access to the sneutrino mass. This idea has already been exploited in Ref. [1], where the lepton-sneutrino decay channel of charginos produced at the ILC has been investigated. It was argued that background effects are sufficiently under control, so a precise mass determination is possible. Here we report on results of our study for determining sneutrino properties in the SPS1a’ scenario assuming a realistic ILC environment which includes beamstrahlung, initial-state radiation, a complete account of reducible backgrounds from SM and SUSY processes, and a complete matrix-element calculation of the SUSY signal encompassing all irreducible background and interference contributions [2] using the event generator WHIZARD [3].

2 Signal and background

The sneutrino mass can be determined by investigating the chargino decay modes \( \tilde{\chi}^+ \rightarrow \tilde{\nu} \ell^+ \), \( \ell = e, \mu \), in chargino pair production process at the ILC. In the following we assume that the first and second generation sneutrinos, \( \tilde{\nu} e \) and \( \tilde{\nu} \mu \), are mass degenerate. Large backgrounds from same-flavor lepton and slepton production can be avoided by selecting events with leptons of different flavor, i.e. one of the charginos decaying to an electron, the other to a muon. Therefore, we search for (semi-)exclusive final states:

\[
e^+ e^- \rightarrow \tilde{\chi}^+ \rightarrow \tilde{\nu} \ell^+ \rightarrow e^- \ell^- \rightarrow e^+ \ell^- \rightarrow e^+ \ell^- \rightarrow e^- \ell^+ \rightarrow e^- \mu^- \rightarrow e^- \mu^- \rightarrow e^+ \mu^- \rightarrow e^+ \mu^-
\]

(1)

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- An additional SM background due to photon-induced muon pairs, not discussed previously, is included.
- We thank Graham Wilson for calling this to our attention.

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In the SPS1a scenario $m_{\chi_i} = 183.7$ GeV, $m_{\tilde{\nu}_e} = 172.5$ GeV and the Born cross section for chargino pair production is predicted to be 173.6 fb at a CM energy of 500 GeV. With a $BR(\tilde{\chi}_1^+ \rightarrow \tilde{\nu}_e \ell^+) = 13\%$, a sufficient sample of events can be expected in this channel. The two-body chargino decay leads to a uniform decay lepton energy spectrum with edges determined by the chargino and sneutrino masses, which provides a method for their experimental determination \cite{1} \cite{2}. Experimentally, the signature for the signal process, Eq. (1), is one electron, one anti-muon and missing energy \cite{1}.

\[ e^+e^- \rightarrow e^-\mu^+ + \not{E}_T. \]  

(2)

The same final state, Eq. (1), can originate from other production processes as well as from interference terms, e.g. multi-peripheral diagrams, chargino decays into neutralino and W, smuon $\tilde{\mu}_1^+ \tilde{\mu}_1^-$ and slepton $\tilde{e}_1^+ \tilde{e}_1^-$ pair production, and single-resonant SM di-boson production etc. They will be called collectively as an ‘irreducible background’, in contrast to the ‘reducible’ SUSY background that includes more neutrinos in the final state. The latter contribution come from processes that lead to one or two leptonically decaying $\tau$’s. They mainly originate from the production of mixed neutralino pairs $\tilde{\chi}_i^0 \tilde{\chi}_j^0$, stau pairs as well as chargino pairs. The latter undergo the subsequent decays to stau and LSP or tau and sneutrino. The Standard Model background processes leading to the same signature of different-flavor opposite-sign lepton pairs and missing energy (carried away by neutrinos) 

\[ e^+ e^- \rightarrow \not{E}_T. \]  

(1)

Equally well, one can consider $e^+ \mu^- + \not{E}_T$ as a final signature or use both channels.

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**Table 1:** Cross sections for signal and relevant background processes for an ILC \( \sqrt{s} = 500 \) GeV. ISR and beamstrahlung are always included. The ‘presel.’ column includes a 5° cut for the final electron to cut out collinear regions, and for the $ee\mu\mu$ SM as well as all $\gamma$-induced processes a 1° cut for particles vanishing in the beampipe. The last column shows cross sections after the cuts. In parentheses are the WHIZARD integration errors.

| Process | 500 GeV $\sigma$ [fb], presel. | $\sigma^{\text{cut}}$ [fb] |
|---------|--------------------------------|-----------------------------|
| Signal  | $ee \rightarrow e\mu_\nu_\nu\nu \chi_1^0 | \chi_1^0$ | 3.940 (8) 1.639 (3) |
| SUSY $\tau$ Bkgd. | $ee \rightarrow \tau \tau \chi_1^0 | \chi_1^0 \rightarrow e\mu_\nu_\nu_\nu \nu \chi_1^0 | \chi_1^0$ | 4.107 (7) 0.978 (2) |
| SUSY $\tau\nu$ Bkgd. | $ee \rightarrow \tau \nu_\nu_\nu_\nu \nu \chi_1^0 | \chi_1^0 \rightarrow e\mu_\nu_\nu_\nu \nu \chi_1^0 | \chi_1^0$ | 3.245 (10) 0.818 (3) |
| SUSY $\tau\nu$ Bkgd. | $ee \rightarrow \tau \nu_\nu_\nu_\nu \nu \chi_1^0 | \chi_1^0 \rightarrow e\mu_\nu_\nu_\nu \nu \chi_1^0 | \chi_1^0$ | 3.691 (9) 1.102 (8) |
| SUSY $\nu$ Bkgd. | $ee \rightarrow e\nu_\nu_\nu_\nu \nu \chi_1^0 | \chi_1^0 \rightarrow e\mu_\nu_\nu_\nu \nu \chi_1^0 | \chi_1^0$ | 2.617 (10) 0.966 (8) |
| SM $ee\mu\mu$ Bkgd. | $ee \rightarrow e\mu_\nu_\nu_\nu \nu \chi_1^0 | \chi_1^0 \rightarrow e\mu_\nu_\nu_\nu \nu \chi_1^0 | \chi_1^0$ | 522400 (700) 0.105 (3) |
| SM $e\tau$ Bkgd. | $ee \rightarrow e\tau \nu_\nu_\nu_\nu \nu \chi_1^0 | \chi_1^0 \rightarrow e\mu_\nu_\nu_\nu \nu \chi_1^0 | \chi_1^0$ | 21392 (70) 0.273 (2) |
| SM $\mu\nu$ Bkgd. | $ee \rightarrow \mu\nu_\nu_\nu_\nu \nu \chi_1^0 | \chi_1^0 \rightarrow e\mu_\nu_\nu_\nu \nu \chi_1^0 | \chi_1^0$ | 10894 (4) < 0.001 |
| SM $\gamma \rightarrow W$ Bkgd. | $ee \rightarrow \gamma_\nu_\nu_\nu_\nu \nu \chi_1^0 | \chi_1^0 \rightarrow e\mu_\nu_\nu_\nu \nu \chi_1^0 | \chi_1^0$ | 1.949 (6) 0.079 (1) |
| SM $\gamma \rightarrow \tau\nu$ Bkgd. | $ee \rightarrow \gamma_\nu_\nu_\nu_\nu \nu \chi_1^0 | \chi_1^0 \rightarrow e\mu_\nu_\nu_\nu \nu \chi_1^0 | \chi_1^0$ | 0.077 (1) < 0.001 |
| SM $\gamma \rightarrow \ell\tau$ Bkgd. | $ee \rightarrow \gamma_\nu_\nu_\nu_\nu \nu \chi_1^0 | \chi_1^0 \rightarrow e\mu_\nu_\nu_\nu \nu \chi_1^0 | \chi_1^0$ | 0.404 (2) 0.055 (2) |
include WW pairs, single W production and τ⁺τ⁻ pairs. The most severe contribution here is due to photon-induced processes, especially photon-induced µ⁻ and τ⁻ pair production. Therefore, the proper simulation of these processes is crucial in our analysis. As stressed in [2], one has to go beyond the usual equivalent photon approximation (EPA), since EPA tweaks kinematic distributions which results in underestimating the number of background events. The exact matrix elements for the photon-induced processes need to be generated using quadruple-precision.

As seen in Tab. 1, the most severe background (that exceeds the signal by a factor ≥10⁴) comes from gamma-induced µ and τ pairs which produce a soft eµ system with small total transverse momentum \( p_\perp \) and large angular separation \( \Delta \phi \). Therefore, a cut on transverse momentum of leptons and a cut on azimuthal separation of e and µ reduces gamma-induced backgrounds by 3 to 5 orders of magnitude. The other large source of SM background – WW pair production – can be reduced by applying an upper cut on the lepton energy, since most leptons from W decays have energies larger than 40 GeV. We also require two well-visible leptons in the central part of the detector. All cuts are summarized in Tab. 2. These cuts are less effective in suppressing the SUSY background processes, since leptons originating from decays of heavy SUSY states, with almost degenerate spectrum like SPS1a [4], are rather soft and angularly uncorrelated.

### Table 2: Cuts used in the analysis for an ILC with 500 GeV.

| Cut                        | lower | upper |
|---------------------------|-------|-------|
| \( E(e^-); E(\mu^+) \)    | 1 GeV | 40 GeV |
| \( \theta(e^-) \)         | 15°   | 155°  |
| \( \theta(\mu^+) \)       | 25°   | 165°  |
| \( \Delta \phi(e^-, \mu^+) \) | -150° | 150°  |
| \( p_\perp(e^-), p_\perp(\mu^+) \) | 2 GeV |       |
| \( |\vec{p}_\perp(e^-) + \vec{p}_\perp(\mu^+) | \) | 4 GeV |      |

3 Sneutrino mass determination

The most straightforward way to determine the mass of otherwise invisible sneutrinos is the measurement of the total cross section for the process Eq. (2). A fit of the collider data to samples of MC data for varying sneutrino mass (assuming masses of other particles
known) allows one to determine the sneutrino mass with an accuracy of \(\sim 0.75\) GeV. A less model-dependent possibility is to use the on-shell kinematics of chargino decay, where the information about particle masses is encoded in the positions of lower and upper edges of the lepton energy spectra. The energy spectra of electrons and muons, including ISR and beamstrahlung, after cuts are shown in Fig. 1. The lepton spectrum from SM processes is flat and can easily be subtracted. On the other hand, leptons from the signal and SUSY background exhibit a similar energy dependence. The lower edge of the lepton spectrum is essentially smeared out, mostly due to \(p_\perp\) and \(\Delta\phi\) cuts which are necessary to kill the photon-induced SM background. The upper edge, however, remains pronounced. If the chargino mass is determined from elsewhere (e.g. the threshold scan), the upper edge allows one to determine the sneutrino mass with an accuracy of roughly 1%. The most sophisticated method of mass determination by fitting the entire 'experimental' lepton energy distributions to the MC samples generated for varying sneutrino mass allows one to go down with the sneutrino mass error to 0.3 GeV.

4 Conclusions

The chargino pair production process with the subsequent two-body leptonic decay at the ILC with \(\sqrt{s} = 500\) GeV has been investigated including all relevant SM and SUSY backgrounds as well as ISR and beamstrahlung. With the event generator WHIZARD, the full matrix element for production and decay together with off-shell and interference effects were taken into account. We have demonstrated that this process can allow us to determine the sneutrino mass with the accuracy well below 1%. In scenarios where sneutrinos are otherwise invisible, this is the only method of their detection and mass measurement. The expected high experimental precision at the ILC, however, calls for more precise theoretical methods, so a full NLO calculation of the signal process is a possible future improvement of the present study [5].

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