Supersymmetric Signals in \(e^-e^-\) Collisions

Frank Cuypers\(^a,1\)
Geert Jan van Oldenborgh\(^b,2\)
Reinhold Rückl\(^a,c,d,3\)

\(^a\) Sektion Physik der Universität München, D–8000 München 2, FRG
\(^b\) Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland
\(^c\) Max-Planck-Institut für Physik, Werner-Heisenberg-Institut, D–8000 München 40, FRG
\(^d\) CERN, CH-1211 Genève 23, Switzerland

Abstract

We consider the production and decay of selectrons and charginos in \(e^-e^-\) collisions. The advantage over usual \(e^+e^-\) collisions is the very low level of standard model backgrounds which should make the discovery of selectrons or charginos relatively straightforward. The use of polarized beams provides an additional powerful tool to determine the supersymmetry parameters.

\(^1\) Email: frank@hep.physik.uni-muenchen.de
\(^2\) Email: gj@csun.psi.ch
\(^3\) Email: rer@dmumpiwh.bitnet

* Work partially supported by the German Federal Ministry for Research and Technology under the contract No. 05 6MU93P and by the CED Science Project No. SCI-CT 91-0729.
1 Introduction

A large international effort is currently under way to study the technical feasibility and physics possibilities of linear $e^+e^-$ colliders in the TeV range. A number of designs have already been proposed (NLC, JLC, TESLA, CLIC, VLEPP, . . . ) and several workshops have recently been devoted to the subject.

From the experimental point of view such a machine would provide exciting new possibilities, including the use of highly polarized beams [1] or the production of high energy photon beams [2]. Another very useful option feasible at a linear collider facility consists in colliding electrons with electrons. Of course, in the realm of the standard model this option is not particularly interesting because mainly Møller scattering and Bremsstrahlung events are to be observed. However, it is just for that reason that $e^-e^-$ collisions can provide unique information on exotic processes, in particular on processes involving lepton and/or fermion number violation. For example, heavy dileptons would yield an unmistakable signal [3], Majorana neutrinos would strongly enhance the production of $W$ pairs [4], and selectrons may be abundantly produced [5] and detected through their decays.

We reexamine here this last possibility and extend the analysis of Ref. [5] to a full study of the supersymmetry parameter space with more realistic assumptions, taking into account the knowledge accumulated in the past years. In addition, we also consider the production of charginos. For definiteness, we focus our analysis on a 500 GeV collider, and indicate how the cross sections evolve with the energy.

In sections 2 and 3 we describe how selectron and chargino pairs can be produced in $e^-e^-$ collisions, and give the relevant cross section formulae. Section 4 is devoted to a short discussion of the decay modes of the selectron and of charginos. We then examine in section 5 the signals and main standard model backgrounds in unpolarized $e^-e^-$ collisions. Finally, in section 6, we show how the backgrounds can be reduced to a very low level with the help of polarized beams and how information on the values of the supersymmetry parameters can be gathered that is complementary to what can be learned from unpolarized tests.

2 Selectron Production

Selectron pairs can be produced in $e^-e^-$ collisions by the u- and t-channel exchange of neutralinos, as is shown on Fig. 1. Note that this reaction violates fermion number conservation, which comes as no surprise since the neutralinos are Majorana fermions.

The yield of selectrons depends very crucially on the properties of the exchanged neutralinos [6], i.e., their masses and their couplings to electrons, because strong interferences can take place between the different channels and dramatically influence the production cross section. In the minimal model, the masses
The mass parameters can take complex values. Moreover, the masses $m_{\tilde{e}_{L,R}}$ of the left- and right-selectrons are arbitrary and need not be the same. We are thus dealing with an appreciable number of degrees of freedom, which can however be reduced by a few reasonable and customary assumptions:

- $\mu$ and $M_2$ are taken to be real.
- $M_1 = 5/3M_2\tan^2\theta_{w}$, where $\theta_{w}$ is the weak mixing angle. This is a consequence of the renormalization group evolution from a common value $M_1 = M_2$ at the GUT scale.
- All sleptons have the same mass and are much lighter than the strongly interacting squarks and gluinos $m_{\tilde{\ell}_L} = m_{\tilde{\ell}_R} = m_{\tilde{\nu}_\ell} \ll m_{\tilde{q}}, m_{\tilde{g}}$. If renormalization group relations for scalar masses are used, this corresponds to assuming a relatively large value for the common scalar mass parameter $m_0$.
- The lightest supersymmetric particle is a neutralino.
- R-parity remains unbroken. Therefore, supersymmetric partners are always produced in pairs and the lightest neutralino is stable (in virtue of the previous assumption).

As it turns out, for $\tan \beta \geq 2$, the dependence on $\tan \beta$ is generally weak. For definiteness, we thus set $\tan \beta = 10$ in the following. In contrast, the results are very sensitive to the values of $\mu$ and $M_2$. To cover the whole parameter space, it is sufficient to consider positive and negative values of $\mu$ and only positive values of $M_2$. We shall later display our results in this $(\mu, M_2)$ half-plane. For the time being, however, and for definiteness we choose to work with $\mu = -300$ GeV and $M_2 = 300$ GeV. In this case the masses of the lightest neutralino and chargino are $m_{\tilde{\chi}^0_1} = 147$ GeV and $m_{\tilde{\chi}^{\pm}_1} = 255$ GeV. These values lie well beyond the existing experimental constraints.
The polarized differential cross sections for selectron production are given by

\[
\frac{d\sigma(e_L^{-} e_R^{-} \rightarrow \bar{e}_L^{-} \bar{e}_R^{-})}{d t} = \frac{\pi \alpha^2}{s^2} \sum_{i,j=1}^{4} g_{iL} g_{iR} g_{jL}^* g_{jR}^* \frac{tu - m_i^2}{(m_{\chi_i^0}^2 - t)(m_{\chi_j^0}^2 - t)},
\]

(1)

\[
\frac{d\sigma(e_L^{-} e_L^{-} \rightarrow \bar{e}_L^{-} \bar{e}_L^{-})}{d t} = \frac{\pi \alpha^2}{2s^2} \sum_{i,j=1}^{4} g_{iL} g_{jL}^* g_{iR} g_{jR}^* s m_{\chi_i^0} m_{\chi_j^0}
\times \left( \frac{1}{m_{\chi_i^0}^2 - t} + \frac{1}{m_{\chi_j^0}^2 - u} \right) \left( \frac{1}{m_{\chi_i^0}^2 - t} + \frac{1}{m_{\chi_j^0}^2 - u} \right),
\]

(2)

\[\alpha \approx 1/128\] being the fine structure constant, and \(s, t, u\) being the usual Mandelstam variables. The formulas for the RL and RR cross sections are obtained from the expressions above in an obvious manner. The corresponding total cross sections are

\[
\sigma(e_L^{-} e_R^{-} \rightarrow \bar{e}_L^{-} \bar{e}_R^{-}) = \frac{\pi \alpha^2}{s} \sum_{i,j=1}^{4} g_{iL} g_{iR} g_{jL}^* g_{jR}^* \left\{ -\lambda \frac{1}{s} - \frac{1}{(m_{\chi_i^0}^2 - m_{\chi_j^0}^2)s} \right\}
\times \left[ (m_{\chi_i^0}^2 s + (m_{\chi_i^0}^2 - m_{\epsilon}^2)^2) L_i - (m_{\chi_j^0}^2 s + (m_{\chi_j^0}^2 - m_{\epsilon}^2)^2) L_j \right],
\]

(3)

\[
\sigma(e_L^{-} e_L^{-} \rightarrow \bar{e}_L^{-} \bar{e}_L^{-}) = \frac{\pi \alpha^2}{s} \sum_{i,j=1}^{4} g_{iL} g_{jL}^* g_{iR} g_{jR}^* \frac{m_{\chi_i^0} m_{\chi_j^0}}{(m_{\chi_i^0}^2 - m_{\chi_j^0}^2)(s + m_{\chi_i^0}^2 + m_{\chi_j^0}^2 - 2m_{\epsilon}^2)}
\times \left[ (s + 2m_{\chi_i^0}^2 - 2m_{\epsilon}^2) L_i - (s + 2m_{\chi_j^0}^2 - 2m_{\epsilon}^2) L_j \right],
\]

(4)

where

\[
\lambda = \lambda(s, m_{\epsilon}^2, m_{\chi_j^0}^2) = \sqrt{s^2 - 4m_{\epsilon}^2 s}
\]

(5)

and

\[
L_i = \ln \frac{s + 2m_{\chi_i^0}^2 - 2m_{\epsilon}^2 + \lambda}{s + 2m_{\chi_i^0}^2 - 2m_{\epsilon}^2 - \lambda}.
\]

(6)

For \(i = j\) the limit of these expressions has to be taken carefully and agrees with the results obtained for the exchange of a single photino in Ref. \[3\].

The energy dependence of the selectron production cross section is shown in Fig. 2 for several selectron masses. Clearly, the highest cross sections are obtained just above threshold. Away from threshold the dependence on the selectron mass is quite weak, as can be seen more clearly in Fig. 3 where we have plotted the dependence of the selectron production cross section as a function of the selectron mass for unpolarized as well as for polarized electron beams and for the centre-of-mass energy \(\sqrt{s} = 500\) GeV.
3 Chargino Production

Chargino pairs can be produced in $e^-e^-$ collisions by the u- and t-channel exchange of a sneutrino, as is also shown in Fig. 1. Since charginos only couple to left-handed leptons, only the LL component of a given $e^-e^-$ initial state contributes. The polarized differential cross sections are given by

$$\frac{d\sigma}{d\alpha}\left(\bar{e}^-_L e^-_L \rightarrow \tilde{\chi}^-_i \tilde{\chi}^-_j\right) = \frac{1}{1 + \delta_{ij}} \frac{\alpha s^2}{\pi} |g_i g_j|^2 \left(\frac{m_{\tilde{\chi}}^2 - t}{m_{\tilde{\nu}}^2 - t} + \frac{m_{\tilde{\chi}}^2 - u}{m_{\tilde{\nu}}^2 - u} \right)$$

$$\times \left\{ \left[\frac{m_{\tilde{\chi}}^2 - t}{m_{\tilde{\nu}}^2 - t} + \frac{m_{\tilde{\chi}}^2 - u}{m_{\tilde{\nu}}^2 - u} \right] - \frac{\left[m_{\tilde{\chi}}^2 - u\right] \left[m_{\tilde{\chi}}^2 - t\right]}{m_{\tilde{\nu}}^2 - t} \right\}.$$ (7)

The masses $m_{\tilde{\chi}}$ of the charginos and their couplings to selectrons $g_i$ are also functions of the three supersymmetry parameters $\tan\beta$, $\mu$ and $M_2$. For the total cross section one obtains

$$\sigma(e^-_L e^-_L \rightarrow \tilde{\chi}^-_i \tilde{\chi}^-_j) = \frac{1}{1 + \delta_{ij}} \frac{2\alpha s^2}{\pi} |g_i g_j|^2$$

$$\times \left\{ 2\lambda + \left[\Pi - m_{\tilde{\nu}}^2 \Sigma + m_{\tilde{\nu}}^2 \right] F + \frac{\Sigma^2 + 2\Pi + 6m_{\tilde{\nu}}^2 - 6m_{\tilde{\nu}}^2 \Sigma + 4m_{\tilde{\nu}}^2 s - s \Sigma}{\Sigma - 2m_{\tilde{\nu}}^2 - s} L \right\},$$ (8)

where

$$\Sigma = m_{\tilde{\chi}}^2 + m_{\tilde{\chi}}^2$$

$$\Pi = m_{\tilde{\chi}}^2 - m_{\tilde{\chi}}^2$$

$$\lambda = \lambda(s, m_{\tilde{\chi}}^2, m_{\tilde{\chi}}^2) = \sqrt{s^2 + m_{\tilde{\chi}}^4 + m_{\tilde{\chi}}^2 - 2sm_{\tilde{\chi}}^2 - 2m_{\tilde{\chi}}^2 - 2m_{\tilde{\chi}}^2 m_{\tilde{\chi}}^2}$$

$$F = \frac{\lambda}{m_{\tilde{\nu}}^2 + m_{\tilde{\nu}}^2 (s - \Sigma) + \Pi}$$

$$L = \ln \frac{s + 2m_{\tilde{\nu}}^2 - \Sigma + \lambda}{s + 2m_{\tilde{\nu}}^2 - \Sigma - \lambda}.$$ (11)

The dependence of the unpolarized cross section $\sigma(e^-e^- \rightarrow \tilde{\chi}^-_i \tilde{\chi}^-_i)$ on the collider energy is shown in Fig. 2 for several values of the mass of the exchanged sneutrino. We repeat that this plot has been obtained for $\tan\beta = 10$, $\mu = -300$ GeV and $M_2 = 300$ GeV, i.e. for a chargino mass $m_{\tilde{\chi}}^2 = 255$ GeV.
4 Decays of the Selectron and Charginos

Since all the (s)particles considered here decay through electroweak interactions, their lifetimes are typically long in comparison to their mass scale. It is therefore safe to use the narrow width approximation, which we will do in the following.

The simplest decay mode of the selectron is into an electron and the lightest neutralino:

$$\tilde{e}^- \rightarrow e^- \tilde{\chi}_1^0 .$$  \hspace{1cm} (14)

Since we assume the neutralino to be the lightest supersymmetric particle, only the electron is visible. In the $e^-e^- \rightarrow \tilde{e}^-\tilde{e}^-$ reaction, this decay yields a clean $e^-e^- + p_\perp$ event which we suggest to use as a signal for the production of selectrons.

If kinematically allowed, other decays can take place in addition, most importantly,

$$\tilde{e}^- \rightarrow e^- \tilde{\chi}_2^0 ,$$  \hspace{1cm} (15)

$$\rightarrow \nu_e \tilde{\chi}_1^- ,$$  \hspace{1cm} (16)

and similar decays into the heavier neutralino and chargino states. The supersymmetric particles produced in this way will decay into lighter (s)particles, which themselves might undergo further decays until only conventional particles and a number of the lightest neutralino remain. The end-product of such cascade decays can sometimes again be an electron accompanied by invisible particles only. For the $e^-e^- \rightarrow \tilde{e}^-\tilde{e}^-$ reaction, this mechanism can thus provide an important enhancement of the $e^-e^- + p_\perp$ signal in regions of the supersymmetric parameter space where the direct decay (14) is not dominant [6]. To compute the branching ratio for the decay $\tilde{e} \rightarrow e^- + \text{invisible}$, we shall make use of the two-body decay algorithm described in [6].

The decays of charginos are even more complicated. Concentrating on the lightest chargino, if kinematically allowed to do so, it will decay into leptons and sleptons or $W^\pm$s and neutralinos:

$$\tilde{\chi}_1^- \rightarrow \ell^- \tilde{\nu}_\ell ,$$  \hspace{1cm} (17)

$$\rightarrow \tilde{\ell}^- \nu_\ell ,$$  \hspace{1cm} (18)

$$\rightarrow W^- \tilde{\chi}_1^0 .$$  \hspace{1cm} (19)

For simplicity, we discard the possibility

$$\tilde{\chi}_1^- \rightarrow H^- \tilde{\chi}_1^0$$  \hspace{1cm} (20)

by assuming the charged Higgs boson to be too heavy. If the chargino is heavier than the sleptons, it will preferentially decay with approximately a 50% branching ratio in each of the channels (17) and (18) and with democratic probabilities
for the different flavours \[3\]. In this case, the sleptons can only decay further into leptons and neutralinos and will eventually yield a \(\ell^-\ell^- + p_{\perp}\) signal in the \(e^-e^- \rightarrow \tilde{\chi}_1^-\tilde{\chi}_1^-\) reaction. If the chargino is lighter than the sleptons but can still decay according to the reaction \(14\), one has to deal with a \(W^-W^-\) signal. It can also happen that none of the two-body decays \(17-20\) is kinematically allowed. If this is the case and if the mass of the sleptons is much larger than the mass of the \(W\), the decay through a virtual \(W\) dominates. The branching ratio of the leptonic decay \(\tilde{\chi}_1^- \rightarrow \ell^- \bar{\nu}_\ell \tilde{\chi}_0^1\) is then approximately 42\% \[10\]. In the next section, we will concentrate our analysis of the chargino production in \(e^-e^-\) collisions on the \(\mu^-\mu^- + p_{\perp}\) signal.

### 5 Unpolarized Electron Beams

To select \(e^-e^- + p_{\perp}\) events containing the selectron signal we impose the following kinematical cuts on the two observed electrons:

- the rapidity cut
  \[
  |\eta_e| < 3 ; 
  \tag{21}
  \]
- the energy cut
  \[
  E_e > 5 \text{ GeV} ; 
  \tag{22}
  \]
- the acoplanarity cut
  \[
  \left| |\phi(e_1^-) - \phi(e_2^-)| - 180^\circ \right| > 2^\circ , 
  \tag{23}
  \]

where \(\phi\) is the azimuthal angle of the electrons with respect to the beam axis.

The two cuts \(21,22\) are supposed to guarantee good detector acceptance. The acoplanarity cut \(23\) is designed to eliminate the abundant Møller electron pairs. The leading standard model backgrounds which then remain originate from \(W^+\) and \(Z^0\) Bremsstrahlung:

\[
e^-e^- \rightarrow e^-\nu_e W^- , 
\tag{24}
\]
\[
e^-e^- \rightarrow e^-e^- Z^0 \xrightarrow{\nu\bar{\nu}} . 
\tag{25}
\]

These backgrounds, whose typical leading order Feynman diagrams are depicted in Fig. 4, are quite sensitive to the cuts \(21-23\) because their cross sections are dominated by large collinear logarithms. After cuts and including the relevant branching ratios, the cross sections are 150 fb for \(W^-\) Bremsstrahlung \(24\) and 40 fb for \(Z^0\) Bremsstrahlung \(25\).

On the other hand, the acceptance cuts \(21,22\) have almost no impact on the supersymmetric \(e^-e^- + p_{\perp}\) signal from selectron production, except for the
very small region of parameter space where \( m_{\tilde{e}} - m_{\tilde{\chi}^0_1} < 10 \) GeV and the decay electrons have little energy. Also the acoplanarity cut (24) reduces the signal by at most 3%. In Fig. 4 we have displayed the contours in the \((\mu, M_2)\) half-plane where the signal cross section for a 200 GeV selectron reaches 0.1 and 1 pb, respectively. Comparing this result with the above background estimates we conclude that over a large part of the parameter space beyond the region which will be explored by LEP2, the signal to background ratio is of order one or more. Moreover, the 1 pb contour cuts through an area of parameter space where there are no cascade decays. In contrast, the 0.1 pb contour is located in a region where cascade decays are important and have to be taken into account. However, for the moderate energy cut (22) most of those electrons which emerge at the end of a cascade like the ones from \( \tilde{\chi}^0_2 \) and \( \tilde{\chi}^-_1 \) decays in (15) and (16), still carry enough energy to be observable. We have also outlined in Fig. 5 the contours which are obtained when only the direct decay (14) is considered and cascade decays of the type (15,16) are neglected.

Here we should point out that in order to obtain the branching ratios for cascade decays, we have used a two-body decay algorithm [6] which yields imprecise results when some of the two-body decays become kinematically impossible and three-body decay formulae [11] have to be used. This happens when \( m_{\tilde{\chi}^0_2} < \min(m_{\tilde{\ell}}, m_{\chi^0_1} + m_Z) \) or \( m_{\tilde{\chi}^-_1} < \min(m_{\tilde{\ell}}, m_{\chi^0_1} + m_W) \) as is the case for low values of \( \mu \) or \( M_2 \). Our contours including cascade decays might thus not be too precise. However, they certainly cannot reach beyond the dotted contours. Since most of this region of parameter space will already be explored by LEP2 anyway, this uncertainty is not really relevant.

If selectrons are too heavy to be produced in pairs, charginos can still save the day. Concentrating on the \( \mu^- \mu^- + p^\perp \) signal, the background arises mainly from double \( W \) Bremsstrahlung (26):

\[
e^+e^- \rightarrow W^-\nu_e W^-\nu_e \quad \leftrightarrow \mu^-\bar{\nu}_\mu \quad \leftrightarrow \mu^-\bar{\nu}_\mu
\]

This process is very laborsome to evaluate. An order of magnitude estimate suggests that the cross section should be less than 10% of the cross section obtained for the single \( W \) Bremsstrahlung process (24), \( i.e. \) approximately 100 fb. Consequently, the cross section for obtaining a \( \mu^- \mu^- + p^\perp \) event from this standard model source within the cuts should not exceed 1 fb. Concentrating on chargino production and assuming 300 GeV for the mass of the exchanged sneutrino we have plotted in Fig. 6 the contours in the \((\mu, M_2)\) half-plane along which the observable cross section for the \( \mu^- \mu^- + p^\perp \) signal from the decay modes (17,18) is 1, 10 and 100 fb. We find that as long as \( M_2 \lesssim 300 \) GeV, the signal to background ratio should comfortably exceed one.
6 Polarized Electron Beams

In chargino pair production, polarization can only enhance the signal (as well as the background) by a factor up to four. For selectrons, however, the use of polarized electron beams completely changes the picture.

Besides a possible enhancement of the $e^-e^- + p$, signal for some values of the supersymmetry parameters, working with right-handed polarized beams has the immense advantage of eliminating the most important background from $W^-$ Bremsstrahlung \cite{24}. In this situation, it is then worthwhile to try to also eliminate the background from $Z^0$ Bremsstrahlung \cite{25}, in order to select a really clean sample of supersymmetric events with no, or negligibly little, background from standard model processes. This is indeed possible since the energies $E_1$ and $E_2$ of the electron pairs which originate from $Z^0$ Bremsstrahlung and from selectron production and decay are very distinctly distributed in the phase space. The respective boundaries are given by

$$E_1 + E_2 > \frac{s - m_Z^2}{2s}$$

(27)

$$(\sqrt{s} - 2E_1)(\sqrt{s} - 2E_2) > m_Z^2$$

for $e^-e^- \rightarrow e^-e^-Z^0$, and by

$$E_1, E_2 > \frac{\sqrt{s}}{4} \left(1 - \frac{m_{\tilde{e}_10}^2}{m_{\tilde{e}_10}}\right) \left(1 - \sqrt{1 - \frac{4m_{\tilde{e}_10}^2}{s}}\right)$$

(28)

$$E_1, E_2 < \frac{\sqrt{s}}{4} \left(1 - \frac{m_{\tilde{e}_10}^2}{m_{\tilde{e}_10}}\right) \left(1 + \sqrt{1 - \frac{4m_{\tilde{e}_10}^2}{s}}\right)$$

for $e^-e^- \rightarrow \tilde{e}^-\tilde{e}^- \rightarrow e^-e^-\chi_1^0\chi_1^0$. A typical example of such boundaries is shown in the Dalitz plot of Fig. 7. As it can be seen, by imposing the high energy cut

$$E_{e_1} + E_{e_2} < \frac{s - m_Z^2}{2\sqrt{s}} \approx 242 \text{ GeV}$$

(29)

one can eliminate all electron pairs which originate from $Z^0$ Bremsstrahlung without affecting much the signal. At worst 55% of the electron pairs which originate from selectron production can be lost by this cut, and for many values of the selectron and neutralino masses it has no incidence.

The overall discovery potential of such a polarization experiment is illustrated in Fig. 8. As in Fig. 5 for the unpolarized case we display the 0.1 pb and 1 pb contours in the $(\mu, M_2)$ half-plane. The contours which would be obtained if cascade decays are neglected, are outlined by the dotted curves. Outside of the area which will be covered by LEP2 the influence of cascades is only marginal.
In comparison to the unpolarized case, the area where the cross section exceeds 1 pb has grown noticeably. On the other side, there are now two bands with small cross sections (less than 0.1 pb) along the lines $M_2 = 2|\mu|$ which are quite narrow but which reach deeply into the unexplored $(\mu, M_2)$ regions. This effect is caused by subtle interferences between the different neutralinos exchanged in the u- and t-channel. A similar destructive interference is observed along the lines $M_2 = |\mu|$ in the case of left-handed polarization. This also explains the huge differences in cross section for different polarizations observed already in Fig. 3. Obviously, this characteristic feature can be used to determine or, at least, constrain the supersymmetry parameters by comparing the $e^-e^- + \not{p}_T$ yield for different combinations of polarizations of the electron beams.

Furthermore, if the upper and lower limits $E_{\text{max}}$ and $E_{\text{min}}$ of the electron energies in the signal events (see (28)) can be determined more or less accurately, it should be possible to derive rough values for both the mass of the selectron and the mass of the lightest neutralino:

$$m_{\tilde{e}} = \sqrt{s} \sqrt{\frac{E_{\text{max}}E_{\text{min}}}{(E_{\text{max}} + E_{\text{min}})^2}}$$

$$m_{\tilde{\chi}^0_1} = m_{\tilde{e}} \sqrt{1 - 2(\frac{E_{\text{max}} + E_{\text{min}}}{\sqrt{s}})}.$$

Note that this mass determination is of purely kinematical nature. It does not depend on the values taken by any of the remaining supersymmetry parameters and is thus entirely model-independent. The effects of smearing due to initial state Bremsstrahlung should be further investigated.

7 Conclusions

Because of the low level of standard model backgrounds, $e^-e^-$ collisions are an ideal reaction for discovering and investigating supersymmetry at linear colliders. The selectron and chargino production cross sections are of the same order as in $e^+e^-$ collisions but the backgrounds are down by more than one order of magnitude. Moreover, in contrast to $e^+e^-\gamma$ [12], $e^-\gamma$ [13] or $\gamma\gamma$ [9] collisions, possible cascade decays of the selectron would be clearly observed, since no strong transverse momentum cuts are necessary here to differentiate a supersymmetric $e^-e^- + \not{p}_T$ signal from the standard model background.

For selectron production, right-handed polarization of the electron beams can further enhance the signal to background ratio and in principle allow for a direct, model-independent measurement of the selectron and neutralino masses. In addition, comparison of cross sections for different polarizations can provide information on the values taken by the various gaugino/higgsino mixing parameters.
Part of the cross sections we used have been computed with the help of the
dedicated computer algebra program CompHEP [14]. We are very much indebted
to Edward Boos and Mishael Dubinin for having provided us with this software.

References

[1] C. Damerell, private communication.
[2] I.F. Ginzburg, G.L. Kotkin, V.G. Serbo and V.I. Telnov, Nucl. Instr. Meth. 205 (1983) 47.
[3] P. Frampton and D. Ng, Phys. Rev. D 45 (1992) 4240.
[4] C. Heusch and P. Minkowski, in preparation.
[5] W.-Y. Keung and L. Littenberg, Phys. Rev. D 28 (1983) 1067.
[6] F. Cuypers, Yad. Fis. (in press).
[7] H.E. Haber and G.L. Kane, Phys. Rep. 117 (1985) 75, H.P. Nilles, Phys. Rep. 110 (1984) 1.
[8] R. Van Kooten, CERN preprint CERN-TH.6707/92-PPE/92-180.
[9] F. Cuypers, G.J. van Oldenborgh and R. Rückl, Nucl. Phys. (in press).
[10] A. Bartl et al., Large Hadron Collider Workshop, eds G. Jarlskog and D. Rein, CERN 90-10, ECFA 90-133, Vol. II, p. 1033.
[11] A. Bartl, H. Fraas and W. Majerotto, Z. Phys. C 41 (1988) 475.
[12] J.F. Grivaz, Proceedings of the Workshop on $e^+e^-$ Collisions at 500 GeV: The Physics Potential, DESY, Hamburg, 1991.
[13] F. Cuypers, G.J. van Oldenborgh and R. Rückl, Nucl. Phys. B 383 (1992) 45.
[14] E. Boos et al., in: New Computing Techniques in Physics Research, ed. D. Perret-Gallix and W. Wojcik, Paris, 1990, p. 573.
Figure 1: Lowest order Feynman diagrams contributing to selectron and chargino production.
Figure 2: Energy dependence of the unpolarized production cross sections of $e^- e^- \rightarrow \tilde{e}^- \tilde{e}^-$ (full curves) and $e^- e^- \rightarrow \tilde{\chi}_1^- \tilde{\chi}_1^-$ (dotted curves) for $m_{\tilde{e}} = m_{\tilde{\nu}} = 150, 200, \ldots, 800$ GeV, assuming $\tan \beta = 10$, $\mu = -300$ GeV and $M_2 = 300$ GeV. For this choice of parameters, $m_{\tilde{\chi}_1} = 255$ GeV.
Figure 3: Dependence of the total production cross sections for selectron pairs on the mass of the selectron in polarized and unpolarized $e^-e^-$ scattering at $\sqrt{s} = 500$ GeV. The choice of supersymmetry parameters is the same as in Fig. 2, in particular, $m_{\tilde{e}_L} = m_{\tilde{e}_R} = m_{\tilde{e}}$. 
Figure 4: Lowest order Feynman diagrams contributing to the standard model background processes considered.
Figure 5: Contours in the supersymmetry parameter space corresponding to the unpolarized cross sections \( \sigma(e^-e^- \rightarrow \tilde{e}^-\tilde{e}^- \rightarrow e^-e^- + p_T) = 0.1 \) and 1 pb for \( m_{\tilde{e}} = 200 \) GeV, \( \tan \beta = 10 \), and the cuts defined in (21-23). The regions labelled ‘unphysical’ are excluded since there \( m_{\tilde{e}} < m_{\chi_1^0} \) in contradiction to our assumption of the \( \chi_1^0 \) being the lightest supersymmetry particle. The contours which would be obtained if cascade decays are ignored are also shown with dotted lines.
Figure 6: Contours in the supersymmetry parameter space corresponding to the unpolarized cross sections \( \sigma(e^- e^- \rightarrow \tilde{\chi}_1^- \tilde{\chi}_1^- \rightarrow \mu^- \mu^- + p_\perp) = 1, 10 \) and 100 fb including the cuts (21-23). The chargino mass \( m_{\tilde{\chi}_1^-} \) varies with \( M_2 \) and \( \mu \), while the sneutrino mass is set to 300 GeV and \( \tan \beta = 10 \).
Figure 7: Allowed range of energies for the final state electrons in the processes $e^- e^- \rightarrow e^- e^- Z^0$ and $e^- e^- \rightarrow \tilde{e}^- \tilde{e}^- \rightarrow e^- e^- \tilde{\chi}^0_1 \tilde{\chi}^0_1$. For the latter reaction we have assumed $m_{\tilde{e}} = 200$ GeV and $m_{\tilde{\chi}^0_1} = 100$ GeV.
Figure 8: Same as Fig. 5, for electron beams with right-handed polarization and including the energy cut (29). The contours which would be obtained if cascade decays are ignored are indicated by dotted lines.