SELECTRON SEARCHES IN $e^-e^-$ SCATTERING

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Abstract

We review the pair-production and decay of selectrons in $e^-e^-$ collisions and show how the standard model backgrounds can be virtually eliminated with polarized beams. The exceedingly simple analysis involved and the large sample of background-free supersymmetric events make this linear collider operating mode ideal for discovering selectrons and measuring the mass of the lightest neutralino.

In spite of their economy of principles, supersymmetric extensions of the standard model involve an opulent number of free parameters. Although the strengths of the interactions must be precisely the same as those of the standard model, at this stage the masses and mixings of the supersymmetric partners of the conventional particles cannot be predicted from first principles.

To see clear through this jungle of parameters it is important to perform as many independent experiments as possible. A particularly promising candidate is the pair-production of selectrons in $e^-e^-$ collisions

\[ e^-e^- \rightarrow \tilde{e}^-\tilde{e}^- . \]

This reaction has been studied in detail previously and we summarize here the main conclusions.

Since the strongly interacting sector plays only a minor role (at best) in $e^-e^-$ collisions, the relevant supersymmetry parameters are the mass parameters $M_1, M_2, \mu$ associated with the $U(1)$ and $SU(2)_L$ gauginos and the higgsinos respectively, the ratio $\tan \beta = v_2/v_1$ of the Higgs vacuum expectation values and the selectron masses. We work in the context of the minimal supersymmetric standard model and make the following assumptions:

- $R$-parity is a conserved quantum number.
- The lightest neutralino $\chi_1^0$ is the lightest supersymmetric particle.
• All selectrons have the same mass and are much lighter than the strongly interacting squarks and gluinos: $m_{\tilde{e}_L} = m_{\tilde{e}_R} \ll m_{\tilde{q}}, m_{\tilde{g}}$.

• The mass parameters $M_1, M_2, \mu$ are real.

• At the GUT scale $M_1 = M_2$, so that after renormalization to accelerator energies $M_1 = 5/3 M_2 \tan^2 \theta_w$, where $\theta_w$ is the weak mixing angle.

The first two assumptions are essential, because they dictate the whole supersymmetric phenomenology: all sparticles decay directly or via a cascade into the lightest supersymmetric particle which is stable and escapes detection. These are very conservative constraints. Indeed, if $R$-parity were to be broken the situation would be much simpler, since supersymmetry would show up with blatant like lepton number violating processes or neutralino decays in the detector. The last three working hypotheses are merely for simplicity and can be relaxed without qualitatively modifying the conclusions. Their virtue is to reduce the number of relevant independent parameters to only four:

$$\tan \beta \ M_2 \ \mu \ m_{\tilde{\ell}}.$$  \hspace{1cm} (2)

Of these four parameters, $\tan \beta$ is the least influential, at least when it is larger than 2. In contrast, the results are very sensitive to variations of the other three parameters.

Since the selectron decays only through electroweak interactions, its lifetime is typically long in comparison to its mass scale, and it is therefore safe to use the narrow width approximation. Its simplest decay mode is into an electron and the lightest neutralino:

$$\tilde{e}^- \to e^- \tilde{\chi}_1^0.$$  \hspace{1cm} (3)

According to our assumptions on $R$-parity and the lightest supersymmetric particle being a neutralino, only the electron is visible. If kinematically allowed, other decays can take place like

$$\tilde{e}^- \to e^- \tilde{\chi}_2^0$$  \hspace{1cm} (4)

$$\to \nu_{e} \tilde{\chi}_1^-$$  \hspace{1cm} (5)

as well as similar decays into the heavier neutralino and chargino states. The supersymmetric particles produced this way eventually decay into lighter (s)particles, which themselves might undergo further decays until only conventional particles and a number of lightest neutralinos remain. The end-product of such cascade decays can sometimes again be an electron accompanied by invisible particles only. In the following we concentrate on this very decay signature

$$\tilde{e}^- \to e^- + \not{p}_T,$$  \hspace{1cm} (6)

whose branching ratio we compute with the two-body decay algorithm described in Ref. [3].
Selectron pair-production takes place in $e^-e^-$ collisions via the exchange of neutralinos, as depicted in Fig. 1. Note that all four neutralinos play an important role in this reaction. The dependence on the supersymmetry parameters is thus rather complex because it enters at three different levels:

1. through the masses of the four different neutralinos;
2. through their mixings among each other which affects their couplings to electrons and selectrons;
3. through the mass and branching ratios of the selectron.

The energy dependence of the cross section is also shown in Fig. 1, for unpolarized beams. For this we imposed the following rapidity, energy and acoplanarity cuts on the observed leptons:

$$|\eta_e| < 3 \quad , \quad E_e > 5 \text{ GeV} \quad , \quad \left|\phi(e_1^-) - \phi(e_2^-) - 180^\circ\right| > 2^\circ,$$

where $\phi$ is the azimuthal angle of the decay electrons with respect to the beam axis.

The yield is sharply peaked just above threshold so that an energy scan can provide precise information about the mass of the selectron.

Concentrating on the selectron decay Eq. (6) leads to the following observable signal:

$$e^-e^- \to \tilde{e}^-\tilde{e}^- \to e^-e^- + \not{p}_T .$$

Figure 1: Lowest order Feynman diagram describing selectron production in $e^-e^-$ collisions and typical energy dependence of the corresponding cross section.
The most important standard model backgrounds originate from $W^-$ and $Z^0$ Bremsstrahlung

\[ e^-e^- \rightarrow e^-\nu_e W^- \leftrightarrow e^-\bar{\nu}_e \]  
\[ e^-e^- \rightarrow e^-e^- Z^0 \leftrightarrow \nu\bar{\nu} \]  \hspace{1cm} (9) \hspace{1cm} (10)

After imposing the acceptance cuts (7) and including the relevant branching ratios, the cross sections for $\sqrt{s_{ee}} = 500$ GeV are 150 fb for $W^-$ and 40 fb for $Z^0$ Bremsstrahlung [2]. The potential background from Møller scattering is entirely eliminated by the acoplanarity cut. The supersymmetric signal, on the other hand, is not significantly reduced by these mild cuts, which roughly simulate a typical detector acceptance. As a result, over all the kinematically accessible supersymmetry parameter space (i.e. if the collider energy is sufficient to pair-produce the selectrons) the signal-to-background ratio is never significantly less than one. Simply counting the rates is thus largely sufficient to discover the selectrons.

![Figure 2: Dalitz plot of the allowed energy ranges of the final state electrons in the processes $e^-e^- \rightarrow e^-e^- Z^0$ (diagonal line and hyperbola) and $e^-e^- \rightarrow \tilde{e}^-\tilde{e}^- \rightarrow e^-e^- \tilde{\chi}^0_1\tilde{\chi}^0_1$. (square). For the latter reaction we have assumed $m_{\tilde{e}} = 200$ GeV and $m_{\tilde{\chi}^0_1} = 100$ GeV.](image)

The signal to background ratio can be strongly enhanced with right-handed electron beams, for which the $W^-$ Bremsstrahlung background disappears. It is then
worthwhile to also eliminate the background from $Z^0$ Bremsstrahlung, in order to select a clean sample of supersymmetric events with no, or negligibly little, background from standard model processes. As can be gathered from Fig. 2, where we plotted the kinematically admissible energies of the emerging electrons, the $Z^0$ events can be filtered out by rejecting all $e^-e^-$ events with a total deposited energy exceeding about half the centre of mass energy

$$E_{e_1} + E_{e_2} < \frac{s - m_{Z^0}^2}{2\sqrt{s}}.$$  

If this cut is imposed, none of the $Z^0$ contributes and at worst 55% of the electron pairs which originate from selectron production are lost. The next order irreducible background then originates from double $W^-$ Bremsstrahlung

$$e^-e^- \rightarrow W^-\nu_e W^-\nu_e \leftrightarrow e^-\bar{\nu}_e \leftrightarrow e^-\bar{\nu}_e,$$

and amounts to about .1 fb at 500 GeV \[.\] We have plotted in Fig. 3 the contours in the $(\mu, M_2)$ half-plane along which the observable cross section for the $e^-e^- + p_T$ signal from the production of 200 GeV selectrons is 1 and 0.1 pb.

This nearly total absence of backgrounds is a unique opportunity for performing studies which would be arduous or impossible in any other environment, like $e^+e^-$

\[\boxed{e_R\bar{e}_R \rightarrow e^-e^- + p_T}\]

\[\sqrt{s_{ee}} = 500 \text{ GeV}\]
\[\tan \beta = 10\]
\[m_{\tilde{\ell}} = 200 \text{ GeV}\]

Figure 3: Contours in the supersymmetry parameter space of constant cross sections for the selectron signal. The cuts (7,11) are included. The regions where $m_{\tilde{\ell}} < m_{\tilde{\chi}_1^0}$ are excluded by assumption and are labeled “unphysical”.

This nearly total absence of backgrounds is a unique opportunity for performing studies which would be arduous or impossible in any other environment, like $e^+e^-$
annihilations. In particular, one can think of the measurement of the neutralino mass [2] and the study of cascade decays [3], to which we turn now.

The mass of the lightest neutralino can be determined kinematically from the endpoints \( E_{\text{min, max}} \) of the electron energy distribution:

\[
m_{\tilde{\chi}^0_1}^2 = \sqrt{s_{ee}} \frac{E_{\text{max}} E_{\text{min}}}{E_{\text{max}} + E_{\text{min}}} \left( \frac{\sqrt{s_{ee}}}{E_{\text{max}} + E_{\text{min}}} - 2 \right).
\]  

(13)

This is a totally model-independent measurement of the mass of the lightest supersymmetric particle, which no other experiment can perform as precisely. Of course, there is always some smearing due to initial state Bremsstrahlung and beamstrahlung, and the incidence of these effects should be further investigated.

Softer electrons emerging at the end of a longer cascade such as the ones initiated by the decays \( (4,5) \) will not be very much affected by the cuts \( (7,11) \). This makes the \( e^-e^- \) linear collider mode an ideal and unique tool for observing and studying supersymmetric cascades. Neither hadronic nor \( e^+e^- \), \( e^-\gamma \) or \( \gamma\gamma \) collisions can perform well in this field, because they all require high transverse momentum cuts in order to enhance the signal to background ratio.

To conclude, we have shown that the \( e^-e^- \) operating mode of a linear collider is ideal for discovering and studying selectrons. This is mainly due to the low standard model activity of \( e^-e^- \) collisions, which provides a low background environment. Kinematically accessible selectrons would be revealed by a simple counting experiment. Moreover, an extremely pure sample of right-selectrons can be obtained with polarized beams. This in turn allows the precise measurement of the neutralino mass and the opportunity to observe and analyze cascade decays of the selectron.

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