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Supersymmetry at Linear Colliders

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1 Introduction

The next generation of linear electron colliders will provide excellent possibilities for studying physics beyond the standard model. Indeed, in addition to the usual e^+e^- reactions, such colliders will also be able to collide e^-e^-, $e^-\gamma$ and $\gamma\gamma$ beams. In addition, fully polarized electron or photon beams should be obtainable without any appreciable loss of luminosity [1].

In the following, we first quickly describe the high energy photon beams that can be obtained at linear colliders and then concentrate on a few particularly promising reactions involving the production of selectrons. We consider their decay into a single electron accompanied only by invisible particles and compare the prospects for discovering and/or studying supersymmetry in e^-e^-, $e^-\gamma$ and $\gamma\gamma$ collisions. Some of the conclusions also apply to muon channels.

2 Photon Energy Spectrum

High energy photon beams can be obtained by back-scattering high intensity laser rays on high energy electron beams. This mechanism was proposed and is described in Ref. 2. The energy spectrum of the resulting beam of real photons is very hard, and the conversion efficiency can reach 100%. Neglecting higher order effects, the distribution $P(y)$ of the energy fraction y of an electron transferred to a photon, $y = E_\gamma/E_e$, is given by [2]

$$P(y) = \frac{1}{N}\left(1 - y + \frac{1}{1-y} - \frac{4y}{x(1-y)} + \frac{4y^2}{x^2(1-y)^2}\right) , \tag{1}$$

where

$$0 \le y \le \frac{x}{x+1} \tag{2}$$

and

$$x = \frac{4E_e E_{\text{laser}}}{m_e^2} . \tag{3}$$

The factor N normalizes $\int dy\, P(y)$ to 1. The electron and laser beams are taken to be aligned and their respective energies are E_e and E_{laser}. In what follows, we assume a 100% conversion efficiency and neglect the angular dispersion of the back-scattered photons, multiple scattering and higher order effects. When x reaches the value $2(1+\sqrt{2}) \approx 4.83$, the back-scattered and laser photons have enough energy to produce

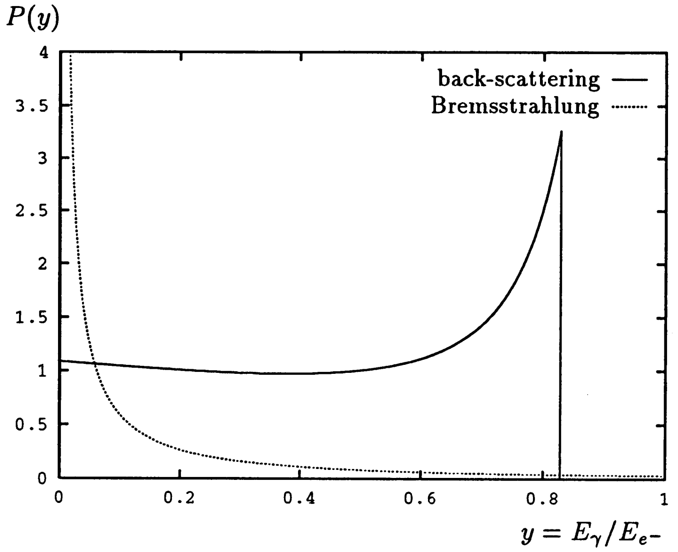

Figure 1: Distribution of photon energies for laser Compton back-scattering ($x = 2 + 2\sqrt{2}$) and Bremsstrahlung in the Weizsäcker-Williams approximation for a 250 GeV electron beam.

e^+e^- pairs. Since the conversion efficiency drops considerably for larger values of x, we assume the laser energy to be tuned in such a way as to obtain $x = 2(1 + \sqrt{2})$. The corresponding energy spectrum (1) is displayed in Fig. 1. It sharply contrasts with the energy spectrum of Bremsstrahlung photons, which is much softer and, hence, less useful for heavy particle searches.

The cross sections of $e\gamma$ and $\gamma\gamma$ reactions involving such a back-scattered photon beam have to be folded with the energy distribution (1). The laboratory frame is thus not the centre of mass frame and the $e\gamma$ and $\gamma\gamma$ centre of mass energies, $\sqrt{s_{e\gamma}}$ and $\sqrt{s_{\gamma\gamma}}$ respectively, are given by

$$s_{e\gamma} = y s_{ee} \tag{4}$$

$$s_{\gamma\gamma} = y_1 y_2 s_{ee} \ , \tag{5}$$

where $\sqrt{s_{ee}} = 2E_e$ is the collider energy and the different y's are the photon energy fractions. The convoluted cross sections are obtained from

$$\sigma(s_{ee}) = \int_{y_{min}}^{y_{max}} dy \ P(y)\sigma(s_{e\gamma}) \tag{6}$$

$$\sigma(s_{ee}) = \int_{y_{min}}^{y_{max}} dy_1 \int_{y_{min}/y_1}^{y_{max}} dy_2 \ P(y_1)P(y_2)\sigma(s_{\gamma\gamma}) \ , \tag{7}$$

where the upper integration limits y_{max} are given by Eq. 2 whereas the lower limits are set by the kinematical threshold of the considered process.

3 Supersymmetric Processes

We concentrate here on very simple signals: one or two high $p_\perp$ electrons and otherwise only invisible particles giving rise to missing $p_\perp$. This kind of signal is obtained in minimal supersymmetric extensions of the standard model [3] where the lightest supersymmetric particle is the lightest neutralino $\tilde{\chi}_1^0$. A selectron pair $\tilde{e}^\pm\tilde{e}^-$ or selectron-neutralino pair $\tilde{e}^-\tilde{\chi}_1^0$ is produced with the selectron subsequently decaying into an electron-neutralino pair $e^\pm\tilde{\chi}_1^0$. In e^-e^- collider searches more complicated cascade decays can also

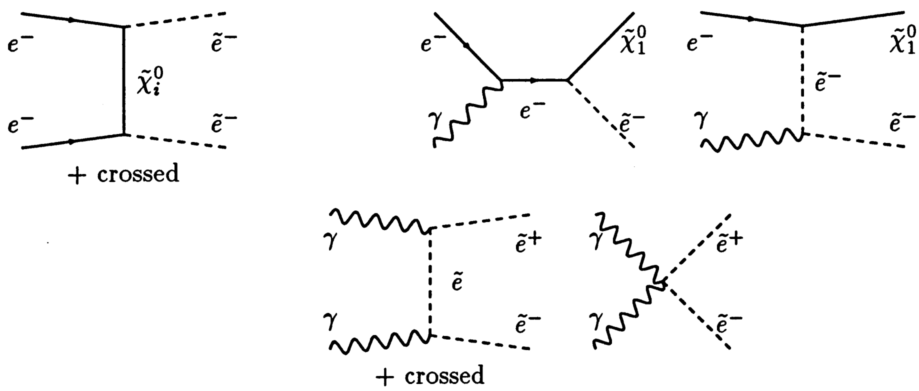

Figure 2: Feynman diagrams contributing to the supersymmetry signal in e^-e^- (top left), $e^-\gamma$ (top right) and $\gamma\gamma$ (bottom) reactions.

be included, since in this case lower $p_\perp$ electrons are observable. This scenario assumes R-parity to be conserved, so that the lightest supersymmetric particle is stable and remains unobserved.

We examine the following processes in the narrow width approximation:

$$e^-e^- \rightarrow \tilde{e}^-\tilde{e}^- \rightarrow e^-\tilde{\chi}_1^0\, e^-\tilde{\chi}_1^0 \tag{8}$$

$$e^-\gamma \rightarrow \tilde{e}^-\tilde{\chi}_1^0 \rightarrow e^-\tilde{\chi}_1^0\, \tilde{\chi}_1^0 \tag{9}$$

$$\gamma\gamma \rightarrow \tilde{e}^+\tilde{e}^- \rightarrow e^+\tilde{\chi}_1^0\, e^-\tilde{\chi}_1^0\, . \tag{10}$$

The lowest order Feynman diagrams describing the production are shown in Figs 2. Note that the e^-e^- reaction, which violates fermion number conservation, is allowed because the neutralinos are Majorana fermions. Moreover, since e^-e^- and e^+e^- reactions only differ by the presence of an additional γ and Z^0 boson exchange in the s-channel, at high energies both types of reactions yield the same results. The backgrounds in e^+e^- collisions are much higher, though, so we do not consider these here.

The cross sections times branching ratios for the three processes (8,9,10) depend on four supersymmetry parameters [3]:

- the soft supersymmetry breaking mass parameters M_2 and μ associated with the $SU(2)_L$ gauginos and higgsinos, respectively (for the $U(1)_Y$ gaugino mass parameter M_1 we assume $M_1 = \frac{5}{3}M_2\tan^2\theta_w$, where θ_w is the weak mixing angle, in accordance with the renormalisation group evolution from a common value $M_1 = M_2$ at the GUT scale);
- the mass of the sleptons (for simplicity we assume the supersymmetric partners of the left- and right-handed leptons to have equal masses: $m_{\tilde{\nu}_\ell} = m_{\tilde{\ell}_L} = m_{\tilde{\ell}_R}$);
- the ratio $\tan\beta = v_2/v_1$ of the Higgs vacuum expectation values (as long as $|\mu| \gtrsim M_2/2$, this is not an essential parameter).

Roughly, for $|\mu| \gtrsim M_2/2$ the higgsino admixture to the lightest neutralino is small. This is an important condition to obtain measurable cross sections for some of the processes studied here, since the higgsino-electron Yukawa coupling is suppressed by the mass of the electron. In this region of parameter space, when $\tan\beta \gtrsim 2$, the gaugino masses and couplings do not depend much on the values assumed by $\tan\beta$. If in addition $M_2 \gtrsim m_Z$, one finds roughly $m_{\tilde{\chi}_1^0} \approx M_2/2$ and $m_{\tilde{\chi}_2^0} \approx m_{\tilde{\chi}_1^\pm} \approx M_2$.

For the lightest neutralino $\tilde{\chi}_1^0$ to be the lightest supersymmetric particle, hence lighter than the selectron, we must require $M_2 \lesssim 2m_{\tilde{e}}$ or $|\mu| \lesssim m_{\tilde{e}}$. If the selectron is lighter than the second lightest chargino or neutralino, the $\tilde{e}^- \rightarrow e^-\tilde{\chi}_1^0$ branching ratio [4] is 100%. If there are charginos or other

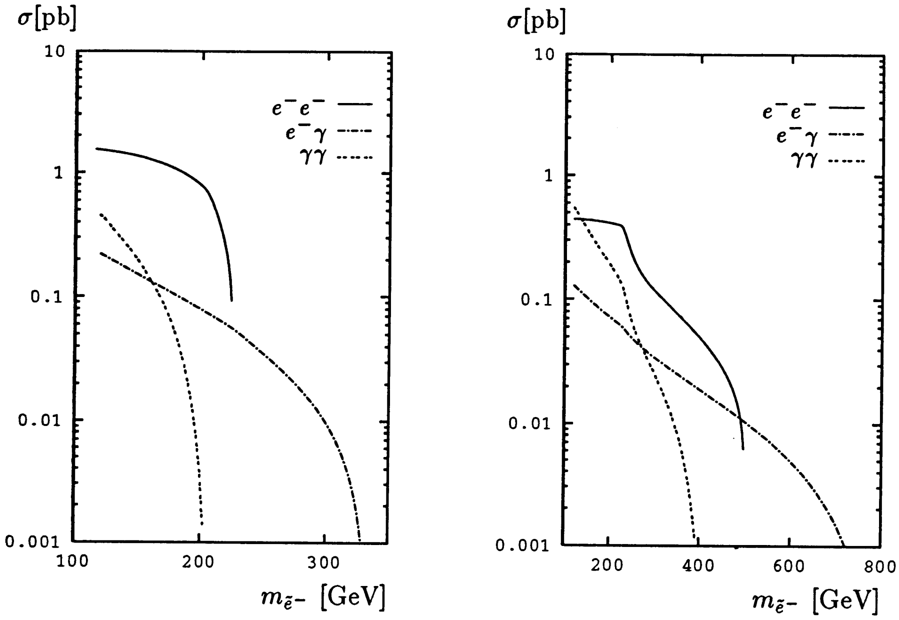

Figure 3: Total cross sections times branching ratios for $e^-e^- \to \tilde{e}^-\tilde{e}^-$, $e^-\gamma \to \tilde{e}^-\tilde{\chi}_1^0$ and $\gamma\gamma \to \tilde{e}^+\tilde{e}^-$ for collider energies $\sqrt{s_{ee}} = 500$ GeV (left) and 1000 GeV (right).

neutralinos which are lighter than the selectron, the $\tilde{e}_L^- \to e_L^-\tilde{\chi}_1^0$ branching ratio can be considerably less than 100%. The $\tilde{e}_R^- \to e_R^-\tilde{\chi}_1^0$ branching ratio, however, remains close to 100% over a large portion of the (μ, M_2) parameter space.

For a typical scenario where

$$\begin{aligned} \mu &= 375 \text{ GeV} \\ M_2 &= 250 \text{ GeV} \\ \tan\beta &= 4\,, \end{aligned}$$

we have plotted on Fig. 3 the total cross sections times branching ratios of the reactions (8,9,10) as functions of the selectron mass. Note that with this choice of supersymmetry parameters we have $m_{\tilde{\chi}_1^0} =$ 120 GeV and $m_{\tilde{\chi}_1^\pm} = 220$ GeV. Therefore, when the selectron mass exceeds 220 GeV the $\tilde{e}_L^- \to e_L^-\tilde{\chi}_1^\pm$ branching ratio grows, which explains the sudden drop in the signal beyond this mass.

4 Electron-Electron Collisions

Colliding electrons with electrons is not a particularly exciting experiment within the framework of the standard model: besides a wealth of Møller scattered electrons with a well-known forwardly-peaked distribution and low transverse momentum Bremsstrahlung events, one is essentially dealing with conventional two photon physics.

This is exactly why e^-e^- collisions are a privileged probe of physics beyond the standard model. In particular, two negatively charged selectrons can be produced via the t-channel exchange of neutralinos [5]. If one concentrates on the $e^-\tilde{\chi}_1^0$ decay channel of the selectron, the observed signal is a pair of electrons with missing energy. The background from Møller scattering, with and without initial state radiation, is entirely eliminated by triggering only on non-coplanar electron pairs. The background from W^- and Z^0 Bremsstrahlung can be made negligible by a moderate transverse momentum cut, leaving a signal to background ratio of the order of $\alpha/(2\pi)\log(s/p_{\perp min}^2)$ In the following, we can therefore safely simplify our analysis of the selectron production in electron-electron collisions by computing only total cross sections.

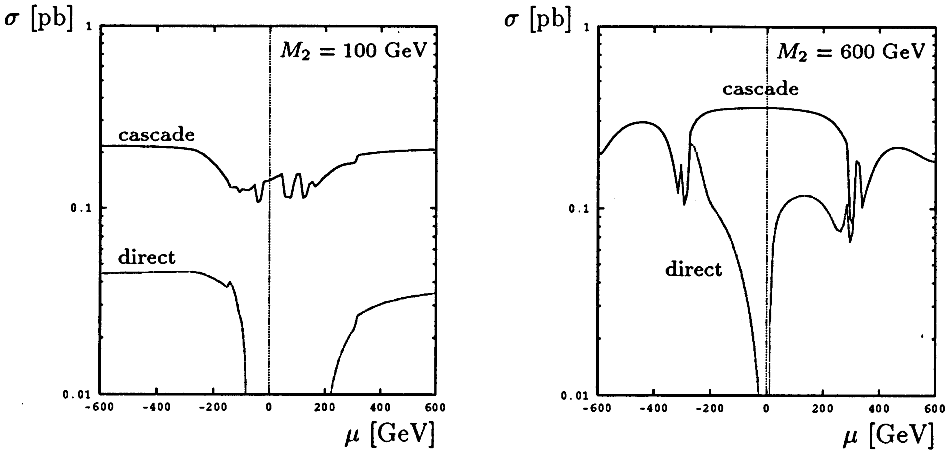

Figure 4: Total cross sections for observing two electrons and missing energy from the production and decay of two 300 GeV selectrons in 1 TeV electron-electron collisions.

Because there is no need for high transverse momentum cuts to observe the supersymmetric signal (in contrast to all other reactions), cascade decays of the selectron will play an important role in e^-e^- collisions. Indeed, if the selectron is kinematically allowed to decay into other channels than $\tilde{e} \to e^-\tilde{\chi}_1^0$, the same '$e^-$ + missing energy' signal may still be observed. Generally, when these electrons emerge at the end of a cascade, they have a strongly degraded transverse momentum. This prevents them from being observed in the other reactions studied here, because strong transverse momentum cuts are then necessary to reduce the important standard model backgrounds. Since only much milder cuts are needed in e^-e^- collisions, these provide the ideal reaction to observe such decays. In particular, as is shown on Fig. 4, when cascade decays are taken into account, the small-$|\mu|$ region in the supersymmetric parameter space may become accessible. Note that in e^+e^- collisions, one has to use other channels to investigate this region. By LEP searches the region $|\mu| < 50$ GeV has already been excluded.

The unruly behaviour of the curves is due to the fact that when several particles are exchanged, their interference patterns are very complicated. This in turn is reflected by the erratic dependence of the cross section on the supersymmetry parameters, because these determine in a very complicated manner the masses and couplings of the neutralinos. Hence the irregular interference patterns.

The main drawback of the e^-e^- reaction is its sensitivity to the supersymmetry parameters. Indeed, the model dependence occurs at three different levels: at the electron-selectron-neutralino vertices, in the neutralino propagators and at selectron decay. As a result, very different set of parameters can yield the same cross sections. At a first stage, this reaction might thus not be suited for determining the supersymmetry parameters.

5 Photon-Photon Collisions

In contrast to electron-electron collisions, a much cleaner signal from supersymmetry can be obtained when colliding two photon beams [6]. Indeed, since photons only couple to the electromagnetic charge, the only model dependence occurs at the level of the selectron decay and not any longer at the production level. This also implies that the same analysis for smuon production.

The numerous sources of background have to be considered carefully here. As it turns out [6], a mild transverse momentum cut eliminates them all but one. This background consists of an electron-positron pair originating from W^+W^- pair production. It can, however, be dramatically reduced by appropriate kinematical cuts. In particular, a combined set of cuts on the electrons' transverse momenta, energies and rapidities, reduces this backgrounds by about a factor 20. (Unfortunately, the necessity of a high transverse momentum cut prevents cascade decays from being observed here.) For large portions of the supersymmetry parameter space, reaction (10) with these cuts gives rise to observable deviations from the

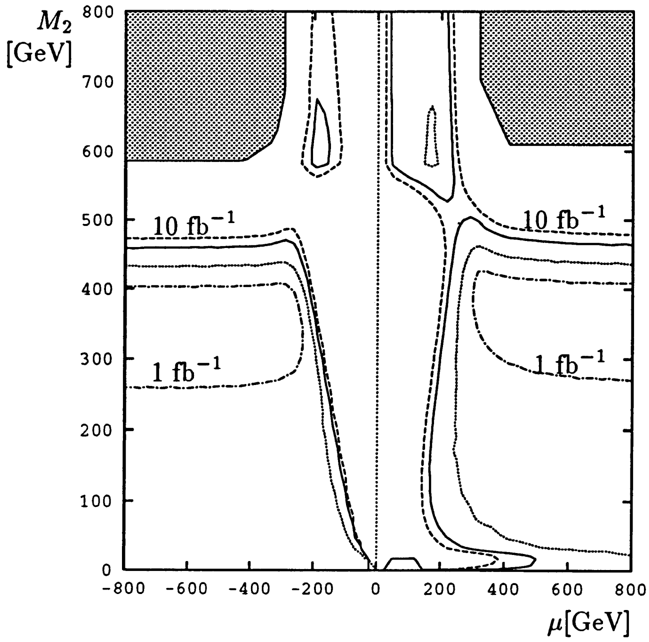

Figure 5: Regions in the (μ, M_2) plane where a supersymmetry signal due to a 300 GeV selectron can be distinguished from the standard model background at a 1 TeV collider. The lines of required luminosities 1, 2, 5 and 10 fb^{-1} to observe the supersymmetric signal with a 3σ confidence are shown. The dark shaded areas, in which $m_{\tilde{e}} < m_{\tilde{\chi}_1^0}$, are unphysical.

standard model predictions. This is shown on Fig. 5, where we have plotted the limits of observability in the (μ, M_2) plane of a 300 GeV selectron at a 1 TeV collider for four integrated luminosities. We determine the required luminosity by demanding that the signal be at least three standard deviations stronger than the background's Poisson fluctuations: $n_{SUSY} > 3\sqrt{n_{SM}}$.

The main drawback of the $\gamma\gamma$ reaction is the need for high collider energies. Indeed, to start pair-producing selectrons, the nominal collider energy has to exceed twice the selectron mass because of the reduction in the photon energies, as displayed in Fig. 1.

6 Electron-Photon Collisions

In the case where the maximum energy of the collider is not sufficient to pair-produce selectrons in the electron-electron and, a fortiori, photon-photon operation modes, electron-photon collisions can still probe their existence [7]. In this kind of reaction only one selectron is produced, accompanied by a lighter and invisible neutralino.

Unfortunately, the supersymmetric signal is weak compared to the standard model backgrounds. These backgrounds mainly stem from single W^- and Z^0 production. They can be significantly reduced by appropriate kinematical cuts. In particular, most of the background electrons are emitted in the backward direction, whereas the signal electrons don't display any preference. Nevertheless, since the supersymmetric signal is anyway weak from the start, at least 10 fb^{-1} of unpolarized beams will be necessary to probe a significant portion of the supersymmetry parameter space. This is shown in Fig. 6, where we have plotted the limits of observability in the (μ, M_2) plane of a 250 GeV selectron at a 500 GeV collider for 10 and 20 fb^{-1}. Again, we determine the required luminosity by demanding that the signal be at least three standard deviations stronger than the background's Poisson fluctuations.

This situation can, nevertheless, be improved by using a right-handed polarized electron beam to

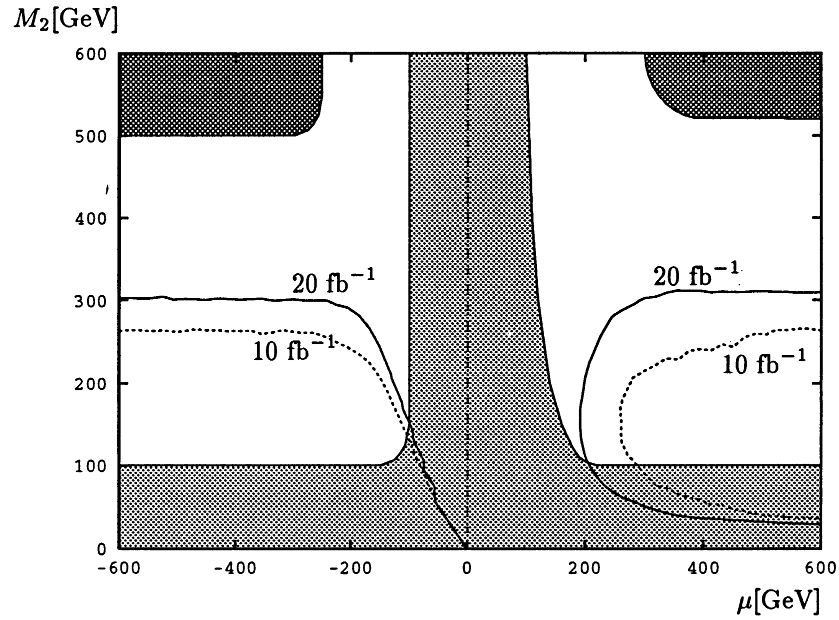

Figure 6: Regions in the (μ, M_2) plane where a supersymmetry signal due to a 250 GeV selectron can be distinguished from the standard model background at a 500 GeV collider. The lines of required luminosities 10 and 20 fb^{-1} to observe the supersymmetric signal with a 3σ confidence are shown. The dark shaded areas, in which $m_{\tilde{e}} < m_{\tilde{\chi}_1^0}$, are unphysical. The light shaded areas will be explored by LEP II

eliminate the background from W^- production, and a circularly polarized photon beam to reduce the background from Z^0 production [8]. A realistic study of this process is yet to be performed, though.

7 Conclusions

The next generation of linear colliders will provide us with a cornucopia of new types of experiments. Not only will they be able to collide electrons with positrons, but also electrons with electrons, electrons with photons and photons with photons, in any combination of polarizations! The prospects for discovering and studying new physics are tantalizing, and are summarized for supersymmetry in Table 1.

collider mode	e^-e^-	$\gamma\gamma$	$e^-\gamma$
required energy	$\gtrsim 2m_{\tilde{e}}$	$\gtrsim 3m_{\tilde{e}}$	$\gtrsim 1.5m_{\tilde{e}}$
required luminosity	$\gtrsim .1$ fb^{-1}	$\gtrsim 1$ fb^{-1}	$\gtrsim 10$ fb^{-1}
model dependence	strong	weak	moderate

Table 1: Prospect for discovering and studying supersymmetry at linear colliders. The numbers given are of course only indicative, in the sense that they correspond to what is needed to probe a 'large' and 'representative' portion of the supersymmetry parameter space.

It appears that e^-e^- collisions will provide a very sensitive test of physics beyond the standard model. In particular, the signal for producing a pair of selectrons will be quite spectacular. The cross sections are the same as in e^+e^- collisions, but the backgrounds are far less. This is thus the ideal linear collider operation mode to discover selectrons. Unfortunately, this reaction does not provide many clues about the values of the supersymmetry parameters.

In contrast, when selectrons are pair produced in $\gamma\gamma$ collisions, the signal is particularly clean because the supersymmetric model dependence is introduced only at the level of the decay of the selectrons. The standard model background is large, but can be strongly reduced kinematical cuts. This is thus a privileged linear collider operation mode to study supersymmetry. However, higher energies are needed to obtain an observable signal.

If the collider's energy does not reach the kinematical threshold to produce a pair of selectrons, a single selectron can still be produced in $e^-\gamma$ collisions. This is thus the only option for discovering a heavy selectron. Unfortunately the signal to background ratio is low, so that even after cuts high luminosities are required. This drawback can, however, be partially cured with the use of polarized beams.

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