Supersymmetric Signals in $\gamma\gamma$ Collisions

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Abstract

We study the occurrence of final states with only an electron-positron pair and missing transverse momentum as a signal of supersymmetry in photon-photon collisions. Suitable high energy photon beams may be provided at linear colliders by back-scattering laser beams on electron beams. The final states considered represent a typical signature for the production and decay of selectron and chargino pairs within the minimal supersymmetric standard model. We show that, away from the kinematical threshold, selectrons produce this signal far more abundantly than charginos. The standard model background is dominated by W-pair production. We propose a series of kinematical cuts which reduce this background to an acceptable level. With a 1 TeV collider operated in the $\gamma\gamma$-mode, we find that interesting and complementary tests of supersymmetric models can be performed for electron masses up to 350 GeV.

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1 Introduction

Photon-photon collisions are a very attractive tool to search for physics beyond the standard model because the production rates for new hypothetical particles are essentially known once their electromagnetic charges are specified. On the other hand, new states are generally expected to be heavy and can thus only be produced in high-energy collisions. As a matter of fact, it appears feasible to obtain suitable energetic photon beams at linear colliders by back-scattering a laser ray on an electron beam.

In this paper, we show how an $e^+e^-$ linear collider operated in the $\gamma\gamma$ mode can be used to probe and investigate supersymmetry. We focus on experimentally clean and theoretically interesting processes: the production and subsequent decay of pairs of selectrons ($\tilde{e}$) and charginos ($\tilde{\chi}^\pm_1$). For our study we assume the minimal supersymmetric standard model (MSSM). In this case there are two chargino and four neutralino mass eigenstates of which the lightest ones are denoted by $\tilde{\chi}^\pm_1$ and $\tilde{\chi}^0_1$. If R-parity is conserved, as in the conventional MSSM, the lightest supersymmetric particle (LSP) is stable and escapes detection. A likely candidate for the LSP is the lightest neutralino state $\tilde{\chi}^0_1$. Moreover, the selectron and lightest chargino are expected to decay into the channels $\tilde{e}^\pm \rightarrow e^\pm \tilde{\chi}^0_1$ and $\tilde{\chi}^\pm_1 \rightarrow e^\pm \nu_e \tilde{\chi}^0_1$, which give rise to final states with only an electron-positron pair and missing transverse momentum.

Although the production cross sections are unambiguously predicted as functions of the sparticle masses, the branching ratios for the decay of the selectrons and charginos into the required final states depend on further supersymmetry parameters. This dependence has to be carefully taken into account when estimating the sensitivity limits for photon-photon collisions. Conversely, these parameters can be constrained if a positive signal is observed.

The $e^+e^- + \not{p}_T$ signal should be compared to the background resulting from several standard model processes, dominantly from W-pair production followed by the decay $W \rightarrow e\nu$. We indicate the cuts necessary to suppress the background sufficiently and to observe a potential signal. Moreover, we outline the range of supersymmetry parameters accessible in such an experiment.

Searches in $\gamma\gamma$ collisions are complementary to searches in $e^+e^- \ [1, 2, 3]$ and $e^-\gamma \ [4, 5, 6]$ collisions conducted at the same linear collider. They provide useful cross-checks of signals which might be observed in the latter reactions, help to determine certain supersymmetry parameters and corroborate possible bounds. Still, the most important test of the minimal supersymmetric standard model remains the search for a light Higgs boson, which is best performed in the $e^+e^-$ mode.

In the next section we describe the relevant characteristics of the photon beams. Then, in sections 3 and 4, we compute the cross sections for the $e^+e^- + \not{p}_T$ signal from pair-production and decay of selectrons and charginos. Section 5 is devoted to the computation of the most dangerous standard model backgrounds.
In section 6 we investigate how to suppress the backgrounds by kinemtical cuts. Finally, we compare the supersymmetric signals with the irreducible background and discuss the range of supersymmetry parameters which can be probed at a 1 TeV collider.

2 High-Energy Photon Beams

High-energy photon beams can be produced at linear colliders by back-scattering a high-intensity laser ray on a high-energy electron beam [7]. In principle, if the laser intensity is high enough, every electron in a bunch can interact and yield a Compton photon. With very powerful lasers an electron can scatter more than once, so the number of scattered photons can even exceed the original number of electrons in the bunch. Neglecting multiple scattering and higher order effects the resulting Compton photon energy spectrum is given by

\[ P(y) = \frac{1}{N} \left( 1 - y + \frac{1}{1 - y} - \frac{4y}{x(1-y)} + \frac{4y^2}{x^2(1-y)^2} \right) \]

where the factor \( N \) normalizes the distribution to unity, \( \int_0^{y_{\text{max}}} dy P(y) = 1 \), and \( y = E_\gamma/E_e \) is the energy fraction of the electrons transferred to the photons. It is bounded by

\[ 0 \leq y \leq \frac{x}{x+1} \]

where

\[ x = \frac{4E_eE_{\text{laser}}}{m_e^2} \leq 2(1 + \sqrt{2}) \approx 4.83 \, . \]  

The electron and laser beams are taken to be aligned and their respective energies are \( E_e \) and \( E_{\text{laser}} \). For values of \( x \) exceeding the upper bound imposed by (3), the laser and Compton photons can pair-produce \( e^+e^- \) pairs and the conversion efficiency drops dramatically. In what follows, we take \( x = 2(1 + \sqrt{2}) \). Since both electron beams are to be converted, the maximum attainable energy in the photon-photon center of mass system is thus

\[ \sqrt{s_{\gamma\gamma}} \leq 2(\sqrt{2} - 1)\sqrt{s_{ee}} \approx .83\sqrt{s_{ee}} \]

where \( \sqrt{s_{ee}} = 2E_e \). Moreover, we assume the \( \gamma\gamma \) luminosity to be the same as the projected \( e^+e^- \) luminosity of the linear collider, that is \( \mathcal{L}_{\gamma\gamma} = 10^{33} \div 10^{34} \, \text{cm}^{-2}\text{s}^{-1} \).

3 Production and Decay of Selectrons

To lowest order, selectrons are pair-produced in photon-photon scattering according to the Feynman diagrams of Fig. 1 (top). The production cross section only

\[ \text{This mainly enhances the low-energy tail of the photon energy distribution (1), which is irrelevant for the production of heavy (s)particles.} \]
depends on the mass and charge of the selectron. We show, in Fig. 2, the dependence of the integrated cross section on the collider energy $\sqrt{s_{\text{ee}}}$ for a 200 GeV selectron. Results are given for monochromatic photon beams with the nominal energy $\sqrt{s_{\gamma\gamma}} = \sqrt{s_{\text{ee}}}$, and for photon beams with the energy spectrum (1). In the latter case, the cross section is given by the convolution formula

$$
\sigma(s_{\text{ee}}) = \int_0^{y_{\text{max}}} dy_1 \int_0^{y_{\text{max}}} dy_2 P(y_1)P(y_2)\sigma(s_{\gamma\gamma})\theta(y_1 y_2 s_{\text{ee}} - 4m_{\tilde{\ell}}^2),
$$

The remarkable change in the energy dependence of the cross sections induced by the convolution over the Compton photon energy spectrum is easily understood. Close to the kinematic threshold of pair production, only the most energetic of the Compton photons can contribute. Hence the cross section is substantially reduced. At higher energy, more Compton photons contribute and those photon pairs whose centre of mass energy is just above threshold have the highest cross section for pair-producing selectrons. Therefore, the folded cross section exceeds the cross section expected with monochromatic beams.

Since the selectrons decay by weak interactions their width is typically much smaller than their mass ($\Gamma_{\tilde{\ell}}/m_{\tilde{\ell}} \sim 1 \div .1\%$). It is therefore safe to use the narrow width approximation in the calculations. We focus on the decay channel

$$
\tilde{\ell} \to e^\pm \chi^0_1
$$

where the lightest neutralino $\chi^0_1$ is assumed to be the lightest supersymmetric particle and therefore stable. The branching ratio for this decay is a complicated function of all the masses and mixings in the gaugino-higgsino sector [1, 8, 9] which themselves are very dependent on the choice of the supersymmetry parameters. Later, we shall explore systematically the accessible region of the parameter space. However, for definiteness and in order to determine an optimized set of kinematical cuts, we choose as a rather favourable scenario

$$
\tan \beta = 4, \quad \mu = -400 \text{ GeV}, \quad M_2 = 300 \text{ GeV}
$$

where $\tan \beta = v_2/v_1$ is the ratio of the Higgs vacuum expectation values, and $\mu$ and $M_2$ are the soft supersymmetry breaking mass parameters associated with the higgsinos and the $SU(2)_L$ gauginos, respectively. The $U(1)_Y$ gaugino mass parameter $M_1$ is assumed to evolve from the common value $M_1 = M_2$ at the GUT scale according to the relevant renormalization group equation so that $M_1 = 5/3 M_2 \tan^2 \theta_w$, where $\theta_w$ is the weak mixing angle. For simplicity, we also assume all sleptons to have the same mass, and to be much lighter than the strongly interacting squarks and gluinos:

$$
m_{\tilde{\ell}_L} = m_{\tilde{\ell}_R} = m_{\tilde{\nu}_\ell} \ll m_{\tilde{q}}, m_{\tilde{g}}.
$$

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2This last condition will only become relevant in the next section when we deal with the decay of charginos.
In particular, if $m_e = m_\mu$ all what is said about selectron production and decay is also true for the production of smuons and their subsequent decay into muons and invisible particles.

The branching ratio for a selectron to decay into an electron and the lightest neutralino is 100% if the selectron is lighter than all other neutralinos and charginos. If the selectron is also kinematically allowed to decay into other channels, this branching ratio depends on the masses of the involved particles and the gaugino content of the neutralinos and charginos. Typically, the left-selectron (i.e. the partner of the left-handed electron) has a lower branching ratio for the decay (8) than the right-selectron, because the latter cannot decay into charginos. A more detailed discussion of the decay patterns can be found in Refs [10, 11].

For the choice of parameters (8) and a selectron mass of 300 GeV, the left- and right-selectrons decay, respectively, 95% and 100% of the time into the channel (8). The left-selectron also decays with a 5% branching ratio into $\tilde{e}_L^\pm \to \nu_e \tilde{\chi}_1^\mp$. If $M_2$ is lowered to 150 GeV, keeping all other parameters fixed, one instead predicts $BR(\tilde{e}_L \to e_L \tilde{\chi}_1^0) = 16\%$ while the branching ratio of the right-selectron remains unaffected. The integrated cross section of the $e^+e^- + \not{p_T}$ signal from selectron pair-production is shown as a function of the collider energy in Fig. 3 for three different selectron masses.

Note that because of assumption (8) and (s)lepton universality in the minimal supersymmetric standard model, smuons and staus are pair-produced at the same rate as selectrons. The $\tilde{\tau}^+\tilde{\tau}^-$ pairs can also give rise to an $e^+e^- + \not{p_T}$ signal with the branching ratio $BR(\tilde{\tau}^+\tilde{\tau}^- \to e^+e^- + \not{p_T}) = BR(\tilde{\tau}^+\tilde{\tau}^- \to e^+e^- + \not{p_T})BR(\tau \to e\nu\nu)^2$. There is thus an additional 3% contribution to the integrated supersymmetric signal from stau production. However, since this a small correction and since the transverse momentum of these $e^+e^-$ pairs is somewhat degraded, we do not consider it further.

### 4 Production and Decay of Charginos

To lowest order, charginos are pair-produced in photon-photon scattering as depicted in Fig. 1 (bottom). The dependence on the collider energy of the integrated cross section for producing 200 GeV charginos is shown in Fig. 2 for monochromatic and Compton back-scattered photons. Again, the convolution over the Compton photon energy spectrum significantly modifies the energy dependence of the cross section.

As in the case of selectrons, it is sufficient to use the narrow width approximation in estimating the cross section for $\gamma\gamma \to \tilde{\chi}_1^\pm \tilde{\chi}_1^0 \to e^+e^- + \not{p_T}$. We focus on three different decay channels which all ultimately yield the same final state:

$$\tilde{\chi}_1^\pm \to e^\pm \tilde{\nu}_e \to \nu_e \tilde{\chi}_1^0$$  (8)
\[ \tilde{\chi}^\pm_1 \rightarrow \tilde{e}^\pm \nu_e \leftarrow e^\pm \tilde{\chi}^0_1 \] (9)

\[ \tilde{\chi}^\pm_1 \rightarrow W^\pm \tilde{\chi}^0_1 \leftarrow e^\pm \nu_e \] (10)

In principle three-body decays \[ \text{[12]} \] should also be included in this list. However, their contribution is only sizable below the two-body decay threshold \( m_{\tilde{\chi}^\pm_1} - m_{\tilde{\chi}^0_1} < m_W \), and their neglect is of no consequence here.

As for \( \tilde{e} \rightarrow e \tilde{\chi}^0_1 \) the branching ratios of the decays (8,9,10) depend sensitively on the choice of the supersymmetry parameters. The most important of these parameters is the slepton mass. Indeed, if the lightest chargino is lighter than the selectron or the sneutrino, it can only decay into \( W \)'s via the reaction (10) and into charged Higgs bosons via \( \tilde{\chi}^\pm_1 \rightarrow H^\pm \tilde{\chi}^0_1 \). While \( H^\pm \rightarrow e \nu_e \) is strongly suppressed, the \( W \) decays into an electron and neutrino, however with a branching ratio of only about 10%. Since this decay has to occur twice, the total branching ratio into an \( e^+e^- \) pair is 1%, and the signal is hopelessly weak (in principle, though, it may be increased by a factor 4 by also looking for \( e\mu \) and \( \mu\mu \) signals). On the other hand, if the chargino is kinematically allowed to decay into sleptons, it will preferably do so. In this case, because of (s)lepton universality and because we assumed in (7) that all sleptons have the same mass, a chargino will decay with equal probability into the three lepton families. The branching ratios of the reactions (8) and (9) turn out to be almost equal and roughly 17% each in the relevant region of the supersymmetry parameter space, while the decay into the \( W \) channel is inhibited. Nevertheless, since the chargino is then heavy, its production cross section is low and the expected \( e^+e^- + p_\perp \) signal remains weak. This can be seen in Fig. 3, where we have plotted the energy dependence of the signal cross section for the chargino channel. In accordance with the scenario (3), the chargino mass is approximately 290 GeV, and we have considered a selectron mass of 200 GeV. The result is approximately the same for \( m_{\tilde{\chi}^0_1} < m_{\tilde{e}} \lesssim 250 \) GeV. If the sleptons are heavier than 290 GeV the expected signal cross section is approximately ten times lower.

Note that when a chargino decays into a tau lepton, the latter can also subsequently decay into electrons. This provides an additional 38% contribution to the supersymmetric \( e^+e^- + p_\perp \) signal, which we take into account. In contrast, the heavier chargino \( \tilde{\chi}^\pm_2 \) does not contribute significantly to the supersymmetry signal. Indeed, for a sizable region of the supersymmetry parameter space its mass is much higher than the mass of the lighter chargino \( \tilde{\chi}^\pm_1 \) and its branching ratio into a lepton and invisible particles is much less than one.

If one sticks to the assumption (4) that the selectron and sneutrino have similar masses, away from threshold the \( e^+e^- + p_\perp \) signal originating from the chargino production is about an order of magnitude weaker than the signal from selectron production. This remains true for a large portion of the supersymmetry parameter space. It is only in very special circumstances, for example, when
that the chargino signal dominates the selectron signal. We do not consider this unlikely possibility here and in the following we will optimize the cuts for the selectron signal only.

5 Backgrounds from the Standard Model

The main standard model background processes which also lead to an $e^+e^-$ pair (and unobserved particles) are the following:

\begin{align}
\gamma\gamma & \rightarrow e^+e^-(\gamma) \quad (11) \\
\gamma\gamma & \rightarrow e^+e^- Z^0 \rightarrow \nu\bar{\nu} \quad (12) \\
\gamma\gamma & \rightarrow e^\pm \nu W^\mp \rightarrow e^\mp \bar{\nu} \quad (13) \\
\gamma\gamma & \rightarrow \tau^+\tau^- \rightarrow e^-\bar{\nu}_e \nu_\tau \rightarrow e^+\nu_e \bar{\nu}_\tau \quad (14) \\
\gamma\gamma & \rightarrow W^+W^- \rightarrow e^-\bar{\nu}_e \rightarrow e^+\nu_e \quad (15) \\
\gamma\gamma & \rightarrow W^+W^- \rightarrow \tau^+\nu_\tau \rightarrow e^+\nu_e \bar{\nu}_\tau \quad (16)
\end{align}

The most frequent process by far is the u- and t-channel electron-positron pair-production (11), with a total cross section of the order of several hundred picobarn. Nevertheless, this background is also the easiest to eliminate. Indeed, here the $e^+e^-$ pairs are produced in a plane which contains the beam axis. Therefore, this background is totally eliminated if we only consider acoplanar $e^+e^-$ events where

$$|\|\phi(e^+) - \phi(e^-)\| - 180^\circ| > 2^\circ.$$  \hspace{1cm} (17)

Here, $\phi$ is the azimuthal angle with respect to the beam axis. By the requirement (17) we exclude all $e^+e^-$ pairs which lie on opposite sides within a wedge of $2^\circ$ whose axis is the beam axis. Since the current detector angular resolution exceeds 3 mrad, this is a conservative cut which should also take care of all the unresolved Bremsstrahlung photons.

However, this cut fails to eliminate events which arise when the electron emits a $Z^0$, which subsequently decays into neutrinos (12). Nevertheless, the cross section is only sizeable when either the electron or the positron or both have small transverse momentum $p_\perp$. Hence, a moderate cut, such as

$$\min(p_\perp(e^+), p_\perp(e^-)) > 10 \text{ GeV},$$  \hspace{1cm} (18)
sufficiently suppresses also this source of background. The selection criteria (17) have been implemented in Figs. 4 where we show how the transverse momentum of the electrons and positrons are distributed at a 1 TeV collider. Every event on this scatter plot carries a weight of 50 attobarn.

The $e\nu_\tau W$ background (13) is more difficult to compute because it includes the off-shell part of the $W^+W^-$ reaction (15). A careful study (13), though, reveals that the interference between the resonant and radiative diagrams is small. The latter is expected to yield a contribution of the same order as the $e^+e^-Z^0$ background (12).

The transverse momentum cut (18) also almost entirely eliminates the $e^+e^-$ pairs originating from the $\tau$ production (14). In Fig. 3 we display the cross section for the channel $\gamma\gamma \to \tau^+\tau^- \to e^+e^-+\text{neutrinos}$. The scatter plot in Fig. 4 reveals that the decay electrons and positrons clutter in the very low transverse momentum region. This is a manifestation of the $u$- and $t$-channel poles in the $\tau$ production amplitude, leading to a distribution of the $\tau$-leptons (and hence the decay electrons and positrons) which strongly peaks in the forward and backward direction.

The most important background consists of $e^+e^-$ pairs which arise from the decay of on-shell $W^+W^-$ pairs (13) (14). In Fig. 3 we display the cross section for the channel $\gamma\gamma \to W^+W^- \to e^+e^-+\text{neutrinos}$. As is shown in Fig. 4, some of these $e^+e^-$ pairs can be produced at very high transverse momentum, but most of them populate the region close to $p_\perp(e^+) \approx p_\perp(e^-) \approx 40$ GeV.

A non-negligible addition to this background consists of electrons or positrons originating from the decay of a $\tau$ which itself is a decay product of one of the $W$'s (16). When no cuts are applied, it increases the background from $W^+W^-$ production by 38%. However, when the transverse momentum cut (18) is applied, this contribution drops to less than 20% because the transverse momentum of the $e^\pm$ undergo a further degradation in the additional cascade.

Of course, there are more sources of background, but all are significantly smaller than the ones already considered.

6 Results

The search for supersymmetry signals of the kind considered here is facilitated by the fact that the standard model backgrounds can be evaluated theoretically to a high accuracy. The validity of these calculations can even be checked experimentally for $W^+W^-$ and $\tau^+\tau^-$ pairs yielding $e\mu$ events, which cannot be obtained from selectron pair production (chargino pair production, though, could also yield such $e\mu$ events, but we have seen that this is generally a negligible contribution). Any statistically relevant deviation from the standard model prediction could thus be a sign for supersymmetry. The task is then to discriminate this hypothesis against other interpretations.
To obtain an appreciable signal to background ratio, it is necessary to impose further cuts to reduce the $W$ background (15). As can be seen from Figs 4, for not too heavy selectrons, this is the only dangerous background left after the cuts (17,18) have been implemented. We suggest the following low transverse momentum and high rapidity cuts:

$$p_{\perp}(e^+)p_{\perp}(e^-) > m_W^2,$$

$$|\eta(e^+)| < 1.$$  

As is shown on the scatter plot of Fig. 4 for the choice of parameters (15), the transverse momentum distribution of $e^+e^-$ pairs originating from 300 GeV selectrons is peaked around $p_{\perp}(e^+) \approx p_{\perp}(e^-) \approx 100$ GeV and the supersymmetric signal is not exaggeratedly curtailed by the low transverse momentum cut (19). Similarly, few of the electrons or positrons are emitted at low angles. This can be observed on the scatter plot of Fig. 5, where we have displayed the correlation between the rapidity and the transverse momentum of the electron (or positron).

If supersymmetry has been discovered and the masses of the selectron and lightest neutralino are known, or if the data analysis is performed with varying cuts, one can even further enhance the signal to background ratio. Indeed, the energy of the signal electrons or positrons is kinematically bounded from above and from below:

$$E_e \in \frac{E}{4} \left[ 1 - \frac{m_{\tilde{\chi}_0^1}^2}{m_{\tilde{e}}^2} \right] \left[ 1 \pm \sqrt{1 - \frac{4m_{\tilde{e}}^2}{E^2}} \right]$$  

where $E = \sqrt{s_{ee}}/(x + 1) \approx .83\sqrt{s_{ee}}$ is the maximum attainable centre of mass energy in the photon-photon collision. These two boundaries are depicted by the boomerang curves in Fig. 4. Clearly, a lot of $W$ background can be further eliminated by imposing the energy cuts (21) on the electrons and positrons, without affecting the signal.

In Fig. 4 we show how the selectron and chargino signals compare to the standard model background at a 1 TeV collider as a function of the selectron mass. The supersymmetric signals and standard model backgrounds are displayed for the different types of cuts discussed above:

(A) only the acoplanarity and low transverse momentum cuts (17,18);

(B) the cuts (A) plus the transverse momentum and rapidity cuts (19,20);

(C) the cuts (B) plus the energy cuts (21).

We first comment on the process $\gamma\gamma \rightarrow \tilde{e}^+\tilde{e}^- \rightarrow e^+e^- + \tilde{\chi}_1^0\tilde{\chi}_1^0$. Since the maximum energy (21) of the electrons or positrons originating from selectrons is proportional to the difference of the masses of the selectron and the neutralino the
signal is lost with the transverse momentum cut (18) if the selectron mass is close to 150 GeV (the lightest neutralino mass, according to the scenario (6)). Because left-selectrons of more than 290 GeV (the lightest chargino mass, according to the scenario (6)) can also decay into charginos, the signal drops noticeably beyond this selectron mass. The transverse momentum and rapidity cuts (19,20) reduce the standard model background by approximately a factor 20, while the selectron signal is only slightly reduced for \( m_{\tilde{e}} \gtrsim 250 \) GeV. At least for \( m_{\tilde{e}} \lesssim 300 \) GeV, the mass dependent energy cut (21) leads to a further significant improvement of the signal to background ratio.

Turning to the process \( \gamma\gamma \to \tilde{\chi}^+ \tilde{\chi}^- \to e^+e^- + \tilde{\chi}_1^0 \tilde{\chi}_1^0 \nu \bar{\nu} \) we note that the cross section including the set of cuts (17,18) is almost independent of the selectron mass, except when the latter is close to the lightest chargino mass, that is 290 GeV. Beyond this point the chargino cannot decay anymore into selectron-neutrino or electron-sneutrino pairs. In that case, the \( e^+e^- + p_{\perp} \) signal is only obtained from the decay of charginos into neutralinos and \( W \)'s, which subsequently decay with a branching ratio of \( BR(W \to e\nu)^2 = 1\% \) into electrons and neutrinos. Because of this low branching ratio, the chargino channel yields very few \( e^+e^- \) pairs for heavy selectrons. If the transverse momentum cut (19) is applied, the signal becomes even more suppressed the closer the chargino and slepton masses are. The mass dependent energy cut (21) makes of course matters even worse.

In order to transcend the illustrative scenario (6) and to show the dependence of the \( e^+e^- + p_{\perp} \) signal on the supersymmetric parameters, we plot in Fig. 7 the limits of observability in the \((\mu, M_2)\) plane for a 300 GeV selectron at a 1 TeV collider for four integrated luminosities: 1, 2, 5 and 10 fb\(^{-1}\). For this, we demand that the signal be at least three events and at least three standard deviations above the background’s Poisson fluctuations:

\[
n_{SUSY} > 3\sqrt{n_{SM}}. \tag{22}
\]

Note that these results are conservative in the sense that we only considered here the decay of selectrons into electrons/positrons and the lightest neutralino. Particularly for low values of \( \mu \) or \( M_2 \), cascade decays of the selectron are important and are likely to contribute to the \( e^+e^- + p_{\perp} \) signal, with a further degradation of the transverse momentum though.

### 7 Conclusions

Sleptons and charginos can be pair-produced with sizeable rates at linear electron-positron colliders operated in the photon-photon mode. Although the discovery potential in this mode cannot compete with the potential of other reactions, the prospects for complementary studies of supersymmetry in \( \gamma\gamma \) collisions are particularly interesting. This is because there is no model dependence at the
production level so that the decay properties can be investigated in a clean way. This may yield important information on the gaugino-higgsino sector.

A very promising signature for selectron pair production consists of an acoplanar $e^+e^-$ pair. The same signal can be obtained from pair-produced charginos, but for most choices of supersymmetric parameters their branching ratios into electrons remain small. As a consequence, away from threshold, the $e^+e^- + \not{p}_T$ signal from selectron pair production dominates by about one order of magnitude the one expected from chargino pair production.

The only significant standard model background which remains after mild acoplanarity and transverse momentum cuts consists of $e^+e^-$ pairs resulting from the decay of pair-produced $W$'s. This background can be reduced by a factor 20 with more stringent low transverse momentum and high rapidity cuts. A further energy cut, which assumes the masses of the selectron and lightest neutralino to be known, can even yield a signal to background ratio of one. Of course, all these results are trivially extended to the pair production of smuons and their subsequent decay into $\mu^+\mu^-$ pairs and missing energy.

We conclude that high energy linear $e^+e^-$ colliders operated in the $\gamma\gamma$ mode provide novel possibilities for supersymmetry searches with integrated luminosities as low as 1 fb$^{-1}$. Particularly interesting results should be obtained in conjunction with similar searches in $e^\pm e^- [1, 2, 3]$ and $e^-\gamma [4, 5, 6]$ collisions.

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References

[1] A. Bartl, H. Fraas and W. Majerotto, Z. Phys. C 34 (1987) 411.
[2] W.-Y. Keung and L. Littenberg, Phys. Rev. D 28 (1983) 1067.
[3] F. Cuypers, Yad. Fis. (in press)
[4] M.K. Gaillard, L. Hall and I. Hinchliffe, Phys. Lett. B 116 (1982) 279,
M. Glück, Phys. Lett. B 129 (1983) 255,
J.A. Grifols and R. Pascual, Phys. Lett. B 135 (1984) 319 (E: B 142 (1984) 455.
[5] F. Cuypers, G.J. van Oldenborgh and R. Rückl, Nucl. Phys. B 383 (1992) 45.
[6] D. Borden, D. Bauer and D. Caldwell, SLAC preprint SLAC-PUB-5715 (1992).

[7] I.F. Ginzburg, G.L. Kotkin, V.G. Serbo and V.I. Telnov, Nucl. Instr. Meth. 205 (1983) 47.

[8] A. Bartl, H. Fraas and W. Majerotto, Nucl. Phys. B 297 (1988) 479.

[9] H. Komatsu and R. Rückl, Nucl. Phys. B 299 (1988) 407.

[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 et al., Lecture Notes in Physics 405, Eds W. Hollik, R. Rückl and J. Wess, Springer Verlag, Heidelberg, 1992, p. 119.

[12] A. Bartl, H. Fraas and W. Majerotto, Z. Phys. C 41 (1988) 475.

[13] A. Aeppli and G.J. van Oldenborgh, Munich preprint LMU-21/92 (1992).

[14] I.F. Ginzburg, G.L. Kotkin, S.L. Panfil and V.G. Serbo, Nucl. Phys. B 228 (1983) 285.
Figure 1: Lowest order Feynman diagrams contributing to selectron (top) and chargino (bottom) production.
Figure 2: Energy dependence of the pair-production cross sections of 200 GeV selectrons and charginos. The dotted curves are obtained for monochromatic photons taking $\sqrt{s_{\gamma\gamma}} = \sqrt{s_{ee}}$. The full curves result from the convolution of the $\gamma\gamma$ cross sections with the Compton photon spectrum (1).
Figure 3: Energy dependence of the signal cross sections for $\gamma\gamma \rightarrow \tilde{e}^+ \tilde{e}^- \rightarrow e^+ e^- + \not{p}_T$ and $\gamma\gamma \rightarrow \tilde{\chi}^+ \tilde{\chi}^- \rightarrow e^+ e^- + \not{p}_T$ assuming scenario (I). The chargino prediction is obtained for sleptons lighter than 250 GeV. The background cross sections for $\gamma\gamma \rightarrow W^+ W^- \rightarrow e^+ e^- + \not{p}_T$ and $\gamma\gamma \rightarrow \tau^+ \tau^- \rightarrow e^+ e^- + \not{p}_T$ are also shown.
Figure 4: Scatter plot of the electron and positron transverse momentum at a 1 TeV collider in the Z, τ, W and ℓ̄ channels (respectively Eqs (12), (14), (15) and (5)). The selectron mass has been set to $m_{\tilde{e}} = 300$ GeV. The remaining supersymmetry parameters have been chosen according to the scenario (6). The set of cuts (A) has been implemented, and the region below the hyperbola is excluded when the cut (19) is used.
Figure 5: Distribution of the decay leptons’ transverse momentum versus rapidity at a 1 TeV collider in the $W$ and $\tilde{e}$ channels (respectively Eqs (15) and (5)). The selectron mass has been set to $m_{\tilde{e}} = 300$ GeV. The remaining supersymmetry parameters have been chosen according to the scenario (B) and the set of cuts (A) has been implemented.
Figure 6: Dependence on the selectron mass of the cross section of the $e^+e^- + p_T$ signals at a 1 TeV collider. The selectron and chargino channels as well as the standard model background are shown for the three sets of cuts (A,B,C) discussed in the text. The chargino mass is 290 GeV, in accordance with scenario (3).
Figure 7: Regions in the ($\mu, M_2$) plane where the supersymmetric signal due to a 300 GeV selectron can be distinguished from the standard model background at a 3$\sigma$ confidence level. The assumed collider energy is 1 TeV and results are shown for 1, 2, 5 and 10 fb$^{-1}$ of integrated luminosities. The shaded areas, in which $m_\tilde{e} < m_\tilde{\chi}_1^0$, are excluded and $\tan \beta = 4$.  

$\gamma\gamma \rightarrow e^+e^+ + p_T$