Slepton Pair Production at a Linear Collider

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Accurate theoretical calculations of slepton pair production processes at threshold are necessary for an accurate determination of slepton masses. We discuss the gauge invariant calculation of these processes for selectron and smuon pairs, including finite width effects and Coulomb corrections. Energy cuts to reduce irreducible supersymmetric backgrounds are presented.

In any investigation of supersymmetry (SUSY) it is crucial to determine the masses of the particles to a very high accuracy, since a precise knowledge of the SUSY spectrum can constrain the various models of supersymmetry breaking. In this contribution we will discuss the measurement of the selectron and smuon masses at a future linear collider, where the slepton mass can be directly measured from a threshold scan of slepton pair production. This contribution is based on the research presented in Ref.[1].

Let us first consider selectron pair production. Each selectron has two scalar partners, $\tilde{e}_L$ and $\tilde{e}_R$, corresponding to the two chiral electron states. Neglecting mixing effects in the first and second generations, we regard these chiral states as the mass eigenstates. In our analysis, we adopt the parameters given by the SUSY reference point *RR2* [2], for which right-chiral selectrons decay predominantly into an electron and neutralino, while the heavier left-handed selectrons may also decay into a neutrino and chargino if kinematically allowed.

In electron-positron collisions, selectron pairs can be formed by s-channel γ and Z exchange or by t-channel $\tilde{\chi}_i^0$ exchange. The s-channel process, and t-channel process where both selectrons are of the same chirality, produce selectrons in a P-wave thereby leading to a cross-section which increases $\sim \beta^3$ near threshold (where β is the selectron velocity in the centre-of-mass frame). This slow rise makes the threshold cross section measurement difficult. S-wave production, where the cross-section rises with β, is only possible for mixed chirality selectron production (i.e. $\tilde{e}_R^+ \tilde{e}_L^-$ or $\tilde{e}_L^+ \tilde{e}_R^-$), which is clearly less desirable due to the dependence on both selectron masses. Furthermore, the resulting signals are unfortunately plagued by many Standard Model (SM) and SUSY background processes, in particular the production of neutralino and chargino pairs (with their subsequent cascade decays), rendering them unattractive for the selectron mass measurement.

In contrast, in $e^- e^-$ collisions, selectron pairs of the same chirality are produced via t-channel $\tilde{\chi}_i^0$ exchange, as an S-wave. Consequently the production cross-section near threshold grows $\sim \beta$, giving a much more easily measured signal. Furthermore, the $e^- e^-$ initial state switches off the majority of the contributing background processes. As a result, it is much easier to measure the selectron mass in $e^- e^-$ collisions than in $e^+ e^-$ collisions.

For right-chiral selectrons our signal process is then $e^- e^- \to \tilde{e}_R^- \tilde{e}_R^- \to e^- e^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$ resulting in a signature of two electrons and missing energy. For left-chiral smuons we have $e^- e^- \to \tilde{e}_L^- \tilde{e}_L^- \to \nu_e \nu_e \tilde{\chi}_1^- \tilde{\chi}_1^-$ and choose a leptonic decay for the first chargino, $\tilde{\chi}_1^- \to l^- \bar{\nu}_l \tilde{\chi}_1^0$ ($l \neq e$), and a hadronic decay for the other, $\tilde{\chi}_1^- \to q\bar{q}' \tilde{\chi}_1^0$, resulting in a signature of $lq\bar{q}'$ and missing energy.

In order that the selectron mass may be as accurately measured as possible, it is essential to have very good accuracy in the theoretical calculation. To this end, we must include finite selectron widths and Coulomb rescattering effects. The finite widths are incorporated by introducing a complex selectron mass,

$$m_{\tilde{e}}^2 \; \to \; M_{\tilde{e}}^2 = m_{\tilde{e}}^2 - im_{\tilde{e}}\Gamma_{\tilde{e}}, \tag{1}$$

with fixed width $\Gamma_{\tilde{e}}$. The Coulomb interaction due to photon exchange between the slowly selectrons also gives large corrections of the threshold cross-section. At leading order, the correction to the cross-section for *stable particles* is given by the universal Sommerfeld rescattering correction [3], $\sigma_{\rm Born} \to (\alpha\pi/2\beta)\,\sigma_{\rm Born}$. For *unstable* sleptons produced in a state of angular momentum l, this is modified, at leading order, to,

$$\sigma_{\rm Born} \to \sigma_{\rm Born}\frac{\alpha\pi}{2\beta}\left[1 - \frac{2}{\pi}\arctan\frac{|\beta_M|^2 - \beta^2}{2\beta\,\Im m\,\beta_M}\right]\Re e\left\{\left[\frac{\beta^2 + \beta_M^2}{2\beta^2}\right]^l\right\} \tag{2}$$

with the generalized velocities $\beta = \frac{1}{s}\sqrt{(s - m_+^2 - m_-^2)^2 - 4m_+^2 m_-^2}$ and $\beta_M = \sqrt{1 - 4M^2/s}$, for the (complex) slepton pole mass M and the smuon virtualities m_+ and m_-. Initial state radiation from emission of collinear and soft photons, and beamstrahlung effects were also included. For a final theoretical prediction which will be
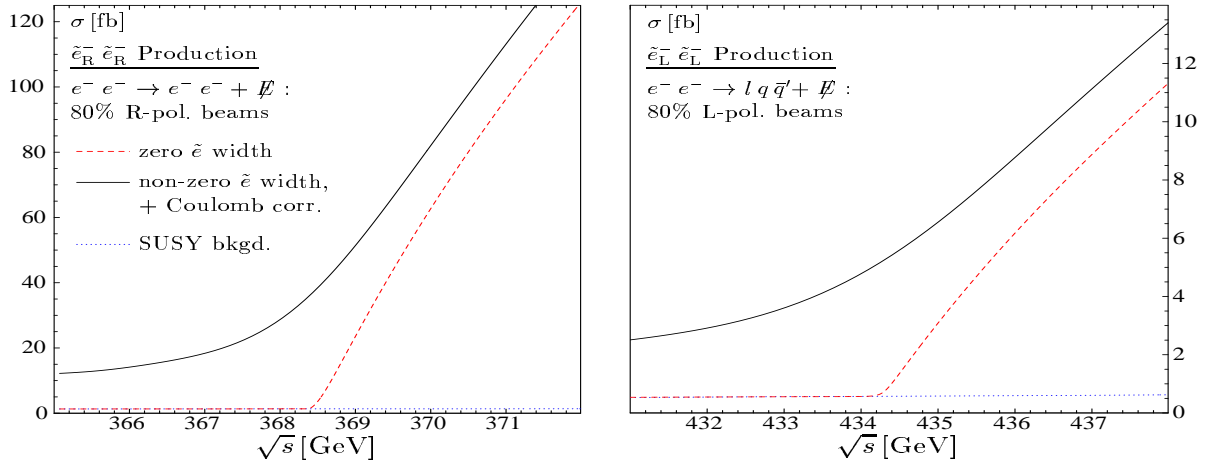
FIG. 1: *The signal cross-section and SUSY backgrounds to $e^- e^- \to e^- e^- + \not{\!\!E}$ near the $\tilde{e}_R \tilde{e}_R$ and $\tilde{e}_L \tilde{e}_L$ thresholds.*

used to extract the slepton masses it is also important to include radiative corrections to the slepton production cross-sections. While not included in this analysis, work on these corrections is ongoing [4].

Due to the complexity of the process and the large number of Feynman graphs which must be calculated, the computer algebra package *FeynArts* [5] was used to calculate helicity amplitudes. These amplitudes were numerically integrated over the allowed phase-space using a multi-channel Monte-Carlo approach with appropriate phase-space mappings. The Monte-Carlo error was reduced by adaptive weight optimization.

The threshold cross-sections for right- and left-chiral selectrons in $e^- e^-$ collisions can be seen in Fig. (1). It is clear that finite width effects and Coulomb rescattering play an important role in the selectron mass measurement. Also included are the important SUSY backgrounds to these processes, which are seen to be small and very flat over the threshold region, and may therefore be subtracted in a model independent way by extrapolating from pre-threshold. Consequently, one can expect that the measurement of the selectron pair threshold cross-sections in $e^- e^-$ collisions will provide a very good determination of the selectron masses. For other recent simulation studies on selectron pair production see Ref.[6].

Turning our attention to smuon pair production we find a more difficult situation. Here there is no t-channel process; smuon pair production is mediated by s-channel γ/Z exchange. The smuons are produced in a P-wave so the cross-section rises $\sim \beta^3$ at threshold, making its measurement more challenging than that of the selectron production discussed above. For this discussion we restrict ourselves to the production of right-chiral smuon pairs, which are generally of lower mass than their left-chiral counterparts. For our parameter choice, the dominant decay is $\tilde{\mu}_R \to \mu \tilde{\chi}_1^0$, giving a signature of two muons and missing energy.

A problem immediately arises: the doubly resonant process $e^+ e^- \to \tilde{\mu}^+ \tilde{\mu}^- \to \mu^+ \mu^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$ is gauge dependent for smuons with finite width. Indeed one must include singly resonant contributions, $e^+ e^- \to \mu^{\pm} \mu^{\mp *} \to \mu^{\pm} \tilde{\mu}^{\mp} \tilde{\chi}_1^0 \to \mu^+ \mu^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$ and $e^+ e^- \to \tilde{\chi}_1^0 \tilde{\chi}_1^{0 *} \to \tilde{\chi}_1^0 \tilde{\mu}^{\pm} \mu^{\mp} \to \mu^+ \mu^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$, to restore gauge invariance. It is this extended set of Feynman diagrams which we must consider as the signal from which the smuon mass is to be extracted. For most practical purposes, this is not a serious concern; one can find 'good' gauges (for example the Coulomb gauge) where the effect of these extra diagrams is small. However, for the theoretical precision required at a linear collider, these extra contributions cannot be discarded. (Notice that this gauge invariance problem is not manifest in the production of selectrons in $e^- e^-$ collisions due to its t-channel nature, but would also be pertinent to s-channel selectron production in $e^+ e^-$ collisions.)

We calculate the many Feynman diagrams of signal and background and perform their integration over phase space using the same methods as described for the selectrons above. Standard Model backgrounds have been examined elsewhere and can be removed with appropriate kinematic cuts [7]. The most important SM background is W boson pair production, $e^+ e^- \to W^+ W^-$, where the W bosons decay via $W \to \mu\nu$. This can be removed by observing that the W decay leptons lie approximately in an azimuthal plane. The SM process $e^+ e^- \to (\gamma/Z)(\gamma/Z)$ where one (γ/Z) decays to muons and the other to neutrinos, also contributes a sizable background. However, this can be easily reduced by removing muon pairs which are collinear (removing $\gamma \to \mu^+ \mu^-$) or have an invariant mass reconstructing the Z (removing $Z \to \mu^+ \mu^-$). These cuts remove approximately half of the signal.

The MSSM backgrounds are more problematic, since they are large and appear very similar to the signal. First of all, there is neutralino pair production, both $e^+ e^- \to \tilde{\chi}_k^0 \tilde{\chi}_1^0$ where the heavier neutralino decays to the lightest one via $\tilde{\chi}_k^0 \to \mu^+ \mu^- \tilde{\chi}_1^0$, and $e^+ e^- \to \tilde{\chi}_2^0 \tilde{\chi}_2^0$ where one neutralino decays to $\mu^+ \mu^- \tilde{\chi}_1^0$ and the other to $\nu \bar{\nu} \tilde{\chi}_1^0$. Chargino pair production, $e^+ e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$ with the decay $\tilde{\chi}_1^{\pm} \to \tilde{\mu}^{\pm} \nu \tilde{\chi}_1^0$ is also important. Z pair
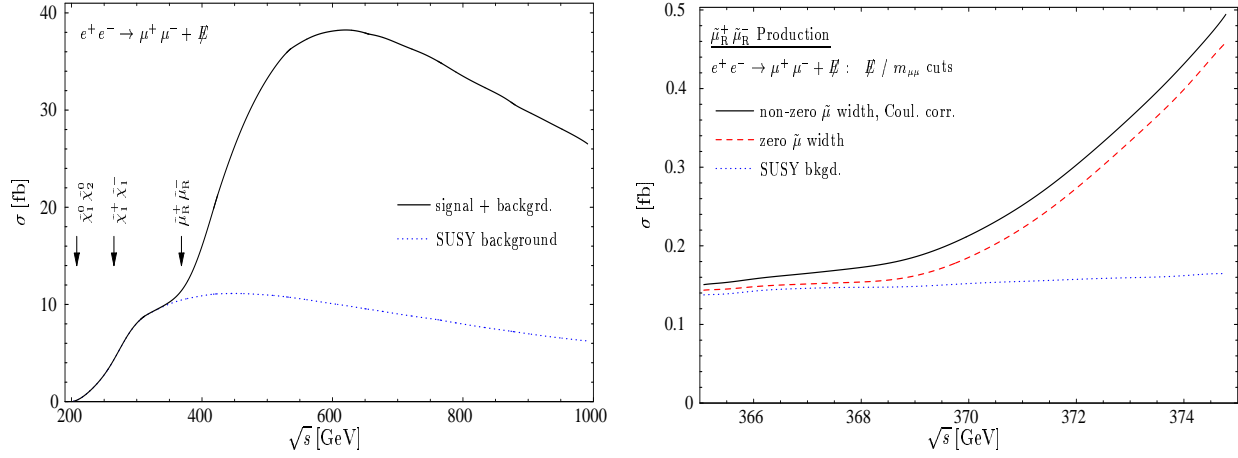
FIG. 2: (left) The total cross-section and SUSY backgrounds to $e^+e^- \to \mu^+\mu^- + \not{E}$, indicating the important nominal thresholds by arrows. (right) *The cross-sections for signal and associated SUSY backgrounds near the threshold, after the missing energy and muon pair invariant mass cuts.*

production can also present a SUSY background if the second Z decays to the invisible neutralinos. Finally we have Higgs-strahlung, $e^+e^- \to Zh$ where the Z decays to muons and the Higgs decays to neutralinos. The contribution of these backgrounds together with the signal is shown in Fig. (2/left). The important thresholds are indicted by arrows.

These SUSY backgrounds can be removed by cuts on the final state's kinematic properties in two ways. Firstly, the cascade decays will lead to increased missing energy in the background processes compared with the signal. This can be optimally exploited by removing all events with missing energy greater than $0.63\sqrt{s}$. Similarly, the muon pair invariant mass will be greater for the signal than for the large $\tilde{\chi}_2^0\tilde{\chi}_1^0$ background, which can be reduced by removing all events with muon pair invariant masses below $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$ (approximately 60 GeV in the case considered here). Alternatively, one may observe that the muon energies in the signal contribution will be clustered around their nominal threshold $(E_{\tilde{\mu}}^2 - m_{\tilde{\chi}_1^0}^2)/2m_{\tilde{\mu}}$. The background exhibits much lower muon energies, so can be removed by selecting events with muon energies in a band $\Delta E_\mu \approx 10$ GeV about this nominal threshold. The resulting signal and background after the missing energy and muon invariant mass cuts have been applied can be seen in Fig. (2/right). Once again, the remaining background is reasonably flat over the threshold region and can be removed by extrapolating from below the threshold. Also note the importance of non-zero width effects and the Coulomb corrections, where the resulting shift in the cross-section is comparable to the expected experimental accuracy.

In summary, the first theoretical steps toward the precise measurement of the selectron and smuon masses at a linear collider have been taken. It is clear that the measurement of the selectron masses from the selectron pair production threshold scan is considerably easier in e^-e^- collisions than in e^+e^- collisions. In the former case, the SUSY backgrounds are found to be very small and easily removed by extrapolation from below threshold. The smuon mass measurement at a linear collider must rely on e^+e^- collisions, where there are large SM and SUSY backgrounds. However, these backgrounds can be removed by the judicious use of cuts on the final state kinematics, allowing the accurate determination of the smuon mass.

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