

MRI-PHY/P970923

September 1997

hep-ph/9709431

Gauge-Mediated Supersymmetry Breaking Signals in an Electron-Photon Collider

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Abstract

We show the usefulness of an $e^- \gamma$ collider with backscattered laser photons in unveiling the signatures of Gauge-Mediated Supersymmetry Breaking models, with a right selectron as the next LSP. We also show how the signal can be distinguished from the Standard Model background as well as from signals of minimal supersymmetry.

PACS numbers: 14.80.Ly, 13.85.Qk, 12.60.Jv

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1. Introduction

Supersymmetry (SUSY), if exists, must be broken, and the intriguing question is how. Due to the fact that it cannot be broken in a phenomenologically consistent way in the observable sector [1], one is forced to envisage a hidden sector where SUSY breaking takes place. How this breaking is conveyed to the observable sector is a point of debate. The most popular theory is that the breaking is transmitted through gravitational interaction, which is common to both the hidden and the observable sectors [2]. In this class of models, which necessarily have the gravitino whose mass is at or above the electroweak scale, and almost invariably have the lightest neutralino χ_1^0 as the Lightest SUSY Particle (LSP), the one with the minimal particle content is known as the Minimal Supersymmetric Standard Model (MSSM).

Another idea which has recently received considerable attention is that SUSY breaking is dynamically conveyed to the observable sector by means of a messenger sector (MS), through the standard model gauge interactions. To maintain gauge coupling unification, one chooses the simplest ansatz (though by no means a necessary one [3]) that the MS consists of chiral superfields Ψ and $\bar{\Psi}$, which belong to a complete representation of any Grand Unification gauge group (*e.g.*, $5 + \bar{5}$ or $10 + \bar{10}$ of SU(5), or $16 + \bar{16}$ of SO(10)). The hidden sector and the MS are coupled by means of a gauge singlet superfield S , whose scalar and auxiliary components develop vacuum expectation values (VEV) in the hidden sector ¹ This breaks supersymmetry in the MS through a term $\lambda S \bar{\Psi} \Psi$ in the messenger superpotential. The quarks and leptons in the MS transform vectorially under the standard model (SM) gauge groups, and gauginos get their SUSY-breaking masses through one-loop effects involving these MS fields. Consequently, the sfermions get their masses at two-loop level. These class of models are known as Gauge-Mediated SUSY Breaking (GMSB) models [4].

A common feature of all the GMSB models is a light (by the standard of terrestrial experiments) gravitino, which is invariably the LSP. Depending on the structure of the MS, a right slepton or the lightest neutralino can be the Next LSP (NLSP). If we demand perturbative gauge couplings upto the unification threshold, the number of messenger generations N_{gen} (of quarks and leptons) cannot be greater than four if they belong to the $5 + \bar{5}$, and one if they are in either $10 + \bar{10}$ or $16 + \bar{16}$ (a generation of $10 + \bar{10}$ is equivalent to three $5 + \bar{5}$ generations). Generally speaking, the NLSP is the lightest neutralino if $N_{gen} = 1$, and almost always a right slepton if $N_{gen} = 3$ or 4. In addition to the Higgsino mass parameter μ and the quantity $\tan \beta$ (the ratio of the two Higgs VEVs), the complete mass spectrum is more or less determined with one single input, Λ , the ratio of the VEVs of the auxiliary and the scalar components of the superfield S . The overall scale of the messenger sector (to be designated as M here) has a relatively minor role, as it comes in only through the renormalisation group equations giving the evolution of the various parameters.

The question that naturally arises is which one (if any) of the competing schemes of SUSY breaking is more likely to be chosen by nature. This is more than merely a matter of curiosity, since the breaking mechanism in turn affects low-energy phenomenology, based on which the various

¹The scalar component of S may, alternatively, have an explicit mass term.

SUSY search programmes are being carried out in collider experiments. In a GMSB scenario, if the lightest neutralino is the NLSP, it is almost Bino over a large region of the parameter space, and decays into a photon (or a Z) and a gravitino. Thus, the signal will consist of one or two photons in the final state, accompanied by missing energy. Such signals in LEP-2 [5], Fermilab Tevatron [6] and the Next Linear collider (NLC) [7] have been extensively investigated. As there is almost no loss in branching fraction for final-state photons, cross-sections for such processes like $e^+e^- \rightarrow \gamma\gamma$, $e^+e^- \rightarrow e^+e^-\gamma\gamma$ etc. are much larger in GMSB than in MSSM, and detection of GMSB is going to be straightforward.

On the other hand, if a right slepton is the NLSP, then the basic final states arising from its decay sequence are the same as in those in MSSM. This can be best understood by considering the case when the three right sleptons are practically degenerate (described in the literature as the ‘slepton co-NLSP scenario’ [8]). A pair of right selectrons produced in e^+e^- collision will then lead to $e^+e^- + \cancel{E}$, since each selectron is liable to decay into an electron and a gravitino. The very same final state occurs from a selectron pair in MSSM. It has been contended that in GMSB, the selectron will in general show longer tracks, due to its larger lifetime. However, this may not be the case all over the parameter space, particularly when the gravitino mass is on the higher side. One, therefore, has to do a painstaking analysis of kinematic distributions such as the distribution in missing energy, where the baffling factor is always the whole plethora of unknown parameters in any of the models concerned. Also, in such cases, pair-production of the lightest neutralino, which is another possible way of revealing GMSB signals, may be kinematically disallowed due to generally enhanced superparticle masses with a large number of messenger generations. Thus it is very much desirable to look for situations in the selectron NLSP scenario where the dominant final states are different from those expected in MSSM. In this paper, we suggest that an $e^-\gamma$ collision experiment, performed with laser backscattering in a linear electron-positron collider, may be useful for this purpose.

The utility of an $e^-\gamma$ collider in probing a large area of the parameter space has already been pointed out [9]. Typically, a selectron together with the lightest neutralino is expected to be most copiously produced there. The interesting thing is that, while in MSSM the end result is a single electron with missing energy, a GMSB scenario with a selectron NLSP leads to three electrons plus missing energy. In the rest of the paper, we discuss some details of this signal, together with ways of using it to our best advantage vis-a-vis SM backgrounds and residual MSSM effects.

We base our discussion upon events to be seen at the NLC (with $\sqrt{s} = 500$ GeV) running in the $e^-\gamma$ mode. With a brief description of the $e^-\gamma$ collider in the next section, we show our results in section 3. Section 4 concludes the paper.

2. The $e^- \gamma$ Collider

In the $e^- \gamma$ collider, a low-energy but high-intensity laser beam backscatters off the positron beam of the original e^+e^- machine [10]. The energy of the incident photons must be so low that no multiple scattering (*i.e.*, e^+e^- pair production) takes place, whereas the intensity should be sufficiently high so that Compton-conversion can take place with maximum efficiency. Pair production from the incident beam decreases the conversion efficiency and can produce serious background effects. If the energy is just below the pair-production threshold, and if the beam is intense enough, almost all the positrons get Compton-converted and the photon beam has almost the same luminosity as of the positron beam. This process produces a hard collimated photon beam, with a distribution in the energy of the photons. The positron beam, depleted of its energy, is dumped.

If the initial photon beam is collinear with the e^+ beam, its energy E_{laser} is bounded by

$$\frac{4E_{e^+}E_{laser}}{m_e^2} \equiv x \leq 2(1 + \sqrt{2}), \quad (1)$$

to prevent pair creation of e^+e^- . The photon energy spectrum $\mathcal{P}(y)$, where $y = E_\gamma/E_{e^+} = \sqrt{s}_{e-\gamma}/\sqrt{s}_{e^+e^-}$, is given by [9, 11]

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

where

$$N = \frac{1}{2} + \frac{8}{1+x} + \frac{7}{2x(1+x)} + \frac{1}{2x(1+x)^2} + \left(1 - \frac{4}{x} - \frac{8}{x^2} \right) \ln(1+x) \quad (3)$$

normalizes $\int \mathcal{P}(y)dy$ to unity. In the above formulae, we take both the e^+ beam and the initial laser beam to be unpolarized. In the next section, we will present our results with a right polarized e^- beam hitting this photon beam. As we shall see, this is very useful for reducing the SM backgrounds to the three-electron plus missing energy signal.

3. Results

For $e^- \gamma$ collisions, the lab frame and the centre-of-mass (cm) frame are different. We first calculate $d\sigma/dt$ for the process $e^- \gamma \rightarrow \tilde{e}_R \chi_1^0$ in the cm frame, wherein all the Mandelstam variables are defined:

$$\begin{aligned} \frac{d\sigma}{dt} = \frac{1}{16\pi s^2} & \left[C^2(t - m_{\chi_1^0}^2)(t + m_{\tilde{e}_R}^2) + C'^2 s(s + t - m_{\tilde{e}_R}^2) \right. \\ & \left. + 2CC'(m_{\chi_1^0}^4 - tm_{\chi_1^0}^2 - \frac{1}{2}sm_{\chi_1^0}^2 + tm_{\tilde{e}_R}^2 - m_{\chi_1^0}^2 m_{\tilde{e}_R}^2 - \frac{1}{2}st) \right] \end{aligned} \quad (4)$$

where

$$C = \sqrt{2}ge \tan \theta_W N_{12} \frac{1}{t - m_{\tilde{e}_R}^2}, \quad (5)$$

$$C' = \sqrt{2}ge \tan \theta_W N_{12} \frac{1}{s}. \quad (6)$$

The above expressions were derived with a fully right-polarized e^- beam. N_{12} gives the Bino component of the lightest neutralino; the other components, obviously, either do not contribute or are suppressed by m_e/m_W .

The total cross-section can be obtained by integrating over t and at the same time folding with the photon energy distribution function given in (2). The maximum possible value of y is $x/(x+1)$; we set x , defined in (1), to its maximum value of 4.83. The lower limit is given by the kinematic threshold $(m_{\chi_1^0} + m_{\tilde{e}_R})^2/s_{e^+e^-}$. However, for small sparticle masses, we set $y_{min} = 0.4$, because photons with smaller y are scattered over such a large angle that they are effectively lost at the interaction region. We assume $\text{BR}(\chi_1^0 \rightarrow e_R \tilde{e}_R) = 1/3$ and $\text{BR}(\tilde{e}_R \rightarrow e_R G) = 1$, which implies that all right sleptons are degenerate in mass. We have checked that only right sleptons can be lighter than the lightest neutralino in the parameter space of our interest.

Here let us justify our choice of a right-polarized e^- beam. The role of beam polarization at NLC in discovering new physics has already been highlighted [12]. If μ is not too small, χ_1^0 is almost always dominated by its Bino component, and its coupling to e_R is larger due to the hypercharge of the latter. Moreover, the left-polarized electrons do not play any role in our signal of three lepton plus missing energy (to be precise, production of left sleptons — if kinematically possible — alongwith χ_1^0 will give rise to five leptons in the final state, as can easily be seen). Thus, the possible loss in luminosity due to a polarized beam may be compensated by its 100% efficiency in signal generation. Some of the possible Standard Model (SM) backgrounds that come from one or more W s radiating off the electrons are also eliminated by using a right-polarized beam.

The most serious SM backgrounds come from the processes $e^- \gamma \rightarrow e^- W^+ W^-$, $e^- \gamma Z$, $e^- Z Z$. The first process has a cross section of the order of a few hundredths of a femtobarn, and is totally negligible compared to our signal cross-section. This is because, compared to the process $e^- \gamma \rightarrow e^- Z$, this process is suppressed by the Z -propagator as well as by the branching fraction of two W s to specific lepton channels. Serious background contributions may come from the last two processes, with one or two soft electrons in the t -channel contributing to a logarithmic enhancement. The second process may produce significant background if the radiated photon is soft. This is circumvented by applying a softness cut on any two electrons, and demanding that no two electrons can have energy less than 20 GeV. The third process can be eliminated if we put an invariant mass cut centred on the Z -pole on all possible lepton pairs. However, for $M_{breaking} \leq 100$ TeV, the signal also gets heavily suppressed. We therefore use an alternative cut, namely, one on the opening angle of two leptons in the azimuthal plane. This is based on the fact that for leptons produced from an on-shell Z , the opening angle is almost 180° . Thus, an opening angle cut at 160° largely suppresses the background. We have also applied a \cancel{p}_T cut of 20 GeV to discriminate the signal from the three-lepton background without missing energy, and an angular cut $10^\circ \leq \theta_e \leq 170^\circ$ to ensure that no leptons are lost in beam pipe.

The signal cross-section, with all these cuts, is plotted in Figure 1 against the SUSY breaking

scale M . We have taken $M/\Lambda=2$ since the dependence of the cross-section on this factor is not very significant (for $M/\Lambda = 10$, the cross-section decreases by 10%). The reason is that all the sparticle masses at M are determined by Λ alone, and only the renormalization-group equations of the couplings contain M . It can be seen that the cross-section also depends nominally on $\tan\theta$ and μ .

In Figure 2 we show the missing E_T distribution for the process. From now on, we use $\mu = 300$, $\tan\beta = 2$ and $M/\Lambda = 2$. This plot is shown for two different SUSY breaking scale. Note that for lower M , a missing E_T cut eats more into the signal. Energy distributions of the three leptons are shown in Figure 3a and 3b, for $M = 50$ TeV and $M = 100$ TeV respectively. Here also the peak is towards smaller energy for low M , as expected. In Figure 4, we show the opening angle between a pair of leptons in the azimuthal plane for $M = 100$ TeV. The distribution is rather flat, with a slight hike towards back-to-back leptons. For $M = 50$ TeV, this trend is sharper so that the signal leptons have a distinct peak towards the back-to-back configuration. Thus our cuts tend to reduce the signal significantly for low M , though the available phase space is more compared to high- M case. This feature is reflected in Figure 1. However, we must emphasize that even such a reduced signal can be easily distinguished from the background, which is almost eliminated by the cuts. Also, situations with large superparticle masses (large Λ) are less affected by the opening angle cuts. This is precisely the region where the inadequacy of e^+e^- machines shows up. This again underlines the usefulness of electron-photon collisions in unveiling a selectron NLSP scenario.

A pertinent question is whether the above final state can still arise from MSSM signals. The MSSM process responsible for a similar signal is $e_R^-\gamma \rightarrow \chi_2^0\tilde{e}_R$, $\tilde{e}_R \rightarrow e\chi_1^0$, $\chi_2^0 \rightarrow \chi_1^0\ell^+\ell^-$ (χ_2^0 being the second lightest neutralino). The angular distribution for the last process is given in [13].

Clearly, a gaugino-dominated χ_2^0 is necessary for the above process to be substantial, for otherwise the production is heavily suppressed. Next, the χ_2^0 has to have a large Bino component so that it can be produced with right-polarized electrons. In addition, the χ_1^0 has to be gaugino-dominated, for otherwise final states with τ 's will be favoured to those with electrons. Taking all conditions into account, the tri-electron plus missing energy signal in $e\gamma$ collision can be appreciable in MSSM only if (i) $\mu \gg M_1, M_2$, and (ii) χ_2^0 (χ_1^0) is Bino (Wino) dominated, or alternatively (iii) if the stau and the selectron have a very large mass separation. Of these, (ii) and (iii) are difficult to accommodate in the MSSM, especially in the one based on minimal supergravity.

4. Summary and Conclusions

We have shown that the $e^-\gamma$ collider may be a very useful machine to find GMSB if the number of messenger generations is three (or more), which will make right selectron the NLSP, and, at the same time, make both \tilde{e}_R and χ_1^0 heavier compared to the $N_{gen} = 1$ case (for a fixed Λ), so that it may not be possible for an e^+e^- collider to probe both of them. We have discussed how the signal

can be distinguished from the SM background with the help of different cuts. The signal proves to be better for higher values of the parameter Λ . For the such cases, it is easy to distinguish the signal from the conventional MSSM backgrounds. Such a task can be somewhat difficult for low Λ if both the neutralinos in MSSM are gaugino dominated (to be precise, a Bino-dominated χ_2^0 and a Wino-dominated χ_1^0 if we use a right-polarized electron beam), or if the selectrons turn out to be much lighter than staus. The last mentioned situations mostly fall outside the scope of models based on minimal supergravity.

Though we have not discussed the case for a neutralino NLSP, it is easy to see what happens. First of all, the neutralino pair-production cross-section is larger than the selectron pair-production cross-section in an e^+e^- machine, so most probably the neutralinos will be detected in the e^+e^- mode itself, and can easily be identified as a GMSB signal by two-photon final states. In the $e^- \gamma$ machine, the dominant final state will be $e^- \gamma \gamma$ plus missing energy (if $m_{\chi_1^0} > m_Z$, a small percentage of χ will go to Z and Gravitino). With a softness cut on photon energy, the SM background can be reduced so that one can get a clear signal. Such a cross-check is useful even if one finds the GMSB neutralinos in the e^+e^- machine.

NOTE ADDED: After this work had been completed, we received reference [14] where some related issues in $e\gamma$ collisions were treated. Our study turns out to supplement theirs in a certain way, although it had not been originally intended.

Acknowledgements

The authors thank S. Naik and S. Roy for useful discussions.

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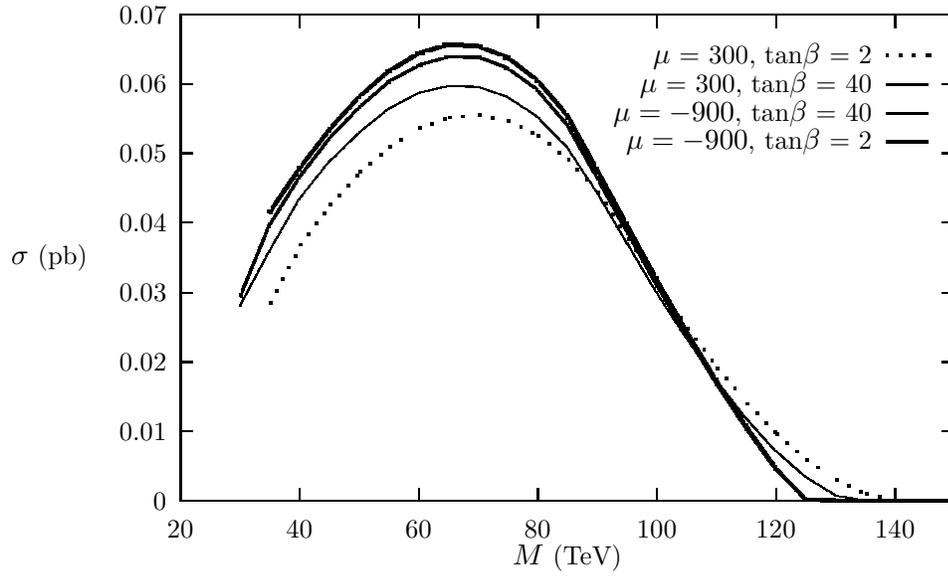


Figure 1

Cross-section for the process $e^- \gamma \rightarrow e^- e^+ e^- + \cancel{E}$, plotted against the SUSY breaking scale M . The cuts are as discussed in the text, and $M/\Lambda = 2$

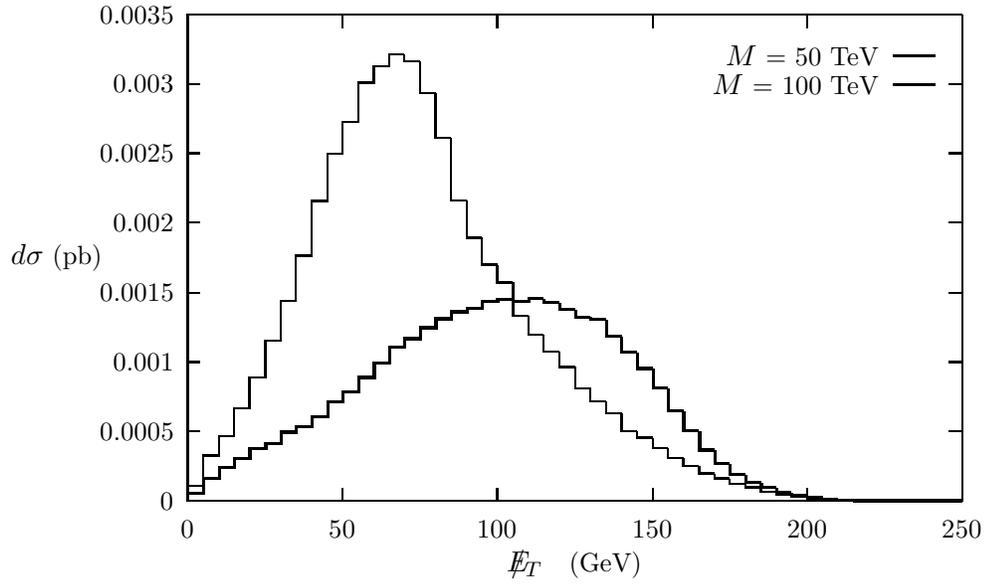


Figure 2

Distribution of \cancel{E}_T for the process $e^- \gamma \rightarrow e^- e^+ e^- + \cancel{E}_T$, for two values of the SUSY breaking scale. We have set $\mu = 300$, $\tan\beta = 2$, and $M/\Lambda = 2$. All cuts except the \cancel{E}_T cut (set to zero) are as discussed in the text.

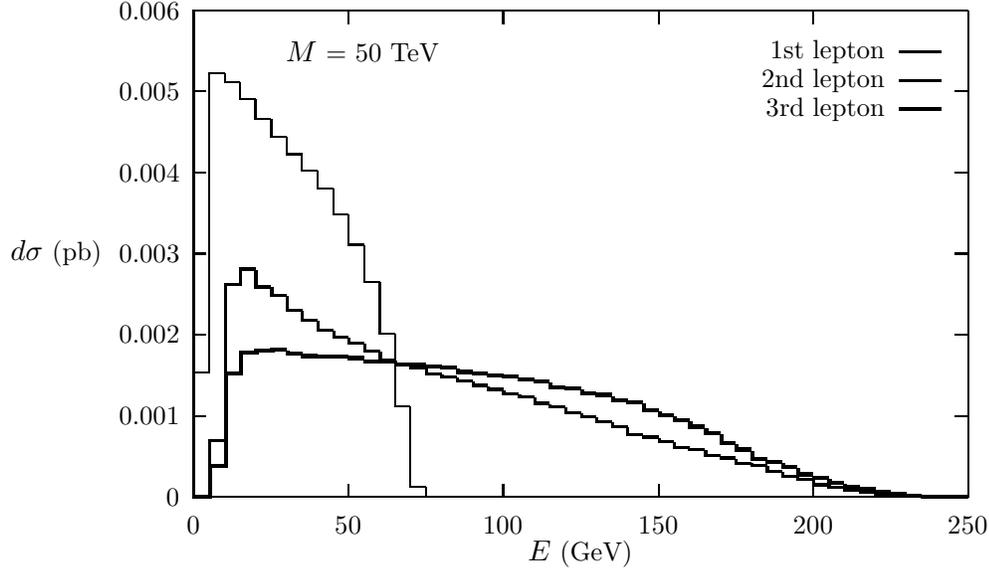


Figure 3(a)

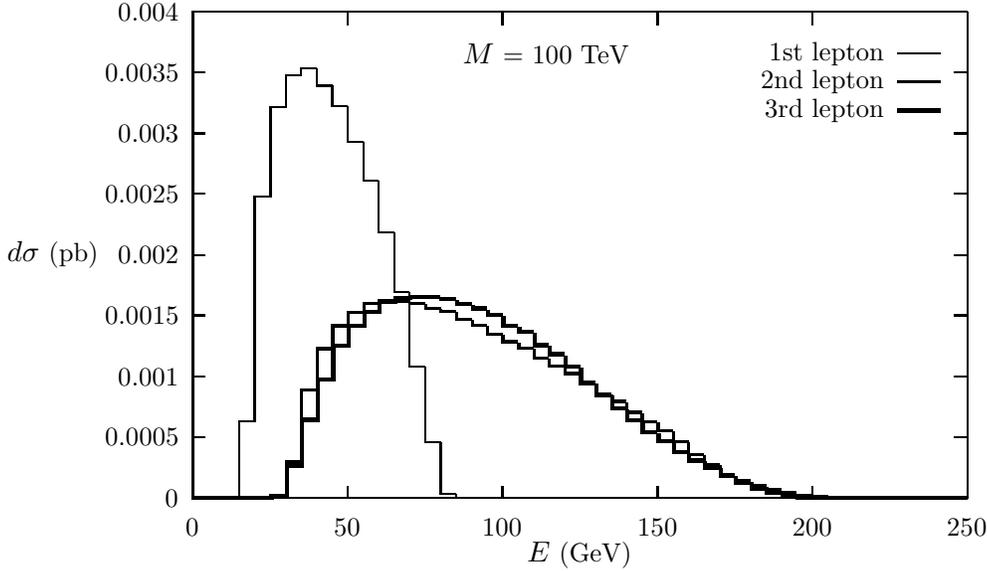


Figure 3(b)

Both the figures represent the distribution of the energies of three leptons for the process $e^- \gamma \rightarrow e^- e^+ e^- + \cancel{E}_T$, for two values of the SUSY breaking scale (a) $M = 50$ TeV (b) $M = 100$ TeV. We have set $\mu = 300$, $\tan\beta = 2$, $M/\Lambda = 2$. All cuts except the softness cut are as discussed in the text; the softness cut has been put to zero. The lepton number assignment follows the convention: $e^- \gamma \rightarrow \tilde{e}_R(1)\chi_1^0$, $\chi_1^0 \rightarrow \tilde{e}_R(2)e(1)$, $\tilde{e}_R(1) \rightarrow e(2)G$, $\tilde{e}_R(2) \rightarrow e(3)G$.

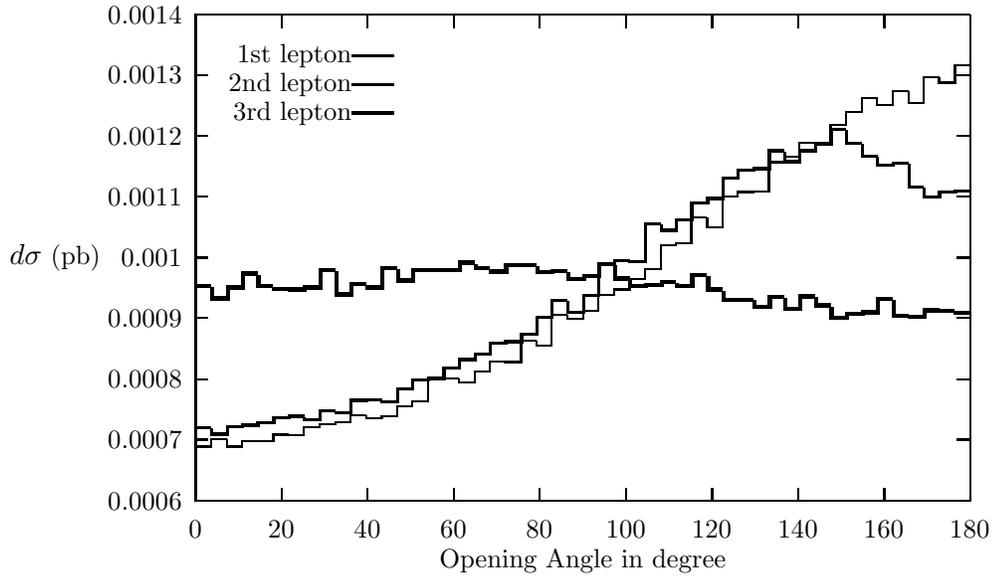


Figure 4

Distribution of azimuthal opening angle of three leptons for the process $e^- \gamma \rightarrow e^- e^+ e^- + \cancel{E}_T$, for $M = 100$ TeV, $\mu = 300$, $\tan\beta = 2$. All cuts except the azimuthal opening angle cut are as discussed in the text; the azimuthal opening angle cut has been put to zero. The lepton number assignment is the same as in Figures 3(a) and 3(b).