Study of Supersymmetric Particle Production at the NLC

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Abstract

This paper studies techniques for finding supersymmetric particles at the NLC (Next Linear Collider). The main focus of this paper is the production of selectrons and neutralinos. Techniques for both signal detection and mass calculation are covered. The paper assumes the NLC to be an e^+e^-collider running with a center of mass energy of up to 1 TeV, and with the capability to produce 80% left polarized electron beams.

Contents

List of Figures

List of Tables

1 Introduction

1.1 The Standard Model

Physicists have been extremely successful in describing the natural world in terms of particles and the forces that act between them. All of the particles and forces taken together are collectively known as the Standard Model. However, the Standard Model is not merely a list of particles and forces such as the periodic table of the elements is in Chemistry. Rather, it is a detailed mathematical framework which characterizes the interactions of the constituent particles. It is the backbone of current high energy particle physics, and describes a wide range of knowledge such as chemistry, optics, nuclear physics, electronics, indeed most of the phenomena in the world around us are reducible to processes described in the Standard Model. The particles that comprise it can be divided into two basic groups, called fermions and bosons. The defining characteristic of the fermions is that they are have units of spin[1] equal to $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$ and so on. There are two fundamental groups of fermions, the leptons and the quarks. The leptons can naturally be grouped into three doublets, called generations.

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

The upper particles in each generation (the neutrinos) have a charge of zero. The lower particles, the electron (e), the muon (μ), and the tau (τ), each have a charge[2] of one. The other fundamental fermions are the quarks. There are six quarks called up (u), down (d), charm (c), strange (s), top (t), and bottom (b). Like the leptons, the quarks can also be grouped into three doublet generations.

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

Here the upper particles in each generation have a charge of $\frac{2}{3}$, and the lower particles have a charge of $-\frac{1}{3}$. All of the matter in the world around us

[1] spin is the intrinsic angular momentum of the particle, measured in units of $\hbar = \frac{h}{2\pi}$ where h is Planck's constant. Thus a spin $\frac{3}{2}$ particle has an intrinsic angular momentum equal to $\frac{3}{2}\hbar$.

[2] In terms of the electron charge, q_e.

is made from the quarks and leptons. The atoms of the periodic table are made of only three of the fermions, the up quark, the down quark, and the electron. Hence all the amazing complexity of the world we see arises from the interactions of but a few particles.

The second fundamental group of particles in the Standard Model is the bosons. Bosons are particles with integer spin. The particles which transmit the forces between matter particles are all bosons. There are four fundamental forces in nature that we are aware of: the strong nuclear force (responsible for binding together the nuclei of atoms), the weak nuclear force (responsible for processes such as radioactive decay), the electromagnetic[3] force (responsible for atomic bonding and structure), and the gravitational[4] force (responsible for the large scale structure of the universe). Each of these forces has associated with it one or more bosons which carry information about the force between particles. The forces and the particles that mediate them are listed in table 1.

Table 1: The fundamental forces and associated particles.

Force	acts on	associated particle(s)
strong force	quarks	eight gluons (g), spin 1
weak force	quarks, leptons, electroweak gauge bosons	$W^{\pm}$, Z^0, spin 1
electromagnetism	charged particles	photon (γ), spin 1
gravity	particles with mass	graviton, spin 2

[3]The electromagnetic force and the weak nuclear force have been demonstrated to be aspects of one electroweak force. The electroweak symmetry is a broken symmetry at low energy and so we observe it as two distinct forces.

[4]No realistic theory of quantum gravity has yet been discovered, and as such gravity is not formally a part of the Standard Model. It is included here because of its importance as one of the known fundamental forces.

1.2 Supersymmetry

Despite all its success, it is known that the Standard Model is not the whole story. There are facets of the Standard Model which are simply inconsistent with the observable world. For instance, it holds that the particles are actually massless, but gain mass by coupling with a scalar field that permeates all space called the Higgs field. However Higgs mass corrections, due to its interactions with Standard Model particles, lead to unphysical infinities. Since there are certainly no infinitely massive particles in the world around us, this means that there must be new physics beyond the Standard Model. Supersymmetry is a theory with the nice feature that it leads to a finite calculation of the Higgs mass. This happens because for every Standard Model term that contributes to the infinite mass of the Higgs there is a supersymmetric contribution that cancels it and thus permits a finite mass. Supersymmetry has other features that have made it popular amongst high energy physicists. One such feature is the unification of the coupling constants for the fundamental forces. The coupling constants are measures of the relative strengths of the forces. The coupling constants change with energy, and in supersymmetric theories at a certain very high energy, all of the coupling constants (for the electromagnetic force, the weak nuclear force, and the strong nuclear force) merge and have the same value. This is essential if the fundamental forces are ever to be unified, long a goal of theoretical physics. Another intriguing feature of supersymmetry is R-parity conservation. R-parity is just a number given by the relation:

$$R = (-1)^{3B+L+2S}$$

where B is boson number, L is lepton number, and S is the spin of the particle. For Standard Model particles R = +1, and for supersymmetric particles R = -1. For example an electron has B=0, L=1, and S=$\frac{1}{2}$, thus R for an electron is $(-1)^2 = 1$. For a selectron, which has B=0, L=1, and S=0, R = $(-1)^1$ = -1. In many supersymmetric theories R-parity is conserved. This means that there must always be an even number of supersymmetric particles at a vertex so that the product of the R-parity for the particles remains one. This also means that that there must be a lightest supersymmetric particle (LSP) that is stable and can't decay. The LSP, which is expected to be neutral, is invisible and undetectable, but if enough of them were created at the beginning of the universe then the LSP could be a possible candidate for dark matter.

There is no single well defined theory of supersymmetry, instead there are many variations on the basic framework. The underlying idea of all supersymmetric models is a simple one, however. Supersymmetry says that there is a symmetry between fermions and bosons, and posits the existence of some operator, Q, that changes bosons into fermions, and a conjugate operator, $Q^\dagger$, which does the opposite. Thus

$$Q|b\rangle = |f\rangle \text{ and } Q^\dagger|f\rangle = |b\rangle.$$

The operator Q leaves all quantum numbers the same except for spin, which it changes by $\frac{1}{2}$. This means that, if nature had an unbroken supersymmetry, every Standard Model fermion would have a supersymmetric partner, or spartner, that had identical properties except that it was a boson, and all Standard Model bosons would have spartners that are fermions, with identical properties except for spin. This would result in many unobserved phenomena such as supersymmetric atoms where super-electrons, or selectrons, were bound to atomic nuclei. This would be a very noticeable effect, because these super-atoms would have different properties from the normal atoms. The selectrons would not obey the Pauli exclusion principle (since the are not fermions), which would allow all of the selectrons in the super-atom to occupy the ground state. This would result in extremely different atomic properties, which are not observed. Thus if nature is supersymmetric then the supersymmetry must be broken at our energy scale, much like the broken electroweak symmetry. The supersymmetry breaking would allow the particles to have remained relatively light while the sparticles became heavy, which is why sparticles have not been detected. With new colliders like the NLC we are reaching the energies where, if supersymmetry exists, the first signals should be observed.

1.3 Terminology and Symbology

Supersymmetry introduces not only a whole slew of new particles, but a plethora of new terminology as well. Luckily the naming conventions are easy to grasp and essentially standardized. The super symmetric particles are referred to as sparticles, (short for super-particles). Following this convention, the super partners to the Standard Model fermions are usually named by attaching an s to the beginning of the name for the Standard Model particle. For example the super-partner of the muon is the *smuon*, the partner of tau neutrino is the tau *sneutrino*. The convention for naming the super-partners to the bosons is to attach the suffix -ino to the name of the Standard Model particle. For example the super-partner to a gluon would be a *gluino*, and the super partner to a W boson is a Wino. There are two special cases to be aware of: The neutralino, which is a mixture of the Zino and the photino, and the chargino, which is a mixture of the Wino and the Higgsino. Symbolically, super-particles are denoted by placing a tilde ($\sim$) over the Standard Model symbol, thus a photino is written $\widetilde{\gamma}$, and a selectron which is the partner of a left polarized electron is written $\widetilde{e}_L^-$. The lightest neutralino is written $\widetilde{\chi}_1^0$, the second lightest is written $\widetilde{\chi}_2^0$, and so on. The lightest chargino is written $\widetilde{\chi}_1^{\pm}$, the second lightest is written $\widetilde{\chi}_2^{\pm}$.

1.4 The NLC

The analysis in this paper applies to supersymmetry at the NLC (Next Linear Collider). The NLC is going to be an e^+e^- collider capable of much higher energies than any linear collider currently in operation. Initially the NLC will operate at a center of mass energy of 500 GeV, and should be upgradable to 1 or 1.5 TeV later on. It will have the ability to produce strongly polarized electron beams and may even be able to polarize positron beams. The beam energy will be tunable allowing certain production cross sections to be enhanced. The NLC will also have an advanced detector. The detector will use a very powerful 4 Tesla magnet, allowing it to be made smaller and providing very precise measurements of momenta. It will incorporate good electromagnetic and hadronic calorimeters to measure particle energies. These features make the NLC a powerful tool for high energy physics.

2 Our Study

2.1 Models and Parameter Points

The supersymmetric models that our group is currently studying are super gravity inspired (SUGRA) models. These models were originally developed in an attempt to develop a quantum theory of gravity, but are now used solely for their appeal as supersymmetric models. We also study one non-SUGRA model. The parameters that serve to characterize these models and their corresponding values are listed in table 2. Each set of parameters is referred to as a parameter point.

Table 2: The five parameter points

	m_0	$m_{1/2}$	A_0	$\tan\beta$	$sign(\mu)$	
Point 1	400	200	0	2	-1	
Point 2	100	300	0	2	-1	
Point 3	200	100	0	2	-1	
Point 5	300	130	-600	2	+1	
	$m_{\tilde{g}}$	$m_{\tilde{q}}$	$m_{\tilde{l}}$	$\tan\beta$	μ	m_A
Point 4	900	1000	1000	10	-100	200

The two parameters m_0 and $m_{\frac{1}{2}}$ are the generic masses of the spin 1/2 and spin 0 particles before the breaking of the supersymmetry. The parameter $\tan\beta$ is the ratio of the vacuum expectation values for the Higgs field. The parameter A_0 is a constant representing the strength of trilinear interactions. The last parameter is $sign(\mu)$. Here μ is the Higgsino mixing term, and only its sign is needed as a parameter because its value can be calculated from the other parameters. The non-SUGRA model that we study is point 4. This model is characterized by a different set of parameters. The parameters $m_{\tilde{g}}$, $m_{\tilde{q}}$, and $m_{\tilde{l}}$ are the generic masses of the squark, the gluino, and the slepton. $\tan\beta$ is still the ratio of the vacuum expectation values of the Higgs field. In the non-SUGRA model the value of μ is needed, not just its sign, since it cannot be predicted from the other parameters of the model. The final parameter of the model is m_A which is the mass of the pseudoscalar Higgs boson.

Having these five distinct points with their differing parameter values has many effects on the models that they produce. One change that varying these values has is to change the decay modes through which a sparticle can decay. Another effect that changing the parameter values has is on the production cross sections of various sparticles for a given energy. One of the most important results of varying the parameter values is changing the mass spectrum (the masses of all the particles) from one point to the next. By having these five distinct points we get five different supersymmetric models, where the masses of the sparticles vary widely from model to model. The mass spectrum for the points we are studying is listed in table 3.

Table 3: Sparticle masses (GeV) for the five points.

	Point 1	Point 2	Point 3	Point 4	Point 5
$\widetilde{\chi}_1^0$	86.050	128.702	44.519	77.834	57.174
$\widetilde{\chi}_2^0$	175.451	257.218	96.998	115.291	111.459
$\widetilde{\chi}_3^0$	492.790	535.721	257.063	146.844	444.800
$\widetilde{\chi}_4^0$	501.853	542.758	273.757	292.407	464.631
$\widetilde{\chi}_1^\pm$	175.366	257.200	96.384	96.056	110.104
$\widetilde{\chi}_2^\pm$	500.898	542.463	257.063	292.457	461.631
h^0	83.254	89.919	68.287	126.957	101.419
H^0	745.465	681.879	379.217	201.056	622.512
A^0	741.215	676.893	371.321	200.000	619.908
$H^\pm$	744.783	680.812	378.714	214.810	623.997
$\widetilde{q}$	603.273	668.380	316.728	1000.000	462.488
$\widetilde{b}_L$	520.573	621.862	274.269	1000.000	380.759
$\widetilde{t}_1$	424.437	535.830	263.725	924.824	150.651
$\widetilde{b}_R$	595.553	653.097	312.965	1000.000	456.583
$\widetilde{t}_2$	550.603	656.470	329.466	1096.285	494.730
$\widetilde{\ell}_L^\pm$	425.922	238.213	215.704	1000.000	320.641
$\widetilde{\nu}_\ell$	421.395	230.022	206.622	1000.000	314.603
$\widetilde{\ell}_R^\pm$	408.796	156.952	206.543	1000.000	307.449
$\widetilde{g}$	550.616	759.035	298.401	900.000	425.521

The reason that we study these five separate points is simple. We don't actually think that if supersymmetry is discovered in nature it will have the parameter values of one of these points, that would be very unlikely. Our strategy is to study five points with widely varying properties so that we can be sure that we are able to make measurements independent of the form that supersymmetry may take in the real world. By studying a wide range of values for the parameters we can show that there are techniques for dealing with all the various ways in which supersymmetry may manifest itself in nature.

2.2 Experimental Method

To do our analysis we use monte carlo simulation programs, called ISAJET, PYTHIA, and HERWIG to generate supersymmetric data and Standard Model background. We specify the parameters of the model that we want to study, and the number of events we want to generate. We assume that the NLC will be running with a luminosity of $5 \cdot 10^{33}\ cm^{-2}s^{-1}$. Since we know what the total cross sections are for the points that we want to study, we can calculate the number of events that we would expect to see in a given amount of time. We typically do our analysis for 10^7 seconds of simulated data, which is approximately a third of a year, this is sufficient to generate an integrated luminosity of 50 fb^{-1}. ISAJET generates data for entire events and stores information about them such as the momentum and energy of the particles that are created. ISAJET does not actually simulate the paths of the particles through the detector. Soon we plan to begin using another program called GEANT which has this capability and produces a much better simulation of the way that the particles are observed in the detector. After the data has been generated we use a program named NLCPROC[6] that formats the data into ntuples that can be read by our analysis program PAW. Using PAW we can plot energies and momenta on an event by event or particle by particle basis. We can then identify the signal that we are looking for and try to get rid of any background that may be obscuring it. After we have cut out as much background as possible we end up with a clean signal which allows us to make measurements of sparticle masses.

3 Sparticle Production at Point Two

The point studied in this paper is point two. Point two has large cross sections for the production of neutralinos, selectrons, and sneutrinos. The sneutrinos are invisible at this point ($\widetilde{\nu}_\ell \rightarrow \widetilde{\chi}_1^0 \nu_l$), and so this is not an observable decay mode. This leaves mainly selectrons and neutralinos to be studied. The cross sections for point 2 production modes appear in Table 5.

At 500 GeV there are two main channels that lend themselves to analysis. One channel that is analyzable is $e^+e^- \rightarrow \widetilde{e}^+\widetilde{e}^-$, where the selectron can be either right or left polarized. The selectrons then decay into electrons and neutralinos, $\widetilde{e}^+ \rightarrow e^+\ \widetilde{\chi}_1^0$. This mode has already been studied[3] and so I studied the other production mode, $e^+e^- \rightarrow \widetilde{\chi}_1^0\widetilde{\chi}_2^0$.

3.1 Neutralino Production at 500 GeV

The $\widetilde{\chi}^0_2$ is not a stable particle and so it will eventually decay into $\widetilde{\chi}^0_1$'s and Standard Model particles. If the Standard Model particles that it decays into are visible then usually one can calculate from their energies the mass of the particle that they came from. The $\widetilde{\chi}^0_2$ can decay in a variety of ways, and many of these appear to be analyzable. The branching ratios for $\widetilde{\chi}^0_2$ decay are listed in table 4 at right. The decays involving neutrinos and sneutrinos are invisible and cannot be used. However, the other decays all produce visible particles and thus it could be possible to measure the mass of the $\widetilde{\chi}^0_2$ from them.

decay mode	fraction
$\widetilde{\overline{\nu}}_\ell \; \nu_\ell$	32.7%
$\widetilde{\nu}_\ell \; \overline{\nu_\ell}$	33.0%
$\widetilde{\ell}^\pm_L \; l^\mp$	31.8%
$\widetilde{\chi}^0_1 \; h^0$	2.1%

Table 4: Branching ratios for the $\widetilde{\chi}^0_2$.

Table 5: Cross sections (in fb) for Point 2

	350 GeV		500 GeV		750 GeV	
	80% L	80% R	80% L	80% R	80% L	80% R
$\widetilde{\chi}^0_1\widetilde{\chi}^0_1$	84	294	107	360	76	246
$\widetilde{\chi}^0_2\widetilde{\chi}^0_2$					74	18
$\widetilde{\chi}^0_1\widetilde{\chi}^0_2$			56	14	75	20
$\widetilde{\chi}^+_1\widetilde{\chi}^-_1$					187	47
$\widetilde{\chi}^+_2\widetilde{\chi}^-_2$						
h^0Z^0	170	140	69	58	27	22
$\widetilde{\nu}_e\widetilde{\nu}_e$			114	31	621	163
$\widetilde{\nu}_\ell\widetilde{\nu}_\ell$			7	6	25	20
$\widetilde{e}^+_L\widetilde{e}^-_L$			7	2	116	35
$\widetilde{e}^\pm_R\widetilde{e}^\pm_L$			145	145	95	94
$\widetilde{e}^+_R\widetilde{e}^-_R$	20	58	85	280	91	329
$\widetilde{\mu}^+_L\widetilde{\mu}^-_L$			5	2	35	16
$\widetilde{\mu}^+_R\widetilde{\mu}^-_R$	12	26	31	69	22	47
$\widetilde{\tau}^+_L\widetilde{\tau}^-_L$			5	2	35	16
$\widetilde{\tau}^+_R\widetilde{\tau}^-_R$	12	26	31	68	22	47
total	297	543	662	1036	1501	1124

3.1.1 The electron/selectron decay mode

The first decay mode that I tried using was where the $\widetilde{\chi}_2^0$ decayed into a slepton and a lepton. At point 2, sleptons decay into a $\widetilde{\chi}_1^0$ and a lepton. This process is demonstrated by the Feynman diagram in figure 1. There are only two visible outgoing particles in this decay, either a pair of electrons or a pair of muons (not taus since taus are not stable). Because of this I looked at events that had only two visible particles and that had either a pair of electrons or a pair of muons. There are other events that also meet this criterion, the important ones being $e^+e^- \rightarrow \widetilde{e}^+\widetilde{e}^-$, and $e^+e^- \rightarrow \widetilde{\mu}^+\widetilde{\mu}^-$. I will refer to these events as the background. There are several techniques that one can employ in order to try to cut away background events to clean up a signal. In the signal, both of the $\widetilde{\chi}_1^0$ and the $\widetilde{\chi}_2^0$ are produced back to back, and traveling away from one another, and both of the observed leptons come from the $\widetilde{\chi}_2^0$. Conversely, for the background events the two sleptons

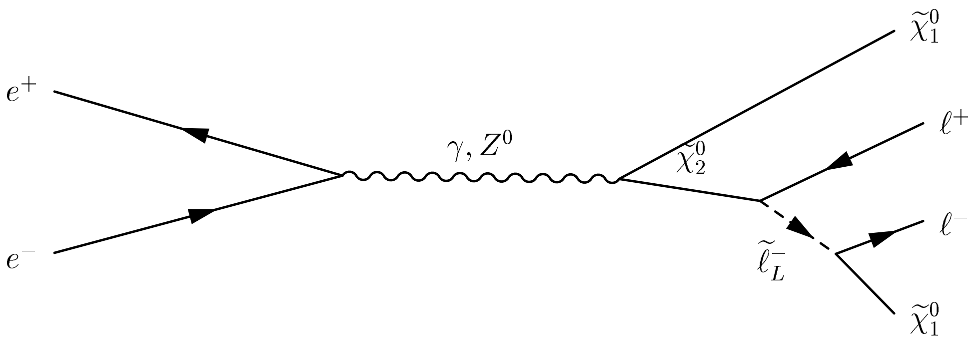

Figure 1: Feynman diagram showing decay mode of signal.

are produced traveling back to back, and one lepton comes from each slepton. This makes it likely that on average the angle, θ, between the two leptons in the signal will be smaller then the angle between the two leptons in the background. To test this idea I wrote a fortran program which calculated the cosine of the angle between the two visible leptons in an event, and then analyzed both the signal and the background using this program. The initial expectation was that the signal would show a peak near one where the angle is small, and that the background would show a peak around negative one where the angle is large. The plot of the cosine of the angle between the leptons is shown in figure 2. This idea did not work. While the plot of the background peaked at -1 the plot of the signal was essentially uniform in $\cos\theta$. A look at the masses of the particles involved in the decay explains why. The $\widetilde{\chi}_2^0$ decays into an lepton and a slepton, but the difference in the mass of the $\widetilde{\chi}_2^0$ and the slepton is only 19 GeV. Thus much of the energy of the $\widetilde{\chi}_2^0$ goes into the mass of the slepton, leaving the slepton essentially standing still in the rest frame of the $\widetilde{\chi}_2^0$, and so the lepton can move in any direction with equal probability. Then the slepton decays into a $\widetilde{\chi}_1^0$ and a lepton. Here the $\widetilde{\chi}_1^0$ is much more massive than the lepton, and so it carries most of the momentum, leaving the lepton free to move in any direction. This accounts for the apparent uniformity of the $\cos\theta$ distribution. There is *some* correlation, but it is very minimal, and does not make $\cos\theta$ a good quantity to cut on.

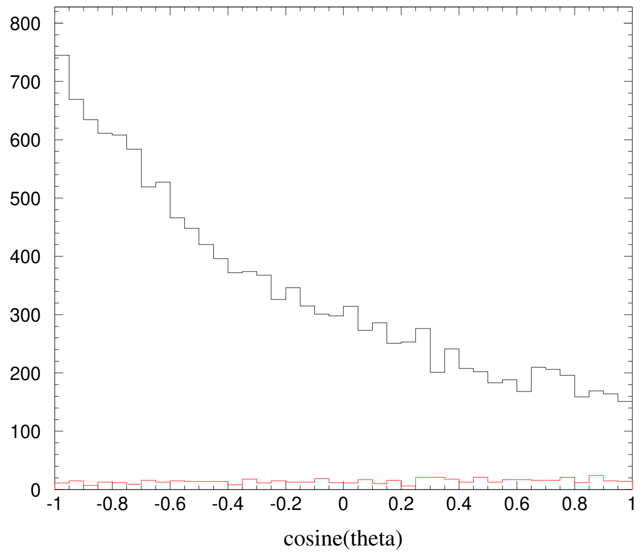

Figure 2: Graph of $\cos\theta$ for the angle between the two outgoing leptons in the decay. The black line is for the background, and shows a preference for the particles to move back to back. The signal is in red and appears to be distributed evenly.

There are other quantities that at first appeared to hold some promise for making good cuts using this decay mode. Among the things that I looked at were transverse momentum, angle from the beam axis, energy differences between the outgoing leptons, and many combinations of these, all fruitless. In short, because of the similarity in the masses of the parent particles, most of the properties of the final leptons were nearly identical between the signal events and the background events. The background events also had an extreme numerical advantage. The effective cross section for producing two final state lepton events from selectron pairs (the background) is 241 fb, versus an effective cross section of only 11.2 fb for the $\widetilde{\chi}_1^0\widetilde{\chi}_2^0$(signal) events. This, of course, was *only* considering supersymmetric events. The number of lepton pairs produced by Standard Model events would have further drowned out the relatively small supersymmetric signal.

3.1.2 The Higgs/neutralino decay mode

The $\widetilde{\chi}_2^0$ undergoes another decay, albeit rarely, that initially held some promise for making measurements. This decay is $\widetilde{\chi}_2^0 \rightarrow h^0\widetilde{\chi}_1^0$. Here the Higgs decays into $b\bar{b}$ or $c\bar{c}$ quark-antiquark pairs, which in turn hadronize into jets with measurable momentum and energy. If one could reconstruct the mass of the jets from the Higgs, then measurements could be made of the $\widetilde{\chi}_2^0$ mass and the $\widetilde{\chi}_1^0$ mass. There is a serious difficulty in doing this, namely that the h^0 and the Z^0 have nearly identical masses ($M_{h^0} = 90$ GeV, $M_{Z^0} = 91$ GeV). There are also copious amounts of Z^0's produced at this point, along with background Higgs particles. The cross section for the $e^+e^- \rightarrow h^0Z^0$ background is 69 fb but the effective cross section for the $\widetilde{\chi}_2^0 \rightarrow h^0\widetilde{\chi}_1^0$ signal is only 1.12 fb. This results in a background which is extremely difficult to separate from the signal events.

3.2 Neutralino Production at 750 GeV

Another method that can be used to make measurements is to change the beam energy. Production cross sections are a function of energy and so at higher (or lower) energies the types of particles that are produced and their relative abundance changes. The dependence of cross section on energy is shown in figure 3. This graph shows that at around 540 GeV there is enough energy available to begin producing $e^+e^- \rightarrow \widetilde{\chi}_2^0\widetilde{\chi}_2^0$ events, and at 750 GeV this cross section has nearly reached its maximum value. I decided to move to this energy to try to measure the $\widetilde{\chi}_2^0$ mass. The specific decays that I looked at were where both $\widetilde{\chi}_2^0$s decayed into sleptons, and then eventually in leptons. There are two distinct ways that this signal is produced, and both of them have the same energy distribution, and so they can be used together to calculate the mass of the $\widetilde{\chi}_2^0$. If both $\widetilde{\chi}_2^0$ particles decay into selectrons or smuons then there will be two sets of electron or muon pairs in the final state. If one $\widetilde{\chi}_2^0$ decays into a selectron and the other one decays into a smuon then there will be one electron pair and one muon pair. The Feynman diagrams representing these decay modes are shown in figures 4 and 5. Both of these decays are very favorable because they produce large amounts of four lepton events, which are very rare. There is very little background to interfere with this signal.

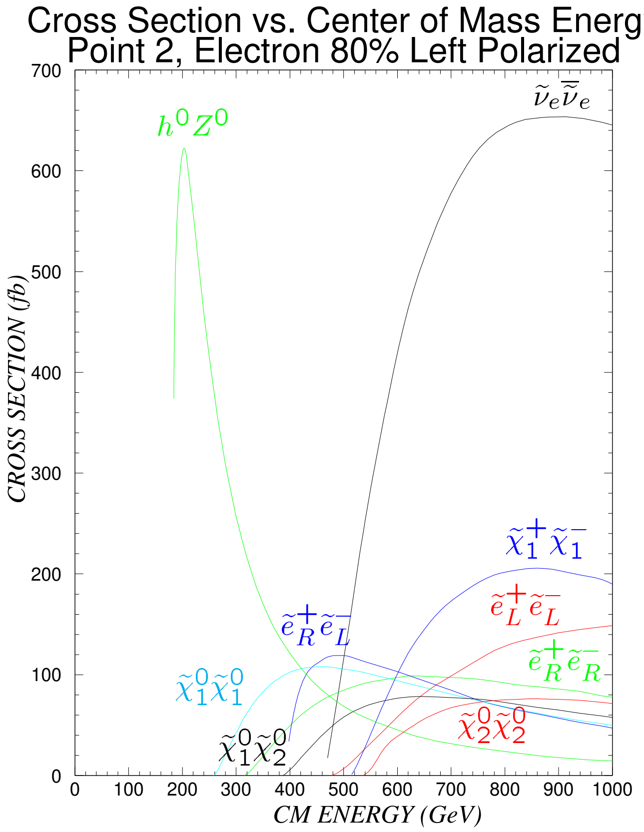

Figure 3: Cross section vs. energy

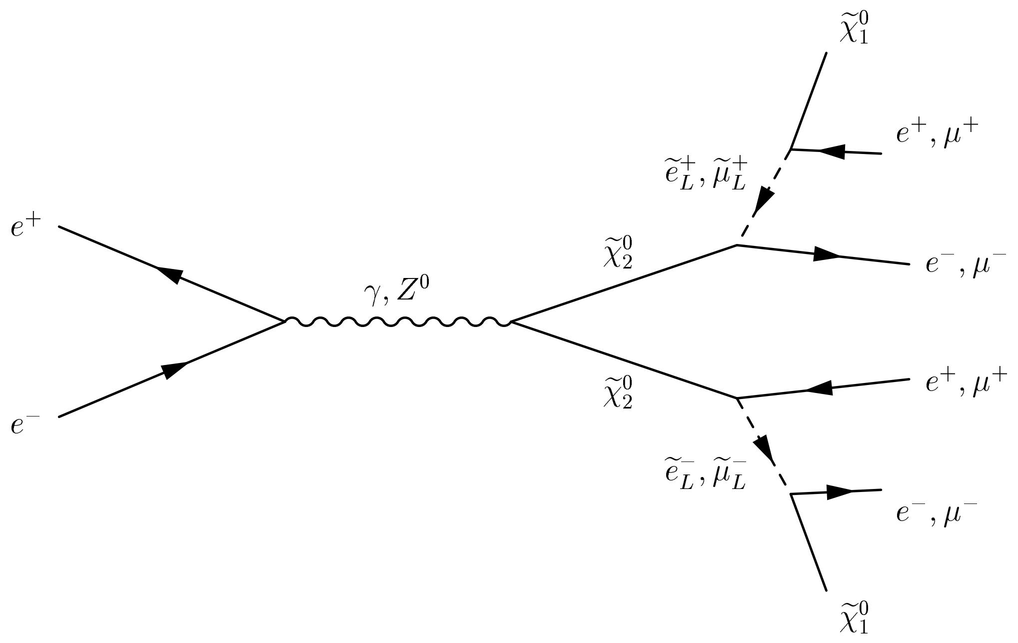

Figure 4: First signal (identical lepton pairs)

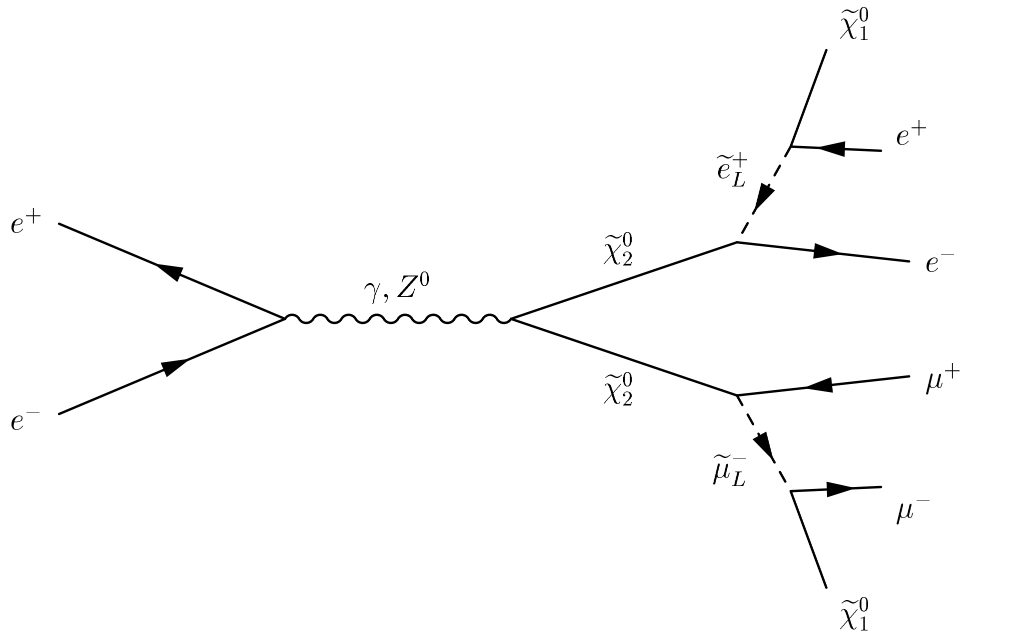

Figure 5: Second signal (mixed lepton pairs)

3.2.1 Supersymmetric Background

The only supersymmetric background event which is able to produce four final state leptons comes from the events where one or both of the $\widetilde{\chi}_2^0$s decays into a $\widetilde{\tau}_L^{\pm}$. These events are not usable because the taus decay into electrons and muons and their respective neutrinos, and the neutrino energy exits the detector undetected. This lost energy from the neutrinos throws off the end-points of the lepton energy distribution, on which the $\widetilde{\chi}_2^0$ mass measurement depends (see section 3.3 for details of the endpoint method). Fortunately these events are not very prolific, and so the background that is present is not abundant enough to be bothersome.

3.2.2 Standard Model Background

There is a more significant contribution to the background from Standard Model events of the type $e^+e^- \rightarrow Z^0Z^0$ where the Z bosons then decay into e^+e^- pairs or $\mu^+\mu^-$ pairs. The Feynman diagram for this decay is shown below in figure 6.

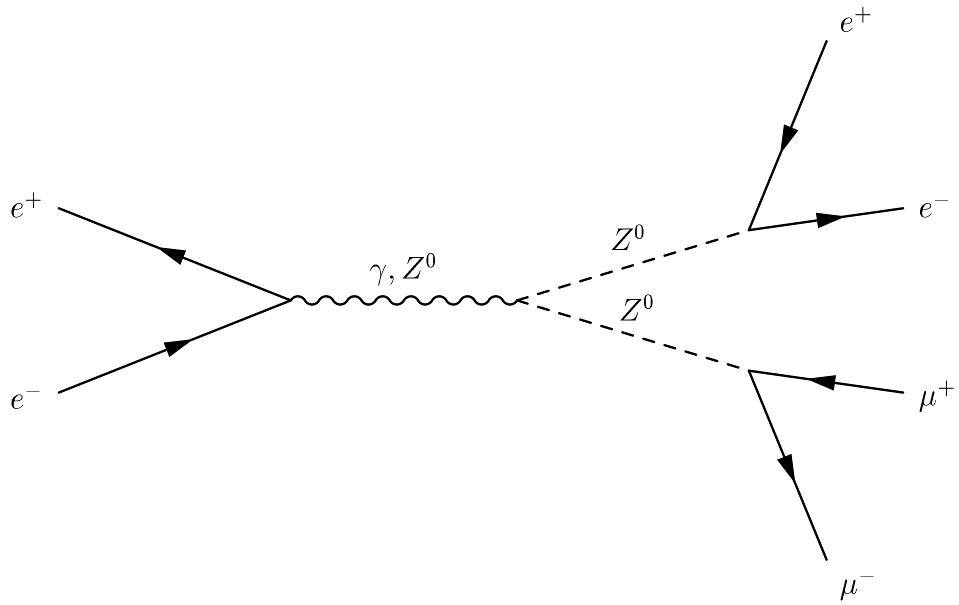

Figure 6: Standard Model Background: The lepton pairs can be mixed (as shown) or identical.

In this background all of the energy of the event is visible, and so there should be no missing energy. This allows the background to be removed by cutting out all the events with visible energy greater then 675 GeV (E_{cm} - 10%E_{cm} to allow for detector resolution). This left only low energy tau events which did not prove to be a problem because there were not enough of them to obscure the data. After making these cuts most of the Standard Model background was removed, and the plots were able to be fit. Figure 7 shows the energy of the final state leptons after all cuts to remove background.

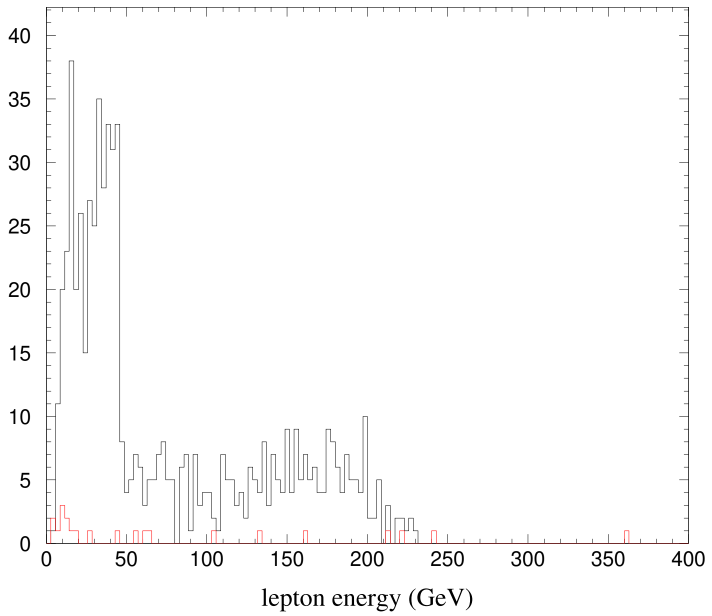

Figure 7: Graph of the energy of the two final state lepton pairs. The tall narrow box is the distribution from the $\widetilde{\chi}_2^0$, the long low distribution is from the $\widetilde{\ell}_L^{\pm}$. The data in red is irreducible background.

3.3 Mass Measurement

Since the signal is clear and not distorted by background, it can be used to find the masses of some of the supersymmetric particles. This is done by looking at the energy distribution of the final state electrons and muons from an event. In a two-body decay (a decay of the form A $\rightarrow$ B + C) if the center of mass energy is known, the mass of C is known, and the energy distribution of C can be measured, then it is possible to measure the masses of A and B[7]. The masses of A and B are given by:

$$M_A^2 = \frac{(M_C^2 + E_{min}E_{max}) \pm \sqrt{(M_C^2 - E_{min}^2)(M_C^2 - E_{max}^2)}}{2(E_{min} + E_{max})^2} s \tag{1}$$

$$M_B^2 = M_A^2 + M_C^2 - 2M_A^2 \frac{(E_{min} + E_{max})}{\sqrt{s}} \tag{2}$$

where $\sqrt{s}$ is the center of mass energy, and E_{min} and E_{max} are the endpoints of the energy distribution of particle C.

Because there are two sets of leptons in the signal, those coming from the decay of the $\widetilde{\chi}_2^0$ and those coming from the decay of the $\widetilde{\ell}_L^{\pm}$, there will be a separate energy distribution for each set. The energy distribution of the leptons from the $\widetilde{\chi}_2^0$ can be used to measure the mass of the $\widetilde{\chi}_2^0$ and the mass of the $\widetilde{\ell}_L^{\pm}$. The energy distribution of the leptons from the $\widetilde{\ell}_L^{\pm}$ can be used to measure the mass of the $\widetilde{\ell}_L^{\pm}$ and the $\widetilde{\chi}_1^0$. The graphs of these energy distributions are shown in figure 7. Note that because the $\widetilde{\ell}_L^{\pm}$ is not one of the original two particles created in the decay, in order to use the distributions of the leptons from its decay we will have to define an average energy for the $\widetilde{\ell}_L^{\pm}$ in the center of mass frame. The energy of the slepton ($E_{\widetilde{\ell}_L^{\pm}}$) must be less then the energy of the $\widetilde{\chi}_2^0$ ($E_{\widetilde{\chi}_2^0}$) by an amount equal to the energy carried off by the leptons from the $\widetilde{\chi}_2^0$ decay. The maximum energy that these leptons can take away is $E_{max,\widetilde{\chi}_2^0}$ and the minimum energy they can carry away $E_{min,\widetilde{\chi}_2^0}$, where $E_{max,\widetilde{\chi}_2^0}$ and $E_{min,\widetilde{\chi}_2^0}$ are the maximum and minimum endpoints of the of the energy distribution from the $\widetilde{\chi}_2^0$ decay. Therefore the average energy carried away by the lepton is simply

$$E_{away} = \frac{E_{max,\widetilde{\chi}_2^0} + E_{min,\widetilde{\chi}_2^0}}{2}.$$

And thus we know that the average energy for the $\widetilde{\ell}_L^{\pm}$ in the center of mass frame is given by:

$$E_{\widetilde{\ell}_L^{\pm}} = E_{\widetilde{\chi}_2^0} - \frac{E_{min,\widetilde{\chi}_2^0} + E_{max,\widetilde{\chi}_2^0}}{2}.$$

We can use this value as the average energy of the slepton in the center of mass frame in equations (1) and (2) to get the masses of the $\widetilde{\chi}_1^0$ and the $\widetilde{\ell}_L^{\pm}$.

A curve can be fit to the graph of the energy distributions in order to determine their endpoints. To do this I wrote a six parameter fitting program which uses another program called fitbox to fit the data. Fitbox takes a flat box distribution and convolutes it with a Gaussian distribution, and varies the parameters, the endpoints and the height of the box, until it gets a good fit. The program that I wrote essentially calls fitbox twice in order to fit both distributions simultaneously. The fitting program returns the values of the endpoints for both distributions and I use these to calculate the masses of the neutralinos and the sleptons. The results of the fit are shown in figure 8.

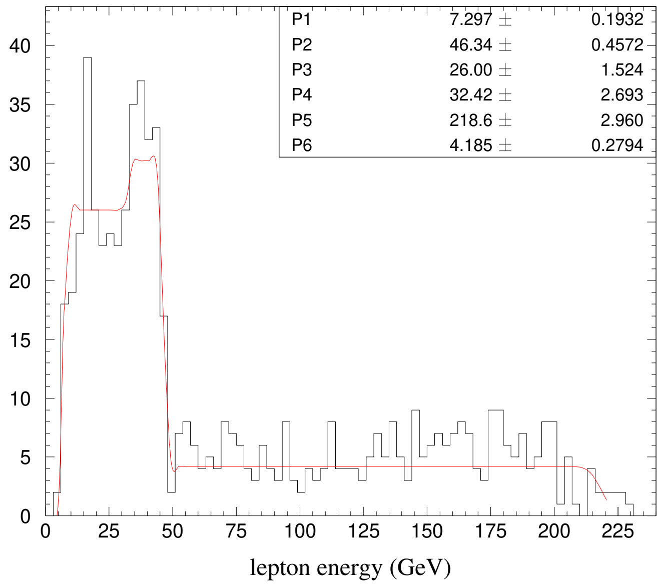

Figure 8: The red line is the computer generated fit to the data. The endpoints are displayed in the upper right corner. The endpoints for the first distribution are 7.3 GeV and 46.3 GeV. For the second distribution the endpoints are 32.4 GeV and 218.6 GeV. The (χ^2/dof) for the fit was 1.12.

Using the endpoints given by the fitting program and the average center of mass energy of the $\widetilde{\ell}_L^{\pm}$ we can calculate the masses of the $\widetilde{\chi}_1^0$, the $\widetilde{\chi}_2^0$, and the $\widetilde{\ell}_L^{\pm}$ using equations (1) and (2). The results of these calculations are shown in the next section.

4 Results and Conclusions

4.1 masses

The masses were calculated using the measured endpoints and compared with their predicted values (the values calculated from the input parameters of the model. The results are shown in table 6.

Table 6: Results of the mass calculations

	Measure Mass	Predicted Mass	% Discrepancy
$\widetilde{\chi}_2^0$	256 GeV	257.22 GeV	.47%
$\widetilde{\ell}_L^\pm$	237 GeV	238.21 GeV	.51%
$\widetilde{\chi}_1^0$	124 GeV	128.70 GeV	3.6%

The masses agreed well with their predicted values. The masses of the $\widetilde{\chi}_2^0$ and the $\widetilde{\ell}_L^\pm$ were closer to the predicted values then was the mass of the $\widetilde{\chi}_1^0$. This is because the fit was better for the first distribution than it was for the second distribution. Overall the technique gave good values for the masses, showing that this type of analysis is quite feasible.

4.2 conclusion

I simulated data that could have been detected in one year of operation at the NLC. The production mode that I originally set out to measure turned out not to be feasible. However, the same information was able to be measured anyway because I was able to simulate a data run at a higher energy where the cross sections were different. This points out one of the very nice features of the NLC, namely a tunable beam energy. The results that I got were encouraging. The data came out clean, and the fit gave result with a high degree of accuracy. All of the techniques used in this paper would be usable at a real collider, indicating that if supersymmetry really is out there, it should be seen at the NLC.

References

[1] M. G. Bowler. *Femtophysics, A Short Course in Particle Physics.* Pergamon Press, Oxford, U.K., 1991.

[2] Nick Danielson. *Determining the Mass of the Sneutrino and the Chargino By Examining the Sneutrino Sneutrino Production Mode.* COLO HEP 404, 1998.

[3] Elizabeth Goodman. *The Search for the Supersymmetric Selectron.* COLO HEP 398, 1997.

[4] Gordon Kane. *Modern Elementary Particle Physics.* Addison-Wesley Publishing Company, Redwood City, CA, 1987.

[5] William B. Rolnick. *The Fundamental Particles and Their Interactions.* Addison-Wesley Publishing Company, Reading, MA, 1994.

[6] David Wagner. *NLC SUSY Generation and Analysis, ver. 1.1.* 1998.

[7] Brook Williams. *Study of the Production of SuperSymmetric Particles.* COLO HEP 402, 1998.