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Measuring Mass and Cross Section Parameters at a Focus Point Region

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The purpose of this study is to determine the experimental uncertainties in measuring mass and cross section parameters of SUSY particles at a 500 GeV Linear Collider. In this study SUSY is a point in the focus point region of mSUGRA parameter space that is compatible with WMAP constraints on dark matter relic density. At this study point the masses of the squarks and sleptons are very heavy, and the only SUSY particles accessible at the Linear Collider would be the three lightest neutralinos, and the two lightest charginos: $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, $\tilde{\chi}_1^+$, $\tilde{\chi}_2^+$, where $\tilde{\chi}_1^0$ is the lightest supersymmetric particle (LSP). The charginos or neutralinos may be pair produced, and the subsequent decay cascades to the LSP allow us to measure the SUSY couplings and mass spectrum. We find that by looking for the signature 2 jets plus 2 leptons plus missing energy we can determine the mass of the LSP to within 1 GeV uncertainty and that the mass differences of $\tilde{\chi}_2^0$ and $\tilde{\chi}_3^0$ with the LSP mass can be determined to better than 0.5 GeV.

1. INTRODUCTION

This study represents work in an effort to establish a connection between measurements at a future linear collider and cosmological data. We assume that the LHC has run and discovered SUSY and that a 500 GeV linear collider has run to make precision measurements. The ultimate goal of this study is to determine whether or not the Linear Collider would be able to make precise enough measurements of mass and cross sections of SUSY particles in order to determine if the relic density of the LSP would be consistent with WMAP constraints [1], and that the SUSY LSP actually is the dark matter.

We have chosen the scenario where the discovered SUSY is mSUGRA in a focus point region [2] with $M_{1/2} = 300$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$, $m_t = 175$ GeV, $m_o = 3280$ GeV. In this focus point region the masses of the squarks and sleptons are very heavy, and the only SUSY particles accessible at the Linear Collider would be the three lightest neutralinos, and the two lightest charginos: $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, $\tilde{\chi}_1^+$, $\tilde{\chi}_2^+$, where neutralino $\tilde{\chi}_1^0$ is the LSP. The signed mass parameters and the production cross sections of the charginos and neutralinos at this focus point region are given in tables I, and II. Note that the mass parameters are signed. The sign of the mass parameter will affect the decay distributions but not the kinematics.

This paper represents preliminary results on the expected experimental uncertainties in determining the mass parameters and production cross sections of SUSY particles at the linear collider. Specifically, we will discuss the 2 jet plus 2 lepton plus missing energy signature of $\tilde{\chi}_2^0\tilde{\chi}_3^0$ production.

*This talk was given by R. Gray, describing ongoing work performed in collaboration with the other authors.

Table I: Neutralino and Chargino Mass Parameters

Particle	**Mass (GeV)**
$\tilde{\chi}_1^0$	-107.7
$\tilde{\chi}_2^0$	-166.3
$\tilde{\chi}_3^0$	+190.0
$\tilde{\chi}_1^+$	-159.4
$\tilde{\chi}_2^+$	-286.6

Table II: Production Cross Sections of SUSY particle pairs in collisions of 95% left or right polarized electrons on unpolarized positrons.

pair	σ_L(fb)	σ_R(fb)
$\tilde{\chi}_1^+\tilde{\chi}_1^-$	940	119
$\tilde{\chi}_1^+\tilde{\chi}_2^-$	48.9	40.3
$\tilde{\chi}_1^0\tilde{\chi}_3^0$	56.8	44.1
$\tilde{\chi}_2^0\tilde{\chi}_3^0$	92.4	70.9

2. SIMULATION AND ANALYSIS CUTS

2.1. SUSY Signature

We will analyze the production of $\tilde{\chi}_2^0\tilde{\chi}_3^0$. Since the squarks and sleptons are so heavy at this point in the parameter space, the dominant means for the $\tilde{\chi}_2^0$ and $\tilde{\chi}_3^0$ to decay is a transition to $\tilde{\chi}_1^0$ (the LSP) by radiating a Z. Since the mass differences between $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$ and $\tilde{\chi}_1^0$ are all smaller than the Z mass, the Z is virtual. In a detector, the two LSPs produced in the decay of the $\tilde{\chi}_2^0\tilde{\chi}_3^0$ pair will be seen only as missing energy. The two Zs produced in the decay will each create one of the following: $l\bar{l}$, $\nu\bar{\nu}$, $q\bar{q}$. A $l\bar{l}$ pair will be visible as tracks, a $\nu\bar{\nu}$ will contribute to the missing energy, and a $q\bar{q}$ will create at least 2 jets. Therefore, we will be looking for one of the following detector signatures for $\tilde{\chi}_2^0\tilde{\chi}_3^0$ production: $2\text{Jet} + E_{\text{miss}}$, $2\text{Lepton} + E_{\text{miss}}$, $4\text{Jet} + E_{\text{miss}}$, $4\text{Lepton} + E_{\text{miss}}$, or $2\text{Lepton} + 2\text{Jet} + E_{\text{miss}}$. For $\tilde{\chi}_2^0\tilde{\chi}_3^0$ production we will use the mode $2\text{Lepton} + 2\text{Jet} + E_{\text{miss}}$ because it has the smallest backgrounds from the other SUSY and Standard Model processes.

2.2. Event Generation

SUSY events were generated at Cornell using Isajet 7.69 [3]. This included production via e^+e^- collisions of the following neutralino and chargino pairs: $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\tilde{\chi}_2^-$, $\tilde{\chi}_1^0\tilde{\chi}_3^0$, $\tilde{\chi}_2^0\tilde{\chi}_3^0$. The Standard Model backgrounds for this analysis were generated at SLAC using WHiZaRD 1.22 [4]. The background include contributions from the following collisions: e^+e^-, $e^-\gamma$, $e^+\gamma$, $\gamma\gamma$. The dominant backgrounds for this analysis generated by these collisions are $t\bar{t}$, W^+W^- and $Z\bar{Z}$. The beam in these event generators is a $\pm$95% polarized electron beam on an unpolarized positron beam. The generators include effects from initial state radiation (Beamstrahlung and Bremsstrahlung) which can reduce the energy available for SUSY production.

2.3. Detector Simulation and Reconstruction

The detector simulation was done using LCD Root FastMC, SD Mar01, which is a root based fast Monte Carlo program produced at SLAC. Once we have tracks and showers the first task is to identify leptons that are isolated from jets and are candidates for having come directly from a neutralino or chargino decay. It is assumed that at the linear collider identification of electrons and muons will be near perfect and so lepton ID uses the Monte Carlo

truth information. These leptons are candidates for direct production from a SUSY decay if the lepton momentum is greater than 10 GeV and the total energy from other particles within 20 degrees of the lepton is less than 2 GeV. After these isolated candidate leptons are identified, perfect track-shower matching is employed to approximate the "energy flow" algorithms that would be used at a real detector and the remaining 4-vectors are divided into jets using the Durham algorithm with a y_{cut} value of 0.004.
We will use b-tagging in this analysis to help identify $t\bar{t}$ backgrounds. Since the detector simulation used in this study is not advanced enough for an honest b-tag, Monte Carlo truth information was used. The jets found by the Durham algorithm were matched to the generator level jets by an energy weighted comparison of the lists of stable particles in the "found jet" and the list of particles in the generator level jet. A match quality is defined by equation 1 where E_i is the energy of particles in list i, E_{iaj} is the energy of particles that are listed in both list i and list j, and E_{inj} is the energy of particles listed in list i but not in list j. If the match quality is 1, the two lists are the same, if the match quality is -1 they have nothing in common. The generator level jet with the highest match quality for a "found jet" is tagged to that found jet. If the "found jet" is matched to a jet that came from a b quark, then we say it has a 50% chance of being b-tagged.

$$Q_{ij} = \frac{2E_{iaj} - E_{inj} - E_{jni}}{E_i + E_j} \tag{1}$$

2.4. Analysis Cuts for $\tilde{\chi}_2^0\tilde{\chi}_3^0 \to l\bar{l}q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0$

The analysis cuts for the 2 jet plus 2 lepton plus missing energy signal are as follows. There must be two leptons of opposite charge and same flavor that both passed our isolation cuts. There must be 2 or 3 jets found in addition to the isolated leptons. The missing energy must be greater than 275GeV. The transverse momentum must be greater than 10GeV. The cosine of each track and jet with the beam axis must be less than 0.95. The energy of each jet and letpon must be less than 110GeV. Each jet is then anti-btagged, or the event is cut if either jet appears to have come from a b quark. This anti-btag cut removes backgrounds from $t\bar{t}$.

3. MASS PARAMETER AND CROSS SECTION MEASUREMENT

3.1. Cross Section Measurement

The cross section will simply be measured by counting the number of events that pass our cuts with backgrounds subtracted, divided by the efficiency for passing those cuts, and divided by the luminosity. With 500 fb^{-1} of luminosity divided evenly between left and right polarized beams we find statistical uncertainties on polarized cross sections of 4% and 5% respectively.

3.2. Mass Parameters from Invariant Mass Distribution

The mass difference between $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$, and the mass difference between $\tilde{\chi}_3^0$ and $\tilde{\chi}_1^0$, may be determined by fitting the invariant mass distribution of the two leptons in the 2 letpon plus 2 or 3 jet data. For any decay $X_i \to l\bar{l}X_f$ the invariant mass of the two leptons will have a maximum possible value of the mass difference between X_i and X_f. Since $\tilde{\chi}_2^0$ and $\tilde{\chi}_3^0$ have different masses we will see two edges in the mass distribution. One edge will be for the $\tilde{\chi}_2^0$ and the other for the $\tilde{\chi}_3^0$. In order to use the whole distribution, rather than just the edges, in our mass determination, we will fit all the data to the expected invariant mass distribution. This expected mass distribution will have very weak dependence on the LSP ($\tilde{\chi}_1^0$) mass, but will depend on the relative sign of the $\tilde{\chi}_2^0$ and $\tilde{\chi}_3^0$ mass parameters with the $\tilde{\chi}_1^0$ mass parameter. You can see from table I that $\tilde{\chi}_2^0$ and $\tilde{\chi}_3^0$ mass parameters have different relative signs. We find that the efficiency for measuring the di-lepton is mostly flat in invariant mass beyond 10 GeV, so we will make no efficiency corrections to the distribution prior to performing the fit.

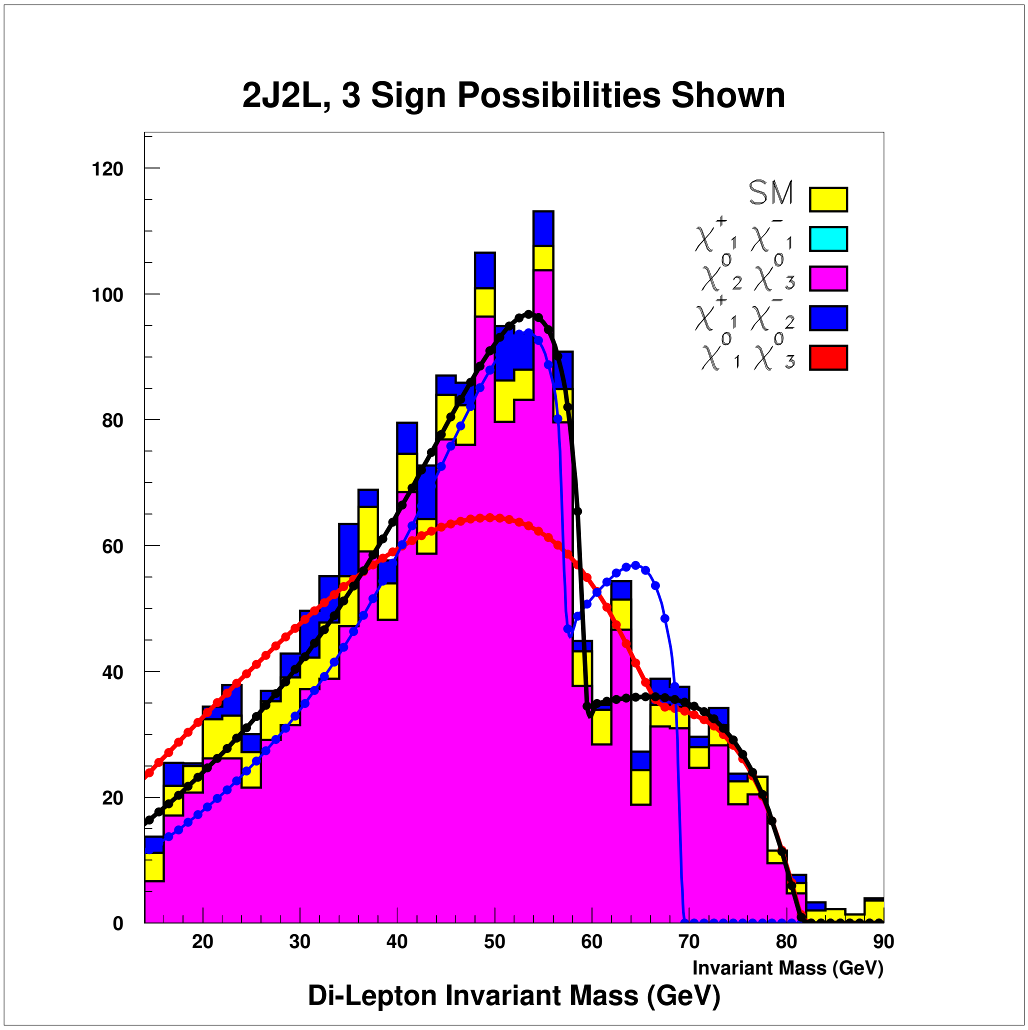

Figure 1: This shows the invariant mass distribution of combined 250fb^{-1} left polarized and 250 fb^{-1} right polarized data. The magenta is the signal. The yellow is standard model backgrounds, and the blue is background from chargino production. The three fits are for the different sign assumptions for the neutralino mass parameters. The red line is for (-,-), the blue line is for (+,+), and the black line is for (+,-). The correct sign assumption is (+,-).

The resulting invariant mass distribution can be seen in figure 1. We expect two edges in the distribution. We expect one at 58.6 GeV for $\tilde{\chi}_2^0$, and one at 82.3 GeV for the $\tilde{\chi}_3^0$. Both edges are visible.

The mass distribution of the background is fit to an order 2 polynomial. The fit to the background distribution is combined with the theoretical prediction for the SUSY component and an unbinned log likelihood fit is performed. The fit is done three times for the three possible combinations of relative signs of $\tilde{\chi}_2^0\tilde{\chi}_3^0$ to the $\tilde{\chi}_1^0$: (-,-), (+,+), (+,-). We find that the possible sign combinations are easily distinguished in the data, and that the best fit for the correct sign combination, (+,-), is at least 13 standard deviations away from the best fit of the incorrect sign combinations. The fits for the different sign combinations are shown in figure 1.

The log likelihood fit for the mass differences yields $M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0} = 58.8GeV \pm 0.3$ and $M_{\tilde{\chi}_3^0} - M_{\tilde{\chi}_1^0} = 82.25GeV \pm 0.2$. The generator level values for these masses are 58.6 GeV, and 82.3 GeV.

It should be noted that theoretically we could do the same study with the invariant mass of the hadronic Z decay. However, reconstruction of di-lepton mass distribution will have much less uncertainty than reconstruction of the di-jet mass distribution. Also the efficiency and sculpting of the di-jet distribution is much more complicated than for the di-lepton due to the jet algorithms.

3.3. LSP Mass From Energy Distribution

The invariant mass distribution of the two leptons had very weak dependence on the LSP mass. However, the distribution of the energy of the two leptons will depend on the LSP mass. It will also depend on the $\tilde{\chi}_2^0$ and $\tilde{\chi}_3^0$ masses, the theoretical invariant mass distribution of the two leptons, the beam energy, the spectrum of initial state radiation, and the spin correlations in the neutralino decays.
The energy distribution is numerically calculated by integrating over all of the above mentioned distributions. It should be noted that the version of Isajet used in this analysis does not calculate the spin correlations of the neutralino decays [5]. The spin correlations of the neutralino decays affect the angular distribution of the virtual Z in the rest frame of the parent neutralino along the boost direction. This angular distribution is flat in the Monte Carlo because of the lack of neutralino spin correlations. This translates to a flat energy distribution in the lab frame for a given value of di-lepton invaraint mass and beam energy.
The data and the calculated energy distribution are shown in figure 2. The standard model background distribution is fit to an order 3 polynomial and is combined with the calculated signal distribution for a log likelihood fit to the data. In the fit the $\tilde{\chi}_1^0$ (LSP) mass is allowed to vary, and the mass differences of the $\tilde{\chi}_2^0$ and the $\tilde{\chi}_3^0$ with the LSP mass are allowed to vary within 3 standard deviations of the measured mass differences obtained from the invariant mass distribution fit. The fit finds an LSP mass of 108.3 GeV $\pm$ 1.0 GeV. The generator level value of the LSP mass is 107.7 GeV.

4. Conclusions and Future Directions

We have presented preliminary results for the expected uncertainties that a 500 GeV linear collider would have in measuring mass and cross sections from $\tilde{\chi}_2^0\tilde{\chi}_3^0$ production in a focus point region using the 2 lepton plus 2 or 3 jet plus missing energy detector signature. We have found that for 250 fb^{-1} of left polarized data and 250 fb^{-1} of right polarized data we could determine the cross sections to within a uncertainty of 4% and 5% respectively. By using the invariant mass distribution of the two leptons of the combined 500 fb^{-1} data set we could measure the mass differences $M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0}$ and $M_{\tilde{\chi}_3^0} - M_{\tilde{\chi}_1^0}$ with 0.3 GeV and 0.2 GeV uncertainty respectively. By using the energy distribution of the two leptons we can measure the $\tilde{\chi}_1^0$ (LSP) mass with an uncertainty of 1.0 GeV.
Other work currently being done by the Cornell/Florida LC Cosmology Group is the study of $\tilde{\chi}_1^0\tilde{\chi}_2^0$ production, $\tilde{\chi}_1^+\tilde{\chi}_1^-$ production, and $\tilde{\chi}_1^+\tilde{\chi}_2^-$. There is also work being done to convert the uncertainties in mass and cross section measurements into uncertainties in the relic density. If the uncertainty in the relic density of the LSP is small enough, we can compare our prediction to WMAP constraints and determine whether or not the LSP actually is the Dark Matter.

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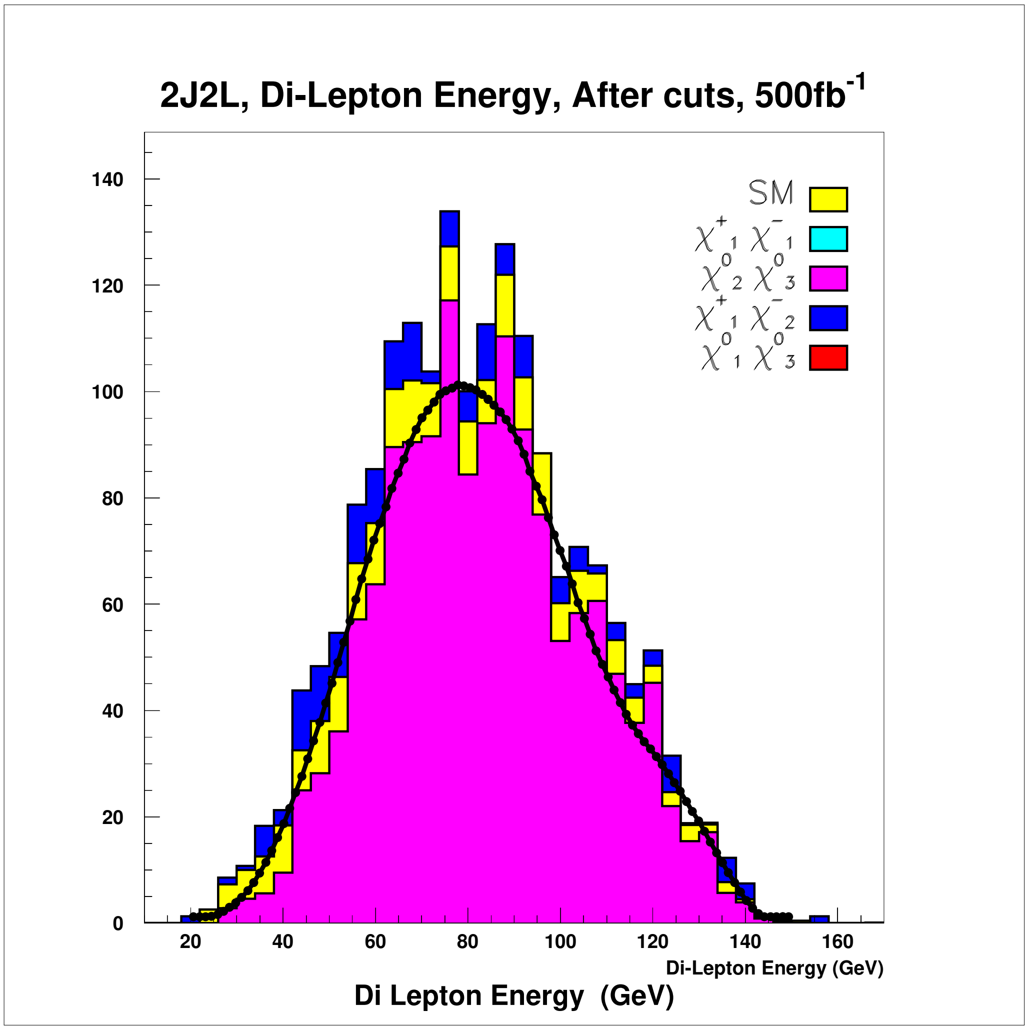

Figure 2: This shows the energy distribution of the two leptons in the 2 lepton 2 or 3 Jet and missing energy decay signature. The magenta color is the signal, the yellow is the contribution from standard model backgrounds and the blue is background from chargino production. The curve on the plot is the calculated energy distribution for the signal.