1 Neutralinos to Two Leptons

Focus-point SUSY neutralinos can be studied by looking for events with missing energy and only two leptons in the final state. Two neutralinos, one being the lowest-mass stable particle, χ_1^0, and the other a heavier neutral combination of winos, binos and Higgsinos, χ_3^0, are created in the e^+e^- annihilation. The χ_3^0 decays into a virtual Z^0 and a second χ_1^0, and both χ_1^0s disappear as missing energy. We consider here the case in which the Z^0 decays into two leptons (e^+e^- or $\mu^+\mu^-$).

In addition to Standard Model backgrounds, this mode has significant SUSY backgrounds, particularly from $\chi_1^+\chi_1^-$ and $\chi_3^0\chi_2^0$. We will see later that the Standard Model and chargino backgrounds can be suppressed by cancelling leptons with uncorrelated flavors, but the other nutralino mode remains. The problem is that this mode has the same $\chi_3^0 \to \ell^+\ell^-\chi_1^0$ transition, and the χ_2^0 can decay invisibly into a χ_1^0 by producing only a $Z^0 \to \nu\bar{\nu}$. This analysis can only measure a weighted sum of the $\chi_3^0\chi_1^0$ and $\chi_3^0\chi_2^0$ cross-sections.

Another measurement, one that is actually aided by the $\chi_3^0\chi_2^0$ contribution, is the difference in mass between χ_3^0 and χ_1^0. Both modes feature a $\chi_3^0 \to \chi_1^0$ transition; the energy from this transition is shared by the final-state χ_1^0 and the virtual Z^0. In the limit in which the χ_1^0 is produced at rest with respect to its parent χ_3^0, the Z^0, and therefore the final-state leptons, carry all the energy difference. Hence, the invariant mass spectrum of the two leptons will have an upper-limit threshold at $m_{\chi_3^0} - m_{\chi_1^0}$.

1.1 Standard Model Backgrounds, Event Selection, Polarization

We considered three potential Standard Model backgrounds: pairs of top quarks, Z bosons, and W bosons. Top quark backgrounds are insignificant to our mode because both sides decay to $W^\pm$ and a b-quark jet, which introduces too many final state charged particles. Z bosons are likewise irrelevant because even if one Z^0 decays to two tracks and the other decays invisibly, the missing energy for such an event is always half the beam energy. That peak can be avoided on a missing energy plot. The W-pairs, however, are a major background, since each $W^\pm$ can decay to a lepton and a neutrino. The lepton flavor, electron or muon, is uncorrelated for W-pairs, but should be the same in our signal. This fact will be exploited later.

Only two event selection criteria are used in this analysis: one is based on missing energy and the other on angular correlations of the two leptons. Missing energy is the center-of-mass energy (500 GeV) minus the energy of all tracks and all unmatched showers. (Since we have already restricted ourselves to two visible tracks and no jets, the missing energy will usually be 500 GeV minus the energy of those two tracks.) This missing energy is required to be greater than 350 GeV (shown graphically in the top plots of Figure 1).

The second requirement takes advantage of the fact that most of the W-pair production is via a t-channel diagram which correlates the trajectories of the W^+ and W^- with the incident e^+ and e^-, respectively. Taking θ^+ and θ^- to be the angles between each final-state lepton and the e^- beam, we want to avoid the corner of (θ^+, θ^-) in which $\cos\theta^+$ is near -1 and $\cos\theta^-$ is near 1. One way to do this is to require $\cos\theta^+ - \cos\theta^-$ to be greater than some threshold. We chose this threshold to be zero (bottom of Figure 1) because this reduces the W-pair background by a much-needed factor of ten and because it is a line of symmetry for

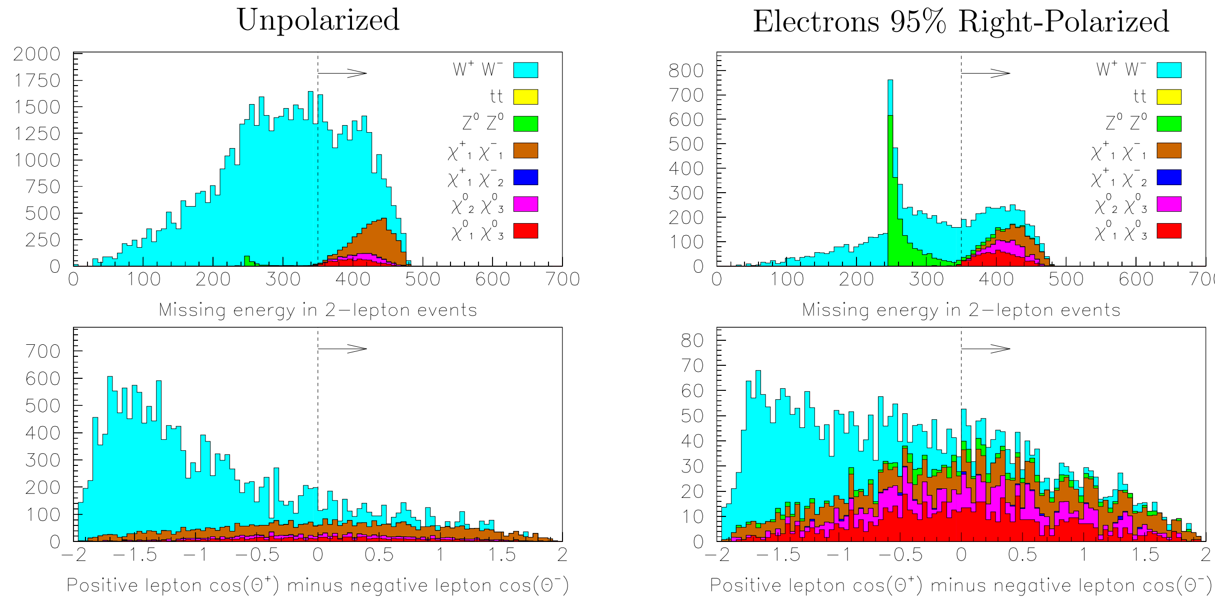

Figure 1: Top: Missing energy of all events with two leptons and no jets. Bottom: θ (or pseudorapidity) correlation of the two leptons for all events with more than 350 GeV missing energy. The vertical axes correspond to the expected numbers of events with 250 fb^{-1}.

our signal. The shape of the invariant mass distribution is unaffected by this cut.

Another option for reducing W-pair background is to polarize the incident beams. $W^{\pm}$ couple only to left-handed fermions, so if the electron beam is right-polarized, the t-channel W-pair production is turned off, which provides a substantial improvement in signal-to-background. In our simulations, the electron beam is taken to be 95% right-polarized and the positron beam to be unpolarized. Plots using polarized beams are displayed on the right-hand sides of Figures 1 and 2.

1.2 SUSY Background and Opposite-Flavor Cancellation

Even after the selection criteria described in the last section, W-pairs are still a significant background in the unpolarized sample. In addition, $\chi_1^+\chi_1^- \to$ two leptons contributes at an even larger scale, as shown in the top plots of Figure 2. Each $\chi_1^{\pm}$ can decay to a $W^{\pm}$, and $\chi_1^+\chi_1^-$ events typically have more missing energy than W^+W^-.

Fortunately, the two leptons from W-pairs and from $\chi_1^+\chi_1^-$ both come from independent $W^{\pm}$ decays, and therefore have uncorrelated flavors (electron or muon). In the signal modes, $\chi_3^0\chi_1^0$ and $\chi_3^0\chi_2^0$, the lepton pair comes from a single Z^0 decay, so it should be either e^+e^- or $\mu^+\mu^-$. If events with same-flavor leptons are added to a histogram (filled with weight 1) and events with opposite-flavor leptons are subtracted (filled with weight -1), both backgrounds will cancel in the average and the signal will add constructively. We used this technique to subtract the remaining backgrounds, yielding the difference in the bottom plots of Figure 2. We assumed an integrated luminosity of 250 fb^{-1} for each of the two samples, polarized and

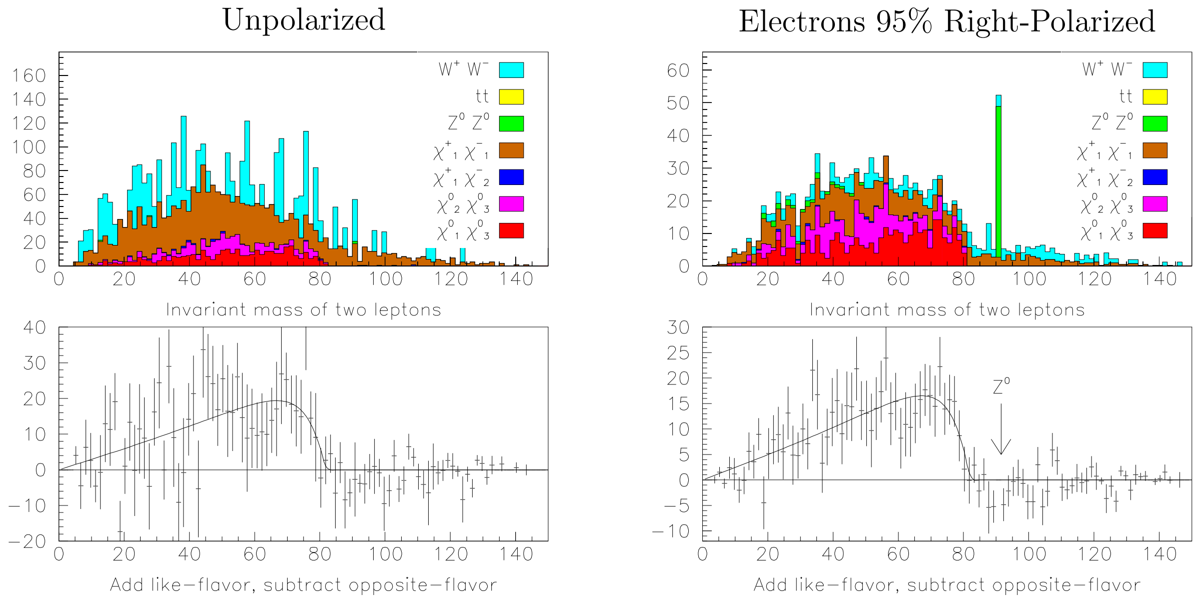

Figure 2: Top: Invariant mass distribution of all contributions. The red and purple distributions are the signals $\chi_3^0\chi_1^0$ and $\chi_3^0\chi_2^0$; the cyan and brown are Standard Model W-pairs and SUSY $\chi_1^+\chi_1^-$. Bottom: Invariant mass distribution where e^+e^- and $\mu^+\mu^-$ events were given a weight of 1 and $e^\pm\mu^\mp$ and $\mu^\pm e^\mp$ events were given a weight of -1. In the polarized sample, we suppressed the bin containing real Z^0 decays. The vertical axes and error bars correspond to the expected numbers of events with 250 fb^{-1}.

unpolarized.

With right-handed electrons, the W-pair background is eliminated and the $\chi_1^+\chi_1^-$ background is significantly reduced. Z-pairs in the polarized sample, however, contribute more to the two-lepton mode (even though the overall cross-section is lower) as seen in the top of Figure 1. Most of these Z-pairs are eliminated with the missing energy cut, but if the missing energy is overestimated by 100 GeV, a few events can leak into the invariant mass plot. This is easily handled, though, because a pair of leptons from a single real Z^0 decay will have an invariant mass at the Z^0 mass, and this bin can be excluded from the fit.

Some care must be taken in interpreting these plots because they represent the case of ideal lepton flavor tagging. If flavor tagging efficiency is only 90%, the signal mound would be reduced in height by a factor of 0.9. Worse yet, if the tagging algorithm favored one flavor over the other, the backgrounds wouldn't exactly cancel, and would distort the shape of the threshold. That said, a realistic detector should have little difficulty distinguishing between $\sim$100 GeV electron showers and minimum-ionizing muon showers, particularly if the muon identification is aided by a muon detector beyond the calorimeters.

	Unpolarized	Electrons 95% Right-Polarized
$\chi_3^0\chi_1^0$	$\mathcal{B}\varepsilon = 3.33\%$ $\sigma = 50.5$ fb	$\mathcal{B}\varepsilon = 2.86\%$ $\sigma = 44.1$ fb
$\chi_3^0\chi_2^0$	$\mathcal{B}\varepsilon = 1.36\%$ $\sigma = 81.6$ fb	$\mathcal{B}\varepsilon = 1.35\%$ $\sigma = 70.9$ fb
Events seen	605 ± 75	528 ± 38

Table 1: Branching fractions times efficiencies $\mathcal{B}\varepsilon$ (the number seen in the invariant mass plot divided by the number generated in Monte Carlo) and cross-sections σ for each of the two signal modes, and the number of events seen in the invariant mass plot, where the two modes can't be separated. The uncertainty in the number of events seen assumes 250 fb^{-1} in each sample.

1.3 Cross-section Constraints

As explained above, we can only measure a weighted sum of the cross-sections of $\chi_3^0\chi_1^0$ and $\chi_3^0\chi_2^0$. The weighting factors depend on the branching fractions of $\chi_3^0\chi_1^0$ and $\chi_3^0\chi_2^0$ to two leptons and on the efficiencies of these modes through our event selection. The event selection efficiencies alone are nearly 50% in all cases, due almost entirely to the angular cut. The branching fractions depend on well-known Z^0 branching ratios and the branching fraction of heavy neutralinos to $Z^0\chi_1^0$, which is 100%. Therefore, we combine all branching fractions and efficiencies into a single factor $\mathcal{B}\varepsilon$ with no uncertainties. The $\mathcal{B}\varepsilon$ factors and cross-sections can be found in Table 1, along with the number of events seen in the invariant mass plot, which is the source of uncertainty in this analysis.

The number of events seen is derived from the branching fractions, efficiencies, and cross-sections like this:

$$(\sigma\mathcal{B}\varepsilon)_{\chi_3^0\chi_1^0} + (\sigma\mathcal{B}\varepsilon)_{\chi_3^0\chi_2^0} = \frac{\text{events seen}}{\text{integrated luminosity}} \tag{1}$$

where the integrated luminosity is 250 fb^{-1}. Inserting our results, we obtain two constraints on $\sigma_{\chi_3^0\chi_1^0}$ and $\sigma_{\chi_3^0\chi_2^0}$.

$$(0.0138\ \text{fb}^{-1})\,\sigma_{\chi_3^0\chi_1^0} \quad + \quad (0.00562\ \text{fb}^{-1})\,\sigma_{\chi_3^0\chi_2^0} \quad = \quad 1 \pm 0.12 \tag{2}$$

$$(0.0135\ \text{fb}^{-1})\,\sigma_{\chi_3^0\chi_1^0,\ \text{pol}} \quad + \quad (0.00639\ \text{fb}^{-1})\,\sigma_{\chi_3^0\chi_2^0,\ \text{pol}} \quad = \quad 1 \pm 0.072 \tag{3}$$

These constraints are, of course, consistent with the generated cross-sections.

1.4 Mass Difference Constraints

Using the three-body fit function described elsewhere, we fit each of our invariant mass distributions for the upper edge of the distribution. Two parameters were floated in the fit:

overall normalization and the mass difference $m_{\chi_3^0} - m_{\chi_1^0}$. The errors obtained from this fit are

$$\pm\, 2.3 \text{ GeV for the unpolarized sample and} \tag{4}$$

$$\pm\, 0.72 \text{ GeV for the polarized sample.} \tag{5}$$

These uncertainties are to be understood as approximate, as some improvement in the fit method will be needed for the full analysis. If the data is simply binned into a histogram for background subtraction by the above method, the fitted value of the threshold varies with the bin spacing. The uncertainty does not vary, however, and an unbinned maximum likelihood fit of the unpolarized sample aggreed approximately with the 2.3 GeV uncertainty quoted above, although even that was difficult to interpret because the maximum of the log likelihood is not a smooth function. (It is difficult to introduce background subtraction into the likelihood, since the probability distribution is zero above the threshold.)

Though a great deal of care will need to be taken to fit the threshold properly, unbiased by bin effects and including the much-needed background subtraction, a few-GeV statistical error on the 83 GeV mass difference should be attainable.