Supersymmetry at LHC and NLC *

Jonathan A. Bagger

Department of Physics and Astronomy, Johns Hopkins University
3400 N. Charles Street, Baltimore, MD 21218

This talk discusses the prospects for supersymmetry studies at the LHC and NLC. The results are based on those of the Supersymmetry Working Group at the 1996 Snowmass Workshop.

1. INTRODUCTION

For years, we supersymmetrys have had to bear a heavy burden. We have been forced to defend the preposterous proposition that nature is supersymmetric – even though not one superpartner has been discovered. Precision measurements [1] have eliminated much of the competition, but they have done nothing to silence the popular press [2]. (For an alternate view, see [3,4].)

Fortunately, this situation will soon change. The upcoming generation of supercolliders will settle the question once and for all. The CERN Large Hadron Collider (LHC), a 14 TeV pp collider, is scheduled for completion in 2005. The Next Linear Collider (NLC), an expandable, 0.5 to 1.5 TeV $e^+e^-$ linear collider, is proposed to begin operation shortly thereafter. These two machines will probe the entire parameter space of weak-scale supersymmetry.

The bottom line is that in less than a decade, our wait will be over. We will finally know whether weak-scale supersymmetry is realized in nature. At SUSY07, we will either celebrate one of the greatest triumphs in the history of science – or join with the sociologists in a searching discussion of how we could have gone so wrong [5].

If supersymmetry is right, SUSY07 will mark the dawn of a new era. Theorists and experimentalists alike will begin to explore a rich set of new physics. Of course, much time and hard work will be required to demonstrate that the new physics is, in fact, supersymmetry. In this talk I will report on some preliminary steps taken in this direction by the Supersymmetry Working Group at the 1996 Snowmass Workshop [6]. This group examined the supersymmetry potential of the LHC and NLC. For each machine, it addressed the following questions:

- Can one identify a signal for new physics?
- If so, can one tell that the new physics is supersymmetry?
- If it is supersymmetry, can one distinguish between various models and measure the underlying parameters?

The group concluded that the LHC and NLC bring complementary approaches to the study of the superparticles and their properties. (In this talk I will not discuss supersymmetry at the Tevatron or LEP. The Tevatron and its possible upgrades were also examined by the Supersymmetry Group at Snowmass [6].)

2. THE MSSM

The Snowmass studies were based on the Minimal Supersymmetric Standard Model (MSSM), the simplest supersymmetric extension of the ordinary Standard Model. The MSSM contains the minimal set of fields: one superpartner for every known particle, as well as two Higgs doublets, together with their associated supersymmetric partners. The MSSM couplings are assumed to respect $R$-parity, which implies that superparticles must be pair produced and that the lightest supersymmetric particle must be stable.

The MSSM contains two types of parameters. The first parametrizes the couplings that

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are related by supersymmetry. For example, at tree-level, supersymmetry requires that the quark-squark-gluino Yukawa coupling be equal to the quark-quark-gluon and squark-squark-gluon gauge couplings. These relations are essential if supersymmetry is to cancel quadratic divergences.

The supersymmetric parameters include all the gauge and Yukawa couplings of the Standard Model, plus the Higgsino mass parameter, \( \mu \). The other parameters in the MSSM describe the supersymmetry breaking. These parameters are soft, in the sense that they do not reintroduce destabilizing quadratic divergences. They include Higgs and gaugino masses, as well as the squark and slepton masses and mixings. The supersymmetry-breaking parameters also include a set of trilinear scalar couplings. In sum, there are over 100 such parameters, each of which must be determined by experiment.

Therefore, if supersymmetry is indeed realized by nature, one must

1. Find the supersymmetric partners;

2. Verify the relations between couplings implied by supersymmetry; and

3. Measure the soft parameters, to shed light on the mechanism of supersymmetry breaking.

At the Snowmass Workshop, the Supersymmetry Working Group assessed the ability of the LHC and NLC to carry out this program. For definiteness, the group chose to work in the mSUGRA scheme, in which the soft supersymmetry-breaking parameters are assumed to unify at the same scale as the running gauge couplings, \( \alpha_1 \), \( \alpha_2 \) and \( \alpha_3 \), as shown in Fig. 1a.

The mSUGRA scenario involves several bold assumptions, any one of which might well be wrong, but it has the tremendous advantage that it reduces the parameter space to just five new parameters: a universal scalar mass, \( M_0 \), a universal gaugino mass, \( M_{1/2} \), a universal trilinear scalar coupling, \( A_0 \), a Higgs mass, \( B_\mu \), and the supersymmetric Higgsino mass, \( \mu \). It is also consistent with all experimental data to date.

The mSUGRA scenario has the additional attraction that radiative corrections from the heavy top quark drive electroweak symmetry breaking, as shown in Fig. 1b. This allows one to trade \( \mu^2 \) and \( B_\mu \) for \( M_Z^2 \) and \( \tan \beta \), the ratio of Higgs vevs. Therefore, in the mSUGRA scenario, the final parameter space is simply:

\[ M_0, \ M_{1/2}, \ A_0, \ \tan \beta, \]

... together with the sign of \( \mu \). The first three parameters are specified at the unification scale, while \( \tan \beta \) is taken at the scale \( M_Z \).
In the mSUGRA scenario, the superpartner masses and mixings are determined by the above parameters and the supersymmetric renormalization group evolution to $M_Z$. The resulting low-energy spectrum tends to have the following properties:

- The weak-scale gaugino mass parameters appear in the ratio $M_1 : M_2 : M_3 \sim \alpha_1 : \alpha_2 : \alpha_3$;
- The $\mu$ parameter tends to be large, $|\mu| \gg M_2$. This implies that the lightest neutralino ($\tilde{\chi}_1^0$) is primarily bino ($\tilde{B}$), while the second-lightest neutralino ($\tilde{\chi}_2^0$) and the lightest chargino ($\tilde{\chi}_1^\pm$) are predominantly wino ($\tilde{W}_1^0, \tilde{W}_1^\pm$);
- Because $|\mu| \gg M_2$, the heavier neutralinos ($\tilde{\chi}_3^0, \tilde{\chi}_4^0$) and chargino ($\tilde{\chi}_2^\pm$) are primarily Higgsino. Their masses tend to be somewhat larger than those of the $\tilde{\chi}_1^0, \tilde{\chi}_2^0$ and the $\tilde{\chi}_1^\pm$;
- If $M_0 \gg M_{1/2}$, the squarks and sleptons are nearly degenerate, and are significantly heavier than the $\tilde{\chi}_1^0, \tilde{\chi}_2^0$ and the $\tilde{\chi}_1^\pm$. If $M_0 \lesssim M_{1/2}$, the squarks are heavier than the sleptons.

These relations will be useful when we discuss supersymmetry signatures at the two machines.

### 3. SUPERSYMMETRY REACH

According to its design specifications, the LHC is a 14 TeV $pp$ collider, capable of achieving an annual integrated luminosity of 100 fb$^{-1}$. For the Snowmass study, it proved sufficient to consider a low-luminosity option, with just 10 fb$^{-1}$ per year.

Crudely speaking, the LHC provides two intense beams of quarks and gluons which collide with a center-of-mass energy in the range of a few TeV. Therefore, a classic supersymmetry signature is given by

$$ g g \rightarrow \tilde{g} + \tilde{g}, $$

where one gluino decays to two jets and missing energy and the other decays to two jets, a lepton, plus missing energy. This suggests that a supersymmetry search should start with events which contain one lepton, jets and missing energy.

The results of such a search are shown in Fig. 2. The figure shows the $M_0 - M_{1/2}$ plane, for $\tan \beta = 2, A_0 = 0$ and $\mu > 0$. Qualitatively speaking, the reach is only weakly sensitive to this choice. In the figure, the bricked (hatched) region is excluded by theoretical (experimental) constraints.

From the figure we see that the LHC gives a gluino reach of between 1.5 and 2.5 TeV, with just 10 fb$^{-1}$ of luminosity. In fact, the LHC subgroup showed that the same cuts and luminosity can be used to detect squarks and gluinos with masses of up to 1 TeV in supersymmetry without $R$-parity [3,11]. (With optimized cuts, the LHC can do even better.) Taken together, these statements form the basis for the assertion that the LHC will probe the entire parameter space of interest for weak-scale supersymmetry.

The NLC, of course, is at an earlier stage of development, so its specifications are less certain.
For the Snowmass Workshop, the NLC was defined to be a linear $e^+e^-$ collider with a center of mass energy between 500 GeV and 1.5 TeV. The luminosity was assumed to be $50 \text{ fb}^{-1}$ per year at 500 GeV and up to $200 \text{ fb}^{-1}$ at 1.5 TeV. It was also assumed that the electrons could be 80% polarized.

At the NLC, two classic supersymmetry signatures are chargino and selectron production,

$$e^+e^- \rightarrow \tilde{\chi}^+_1 + \tilde{\chi}^-_1$$

and

$$e^+e^- \rightarrow \tilde{e}^+_R + \tilde{\bar{e}}^+_{R'}.$$  

In each case, the strategy is to tune the beam energy and search for central events. The corresponding reach plot is shown in Fig. 2 [12]. From the figure we see that the reach of a 1.2–1.5 TeV NLC is comparable to that of the LHC.

It is important to note, though, that at each machine, the quoted reach is achieved through different channels. The LHC reach relies on gluinos, while that of the NLC derives from charginos and sleptons. In the mSUGRA scenario, the lighter mass of the charginos and sleptons tends to compensate the lower energy of the NLC machine. While this is a reasonable guess, it is by no means assured that supersymmetry works out this way.

### 4. SUPERSYMMETRY ANALYSIS

The issue of reach is important, but it is just the first step in the experimental analysis of supersymmetry. One would like to go further and test the expected relations between the supersymmetric parameters and measure the soft supersymmetry-breaking parameters. In this way one can establish whether an observed signal is actually supersymmetry and examine whether it is compatible with mSUGRA or some other supersymmetric framework. To see what can be done, one needs to work with a complete model in which one can analyze a variety of experimental signatures.

At Snowmass the Supersymmetry Working Group studied representative points in the mSUGRA parameter space, five for each machine. One point, the Snowmass comparison point, was chosen to be the same for each: $M_0 = 200 \text{ GeV}$, $M_{1/2} = 100 \text{ GeV}$, $A_0 = 0$, $\tan \beta = 2$ and $\text{sign}(\mu) = -1$. For this choice, $m_{\tilde{g}} = 298 \text{ GeV}$, with the first two generations of squarks about 20 GeV heavier. The slepton masses range between 206 and 216 GeV. The $\tilde{\chi}^+_1$ and $\tilde{\chi}^0_2$ masses are 96 and 97 GeV, while the $\tilde{\chi}^0_1$ mass is 45 GeV. The heavier charginos and neutralino masses are between 260 and 270 GeV. The lighter stop (sbottom) mass is 264 (278) GeV, while the corresponding heavier states are more massive than the gluino.

Note that at the comparison point, all the superparticle masses are rather light. This affects the analysis in at least two ways. The light masses help the LHC because they increase the supersymmetry cross sections. This allowed the LHC subgroup to make hard cuts to isolate pure samples of supersymmetric events. The light masses help the NLC as well because they decrease the energy requirements. In particular, at the comparison point, a 500 GeV NLC is able to access much of the supersymmetric physics. Note too that in this scenario, the Higgs mass is just 68 GeV, so the Higgs would probably have been discovered after Snowmass but before SUSY97!

The analyses at the comparison point take advantage of the following decay chains.

1. The lightest neutralino is primarily bino and the lightest chargino is mostly wino, so the decay into a charged lepton ($\ell = e, \mu$),

   $$\tilde{\chi}^+_1 \rightarrow \ell^\pm + E_T,$$

   has a branching ratio of 22%. Likewise, the decay into jets,

   $$\tilde{\chi}^+_1 \rightarrow 2 \text{ jets} + E_T,$$

   has a branching ratio of 66%.

2. The second-lightest neutralino is primarily wino. Its decay into charged leptons

   $$\tilde{\chi}^0_2 \rightarrow \ell^+ + \ell^- + E_T$$

   has a branching ratio of 33%.
3. Because $m_{\tilde{g}} > m_{\tilde{q}}$, but $m_{\tilde{g}} < m_{\tilde{q}}$ for the first two generations, the decay chain

$$\tilde{g} \rightarrow \tilde{b} + b \rightarrow \tilde{\chi}_2^0 + b \rightarrow \tilde{\chi}_1^0 + \ell^+ + \ell^-$$

has a branching ratio of 25%. This gives rise to spectacular signatures with multiple $b$ jets, leptons and missing energy.

4.1. LHC Strategy

At the LHC, the analysis of supersymmetry is likely to be quite complicated because all the superpartners are produced at once. Indeed, it is often said that at the LHC, the “background to supersymmetry is supersymmetry.” This suggests a systematic approach, perhaps along the following lines:

1. Determine the supersymmetry scale;
2. Study the clean decay chains; and
3. Test specific models by performing global fits to the data.

At Snowmass, the LHC subgroup carried out such an analysis for the comparison point [10,13].

The first step is to determine the overall scale of supersymmetry, which can be defined as the smaller of the squark or gluino mass,

$$M_{SUSY} = \min(m_{\tilde{g}}, m_{\tilde{q}}).$$  \hspace{1cm} (1)

The LHC subgroup proposed the following technique. One first selects a sample of events with at least four jets, no leptons and substantial missing energy. One then computes the scalar sum of the transverse momenta of the four hardest jets, plus the missing energy,

$$M_{EFF} = \sum_{i=1}^{4} |p_{T\text{jet, }i}| + E_T,$$  \hspace{1cm} (2)

for each event. It turns out that the peak in the $M_{EFF}$ distribution is closely correlated with $M_{SUSY}$, at least in the mSUGRA scenario [10,13,14].

The LHC subgroup illustrated this procedure for 100 mSUGRA models (with the same Higgs mass). The results are shown in Fig. 3, where one sees that the ratio $M_{EFF}/M_{SUSY}$ is constant to within 10%. Indeed, one finds $M_{EFF}/M_{SUSY} = 1.9$ to within 10%, at least within the class of mSUGRA models discussed here [10,13,14].
The LHC subgroup then turned its attention to the clean decay chains. Such an analysis is easiest if one starts with a relatively pure sample of supersymmetry events. For the Snowmass comparison point, there are 13.5 million supersymmetry events per 10 fb$^{-1}$ of luminosity. This permits hard cuts to isolate pure samples of supersymmetric decays.

As discussed above, at the Snowmass point, the decay $g \rightarrow b \bar{b} + \ell^+ + \ell^- + E_T$ has a branching ratio of 25%. With 10 fb$^{-1}$ of luminosity and a tagging efficiency of 60% (and $c$ misidentification of 10%) per $b$-jet, this gives rise to 272k events which contain four $b$ jets and two pairs of opposite-sign same-flavor leptons. Moreover, if one of the $\tilde{\chi}^0_2$ is allowed to decay hadronically, there are another 694k events with four $b$ jets, two non-$b$ jets and one pair of opposite-sign same-flavor leptons. This suggests that the supersymmetry sample be selected to contain four or more jets, with at least two tagged as $b$-jets and one or more pairs of opposite-sign same-flavor leptons.

The LHC subgroup collected such a sample and plotted the dilepton mass distribution, as shown in Fig. 4 [10,13,15]. By fitting the sharp edge of the distribution, they determined that the mass difference $\Delta m$ can be measured to $\pm 50$ MeV! This incredible precision follows from the fact that the measurement is systematics limited and the dilepton mass can be calibrated against $M_Z$.

The subgroup then used the technique of partial reconstruction, first developed for $D^+ \rightarrow D^0 \pi$ decays [16], to show that the difference $m_{\tilde{b}} - m_{\tilde{\chi}^0_2}$ can be measured to $\pm 2$ GeV [10,13,17]. The technique goes as follows. One first selects events near the edge of the $\ell^+\ell^-$ mass distribution. Since the leptons come from the decay chain

\[ g \rightarrow \tilde{b} + b \]

\[ \rightarrow \tilde{\chi}^0_2 + b \]

\[ \rightarrow \tilde{\chi}^0_1 + \ell^+ + \ell^-, \]

the events near the edge originate in decays in which the $\tilde{\chi}^0_1$ and the $\ell^+\ell^-$ pair are at rest in the rest frame of the $\tilde{\chi}^0_2$. If one then assumes some mass for the $\tilde{\chi}^0_1$, one can boost back to the lab and reconstruct the entire event. About 6000 gluino and sbottom events can be reconstructed in this way per 10 fb$^{-1}$ of luminosity at the LHC.

Using this technique and assuming a value for $m_{\tilde{\chi}^0_1}$, one can measure the mass of the $\tilde{b}$, as well as the mass difference $m_{\tilde{b}} - m_{\tilde{\chi}^0_2}$, as shown in Figs. 3 and 4. By varying the value of $m_{\tilde{\chi}^0_1}$, one can show that $m_{\tilde{b}} - m_{\tilde{\chi}^0_2}$ is essentially independent of the assumption, up to an error of $\pm 2$ GeV. One also finds that

\[ \Delta m_{\tilde{b}} = 1.5 \left[ m_{\chi^0_1}(true) - m_{\chi^0_1}(assumed) \right] \]

\[ \pm 3 \text{ GeV}. \]

Therefore once $m_{\tilde{\chi}^0_1}$ is known, the $\tilde{\chi}^0_2$ and $\tilde{b}$ masses are determined to the percent level!

The final step in the analysis is to try to determine the soft supersymmetry-breaking parameters. At the LHC, this might be accomplished by performing a global fit to the data. If one is lucky, and the soft parameters originate in some simple model, such as mSUGRA or gauge mediation, the fit will agree with the data. If not, and all 100 parameters need to be measured independently, the global fit will not work and one will
be forced to try something else.

For the case at hand, the global fit works very well. The measured inputs

\[ m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1} = 52.36 \pm 0.05 \text{ GeV} \]
\[ m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1} = 20.3 \pm 2.0 \text{ GeV} \]
\[ m_h = 68.3 \pm 3 \text{ GeV} \]

(Where the Higgs mass measurement comes from LEP, and the error is purely theoretical), imply

\[ M_0 = 200^{+13}_{-8} \text{ GeV} \]
\[ M_{1/2} = 99.9 \pm 0.7 \text{ GeV} \]
\[ \tan \beta = 1.95 \pm 0.05 \]
\[ \text{sign}(\mu) = \text{determined} \]
\[ A_0 > -400 \text{ GeV}. \]

The fit works as follows: Since the \( \tilde{\chi}^0_2 \) and \( \tilde{\chi}^0_1 \) are effectively wino and bino, the value of \( M_{1/2} \) is fixed by \( m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1} \). This, in turn, gives \( m_{\tilde{\chi}^0_1} \) in the mSUGRA scenario. Partial reconstruction then determines \( m_{\tilde{\chi}^0_1} \), hence \( M_0 \). Finally, the value of \( m_h \) is sufficient to fix \( \tan \beta \).

Given this global fit, one can carry out many cross checks to test the consistency of the solution. For example, once \( M_{1/2} \) is known, the gluino mass can be predicted and compared with experiment. Similarly, the event rates and branching ratios can be used to test the fit.

4.2. NLC Strategy

Supersymmetry studies at the NLC exploit the facts that the beam energy is adjustable, the electron polarization can be varied, and signal events are central. The adjustable energy helps one to produce just the particles of interest, while the polarization and event shape help to separate the signal from the background. Operation near threshold permits accurate mass measurements, while precise knowledge of the collision energy greatly facilitates the reconstruction of events with undetected particles in the final state. These facts are illustrated in Fig. 7, where a series of cuts at \( \sqrt{s} = 500 \text{ GeV} \) and 80% polarization have been used to produce a supersymmetric sample with 30:1 ratio of signal to background.

The JLC group [18] has pioneered a program in which they have shown that chargino, neutralino and slepton masses can be accurately measured at
a linear $e^+e^-$ collider. The JLC studies ignored cascade decays and assumed an electron beam polarization of 95%. At Snowmass the NLC group refined this work by including the effects of cascade decays and taking the electron polarization to be a more conservative 80% [19]. (The precision measurements that might be possible at the NLC with cascade decays have also been examined in [12].)

The NLC subgroup began its study of the supersymmetry comparison point by running its machine at $\sqrt{s} = 250$ GeV. At this energy just the lightest chargino and neutralino are produced. Chargino pair production,

$$e^+e^- \to \tilde{\chi}_1^+ + \tilde{\chi}_1^-,$$

where one chargino decays leptonically, and the other hadronically, $\tilde{\chi}_1^+ \to 2 \text{jets} + \tilde{\chi}_1^0$, gives rise to a striking signal in the jet-jet invariant mass distribution. Indeed, as shown in Fig. 8, this signal can be readily separated from the $WW$ background.

A fit to the endpoints of the dijet mass distribution gives a measurement of $m_{\tilde{\chi}_1^+}$ and $m_{\tilde{\chi}_1^-}$, as shown in Fig. 8. With 20 fb$^{-1}$ of data, the NLC subgroup recovered the input values, with an error of 1% on both measurements [19].

The polarization of the beam can be used to determine the wino/Higgsino content of the $\tilde{\chi}_1^\pm$. The key point is that left-polarized electrons can produce the $\tilde{\chi}_1^\pm$ whether it is wino or Higgsino, whereas right-polarized electrons can only produce it if it is Higgsino (see Fig. 10). Therefore, if the left-polarized cross section, $\sigma_L$, is much greater than the right-polarized cross section, $\sigma_R$, the $\tilde{\chi}_1^\pm$ is primarily wino. This analysis is independent of any assumptions about the nature of the soft supersymmetry-breaking terms.

For the case at hand, the NLC subgroup showed that with 20 fb$^{-1}$ of data, the polarized cross sections can be measured to an accuracy of less than 2%. From the cross sections they then inferred that the lightest chargino is indeed a wino, and that the mass of the $t$-channel sneutrino must be less than 250 GeV [19].

Based on this information, the subgroup proposed increasing the NLC energy to 500 GeV, which is sufficient to pair-produce all sleptons.
Indeed, sneutrino pair production,

\[ e^+ e^- \rightarrow \tilde{\nu}_e + \tilde{\nu}_e^* \]

followed by the decays

\[ \tilde{\nu}_e \rightarrow \tilde{\chi}_1^+ + e^- \]
\[ \rightarrow \mu^+ + E_T \]
\[ \tilde{\nu}_e^* \rightarrow \tilde{\chi}_1^- + e^+ \]
\[ \rightarrow 2 \text{jets} + E_T \]

(together with their charge conjugates), gives rise to the electron energy distribution shown in Figure 9. The dijet energy distribution, and the masses obtained by a fit to its endpoints.

Figure 9. The dijet energy distribution, and the masses obtained by a fit to its endpoints.

\[ E_{jj} \ (\text{GeV}) \]

\[ M_{\tilde{\chi}^+_1} \ (\text{GeV}) \]

\[ M_{\tilde{\chi}^-_1} \ (\text{GeV}) \]

\[ \Delta \chi^2 = 1.00 : \text{solid} \]
\[ = 4.00 : \text{dash} \]

\[ \chi^2 = 1.00 : \text{solid} \]
\[ = 4.00 : \text{dash} \]

\[ \text{Best Fit} \]

Figure 10. Left-polarized electrons can produce the $\tilde{\chi}^+_1$ whether it is wino or Higgsino, whereas right-polarized electrons can only produce it if it is Higgsino. ($B$-$W$ mixing is small at NLC energies.)

Fig. 11. The endpoints of the distribution determine $m_{\tilde{\nu}_e}$ and $m_{\tilde{\chi}^+_1}$. With 25 fb$^{-1}$ of data and 80% left-handed polarization, the NLC ZDR study [20] quotes the following masses,

\[ m_{\tilde{\nu}_e} = 207.5 \pm 2.5 \text{ GeV} \]
\[ m_{\tilde{\chi}^+_1} = 97.0 \pm 1.2 \text{ GeV} \]

compared with the input values of 206.6 and 96.1 GeV, respectively.

At Snowmass the NLC subgroup studied right-handed selectron production,

\[ e^+ e^- \rightarrow \tilde{e}_R^+ + \tilde{e}_R^- \]

for $\sqrt{s} = 500$ GeV. They selected events where each selectron decays into an electron and a $\tilde{\chi}^0_1$. For such events, the endpoints of the electron distribution determine the masses of the $e^+_R$ and the $\tilde{\chi}^0_1$. They found that the fit values of the masses did not coincide exactly with the inputs because of backgrounds from other decays. Nevertheless, they stated that this effect is correctable, and estimated an error of $\pm 1\%$ on $m_{e^+_R}$, with 20 fb$^{-1}$ of luminosity and 80% right-handed polarization [19]. (A similar technique works for the $\tilde{\mu}_R$.)
Figure 11. (a) The electron energy distribution in the process $e^+e^- \rightarrow \tilde{\nu}_e + \tilde{\nu}_e \rightarrow e^+ + e^- + \mu^\pm + 2 \text{jets}$. (b) The fit that determines the chargino and sneutrino masses.

Measurement of the $\tilde{\tau}_L^\pm$ mass is difficult because left-polarized electrons have significant Standard-Model backgrounds. The NLC subgroup quoted an uncertainty of $\pm 7\%$ using the six-electron final state.

The four measurements $m_{\tilde{\chi}_1^\pm}$, $m_{\tilde{\chi}_1^0}$, $\sigma_R(e^+R^\pm e^-)$ and $\sigma_R(\tilde{\chi}_1^+\tilde{\chi}_1^-)$ are sufficient to make a model-independent measurement of $\mu$, $M_1$, $M_2$ and $\tan \beta$, without any assumptions about the mechanism of supersymmetry breaking [18]. This allows a direct test of the gaugino mass relation between $M_1$ and $M_2$. Alternatively, one can assume this relation and then determine $M_2$, $\mu$ and $\tan \beta$.

The NLC subgroup took this second approach and determined the parameter $M_2$ to $\pm 1.5\%$ [19].

These results, together with the measurements of the slepton masses, led the NLC subgroup to predict an average squark mass of $322 \pm 7$ GeV in the mSUGRA scenario. They therefore suggested increasing the NLC energy to 800 and 1000 GeV. At these energies they would be able to measure the squark masses, as well as those of the heavier chargino, neutralinos and Higgs bosons [19].

The NLC subgroup measured the top and bottom squark masses using an event sample at $\sqrt{s} = 800$ GeV. Since these squarks decay predominantly through

\[
\tilde{t} \rightarrow b + \tilde{\chi}_1^+
\]
\[
\tilde{b} \rightarrow b + \tilde{\chi}_1^0,
\]

they required each event to contain two $b$ jets.

The resulting jet energy spectrum provides an indication of the third-generation squark mass. The jet energy distribution is shown in Fig. 12 at $\sqrt{s} = 800$ GeV, for 50 fb$^{-1}$ of luminosity with 80% right-handed polarization. By fitting the endpoints, the subgroup measured an average third-generation squark mass of 307 GeV, plus or minus 10% [19].

The NLC has the great advantage that the
supersymmetric masses and cross sections can be measured in a systematic, model-independent fashion. Once one has determined the masses, one can test whether they fit any particular hypothesis about the origin of supersymmetry breaking. For example, measurement of the selectron and smuon masses directly tests the flavor dependence of the slepton masses.

At Snowmass the NLC subgroup fit their measurements to the mSUGRA hypothesis. They found that the best fit corresponded to the input parameters, with the following errors [19]:

\[
\delta M_0 = \pm 2.7 \text{ GeV} \\
\delta M_{1/2} = \pm 2.5 \text{ GeV} \\
\delta \tan \beta = \pm 0.17 \\
\text{sign}(\mu) = \text{determined},
\]

with no constraint quoted on \( A_0 \). (Their fit to \( \tan \beta \) would have been better if they had used the anticipated result from LEP. Note that neither the NLC nor the LHC were able to measure \( A_0 \) because it does not affect the weak-scale phenomenology.) As with the LHC, the predictions from this fit can be cross tested through many other measurements. For example, finding squarks at the expected mass would provide striking support of the mSUGRA scenario.

The NLC also offers the exciting possibility of testing the relationships implied by supersymmetry itself. An example of such a test is provided by the reaction [21]

\[
e^+e^- \rightarrow \tilde{e}_R^+ + \tilde{e}_R^-.
\]

The production cross section involves an \( s \)-channel \( B \) and a \( t \)-channel \( \bar{B} \). At tree level, supersymmetry relates the bino-selectron-electron Yukawa coupling \( g_{\tilde{b}\tilde{e}_R e} \) to the hypercharge gauge coupling, \( g' \). With 100 fb\(^{-1}\) of luminosity, it may be possible to measure the ratio \( g_{\tilde{b}\tilde{e}_R e}/\sqrt{2}g' \) to better than 2%, as shown in Fig. 13 (for a particular set of parameters). This test is so precise that it begins to be sensitive to radiative corrections, which, in turn, are sensitive to the masses of superparticles which may not be kinematically accessible. Indeed, it might even be possible to extract an estimate of the squark mass scale from this ratio [22].

5. CONCLUSIONS

In this talk I have tried to give an indication of the types of supersymmetry measurements that will be possible at the LHC and NLC. If the accelerators and detectors work as designed – and supersymmetry is discovered – I have no doubt that the actual measurements will be better than anything I have reported here. After all, nothing beats real experimentalists with real data.

At Snowmass, it is fair to say that the Supersymmetry Working Group reached the following consensus.

- The LHC is an excellent machine for supersymmetry because of its enormous discovery reach. It can perform some precision measurements and can confirm or exclude specific hypotheses on the origin of supersymmetry breaking.
- The NLC is an excellent machine for supersymmetry because it permits a systematic, model-independent determination of the supersymmetry parameters. It has a discovery reach that is limited by the available center-of-mass energy. However, it can per-
form many precision measurements for the superparticles within its reach.

I think that experiments at the LHC and NLC do indeed provide complementary information. They will discover weak-scale supersymmetry, if it exists, and will carry out detailed measurements of the superparticle properties. The information they provide will help unravel the mysteries of supersymmetry and supersymmetry breaking and will further our understanding of how electroweak gauge symmetry is broken.

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