Summary of the Supersymmetry Working Group

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ABSTRACT

We summarize the results obtained by the Supersymmetry Working Group at the 1996 Snowmass Workshop.

I. INTRODUCTION

Supersymmetry (SUSY) is a novel symmetry which relates the properties of bosons and fermions. It implies that the elementary particles come in pairs, with the same masses and internal quantum numbers, but with spins differing by one-half unit of angular momentum. Such particles do not exist, so SUSY must be broken (a bosonic electron of mass 0.511 MeV could not have escaped detection).

Interest in SUSY phenomenology stems from the fact that in a supersymmetric theory, the masses of elementary scalar particles remain stable under radiative corrections – even if supersymmetry is softly broken. For the case of the standard model (SM), this suggests that the scale of SUSY breaking should be comparable to the weak scale, ~ 250 GeV. In this case, the unobserved SUSY partners must have masses smaller than ~ 1 TeV, and they should be copiously produced at the next generation of colliders, if not before.

The Minimal Supersymmetric Standard Model (MSSM) is the direct supersymmetrization of the SM. It is an $SU(3) \times SU(2) \times U(1)$ gauge theory, with three generations of quarks and leptons, together with their spin-zero partners, the squarks and sleptons. The electroweak symmetry-breaking sector contains two $SU(2)$-doublet scalar fields, along with their spin-$\frac{1}{2}$ partners, the Higgsinos. The remaining fields of the MSSM are the spin-$\frac{1}{2}$ Majorana gauginos, which transform as the adjoint representation of the SM gauge group.

Aside from (model-dependent) mixing effects, the gauge interactions of all the sparticles are completely fixed by gauge invariance. These interactions largely determine the phenomenology of the MSSM, and allow for rather robust predictions. Just as in the SM, the masses of the fermions arise via Yukawa interactions, which are now contained in a superpotential. The superpotential function also contains a supersymmetric Higgs mass term, which is conventionally denoted by μ.

In contrast to the SM, the most general gauge-invariant Lagrangian for the MSSM contains renormalizable interactions which violate baryon and/or lepton number. These interactions lead to squark-mediated weak-scale proton decay, which is clearly unacceptable. Typically, these interactions are *assumed* to be forbidden by a Z_2 symmetry called R-parity, which is defined to be $+1$ for ordinary particles, and -1 for their superpartners.

R-parity conservation implies that supersymmetric particles must be pair-produced in collisions of ordinary particles, and that they must decay into other supersymmetric particles. It also implies that the lightest SUSY particle (LSP) is stable. We note that it is possible to construct phenomenologically viable models where R-parity is not conserved. The phenomenology of such models is significantly different from that of the MSSM, and is discussed elsewhere in this report.

The absence of Bose-Fermi pairs of the same mass implies that supersymmetry must be broken. It is fair to say that there is, as yet, no compelling mechanism for supersymmetry breaking. For phenomenological purposes, however, it is sufficient to parametrize the effects of supersymmetry breaking by introducing a set of soft SUSY-breaking operators which are consistent with the SM symmetries. These operators do not reintroduce the divergences which destabilize the scalar masses. They also play an important role in achieving the spontaneous breakdown of electroweak gauge invariance.

Once electroweak symmetry is broken, gauginos and Higgsinos of the same charge mix to form the mass eigenstates known as the charginos and neutralinos. The gluinos, being the only color-octet fermions, do not mix with any other particles, and so are mass eigenstates. Left-right sfermion mixing, which is proportional to the corresponding *fermion* mass, is negligible except for the third generation. Therefore $\tilde{f}_L$ and $\tilde{f}_R$, the superpartners of the chiral fermions f_L and f_R of the first two generations, are essentially mass eigenstates, whereas there is always substantial mixing between the left- and right-handed top squarks. (The mixing between left- and right-handed bottom squarks and tau sleptons depends on model parameters.)

The MSSM thus contains two Dirac charginos, four Majorana neutralinos, a color-octet gluino, two spin-zero squarks and charged sleptons of each flavor, and a sneutrino for each lepton family. The Higgs sector contains three neutral Higgs states plus a pair of charged Higgs particles. As noted above, sparticles decay into other sparticles until the cascade terminates with the stable LSP. The favored LSP candidate is the lightest neutralino, which is weakly interacting and escapes experimental detection. Thus missing energy and missing momentum are the canonical signatures for SUSY, provided R-parity is conserved.

The soft SUSY-breaking operators have been classified in Ref. [1]. They consist of scalar and gaugino masses, together with trilinear and bilinear scalar interactions (the so-called A- and B-terms). If one neglects flavor mixing in the supersymmetric sector, one finds an independent mass term for each $SU(3) \times SU(2) \times U(1)$ matter, Higgs and gaugino multiplet (for a total of $15 + 2 + 3$ masses). One also finds a soft trilinear scalar coupling for every superpotential interaction. With the most general flavor structure, the sfermion mass parameters are replaced by sfermion mass matrices, and the number of trilinear couplings is greatly increased. The generic model with the minimal particle content contains over one hundred soft SUSY-breaking parameters (and even more if R-parity is not conserved). This makes general SUSY phenomenology intractable.

In the future, a theory of these soft parameters will emerge from a deeper understanding of the mechanism which underlies supersymmetry breaking. For the present, however, one is forced to take a more practical approach and find some other way to reduce their number. A reasonable strategy is to postulate symmetries which hold at some high energy scale. For example, one might suppose that there is an $SU(5)$ grand unified symmetry, where each family falls into one of two $SU(5)$ multiplets. Then, in one common scenario, there are just two sfermion masses for each family, and only one gaugino mass.

As usual in a unified theory, these $SU(5)$ mass relations hold at the unification scale. The physical masses are found by evolving the mass parameters to the weak scale. The evolution equations depend on the interactions of the individual sparticles, so a rich pattern of physical sparticle masses can emerge. For example, in the above scenario one finds that the weak-scale gaugino mass parameters are related by the well-known gaugino mass unification relation,

$$\frac{3M_1}{5\alpha_1} = \frac{M_2}{\alpha_2} = \frac{m_{\tilde{g}}}{\alpha_s}.$$

Of course, the precise physical mass spectrum depends on the assumptions we make about the physics at the high scale. We will return to this point in the next section, where we discuss the canonical model that we use in most of this study, as well as possible variations.

The goals of our study are embodied in the following questions:

- Can one identify a signal for new physics in a supersymmetric context?
- Once a signal is identified, can one tell that the new physics is supersymmetry?
- Having identified the new physics as supersymmetry, can one distinguish between various models and actually measure the underlying parameters?

The future experimental facilities which were included in our charge, and for which we studied these issues, were as follows:

- TeV33, a high luminosity upgrade of the Tevatron collider, operating at $\sqrt{s} = 2$ TeV, with an integrated luminosity $\sim$ 30 fb^{-1},

- LHC, where studies were primarily done for the "low luminosity" option of 10 fb^{-1}/year, and
- NLC, an e^+e^- collider operating $\sqrt{s} = 0.25 - 1.5$ TeV, with a design luminosity of up to 50 fb^{-1}/year, depending on the energy.

Our group divided itself into four subgroups with the following conveners:

- Theory (H. Baer and J. Lykken)
- TeV33 (K. De and S. Lammel)
- LHC (A. Bartl and J. Söderqvist)
- NLC (K. Fujii and D. Wagner).

The summaries of each of the subgroups appear elsewhere in these proceedings.

In Sec. II we outline the assumptions which underlie what has come to be known as the minimal SUGRA framework, and which is used as a canonical model for the experimental studies. We also explore possible variations and discuss their implications, as elucidated by the Theory Subgroup. In Sec. III we briefly review the SUSY reach of the various facilities, as documented in the literature prior to this Snowmass Workshop. In Sec. IV we outline strategies that can be used in future experiments to achieve the goals of this study, and we discuss highlights of the new results that were obtained at the Workshop. We conclude in Sec. V with a comparison of the capabilities of the three experimental options, assuming that weak-scale supersymmetry is indeed realized in nature.

II. MODEL CONSIDERATIONS

As we have just seen, the minimal supersymmetric extension of the SM contains over one hundred free parameters. Clearly, to proceed further, one must make assumptions.

Most recent phenomenological analyses have been done within the so-called minimal SUGRA framework, which we also adopt for most of our analysis. Here, we briefly review the assumptions that underlie this scenario, and then we go on to discuss other theoretical models that were considered at this Workshop, primarily by the Theory Subgroup.

A. The Minimal SUGRA Model

Various difficulties in constructing phenomenologically viable models with spontaneously broken weak-scale SUSY led to the development of the so-called geometric hierarchy models, where SUSY is broken in a hidden sector at a scale $M_{\rm SUSY}$. In these models, the interactions between the hidden and observable sectors are suppressed by some large scale, M. The effective scale of SUSY breaking in the observable sector is M_{SUSY}^2/M, which can be comparable to the weak scale even if $M_{\rm SUSY}$ is much larger.

Supergravity provides a particularly attractive realization of this idea, in which case $M \sim M_{\rm Planck}$. In the supergravity framework, SUSY is promoted to a local symmetry, and the resulting model necessarily includes gravity. The gravitino typically acquires a weak-scale mass and essentially decouples from particle physics. The low-energy effective theory for the SM particles and their superpartners is just the globally supersymmetric theory, with certain soft SUSY-breaking parameters, as discussed in the previous section. If we choose $M_{\rm SUSY} \sim 10^{11}$ GeV, the soft parameters are all $\mathcal{O}(M_{\rm Weak})$, as desired.

In general, the precise values of these parameters are sensitive to the details of physics at the Planck scale. If, however, one makes the further assumption that the so-called Kähler potential takes a certain canonical form (this is the reason for the qualifier "minimal" in minimal SUGRA), the soft parameters reduce to the following simple set: there is one common SUSY-breaking scalar mass parameter, m_0, and one bilinear and one trilinear scalar coupling, B_0 and A_0. It is also customary to assume that an underlying grand unification yields a universal gaugino mass, $m_{1/2}$. Aside from the SM parameters, the model is then completely specified by the parameters (μ, m_0, $m_{1/2}$, A_0, B_0).

We stress here that the minimal SUGRA (mSUGRA) model is not a fundamental theory. It is simply a low-energy effective theory, valid below some very high scale, $M \sim M_{\rm GUT} - M_{\rm Planck}$. Indeed, the simple structure of the soft SUSY-breaking parameters holds only at this super-high scale. As discussed in Sec. I, phenomenological analyses require that the masses and couplings be evolved down to the weak scale. This leads to a diverse (but highly constrained) spectrum of sparticle masses which serves as a test of the assumptions that have been made.

For "practical supersymmetry," one can forget that the mSUGRA model was derived using supergravity. All that supergravity did was to generate a set of soft SUSY-breaking parameters at the ultra-high energy scale. The additional "minimality assumption" fixed universal boundary conditions for these parameters. This is, in fact, *not* a general property of supergravity models, and can only hold if the high-energy dynamics obeys an additional approximate global symmetry, such as a $U(n)$ symmetry for the n matter and Higgs supermultiplets. This symmetry is broken by the superpotential interactions, so the supergravity justification of the universal boundary conditions must be regarded with care.

Regardless of its origin, the mSUGRA model provides an attractive and economical framework for phenomenological studies. A particularly nice feature of this model is that it gives rise to the radiative breaking of electroweak symmetry. Even though all scalars have a common mass at the high scale (which we take to be $M_{\rm GUT} \simeq 2 \times 10^{16}$ GeV), contributions from the top-quark Yukawa interactions to the renormalization group evolution drive $m_{H_u}^2$, the mass squared of the Higgs field responsible for the masses of the up-type fermions, to negative values. This triggers the dynamical breakdown of electroweak symmetry.

The desired symmetry breaking pattern is obtained over a wide (but not complete) range of model parameters. Assuming that this is indeed the origin of electroweak symmetry breaking, one can use the observed value of M_Z to determine μ^2, and eliminate the parameter B_0 in favor of $\tan\beta = v_u/v_d$, the ratio of up- to down-type vacuum expectation values (vevs), so that all sparticle masses and couplings are fixed by the following parameter set:

$$(m_0, m_{1/2}, A_0, \tan\beta, \operatorname{sgn}\mu)$$

plus the SM parameters. It is remarkable that this framework is consistent with all experimental data and also with the grand unification of the gauge couplings, as measured by LEP experiments. As a bonus, the LSP, which is frequently the lightest neutralino, is a viable candidate for cosmological dark matter.

The mSUGRA model has several generic features which are important for phenomenology.

- The first two generations of squarks and sleptons are separately (almost) degenerate in mass. This degeneracy ensures consistency with the suppression of flavor changing neutral currents. Furthermore, the squarks are always heavier than the corresponding sleptons. Finally, the sleptons are much lighter than the squarks only if $m_{\tilde{q}} \simeq m_{\tilde{g}}$.
- Squarks (of the first two generations) are never much lighter than gluinos: if squarks and gluinos are heavier than about 200 GeV, $m_{\tilde{q}} \gtrsim 0.8 m_{\tilde{g}}$.
- Typically, μ is much larger than the electroweak gaugino masses, so the lighter chargino and the two lightest neutralinos tend to be gaugino-like, while their heavier siblings are mostly Higgsino-like.
- The lightest neutral Higgs boson is approximately the Higgs boson of the SM. It must be lighter than about 130 GeV. The other Higgs bosons are typically much heavier.

It should be kept in mind that there are some exceptions to these rules, as discussed by the Theory Subgroup [2].

It is important to remember that, despite its apparent success, the mSUGRA framework rests on untested assumptions about the symmetries of high-scale dynamics. It is possible – indeed probable – that these assumptions may ultimately prove to be incorrect. It is important, therefore, to study alternative scenarios where one (or more) of the assumptions is relaxed. It is equally important to examine how these assumptions can be directly tested in future experiments once supersymmetry is discovered. Both these issues were addressed by our group during the course of the Snowmass Workshop.

B. Modifications of the mSUGRA Model

The mSUGRA framework provides a very constrained pattern of sparticle masses and couplings. This pattern is, however, sensitive to details about the physics at the high scale, so a measurement of sparticle properties can yield information about symmetries of physics at a scale far beyond what might be accessible at accelerators. We review here some of the extensions that were examined at this Workshop, and refer to Ref. [2] for details.

1. New Contributions to Scalar Masses

Naively, one would think that if additional gauge symmetries (beyond the SM) are broken at a very high scale, the effects of these interactions should be suppressed at low energy. The pattern of sparticle masses provides a simple counterexample to this intuition. The point is that if sfermions (or, for that matter, the Higgs bosons) are not singlets of this new gauge group, supersymmetry generates quartic interactions between pairs of ordinary fields and pairs of fields whose vevs break this symmetry. When these fields are replaced by their vevs, these quartic terms provide a new source of mass for observable-sector fields. Such interactions can alter the masses of the squarks, sleptons and Higgs bosons (and indirectly, of other sparticles).

During the Workshop, the Theory Subgroup studied a test case where the extra gauge symmetry was $U(1)_{B-L}$. They showed that the usual hierarchy between slepton masses can become inverted; *i.e.* $m_{\tilde{\ell}_L,\tilde{\nu}} < m_{\tilde{\ell}_R}$ is possible. This would modify the leptonic branching fractions of the charginos and neutralinos, and hence the multilepton signals from cascade decays of gluinos and squarks. For more details, and for a discussion of the impact on the phenomenology of a particular model, we refer the reader to Ref. [2], and references therein.

2. Non-Universal Unification-Scale Boundary Conditions

We have already stressed that the universal boundary conditions adopted in the mSUGRA picture result from untested assumptions about the nature of high-scale physics. This motivated the Theory Subgroup to consider models with non-universal gaugino and scalar masses. Non-universal gaugino masses may arise in models in which a non-minimal gauge-field kinetic term is induced by the vev of a superfield that is charged under the GUT group. Alternatively, there are superstring-motivated models where the boundary conditions are different from those of the mSUGRA scenario.

In general, the pattern of sparticle masses is sensitive to model parameters. Here, we will confine ourselves to noting that the phenomenology at the LHC and NLC can be very different from that expected in mSUGRA. An extreme example is provided by the string-motivated O-II scenario in which the chargino is essentially degenerate (to a fraction of a GeV for the particular parameter choice) with the LSP and also to within 10 GeV of the gluino. The "visible" decay products of the chargino may be too soft to be detected, at even the NLC. (However, this signal can be detected via the $e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \gamma$ reaction, where only a high energy photon is observed.) Very soft jet cuts would be required to dig out the gluino signal at the LHC [3]. While this scenario might be contrived, it exemplifies the importance of general purpose detectors to cope with unexpected surprises.

3. Data Driven MSSM Scenarios

Guided by a handful of unusual events in the Fermilab Tevatron experiments, as well as a small deviation in LEP experiments, some members of the Theory Subgroup attempted to explain these anomalies in terms of supersymmetry. They used selective subsets of the data to guide them to model parameters. For more information on this data-driven approach, we refer the reader to the literature, where the values of parameters "as extracted from the data" are documented [4, 5].

4. R-Parity Violation

A disconcerting feature of supersymmetry is that it is possible to introduce renormalizable interactions consistent with the SM gauge symmetries which violate baryon (B) and/or lepton (L) numbers (and also R-parity). A theory with all such interactions would be a phenomenological disaster since the proton would decay at the weak rate. In the absence of any deeper understanding of this issue, we are forced to impose a discrete symmetry to stabilize the proton. The canonical choice is the conservation of R-parity, but B or L conservation do this job equally well. The phenomenology is, however, sensitive to this choice. If R-parity is violated, the LSP is unstable and can decay into SM particles; hence the missing-energy signal is greatly altered. The impact of this scenario on the reach of the LHC was examined at this Workshop, and is discussed in the next section.

5. Gauge-Mediated Symmetry Breaking

Recently, there has been a resurgence of interest in models where SM gauge interactions, not gravity, act as the messengers of supersymmetry breaking. Supersymmetry is assumed to be dynamically broken in a hidden sector of the theory, which is coupled to a "messenger sector" (with a mass scale M) by a new set of gauge interactions. Some particles in the messenger sector are assumed to have SM gauge interactions. Ordinary gauge interactions then induce soft SUSY-breaking masses for the superpartners of the quarks and leptons, as well as for those of the gauge and Higgs bosons.

An important difference from the mSUGRA model is that the sparticles receive masses according to their gauge couplings. In the simplest models of this class, the gaugino masses satisfy the "mass unification condition" of Sec. I, even though there need be no grand unification. Similarly, the squarks are much heavier than sleptons because of their strong interactions, while $m_{\tilde{\ell}_L}$ is substantially larger than $m_{\tilde{\ell}_R}$ because the $SU(2)$ gauge coupling is larger than the hypercharge gauge coupling.

Typically, gauge-mediated models are rather constrained, and for the minimal model, sparticle masses and mixing patterns are determined by the parameters (Λ, M, $\tan\beta$, $\mathrm{sgn}\,\mu$). Here $\Lambda = M^2_{\rm SUSY}/M$ determines the overall scale of the SUSY spectrum, while the boundary conditions on the soft SUSY-breaking parameters are specified at the scale M. The soft parameters are evolved from M to the weak scale, just as in the mSUGRA model. The A parameter at the scale M is small because it is induced at two loops. As before, μ is fixed via the radiative breaking of electroweak symmetry.

A very important feature of these models is that the SUSY-breaking scale (which determines the gravitino mass) can be smaller than the 10^{11} GeV of the SUGRA framework. If this scale is $\sim$ 100 TeV, the gravitino mass is a fraction of an electron-volt! As has been pointed out by Fayet [6], the longitudinal components of such superlight gravitinos do not decouple, so the lightest neutralino (which is typically the next-to-lightest supersymmetric particle) can decay into a gravitino and a photon (or a Z or Higgs boson) via its photino (zino or Higgsino) component at a rate that might be relevant for collider phenomenology. This leads to novel signatures for supersymmetry involving hard, isolated photons. In models with a larger messenger sector, $m_{\tilde{\ell}_R} < m_{\tilde{\chi}^0_1}$, and the phenomenology can be quite different. We refer the reader to the report of the Theory Subgroup for further discussion of this framework. Several studies [7] have recently appeared discussing the phenomenology of this class of models.

III. THE SUPERSYMMETRY REACH OF FUTURE FACILITIES

The SUSY reach of TeV33 [8, 9, 10] and the LHC [11, 12] has been examined in several studies prior to this Workshop. Besides the standard missing-energy signal, the cascade decays of gluinos and squarks also lead to characteristic events with hard, isolated leptons plus jets and missing transverse energy, $\not{E}_T$. In addition, the production and subsequent leptonic decays of charginos and neutralinos gives rise to multilepton plus $\not{E}_T$ events with low numbers of hadrons, the most striking of which are trilepton events from $\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ production. This channel is especially important for SUSY discovery at TeV33, where the production of gluinos and squarks (which are much heavier than $\tilde{\chi}^\pm_1$ and $\tilde{\chi}^0_2$) is kinematically suppressed, and electroweak chargino and neutralino production is the dominant source of SUSY events.

At e^+e^- colliders, it is well known that the discovery of charged sparticles (and also the sneutrino, if it has visible decays) is relatively straightforward for sparticle masses up to about half the beam energy. The discovery reach is not contingent upon beam polarization, which as we will see, is very useful for untangling the underlying production processes.

Within the mSUGRA framework, the SUSY reach is largely determined by the values of m_0 and $m_{1/2}$, which fix the scales of the sparticle masses. The $m_0 - m_{1/2}$ plane (for fixed values

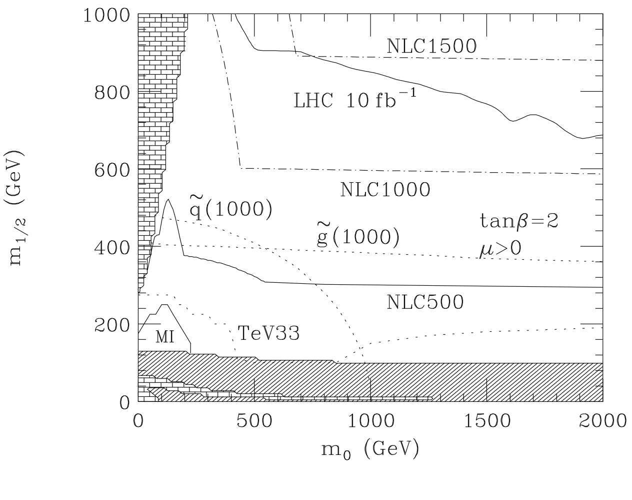

Figure 1: The SUSY reach of various facilities in the mSUGRA model, for $\tan\beta = 2$, $A_0 = 0$ and $\mu > 0$.

of A_0 and $\mathrm{sgn}\,\mu$) provides a convenient panorama for comparing the reach of various facilities, as shown in Fig. 1. (The figure corresponds to $\tan\beta = 2$, $A_0 = 0$ 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 [8]. The region below the lines labeled MI and TeV33 is where experiments at the Tevatron should be able to discover SUSY, assuming an integrated luminosity of 2 and 25 fb^{-1}. The discovery region is a composite of several possible discovery channels, although the $\not{E}_T$ and clean 3ℓ channels dominate the reach. To help orient the reader, we have also shown contours for gluino and squark masses of 1 TeV.

The upper solid line of Fig. 1 shows the boundary of the corresponding region at the LHC [11]; it essentially coincides with the discovery region in the 1ℓ + jets + $\not{E}_T$ channel. Similarly, the solid line labeled NLC500 denotes the reach of the NLC operating at $\sqrt{s} = 0.5$ TeV, as obtained using ISAJET [13]. It consists of three parts: the horizontal portion at $m_{1/2} \sim 300$ GeV essentially follows the $m_{\tilde{\chi}_1^\pm} = 250$ GeV contour, while the rising portion below $m_0 = 200$ GeV follows the $m_{\tilde{e}_R} = 250$ GeV contour. (The reach drops when $m_{\tilde{e}_R} \simeq m_{\tilde{\chi}_1^0}$ because the daughter electron becomes too soft.) An observable signal from $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0$ makes up the intermediate portion of the contour. The dashed-dotted contours mark the boundaries of the region where $\tilde{\chi}_1^\pm$ and/or $\tilde{e}_R$ are kinematically accessible at NLC1000 or 1500. Although new backgrounds from two-to-three- and four-particle production processes have not been evaluated, we believe that this region closely approximates the reach of the NLC operating at these higher energies.

Several comments are worthy of note:

- Although TeV33 can probe an interesting region of parameter space, there is a significant range of parameters, consistent with qualitative upper bounds on sparticle masses from fine tuning arguments, where there is no observable signal. This can even be true if the chargino mass is at its current experimental lower bound. Nevertheless, it is important to search directly for gluinos even in regions of parameter space "excluded" by the LEP experiments, since this exclusion requires an assumption about gaugino mass unification that may prove to be incorrect. Note that the discovery reach of TeV33 is not overwhelmingly larger than that of the Main Injector (MI). Of course, if any signal is discovered during the MI run, the larger data sample from TeV33 would be extremely helpful in elucidating its origin.

- The LHC has a very large reach for supersymmetry and can see gluinos and squarks up to and beyond 1.7 TeV (2.2 TeV if gluinos and squarks are roughly degenerate). This provides a significant safety margin over the upper limits expected from fine-tuning arguments. Furthermore, one expects a SUSY signal in several channels over much of the region with $m_{1/2} \lesssim 500 - 600$ GeV. For comparison, we quote the reach obtained by the ATLAS collaboration [12], using a very different analysis within the MSSM framework: they obtained a reach of $m_{\tilde{g}} = 1600$ (1050) GeV, 2300 (1800)GeV, 3600 (2600) GeV for $m_{\tilde{q}} = 2m_{\tilde{g}}$, $m_{\tilde{q}} = m_{\tilde{g}}$ and $m_{\tilde{q}} = m_{\tilde{g}}/2$, respectively, assuming an integrated luminosity of 100 fb^{-1} (1 fb^{-1}).

- For the purposes of assessing the SUSY reach (and for this purpose alone), we see that an e^+e^- collider operating between $1 - 1.5$ TeV has a reach similar to that of the LHC.

Our considerations have thus far been confined to the mSUGRA framework where the undetected LSP's provide the benchmark $\not{E}_T$ signal. We have, however, seen in Sec. II that if R-parity is violated, the $\not{E}_T$ signal may be greatly degraded. At hadron colliders it is reasonable to suppose that the worst-case scenario is when the LSP's decay hadronically via operators which violate baryon number. In this case, not only is there no $\not{E}_T$ from $\tilde{\chi}_1^0$, but the additional jets from its decay degrade the lepton isolation, and so reduce the cross section for the multilepton signals. Indeed, it has been shown [14] that gluinos and squarks as light as 200 GeV might escape detection at the MI. This led the LHC Subgroup [15] to examine how the SUSY reach is affected in such a scenario. Assuming that the R-parity violating interactions do not affect SUSY production or the decays of any sparticle other than the LSP, it was shown [16] that with a data sample of 10 fb^{-1}, experiments at the LHC can observe gluinos and squarks with masses beyond 1 TeV, even with cuts designed to detect SUSY as realized in the mSUGRA model.

Finally, we mention that while the reach of the NLC was not examined within the context of this scenario, we expect that in the clean e^+e^- environment, these signals would give rise to very spherical events that would likely be detected. In fact, the SUSY reach may even be larger than in the mSUGRA framework because the pair production of LSP's would lead to visible signals (assuming a sufficient cross section).

IV. DETERMINATION OF THE ORIGIN OF NEW PHYSICS SIGNALS

An important goal of this study was to determine methods for establishing whether an observed signal is of supersymmetric origin, and further, to examine whether the new data are compatible with mSUGRA or some other supersymmetric framework. One would also like to know whether it is possible to determine the underlying model parameters from the data.

Since it is not practical to do detailed signal studies over the entire parameter space, even for the mSUGRA model (let alone its variations), our strategy was to choose a few representative scenarios to be studied by the TeV33, LHC and the NLC Subgroups. To highlight the different capabilities of the facilities, we made different choices for the three subgroups. However, to facilitate direct comparison, we chose one common scenario in which the sparticle spectrum was light enough to enable detailed study at each machine. The mSUGRA parameters of this scenario are

$$(m_0, m_{1/2}, A_0, \tan\beta, \mathrm{sgn}\,\mu) = (200, 100, 0, 2, -1),$$

where all mass parameters are in GeV. For this choice, $m_{\tilde{g}} = 298$ GeV, with the first two generations of squarks about 20 GeV heavier. The slepton masses range between 206 and 216 GeV. The lighter chargino and the $\tilde{\chi}_2^0$ masses are 96 and 97 GeV, while the LSP 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.

For the parameters and sparticle masses in the other scenarios studied at the Workshop, we refer the reader to the subgroup reports [15, 17, 18] elsewhere in these proceedings. All but one of these scenarios are within the mSUGRA framework. We are aware that the various assumptions that underlie this framework may ultimately prove to be incorrect. Our attitude is that this framework leads to a rich variety of signals, and that even if it proves to be erroneous, it serves as an excellent theoretical laboratory for a broad comparison of the capabilities of the experimental facilities for the discovery and analysis of supersymmetry (and for that matter, other forms of new physics).

Not surprisingly, the strategy adopted by each of these subgroups was very different. We will, therefore, review the highlights of the results of each subgroup separately, and conclude in the next section with a comparison.

A. Capabilities of the TeV33 Upgrade

1. *Charginos and Neutralinos*

The TeV33 Subgroup studied trilepton signals, requiring that there be no more than one jet in any event, for the common scenario as well as for another mSUGRA point, with $m_0 = 100$ GeV and $m_{1/2} = 150$ GeV (and with the other parameters as for the common point). They estimate about 500 (425) signal events for the common (other) point, assuming an integrated luminosity of 30 fb^{-1}. They find that for the case where $\tilde{\chi}_2^0$ decays via three-body modes, it should be possible to measure $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ by determining the end point of the mass distribution of the closest pair of oppositely-charged same-flavor dileptons in the event. Although they give no quantitative estimate of the precision, it seems clear from the sharp edge in the $m(\ell^+\ell^-)$ distribution shown in Fig. 2 of Ref. [17] that this mass difference can be well determined. Since $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_{1,2}^0$ are gaugino-like over a wide range of mSUGRA parameters, this measurement directly yields $m_{1/2}$.

The TeV33 study of the dilepton distribution for the other scenario reveals the care that must be exercised in arriving at conclusions from the data. In this scenario, the sleptons are lighter than the parent charginos and neutralinos. Therefore the charginos and neutralinos decay to real sleptons whose subsequent decays lead to a trilepton final state. The subgroup finds that although $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ is about 70 GeV (as compared to 51 GeV for the common point), the dilepton mass spectrum cuts off at roughly the same point as in the previous study. By plotting several other distributions, the TeV33 Subgroup can distinguish between the scenarios. Even at the MI, where just ~ 20 signal events are expected, their likelihood analysis (see Fig. 4, Ref. [17]) shows that the chance of confusing these scenarios is just 9%. At TeV33, where there are many more events, the discrimination power should be significantly increased.

2. *Gluinos*

The TeV33 Subgroup examined signals from gluino production for the common scenario. In this case, $B(\tilde{g} \to b\tilde{b}_1) = 0.89$, and $B(\tilde{b}_1 \to b\tilde{\chi}_2^0) = 0.86$. Since the leptonic decays $\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$, with $\ell = e,\ \mu$, have a combined branching fraction ~ 0.33, the main signal for gluino pair production consists of events with several b-jets together with several leptons and $\not{E}_T$.

In their study, the TeV33 Subgroup attempted to separate the SUSY signal from SM and instrumental backgrounds by requiring at least two isolated opposite-sign leptons of the same flavor, accompanied by at least two tagged b-jets and $\not{E}_T > 20$ GeV. They assume a b-tagging efficiency of 66% and show that the dilepton pairs in these events have a mass distribution which cuts off at more or less the same position as that from the trilepton sample discussed previously. This serves as an independent confirmation of their origin in $\tilde{\chi}_2^0$ decays.

The TeV33 Subgroup repeated the technique first used by the LHC Subgroup at this Workshop to identify the gluino origin of this signal. The idea [15, 19] is that for events where the dilepton mass is close to the end point of the $m(\ell^+\ell^-)$ distribution, the dilepton system as well as $\tilde{\chi}_1^0$ are at rest in the rest frame of $\tilde{\chi}_2^0$. For a fixed value of $m_{\tilde{\chi}_1^0}$, which they chose to be $m_{\tilde{\chi}_2^0}/2$, the 3-momentum of $\tilde{\chi}_2^0$ can readily be constructed from the observed momenta of the leptons. The $\tilde{\chi}_2^0$ can be combined with a tagged b-jet (at the cost of a combinatorial background) to reconstruct $\tilde{b}_1$. Finally, the reconstructed $\tilde{b}_1$ can be combined with another tagged b-jet to yield the parent gluino. If multiple b plus multilepton events have their origin in the gluino decay cascade, a scatter plot in the $m_{\tilde{b}_1} - \Delta m$ plane (where $\Delta m = m_{\tilde{g}} - m_{\tilde{b}_1}$ and the masses are reconstructed as described) would show a clustering at the proper values of Δm and $m_{\tilde{b}_1}$, with the rest of the plot being populated by the incorrect assignment of jet and $\tilde{\chi}_2^0$ momenta. From a fit to the projection which yields the Δm distribution, the TeV33 Subgroup claims $\Delta m = 23.3 \pm 1.2$ GeV, which should be compared to the input value of 20 GeV. The systematics associated with this measurement, as well as with the corresponding "measurement" of $m_{\tilde{b}_1}$, have yet to be analyzed.

Although the subgroup was not able to complete an analysis of the multijet signal in the $\not{E}_T$ channel, they suggest that such an analysis will be possible because preliminary estimates for the common scenario indicate that there should be a 10σ excess above the background, even at the MI. They anticipate (although this study has not been performed) that it should be possible to extract gluino/squark masses as well as the gluino/squark admixture in the SUSY sample at TeV33.

3. *A Light Scalar Top*

The left- and right-handed scalar top quarks can have significant mixing, so the lightest mass eigenstate ($\tilde{t}_1$) may be much lighter than the other squarks. The TeV33 Subgroup examined the possibility of discovering $\tilde{t}_1$ at the Tevatron in a mSUGRA model with $(m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \mathrm{sgn}\,\mu) = (200,\ 130,\ -400,\ 2,\ +1)$. In this model, the lighter of the two stop states has a mass of 140 GeV and decays via $\tilde{t}_1 \to b\tilde{\chi}_1^\pm$.

Since the chargino decays via $\tilde{\chi}_1^0 f\bar{f}'$ into SM quarks and leptons, the final states from t-squark pair production have the same topology as those from $t\bar{t}$ production; an important difference is that stop events tend to be softer because a significant portion of the energy in the event resides in the massive LSP's.

The TeV33 Subgroup examined prospects for detecting the scalar top in the dielectron plus jets channel. To separate the SUSY signal from the $t\bar{t}$ background, they require that $\Sigma H_T = \Sigma|p_T^{jet\ i}| + |p_T^{elec\ 1}| < 250$ GeV and $B = |p_T^{elec\ 1}| + |p_T^{elec\ 2}| + |\not{E}_T| < 100$ GeV [20], in addition to the usual acceptance cuts. Their analysis, which does not include a complete detector simulation, predicts a signal of 142 events versus a background of 118 for a data sample of 37 fb^{-1}. The subgroup anticipates that a complete detector simulation will lead to an overall reduction in detection efficiency of both signal and background by a factor of two, and a further reduction by 60% if both b-jets need to be tagged to reduce Drell-Yan and misidentification backgrounds. The subgroup suggests that an integrated luminosity of 20 fb^{-1} will be necessary for an unambiguous detection of this signal [17].

B. Capabilities of the LHC

In Sec. III we saw that the discovery of SUSY is no problem at the LHC, even in the unfavorable case where the LSP decays hadronically into three jets. We also noted that several SUSY reactions can contribute to each final state, and that there are detectable signals in several channels over the range of parameters where sparticle masses are smaller than 1 TeV. Indeed, the dominant backgrounds for any particular SUSY process are *other* SUSY processes.

An especially interesting development at this Workshop was the demonstration that experiments at the LHC have the potential to make precision measurements of some SUSY parameters. Here, we will focus on the comparison scenario for brevity, and only allude to the results for other case studies performed at the Workshop [15]. Further details may be found in Ref. [21].

1. A Measure of Gluino or Squark Masses

Gluinos or squarks are expected to be the most copiously produced sparticles at the LHC. Measurements of their masses are complicated by the fact that every SUSY event contains at least two undetected LSP's. In previous work, a precision of 15-25% has been typically achieved [22] for sparticle masses below about 700 GeV. A different technique was proposed at this Workshop, where it was shown that distributions in the variable [23]

$$M_{\rm eff} = |p_T, 1| + |p_T, 2| + |p_T, 3| + |p_T, 4| + \not{E}_T,$$

defined as the scalar sum of the transverse energies of the four hardest jets plus $\not{E}_T$, yield a measure of the mass scale for gluinos/squarks, defined by $M_{\rm SUSY} = \min(m_{\tilde{g}}, m_{\tilde{u}_R})$, to a precision of about 10%. Here, the choice of $\tilde{u}_R$ to represent the squark mass scale is arbitrary. Since this method appears to require only a moderately clean sample of SUSY events, it should be possible to determine $M_{\rm SUSY}$ for gluinos/squarks as heavy as 1.5 TeV in about three years of low luminosity LHC operation [23]. The efficacy of the method was demonstrated for squarks and gluinos of $900 - 1000$ GeV (cases B and C studied by this subgroup).

2. Precision Measurements

Precision measurements of supersymmetric parameters are possible at the LHC because of large data samples. Indeed, for the comparison scenario, one expects 13.5M SUSY events with just 10 fb^{-1} of integrated luminosity. This enormous data set permits very stringent selection cuts to isolate relatively pure samples of events from particular SUSY processes.

Consider, for example, gluino production. As we saw in TeV33 subsection, the decay chain $\tilde{g} \to b\tilde{b}_1 \to bb\tilde{\chi}_2^0 \to bb\ell^+\ell^-\tilde{\chi}_1^0$ ($\ell = e, \mu$) has a branching fraction of $\sim 25\%$, so that even with a tagging efficiency of 60% (and c misidentification of 10%) per b-jet, gluino pair production leads to 272K events with

- 4 tagged b-jets, and
- 2 pairs of opposite-sign like-flavor isolated leptons, one from each $\tilde{\chi}_2^0$ decay,

per 10 fb^{-1} at the LHC. If only one of the neutralinos is required to decay leptonically, gluino production results in a sample of about 694K almost-as-spectacular events, with

- 4 tagged b-jets,
- 2 isolated opposite-sign, same-flavor leptons, and
- 2 non-b jets.

A clean gluino sample is obtained by selecting events with six or more jets, at least three of which are tagged as b-jets, together with a pair of opposite-sign isolated leptons of the same flavor. The measurement of the end point of the dilepton mass distribution yields $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$. This measurement is limited only by the absolute calibration of the electromagnetic calorimeter, and is quoted to yield a precision ≤ 50 MeV! Within the mSUGRA framework, this leads to a very precise determination of $m_{1/2}$. By comparing events with two or four leptons and four tagged b-jets, it is claimed [21] that the product $B(\tilde{b}_1 \to b\tilde{\chi}_2^0) \times B(\tilde{\chi}_2^0 \to e^+e^-\tilde{\chi}_1^0)$ of branching fractions can be measured to be $14 \pm 0.5\%$.

In the cascade chain $\tilde{g} \to b\tilde{b}_1 \to bb\tilde{\chi}_2^0 \to bb\ell^+\ell^-\tilde{\chi}_1^0$ ($\ell = e, \mu$), the momentum of $\tilde{\chi}_2^0$, and hence the mass of $\tilde{b}_1$, can be reconstructed as described in the TeV33 subsection. The LHC Subgroup showed that about 6K gluino and sbottom events can be reconstructed in this way per year of low luminosity running at the LHC. They find that the mass difference $m_{\tilde{g}} - m_{\tilde{b}_1}$ can be measured to ± 2 GeV and that the measurement is rather insensitive to the assumed value for $m_{\tilde{\chi}_1^0}$; the systematic error from jet energy calibration and the assumed value of $m_{\tilde{\chi}_1^0}$ is not quoted.

The authors of Ref. [21] attempt to reconstruct the masses of the superpartners of the light squarks via their decays $\tilde{q} \to q\tilde{\chi}_2^0$, which has a branching fraction of 10%. There is, of course, an enormous background from gluino events which they try to reject by vetoing events with tagged b-jets. The mass reconstruction is performed as for $\tilde{b}_1$ above. Even with a 90% vetoing efficiency, their final event sample contains a significant fraction of $\tilde{b}_1$ events, which broadens their mass peak. They estimate that the mean squark mass can be measured to about 20 GeV.

The LHC Subgroup also attempted to identify sleptons produced via the Drell-Yan process. They select events with at least three leptons (from the cascade decay of $\tilde{\ell}_L \to \ell\tilde{\chi}_2^0$). They apply a stringent jet veto (no jets with $E_T > 30$ GeV), which is crucial to suppress events from gluino and squark production, and to control backgrounds from $t\bar{t}$ production, where a lepton from the decay of a b-quark is accidentally isolated. They find the resulting event sample to be dominated by trileptons from electroweak gaugino production, so it does not seem possible to isolate the slepton signal.

Nevertheless, the rates for clean trilepton events may be regarded as *predictions* of the mSUGRA framework since, as argued below, it is possible to extract the relevant parameters from the measurements of the hadronic data sample discussed above. While it should, in principle, be possible to extract $m_{\tilde{\ell}_L}$ by reconstructing the $\tilde{\chi}_2^0$ in its decay and combining it with an additional lepton, the technique does not work in practice because the trilepton signal is dominated by events from $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ production. Requiring at least four isolated leptons might eliminate this problem, but then the event rate is too small to be feasible, at least for the low luminosity LHC option.

3. *Extraction of mSUGRA Parameters*

At the common point, the measurements,

- $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = 52.36 \pm 0.05$ GeV (1σ),
- $m_{\tilde{g}} - m_{\tilde{b}_1} = 20.3 \pm 2$ GeV (1σ),

together with the measurement of the light Higgs boson mass,

- $m_h = 68.3 \pm 3$ GeV,

that should be possible at LEP 2 (the ± 3 GeV is a theoretical error which reflects the uncertainty in the computation of m_h in terms of underlying parameters) imply that

- $m_{1/2} = 99.9 \pm 0.7$ GeV,
- $m_0 = 200^{+13}_{-8}$ GeV,
- $\tan\beta = 1.95 \pm 0.05$,
- $\mathrm{sgn}\,\mu = -1$.

The parameter A_0, which mainly affects phenomenology through the masses and mixing angles of third-generation sfermions, is not determined but is constrained to be larger than -400 GeV. Since the trilepton rates from $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ and slepton production are insensitive to A_0, we now understand why the cross section for clean trilepton events serves as a non-trivial test of the model. Another independent test is provided by a measurement of the branching ratio product for the $\tilde{b}_1$ and $\tilde{\chi}_2^0$ decays discussed above. (For this small value of $\tan\beta$, b-squark mixing effects, which depend on the A-parameter, are small.)

The LHC Subgroup argues that it should be possible to test consistency with the gaugino mass unification condition as follows. One first extracts the unification scale from the measured values of the gauge couplings. Next, assuming that $\tilde{\chi}_{1,2}^0$ are predominantly gaugino-like, one uses the measured value of $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$ and the gaugino unification condition to extract $m_{1/2}$, which one then evolves back to the weak scale to obtain $m_{\tilde{g}}$ and the neutralino masses. Even allowing for a 5% error in this calculation, it is non-trivial to find a value of $m_{\tilde{\chi}_1^0}$ that simultaneously yields agreement with the experimental values of $m_{\tilde{\chi}_2^0}$ and $m_{\tilde{g}}$. Such a match can be taken to be a test of gaugino mass unification.

4. *Other Case Studies*

Preliminary work for other cases of mSUGRA parameters was done at the Workshop. A more complete analysis appears in Ref. [21]. In some cases, the LHC Subgroup showed that it is possible to reconstruct a light Higgs, h, produced via cascade decays of gluinos and squarks, through its $b\bar{b}$ decay. The LHC Subgroup estimates that it should be possible to measure the Higgs mass to about ± 1 GeV.

Another case study (case A) involves sleptons lighter than $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$, so two-body decays of these sparticles to sleptons are allowed. (The $\tilde{\chi}_2^0$ slepton decay competes with its decay to Higgs bosons.) In this scenario, squarks and gluinos are rather heavy, so hard cuts on M_{eff} and the hardest jet can be made to enhance the signal over the SM backgrounds [23]. Because the $\tilde{\chi}_2^0$ now decays through a cascade of two-body decays, the kinematic edge of the dilepton mass distribution occurs below $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$. We refer the reader to Ref. [21] for details about the extraction of the slepton mass.

Ref. [21] also includes a study of the mSUGRA parameters for other LHC scenarios. Typically, $m_{1/2}$ can be measured to a precision of a few percent. Even for the extreme case where gluinos and squarks are as heavy as 1 TeV, $m_{1/2}$ can be obtained to within 10%. The precision with which other parameters can be extracted depends on the scenario, but it is found that for the most part, it is possible to obtain allowed ranges of $\tan\beta$ and m_0. Sometimes two possible solutions are found; more detailed measurements would be required to discriminate between them. In brief, these studies underscore the capabilities of LHC experiments and contain the first steps towards an effective measurement strategy at the LHC [11, 21].

C. Capabilities of the NLC

It is well accepted that the discovery of new physics is relatively easy in the clean environment of an e^+e^- collider, provided the machine is operated above threshold for this new physics and that it has sufficient luminosity. Furthermore, at these machines, aside from a few exceptions such as the neutralinos of supersymmetry, all sparticles with non-vanishing electroweak quantum numbers are produced with comparable cross sections.

Electron-positron colliders, therefore, provide the potential for discovery of a wide variety of new physics. We have already seen that the discovery of charged sparticles (and sneutrinos, if they decay visibly) is relatively straightforward. Neutralinos, however, can escape detection. Gauge invariance requires that they couple to the Z boson only via their Higgsino components, which implies that their cross section can be strongly suppressed if they are gaugino-like and selectrons are heavy. The range of mSUGRA parameters where it should be possible to discover SUSY at the NLC via neutralino signals is shown by the intermediate portion of the discovery contour in Fig. 1.

If sparticles are indeed produced at the NLC, it is interesting to ask what can be learned about their properties. The precise knowledge of the collision energy greatly facilitates the reconstruction of events with undetected particles in the final state. The JLC [24] group has pioneered a program where they have shown that it is possible to measure chargino, LSP and slepton masses to a precision of $\sim 2\%$, and further, to make other precision measurements which will allow incisive tests of the assumptions that underlie the mSUGRA framework. The JLC study ignores cascade decays since it is assumed that the machine energy can be tuned so that only one new sparticle is produced. This study makes innovative use of electron beam polarization, which was taken to be 95%.

At this Workshop, the capability of the NLC was examined [18] including the effects of cascade decays as given by ISAJET. The beam polarization was conservatively taken to be 80%. The discovery potential and precision measurements that might be possible at the NLC with cascade decays have also been examined in Ref. [13].

1. Beam Polarization

Although not critical for SUSY discovery, the availability of beam polarization plays a crucial role in sorting out SUSY signals at the NLC. First, the use of a right-handed electron beam greatly reduces [24] the main SM background from WW production. Second, it predominantly selects right-handed selectron processes, as can be seen from Fig. 9 of the subgroup report [18]. Of course, a left-handed electron beam is better suited to study the $\tilde{e}_L$ or charginos of the mSUGRA framework.

The main point here is that beam polarization makes it possible to single out subsets of sparticle reactions. Another important benefit of beam polarization stems from the fact that it increases the number of observables: this has been put to good use for the extraction of model parameters [24], and as we will discuss below, also for direct tests of SUSY [25, 26].

2. Mass Measurements

The energy spectrum of particles produced by the two-body decay of spin-zero particles (*e.g.* the spectrum of electrons produced via $e^+e^- \to \tilde{\ell}_R^+\tilde{\ell}_R^- \to \ell^+\ell^-\tilde{\chi}_1^0\tilde{\chi}_1^0$) is, aside from detector acceptance effects, flat; a measurement of the endpoints of this distribution leads to a precise determination of the selectron and LSP masses. The NLC Subgroup used this technique for the comparison scenario with right-polarized electrons. They obtain best-fit values of 45.1 ± 1.5 GeV and 208.2 ± 0.7 GeV for $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{e}_R}$, which may be compared with the input values of 44.5 GeV and 206.6 GeV, respectively.

Since this kinematic procedure does not depend on whether the daughters of the parent spin-zero particle are stable, it can also be used in the presence of cascade decays if a sample of events from a single SUSY reaction can be isolated. With a left-handed e^- beam, the process $e^+e^- \to \tilde{\nu}_e\bar{\tilde{\nu}}_e \to e^-\tilde{\chi}_1^+e^+\tilde{\chi}_1^- \to e^+e^-\mu^\pm\tilde{\chi}_1^0\tilde{\chi}_1^0jj$, where one of the charginos decays to a muon and the other into jets, provides an opportunity for a simultaneous measurement of $m_{\tilde{\nu}_e}$ and $m_{\tilde{\chi}_1^\pm}$. Assuming an integrated luminosity of 20 fb^{-1} at NLC500, the extracted masses,

- $m_{\tilde{\nu}_e} = 207.5 \pm 2.5$ GeV,
- $m_{\tilde{\chi}_1^\pm} = 97.0 \pm 1.2$ GeV,

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

The same technique was used previously [13] to extract the mass of the lighter stop and chargino for parameters such that $\tilde{t}_1$ decays via $\tilde{t}_1 \to b\tilde{\chi}_1^\pm$. In this study, it was shown that the t-squark mass can be measured to about 6% at 90% CL (and better if the chargino mass is independently determined).

The measurement of sparticle masses is also possible when sparticles decay via three-body decays. The NLC Subgroup analyzed a sample of $4j$ events from chargino pair production (NLC point 5), where both charginos decay hadronically. They find that the end point of the E_{jj} distribution (even with the correct assignments of jets) is not as sharp as for two-body decays. However, by requiring M_{jj} to lie in a narrow range (around 30 GeV in this study), it is possible [13] to simulate a two-body decay. The NLC Subgroup used this technique to fit the energy spectrum and find

- $m_{\tilde{\chi}_1^\pm} = 107.5 \pm 6.5$ GeV,
- $m_{\tilde{\chi}_1^0} = 55.0 \pm 3.5$ GeV,

for an integrated luminosity of 50 fb^{-1}, as compared to the input values of 109.8 GeV and 57.0 GeV, respectively.

It should be mentioned that ISAJET, which is used for these simulations, does not include either initial-state radiation or beamsstrahlung. These effects distort the energy spectra and potentially degrade the precision with which the end points can be determined. The NLC Subgroup studied [18] these effects using SPYTHIA. They conclude that the few percent change in the spectrum can be readily corrected so the precision of the mass measurements is not adversely affected. However, these radiation effects can reduce the production cross sections, so the statistical error may increase somewhat.

3. Model Independent Analysis

The NLC Subgroup also devised a strategy for analyzing a sample of SUSY events without assuming any particular SUSY framework. Although their analysis was performed for the common scenario, the procedure is really quite general. They start by envisioning a machine which would first run at about

350 GeV (which, incidentally, allows a study of the top threshold). If no sparticles are discovered, they would then increase the energy.

For the case at hand, however, chargino signals would be readily discovered during the initial 350 GeV run. Since the masses are most precisely measured just above threshold, the NLC Subgroup advocates *lowering* the machine energy to 250 GeV and making measurements with both left- and right-polarized (80% polarization) electron beams. The reason for this is that the relative importance of the sneutrino-mass-dependent t-channel amplitude is sensitive to the beam polarization. With 20 fb^{-1} of integrated luminosity, the cross sections with an 80% left- (right-) polarized beam can be measured to a precision of 1.5% (2%). These measurements then allow one to *predict* that $m_{\tilde{\nu}_e} < 250$ GeV. Furthermore, the chargino and LSP masses can be measured to a precision of 1% following the methods described above.

The next step is to run the machine above the sneutrino threshold, *i.e.* at $\sqrt{s} = 500$ GeV. Note that $SU(2)$ gauge symmetry dictates that $m(\tilde{e}_L)$ cannot be very different, so it is reasonable to expect $\tilde{e}_L\bar{\tilde{e}}_L$ production as well. With 20 fb^{-1} of integrated luminosity and an 80% right-handed electron beam, the masses of $\tilde{\nu}_e$, $\tilde{e}_R$, $\tilde{\mu}_R$ and $\tilde{e}_L$ can be measured to a precision of 2%, 1%, 1.5% and 7%, respectively.

4. *Is it Supersymmetry?*

The observation of particles with the spins and internal quantum numbers expected in SUSY would be an extremely strong indication that nature is supersymmetric. However, the most convincing proof would come from testing the supersymmetric relations between the couplings of the various particles. Note that unlike the mass relationships, the tree-level SUSY relationships between various dimensionless couplings are preserved even if supersymmetry is softly broken — for instance, the electron-selectron-photino coupling is fixed by the electromagnetic interaction. Indeed, the situation parallels that in spontaneously broken gauge theories, where coupling constant relationships are preserved even though the mass relations implied by gauge symmetry are badly violated.

In practice, a program to directly test the SUSY relationships is complicated by the fact that sparticles are generally model-dependent mixtures of states with definite gauge quantum numbers. Just how one would verify such relations depends on the values of SUSY parameters. The original proposal [25] focused on the pair production of charginos which, in the gaugino (mixed) region, allowed verification of equality of the gaugino-sneutrino-electron (Higgs-Higgsino-gaugino) coupling and the W-boson-neutrino-electron (Higgs-Higgs-W-boson) gauge coupling to a precision of about 30%.

A more precise test [26] was suggested at this Workshop where it was shown that an accurate measurement of the cross section and angular distribution of electrons produced via $e^+e^- \to \tilde{e}_R^+\tilde{e}_R^-$, could, with 100 fb^{-1} of integrated luminosity, lead to a 2% measurement of the electron-selectron-bino coupling. Such a precise measurement begins to be sensitive to radiative corrections, which, in turn, are sensitive to the masses of sparticles which may not be kinematically accessible.

All the tests described here were carried out using parton-level calculations assuming 100% beam polarization. It has yet to be studied how well they survive a more realistic simulation as well as more conservative assumptions about beam polarization.

5. *Testing Gaugino Mass Unification*

A direct test [24] of gaugino mass unification can be carried out at NLC if both $\tilde{e}_R$ and $\tilde{\chi}_1^\pm$ are accessible and if a right-handed polarized electron beam is available. The idea is that a measurement of the two masses, $m_{\tilde{\chi}_1^\pm}$, $m_{\tilde{\chi}_1^0}$, and the two cross sections, $\sigma_R(\tilde{e}_R\tilde{e}_R)$, $\sigma_R(\tilde{\chi}_1^+\tilde{\chi}_1^-)$, can be used to determine the four parameters, $\mu, \tan\beta$ and M_1, M_2, the two soft SUSY-breaking gaugino masses that enter the chargino and neutralino mass matrices. The precision with which each of these parameters can be determined depends on the model. The gaugino masses are well determined if the chargino has substantial gaugino components, so the gaugino mass relation can be tested to a precision of few percent, assuming an integrated luminosity of 20 fb^{-1} (50 fb^{-1}) at $\sqrt{s} = 350$ (500) GeV.

6. *Tests of the mSUGRA Model and Determination of Underlying Parameters*

The direct measurement of sparticle masses allows several non-trivial tests of the constrained mSUGRA framework. The most obvious of these is the unification of scalar masses which can be directly tested from the flavor independence of the masses for each variety of slepton. There is no *a priori* reason why $m_{\tilde{e}_R} = m_{\tilde{\mu}_R} = m_{\tilde{\tau}_R}$ (and likewise for the left-handed sleptons). If the unification of gaugino masses is independently confirmed, the universality of scalar masses can then be tested since $\Delta m^2_{LR} = m^2_{\tilde{e}_L} - m^2_{\tilde{e}_R}$ is largely determined by $m_{1/2}$. Since $\tilde{e}_L$ and $\tilde{e}_R$ belong to different SM multiplets, their masses are unrelated, and are indeed quite different in the various frameworks discussed by the Theory Subgroup. In fact, a measurement of Δm_{LR} might well serve to distinguish between some of these models.

How well do the various precision measurements determine the SUSY parameters? For the comparison scenario, the NLC Subgroup finds [18]

- $\delta m_0 = \pm 2.7$ GeV,
- $\delta m_{1/2} =^{+2.5}_{-1.0}$ GeV,
- $\delta \tan\beta =^{+0.17}_{-0.31}$,
- $\mathrm{sgn}\,\mu = -1$.

At the comparison point these parameters determine the masses of the first two generations of squarks to be just over 320 GeV. Direct detection requires that the NLC run at $\sqrt{s} = 800$ GeV. The NLC Subgroup claims that the squark masses should be measurable to a precision of about 10%. Finding squarks at the expected mass would provide striking support of the mSUGRA framework.

It would also be interesting to examine whether it might be possible to isolate a sample of top squark events and extract information about the remaining parameter, A_0.[1] Other measurements which should be possible at the NLC, *e.g.* of branching fractions of charginos and neutralinos, would provide additional tests of this framework.

V. CONCLUDING REMARKS

Although the mSUGRA scenario provides an economic, consistent and calculable framework for phenomenological studies, one must keep in mind that it is based on untested assumptions about the symmetries of high-scale dynamics. In Sec. II we saw several examples in which alternative assumptions about these symmetries change the sparticle mass and mixing patterns, and therefore expectations about SUSY signals at colliders.

Recently developed models in which SUSY breaking is communicated to the observable sector via gauge interactions are especially interesting because they provide a serious alternative to the canonical scenario where gravity communicates this information. In these gauge-mediated models, SUSY signatures may be quite different [7] from those in mSUGRA: depending on the details of the model and parameters, they may include multilepton plus multijet events with additional hard photons, τ-leptons, or other particles, possibly with displaced vertices or kinked tracks. It should also be remembered that R-parity might not be conserved, in which case the usual $\not{E}_T$ signal might not be observable.

Luminosity upgrades of the Tevatron will probe the regions of SUSY parameter space that are most favored by (subjective) fine-tuning arguments. The reach of the Tevatron with 2 fb^{-1} and 25 fb^{-1} of integrated luminosity is illustrated in Fig. 1. It could well be that the first SUSY signals will be found at the Tevatron, which should be operated to accumulate as much data as can be handled by the detectors. But even with 25 fb^{-1} of integrated luminosity, there is a substantial region of parameter space where gluinos and squarks are lighter than 1 TeV, and there is no detectable signal.

Whether or not weak-scale SUSY exists will be decisively answered at the LHC. Within the mSUGRA framework, the reach of the LHC extends considerably beyond what is generally regarded as "acceptable" if SUSY is to stabilize a perturbatively coupled Higgs sector. Even in the experimentally difficult case where the LSP decays hadronically within the detector, experiments at the LHC should be able to detect the SUSY signal in several leptonic channels provided gluinos or squarks are lighter than 1 TeV. A multitude of detectable signals is also expected within the mSUGRA framework.

Even without the availability of beam polarization, the SUSY reach of the NLC extends essentially to the beam energy, provided there is sufficient integrated luminosity ($\sim$ 20 fb^{-1} for NLC500). An e^+e^- collider operating at $\sqrt{s} = 1300 -$ 1500 GeV would have about the same SUSY reach as the LHC. NLC500 would be a very interesting machine because it would be guaranteed to find at least one of the Higgs bosons of SUSY (or the Higgs boson of the SM) if Higgs-sector interactions are perturbative up to the unification scale. Indeed, if no Higgs boson is discovered there, many accepted ideas would need to be rethought, since we would be forced to conclude that perturbative unification requires additional new physics at a rather low scale.

However, it is possible for NLC500 to miss the direct detection of SUSY altogether. Quite likely, the detailed exploration of the rich spectrum of SUSY particles will require higher energy. In planning the NLC design, it is *crucial* for the energy of the machine to be upgradeable to $1 - 1.5$ TeV. This would ensure that the facility could completely explore the new physics at the TeV scale.

The Supersymmetry Working Group examined other information which might be gleaned from the data and which might serve to clarify the nature of the new physics, discriminate between various theoretical models, and lead to a determination of the underlying model parameters. At the Tevatron, the clean trilepton signal from $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production permits a measurement of the mass difference between the two lightest neutralinos. It also allows one to distinguish between models where the neutralinos decay to real sleptons and those where three-body decays dominate. The TeV33 Subgroup argued [17] that a measurement of $m_{\tilde{g}} - m_{\tilde{b}_1}$ might also be possible. The high luminosity of TeV33 is essential for these measurements.

The LHC and NLC Subgroups developed various tests of the mSUGRA framework and a set of methods for measuring the underlying parameters. The best method depends on what the parameters turn out to be. For the comparison scenario, it was shown that the mSUGRA parameters (other than A_0) can be extracted with comparable precision at both facilities. The LHC Subgroup obtained a better precision on $m_{1/2}$ and $\tan\beta$, while m_0 was more precisely measured at the NLC.

At first sight it seems surprising that precision measurements are possible at the LHC. The point, however, is that the enormous size of the SUSY data sample permits hard cuts which isolate relatively pure samples of events in each SUSY channel. These samples allow the reconstruction of SUSY masses using kinematic constraints. For the comparison scenario, this technique allowed for a measurement of $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$ which was limited only by the systematic error on the calibration of the electromagnetic calorimeter. Squark/gluino mass measurements at the 10% level should be straightforward. In some cases, the LHC Subgroup demonstrated that mass differences between strongly interacting sparticles may also be measurable. It is worth noting that a 10% measurement of a squark-gluino mass difference substantially constrains the model.

At the NLC, a few percent measurement of the chargino and slepton (and perhaps also $\tilde{\nu}$) masses will be possible if the particles are kinematically accessible. In view of current mass bounds from the Tevatron, it would indeed be fortuitous if squarks are accessible at NLC500. Information about gluinos is generally very difficult to obtain at an e^+e^- collider.

The flavor-independence of slepton masses would furnish direct evidence for the unification of scalar masses. While the fea-

[1] At the fixed point of the top-quark Yukawa coupling, the low-energy parameters are determined [27] by m_0, $m_{1/2}$ and $\tan\beta$. They are essentially independent of A_0. In this case it is neither possible nor relevant to determine A_0.

sibility of this measurement was demonstrated only at the NLC, the unification of gaugino masses can be tested at both machines. (The precision with which the equality between multi-electron and multi-muon signal can be established at the LHC has not been examined. This would provide indirect evidence for slepton mass universality.) A direct test of the SUSY particle couplings appears possible only at the NLC.

What if the mSUGRA turns out to be incorrect? Since it is possible to measure several sparticle masses at the NLC, these data will point to the correct theoretical picture. At the LHC it should be straightforward to *exclude* mSUGRA, or any other particular framework, via a standard χ^2 analysis. However, the broader issue of how to proceed from these data to a determination of the correct theoretical picture is less obvious.

We have seen that experiments at the LHC and NLC do indeed provide complementary information. Together, they will not only reveal supersymmetry if it exists at the weak scale, but will also carry out detailed measurements of the sparticle properties. This information will provide clues that may help us unravel the dynamics of supersymmetry breaking, and further our understanding of how electroweak gauge symmetry is broken.

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