Direct investigations of supersymmetry: subgroup summary report

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DATED: DECEMBER 17, 2001

This is the summary report of the Direct Investigations of Supersymmetry subgroup of the P3 “Scales beyond 1 TeV" working group of Snowmass 2001.

1. Introduction

Supersymmetry (SUSY) is generally regarded as the most promising solution to the hierarchy problem associated with the small ratio of the electroweak (EW) scale to the Planck scale or other possible large mass scales. SUSY is a quite predictive framework, and leaves no doubt as to the quantum numbers of the plethora of new particles that it predicts. Much of what we do not already know about SUSY from the theoretical point-of-view has to do with the mechanism of SUSY-breaking, which has as its most important manifestation the masses and the mixing angles of the superpartners. The success of future direct collider investigations of SUSY will therefore hinge on how well and how unambiguously one can disentangle the SUSY-breaking mechanism.

If low-energy SUSY is indeed the solution to the hierarchy problem, then it is most likely that direct evidence for it will be found first either at the Tevatron Run II or the LHC. However, this should be regarded as only part of the process of firmly establishing SUSY as a correct description of nature at the EW scale. The complete set of observables which will need to be investigated at the LHC and beyond include the new particle spins, charges, EW and color quantum numbers, masses, widths, branching ratios, couplings (including mixing angles and CP-violating phases), and production cross-sections. The LHC will probably allow the determination of a small subset of these observables for some of the particles and will allow consistency tests of the hypothesis that SUSY has been discovered.

However, in several areas the LHC is likely to leave crucial questions unanswered, or answered only with important caveats. Superpartner mass differences may possibly be measured with great accuracy at the LHC, but the lightest superpartner (LSP) mass will have a much larger uncertainty. Slepton parameters will be hard to determine. Identifying and measuring the masses of each of the 13 strongly interacting squark and gluino states will present a significant challenge. Determination of the mixing angles in the neutralino and chargino sectors will be extremely difficult at the LHC.

Moreover, there are many “second-level" questions regarding SUSY that would leap to the forefront after discovery. One would like to know whether R-parity is violated; if it appears to be

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conserved, one would like to place an upper limit on modes of R-parity violation. Do the gaugino masses fit a pattern, and if so, are they consistent with the predictions of gauge coupling unification? Do the various slepton masses and squark masses fit patterns? Is there a significant component of CP-violation not associated with the Standard Model (SM) CKM phase? Most such questions are related to the issue of how SUSY is broken.

An e^+e^- linear collider (LC) would provide the observations to understand the properties of the particles that are kinematically accessible. Such a collider is ideal for producing cleanly the particles with purely EW couplings, the sleptons, sneutrinos, charginos and neutralinos. This contrasts with the LHC which is better placed to produce the squarks and the gluino. Using the beam polarisation and the ability to scan in energy, the LC should be able to separate each state and measure the individual couplings, masses, cross-sections and branching ratios in a systematic way largely independently of particular details of the actual scenario. Thus the LC could provide the data which answers definitively many of these important second-level questions.

However with no firm experimental or theoretical guidance, we do not know how heavy the superpartners can be. It is therefore simply not possible to guarantee superpartner discovery at the LHC, nor specify definitively a sufficient centre-of-mass (CM) energy for SUSY exploration at the LC. While a TeV-scale LC ought to be able to carry out crucial measurements for establishing SUSY and telling us what kind of SUSY we have found, it is possible to find scenarios where an upgrade path to higher CM energies would be very desirable especially for the heavier superpartners. Given the unique potential of lepton colliders to probe and understand the interactions of the superpartners, we will also want to explore the heaviest superpartners with lepton colliders. This may require a collider which extends into the multi-TeV regime, where development work on two-beam acceleration schemes such as CLIC for e^+e^-, or the muon collider concept are potential technologies for the future.

The plan of the report is as follows. In the next Section, we provide the reader with a comparison among the computing tools used to carry out the phenomenological studies of SUSY in our group. Sect. 3 defines the theoretical frameworks in which most of the studies of this subgroup have been carried out. Sect. 4 addresses the issue of extrapolating values of SUSY-breaking parameters to very high energy scales using future data from the LHC and a LC. Then, we review the main results of a series of studies concerned with the reconstruction of specific signals of various SUSY-breaking scenarios at different colliders (Sect. 5). Finally, we summarize and draw up our views of what at present the priorities are in pursuing the direct detection of SUSY at future high energy colliders.

2. Tools for SUSY

It is convenient to divide the available programs in two sets and to stay with those actually used in the context of this workshop. [Besides, hereafter, we only consider implementations and discuss the phenomenology of the Flavor-preserving Minimal Supersymmetric Standard Model: see below].

1. Those calculating the spectrum of Superparticles (typically, their masses and couplings), by solving the Renormalization Group Equations (RGEs) with theoretical constraints on soft SUSY-breaking terms chosen by the user and experimental ones from measured SM masses and couplings. Input parameters are normally provided at some unification (GUT) scale, outputs values at the EW one. (Some codes also produce the decay rates involving SUSY particles.) Chief examples of such kind of codes are `ISASUGRA` [1], `SUSPECT` [2] and `SOFTSUSY` [3].

2. Those that, starting from a set of such inputs (masses, couplings, decay rates), enable the simulation of SUSY particle production and decay in the context of modern accelerator machines. Here, the main programs are: `ISAJET` [1], `PYTHIA` [4], `HERWIG` [5, 6], `SUSYGEN` [7, 8], `CompHEP` [9] and `SUSY23` [10].

The former use a variety of approaches (analytical and/or numerical) to solve the RGEs of the theory whereas the latter are based on Monte Carlo (MC) techniques of (pseudo)random event generation.

An important topic of present and future studies of SUSY involves understanding and reducing the theoretical uncertainties entering sparticle mass determinations from underlying parameters.

To this end, Allanach contributed a study [11] where thorough comparisons among ISASUGRA, SUSPECT and SOFTSUSY were carried out, for the part concerning the SUSY spectra generation, along the Slopes A, B and F (see Sect. 3). He documented significant numerical differences between ISAJET and the other two programs in some instances, and between all three programs in rarer cases. These occur at the several percent level for Slopes A and B and are larger for Slope F, and tend to be more important for smaller sparticle masses. This is partly due to errors that can be corrected by using non-default values for accuracy and iterations, and partly due to differences in the way loop corrections are implemented [12]. Considering that permille accuracies are expected to be achieved at a future high luminosity LC (see, e.g., [13]), an increase in accuracy of the theoretical predictions of sparticle masses and couplings by about a factor of ten is a mandatory task for the years to come. A constructive attitude adopted within our group was to nonetheless adopt one of these programs (ISAJET, for sake of illustration, unless otherwise stated) as a benchmark for the present time and use it throughout as representative of the theory, in order to discriminate among high-scale models of SUSY-breaking. A similar comparison for what concerns SUSY decay rates (those computed, e.g., via ISASUSY) is still very much awaited. An independent coding of SUSY decay rates is expected to be available soon, in the program SDECAY [14].

ISAJET, PYTHIA, HERWIG and SUSYGEN are so-called 'event level generators', describing the underlying physics from a simple hard scattering partonic process (high energy scales) down to the fragmentation/hadronisation stages (low energy scales), through 'parton shower' dynamics (also including some modelling of the underlying event at hadronic machines), hence allowing one to emulate a full event as it appears in the actual detectors, whereas CompHEP and SUSY23 are – strictly speaking – 'parton level generators' only, though based on a more involved hard scattering dynamics. Until recently, the two approaches have somewhat co-existed and their development had proceeded on separate tracks. As they clearly have complementary strengths, it has recently been agreed among their authors to provide a generic interface between the two type of programs, enabling the transfer of information regarding multi-particle tree-level event configurations from the partonic stage to the showering and hadronization phases [15] (see also [16]). The involved physics environment provided by SUSY event generation carried out during this workshop has enabled (some of) the authors to refine such interface to encompass several exceptional cases specific to SUSY (such as lepton/baryon number violation, Majorana particles, etc.), which were missing in the SM implementation.

3. The SUSY framework

The most general possible manifestation of SUSY as an extension of the SM could in principle have an infinite number of parameters. This is because, despite the fact that SUSY incontrovertibly predicts the existence of certain superpartners with known quantum numbers, it does not preclude the existence of any number of new particles (with associated masses and couplings) as long as they come in complete supermultiplets. These might include new heavy gauge bosons and gauginos, or vector-like squark-quark or slepton-lepton pairs, or new singlet fermion-boson pairs. In order to have a more manageable parameter space, it is useful to restrict attention to the "General MSSM", which limits the particle content to the minimum needed to contain the SM. The mass eigenstates of this theory include 12 squarks, 6 charged sleptons, 3 sneutrinos, 1 gluino, 4 neutralinos, 2 charginos, and 3 neutral and 1 charged Higgs scalars. With arbitrary SUSY couplings and SUSY-breaking parameters, this model has 296 new parameters [17] (beyond those found in the SM). These include baryon- and lepton-number violating, R-parity violating couplings. At least some of these must be extremely small in order to avoid very rapid proton decay.

The "R-parity-conserving MSSM" is obtained by removing all R-parity violating couplings. This model contains 105 new parameters [18] beyond those found in the SM. However, this is still an unmanageably large parameter space for most studies. Furthermore, this parameter space is very strongly constrained by flavor-violation such as $\mu \to e\gamma$ and neutral kaon mixing.

A much smaller parameter space is obtained by reducing to what might be called the "Flavor-respecting MSSM". In this framework, all SUSY-breaking parameters are assumed to respect flavor-symmetry and introduce no new CP-violating phases. Thus the parameters of the model consist of:

- Gaugino masses M_1, M_2, and M_3,

- Family-independent squark and slepton squared masses $m^2_{\tilde{Q}_L}$, $m^2_{\tilde{u}_R}$, $m^2_{\tilde{d}_R}$, $m^2_{\tilde{L}_L}$, $m^2_{\tilde{e}_R}$,
- Higgs squared masses $m^2_{H_u}$, $m^2_{H_d}$,
- Scalar cubic couplings which are 3×3 matrices proportional to the corresponding Yukawa couplings, with constants of proportionality A_{u0}, A_{d0}, A_{e0},
- The ratio of Higgs expectation values $\tan\beta \equiv \langle H_u^0 \rangle / \langle H_d^0 \rangle$,
- The sign of the supersymmetric Higgs mass parameter μ.

This assumption of flavor-independence also requires a choice of renormalization scale, which is most often assumed to be close to the apparent scale of gauge coupling unification, about 2×10^{16} GeV or the Planck scale 2.4×10^{18} GeV. The 16 or so parameters associated with the Flavor-respecting MSSM lead us to suggest it as a well-motivated compromise between the anarchy of the General MSSM and more restrictive frameworks as described below.

The "Minimal Supergravity" or "mSUGRA" framework (see for example [17] and references therein) further reduces the parameter space to just the following:

- A common gaugino mass $m_{1/2} = M_1 = M_2 = M_3$,
- A common scalar squared mass $m_0^2 = m^2_{\tilde{Q}_L} = m^2_{\tilde{u}_R} = m^2_{\tilde{d}_R} = m^2_{\tilde{L}_L} = m^2_{\tilde{e}_R} = m^2_{H_u} = m^2_{H_d}$,
- A common scalar cubic coupling $A_0 = A_{u0} = A_{d0} = A_{e0}$,
- $\tan\beta$,
- $\mathrm{sign}(\mu)$.

As a practical matter, it is usual to use these parameters as boundary conditions for RGEs starting at the GUT scale rather than the Planck scale.

The Gauge-Mediated SUSY-Breaking (GMSB) framework (for reviews, see [19]) is a different subcase of the Flavor-preserving MSSM parameter space. In this scenario, the flavor-preservation is automatic rather than preserved, since SUSY-breaking is transmitted from a hidden sector to the MSSM particles by messenger fields which share only gauge interactions with the ordinary quarks and leptons. The LSP is a neutral fermion called the Goldstino ($\widetilde{G}$). All other superpartners can decay into a final state containing the Goldstino; this may happen close to the event vertex or arbitrarily far away. The parameters in minimal GMSB consist of

- Λ, the effective mass scale of SUSY-breaking,
- M_{m}, the common messenger particle mass,
- N_5, the number of complete $SU(5)$ $\mathbf{5} + \bar{\mathbf{5}}$ multiplets of messengers,
- $\tan\beta$,
- $\mathrm{sign}(\mu)$,
- C_G, a suppression factor of the Goldstino coupling.

The qualitative effects of these parameters are as follows. Increasing Λ will increase all superpartner masses roughly linearly. Raising N_5 tends to decrease squark and slepton masses relative to gaugino masses. Increasing M_m tends to increase sparticle masses logarithmically. Increasing C_G tends to increase the lifetime of the next-to-lightest SUSY particle.

The Anomaly-Mediated SUSY-Breaking (AMSB) framework [20] is yet another sub-case of the Flavor-preserving MSSM parameter space. A minimal phenomenologically-viable version (mAMSB) depends on the parameters

- $m_{3/2}$ = the auxiliary mass, which sets the overall SUSY-breaking scale,
- m_0^2 = a common scalar squared mass,
- $\tan\beta$,

- sign(μ).

One cannot take m_0^2 to be too small in these models, or else charged sleptons will have negative squared mass. The AMSB models often have a nearly-degenerate neutral and charged wino as the LSP, leading to quite unique phenomenology.

As a way of organizing suggested studies in Snowmass and beyond, we chose to employ the concept of benchmark "model lines". The general philosophy is that each model line consists of a one-parameter family of models. The one parameter is typically the overall superpartner scale (say $m_{1/2}$ for mSUGRA models, Λ for minimal GMSB models, and $m_{3/2}$ for AMSB models). Other dimensionful parameters are then chosen proportional, with dimensionless quantities like $\tan\beta$ and sign(μ) held fixed, and default values for SM quantities, including $m_{\rm top} = 175$ GeV. The discovery reach and other capabilities of various collider options can be studied by choosing several or many points along the model line. More in-depth studies can be conducted at isolated points, chosen appropriately for the particular collider option.

We decided on eight particular model lines ("Snowmass Slopes"). They are given as follows. (For some more details, see [21].)

- **Slope A: mSUGRA with gaugino mass dominance**
  Here $m_{1/2}$ is the varying dimensionful parameter. The others are given by $m_0 = -A_0 = 0.4m_{1/2}$, $\tan\beta = 10$, $\mu > 0$.

- **Slope B: non-unified gaugino masses**
  This is a variation on the mSUGRA framework, with $M_3 = M_2$ (at the GUT scale) as the varying dimensionful parameter. However, $M_1 = 1.6M_2$ (at the GUT scale). The other mSUGRA parameters are $m_0 = 0.5M_2$, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$.

- **Slope C: mSUGRA with heavy scalars**
  Here $m_{1/2}$ is the varying dimensionful parameter. The others are given by $m_0 = m_{1/2}$, $A_0 = 0$, $\tan\beta = 35$, $\mu > 0$.

- **Slope D: GMSB with stau NLSP**
  Here Λ is the varying parameter, and other parameters are given by $M_m = 2\Lambda$, $N_5 = 3$, $\tan\beta = 15$, and $\mu > 0$.

- **Slope E: GMSB with neutralino NLSP**
  Here Λ is the varying parameter, and other parameters are given by $M_m = 2\Lambda$, $N_5 = 1$, $\tan\beta = 15$, and $\mu > 0$.

- **Slope F: Focus Point mSUGRA**
  The common gaugino mass $m_{1/2}$ is the varying parameter, with other parameters then determined according to $m_0 = 2m_{1/2} + 800$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$. (This model line turns to have a practical problem pointed out by Allanach in ref. [11], due to the fact that there is an extreme sensitivity of the `ISAJET 7.51` outputs to inputs, at least with default precision and number of iterations.)

- **Slope G: Anomaly-Mediated SUSY-Breaking**
  $m_{3/2}$ varies as the dimensionful parameter, with $m_0 = 0.0075m_{3/2}$, $\tan\beta = 10$, and $\mu > 0$.

- **Slope H: Co-annihilation region mSUGRA**
  Here $m_{1/2}$ varies, with the other parameters given by $m_0 = 0.25m_{1/2} - 9$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$.

As discussed above, the models were defined to be the output of ISAJET 7.51. As an illustration, fig. 1 shows the masses of all of the superpartners and Higgs mass eigenstates for Slope A, as a function of $m_{1/2}$.

Other groups [22], [23] have proposed discrete choices of benchmark model points, some of which lie on the model lines mentioned above. A compendium and discussion of the various benchmarks is given in ref. [24].

Within a given general model scenarios, the most important single parameter that we would like to know about in SUSY is the overall mass scale of the superpartners; if we knew that, then questions about which collider option to build would be relatively easy to frame. So an advantage

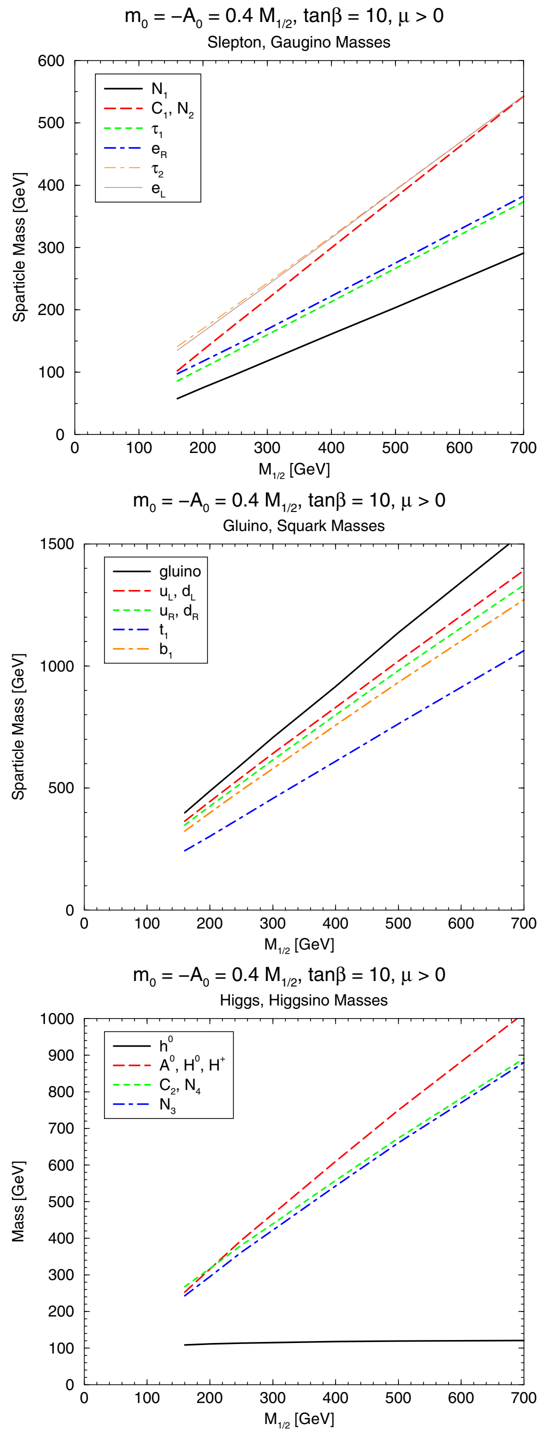

Figure 1: The masses of the sleptons and lighter neutralinos and charginos, squarks and gluino, and Higgs and heavier neutralinos and chargino, on the model line Slope A, as a function of $m_{1/2}$.

of the model line approach is that this parameter is left undetermined, rather than prejudicing studies by assuming some particular and quite arbitrary value. The strengths and weaknesses of different colliders will inevitably depend on what point along each model line one chooses.

We have chosen not to impose indirect experimental constraints, such as cosmological relic abundance of LSP dark matter, $b \to s\gamma$, or the Higgs mass bound from LEP, on the Snowmass Slopes. The reason is that the purpose of the model lines is to investigate general properties of direct probes of SUSY. Minor changes in the model parameter assumptions can lead to complete

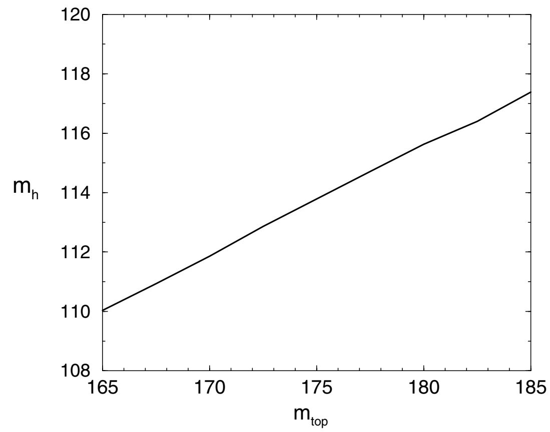

Figure 2: The output value of m_h, for various input values of $m_{\rm top}$, using ISAJET7.51 for a point on Slope A with $m_{1/2} = 250$ GeV, $m_0 = -A_0 = 100$ GeV, $\tan\beta = 10$, $\mu > 0$.

relaxation of the indirect "constraints", without changing the salient features of direct signals. For example, dark matter constraints are easily evaded by cosmological models with late inflation or a small amount of R-parity violation, both of which would have no significant effect on collider physics. Constraints from $b \to s\gamma$ are subject to significant uncertainties, and can be easily evaded by introducing small flavor-mixing A-terms which again would have no significant effect on most collider signals. In fact, since flavor symmetry is somewhat mysterious in supergravity models, it is to be expected that such flavor-violation should be present at least at some level. There is still a significant uncertainty in calculation of the lightest Higgs mass, and it can be changed by slightly increasing $m_{\rm top}$ or by enlarging the Higgs sector in ways which may or may not have an effect on collider signals. While such indirect constraints can eliminate many model parameters which follow *exactly* from precise assumptions about high scale physics, it should be remembered that any simplified model parameter framework is almost certainly wrong in its fine detail. So indirect constraints can be ignored insofar as they can be evaded by minor variations that do not strongly change the collider signals.

As an example, one can consider the variation of the lightest Higgs mass with the top mass. The present 1-sigma experimental uncertainty on the top mass is of order 5 GeV, but there is also a significant theoretical uncertainty of at least a GeV or two coming from the SUSY corrections to the top mass, which have been computed at one-loop order but not at two-loop order. Besides this input uncertainty, there is a theoretical uncertainty in the present Higgs mass calculation of order 2 GeV roughly, even for perfectly known inputs. In fig. 2, we show the variation of m_h with $m_{\rm top}$ for a single point along Slope A with $m_{1/2} = 250$ GeV, using the ISAJET7.51 output. (Other programs will certainly give different results, but will show a similar qualitative behavior.) A larger top mass leads to a larger m_h, all other things being equal. In this example, one finds $\partial m_h/\partial m_{\rm top} \approx 0.4$; the slope increases logarithmically for heavier top squarks. Thus a larger top mass or a refined calculation of m_h can allow it to evade the recent bounds from LEP, again without changing the most important features of collider studies for the superpartner sector.

4. Reconstructing SUSY-breaking parameters

After the discovery of SUSY, one way to try to understand the mechanism of SUSY-breaking would be to extrapolate SUSY-breaking masses and other parameters from the EW scale, where they are measured, to higher scales where they can be compared to candidate organizing principles. For example, one can test the hypothesis that scalar masses unify to m_0 near the GUT scale. Earlier demonstrations that this is possible were made in [25]. At Snowmass, Martin conducted a similar study [26], comparing the ability to test scalar mass unification for various optimistic and pessimistic scenarios for the uncertainty with which sparticle masses and other parameters can be measured. It is crucial to assign uncertainties to all low-scale parameters, since RGE evolution entails mixing of parameter uncertainties proportional to large logarithms. It was shown that the ability to reduce slepton mass uncertainties from, say, the 0.5% level to the 0.1% level will not by itself allow a more precise verification of scalar mass unification and determination of m_0, since theoretical and experimental uncertainties in the gluino and squark masses end up dominating other uncertainties. Certainly more work is feasible to reduce both theoretical and experimental uncertainties. Similar methods were applied to GMSB models in [26], showing that even with rather pessimistic assumptions it should be possible to extrapolate up from low scales to test the assumptions of GMSB models, and to simultaneously measure the parameters Λ and M_m. The latter can be determined with a quite small uncertainty, but the uncertainty in M_m from mass measurements alone is expected to be quite large, since only $\ln(M_m)$ is constrained. Finally, it was shown that it should be possible in some scenarios to constrain the extrapolated value of the scalar cubic coupling A_0, perhaps uniquely fixing its sign near the GUT scale. This hinges on making accurate measurements of the top squark masses and mixing angles.

5. Direct detection of SUSY signals

5.1. The hadronic colliders

The LHC discovery potential of direct SUSY signals has been extensively studied in the past years. Being an hadronic machine, its strength is clearly in the production of colored SUSY particles (squarks and gluino). However, there exist some obvious limitations at the CERN collider, even in this respect. For example, it is not unreasonable in SUSY models to expect all the squarks to have masses in the $\gtrsim$ 2–3 TeV region [27] (the argument goes similarly for the sleptons and heavy Higgs bosons), or else the first two generations of squarks to have even heavier masses, $\lesssim$ 10 TeV (with the gluino one at 2–3 TeV) [28], this implying that their LHC production rates can become very small. The reason is twofold. On the one hand, heavier squarks reflect into larger x-values probed in the Parton Distribution Function (PDFs), where both the gluon and quark luminosity inside the proton is smaller, with that of the former decreasing more rapidly than the one of the latter. (Recall that, in general, gluons carry a color charge in their coupling to the SUSY spartons larger than that of the quarks.) On the other hand, if $\sqrt{\hat{s}} \approx 2M_{\tilde{q}}$ (where $\hat{s} = x_1 x_2 s$ is the partonic CM energy, with $\sqrt{s} = 14$ TeV and $M_{\tilde{q}}$ representing typical squark masses), the available phase space to the SUSY particles can be very small. Such heavy squarks, produced at the edge of the phase space, will typically have small momentum. Hence jets coming from decays from one squark or gluino to a nearly degenerate one will often have very soft p_T.

This scenario prompted several continuing studies carried out in the contributions [29] and [30], where a realistic assessment of the possibilities of learning about SUSY scenarios that are at the edge of the LHC capabilities has been made. In the first case, results suggest that resolving very closely-spaced squarks (specifically on Slope A, see Fig. 1) at the LHC will be very difficult, and further work is definitely needed to assess better ways to realize the power of the CERN machine in this respect. In the second case, it was shown how the observability of SUSY signals induced by models with an inverted mass hierarchy near the GUT scale (GSIMH models, yielding multi-TeV first and second generation matter scalars, and sub-TeV third generation and Higgs scalars) can be very challenging not only at the LHC but also at possible future hadron machines, such as the Very Large Hadron Collider (VLHC).

5.2. The leptonic colliders

The e^+e^- LC concept offers the potential of achieving point-like collisions of electrons with positrons at CM energies up to about 1 TeV with unprecedentedly high luminosities of typically 0.5 ab^{-1} per Snowmass year. The concept also leads to highly polarisable beams of electrons and potentially positrons which can be used to select and measure the chiral couplings of new particles. Given the potential richness of the supersymmetric world that might be unleashed, the experimenter could also measure this world under several different conditions: the CM energy can be changed over a wide span allowing to extinguish kinematically unwanted backgrounds, and the possibility of colliding electrons with electrons comes for free. There is also the intriguing possibility of colliding electrons with photons and photons with photons. The experimental conditions are rather advantageous: no hardware trigger is required, kinematic constraints can be used, precision absolute cross-section measurements can be made, and large precision detectors can be built in a hermetic manner with acceptance very close to the beam direction allowing excellent tagging of missing energy.

Muon colliders potentially offer competitive luminosity at high (multi-TeV) CM energies where e^+e^- colliders start having a much larger energy spread from beamstrahlung. However the inability to produce highly polarised beams and the implications of "dead-cones", regions of experimental non-detection of 20° angle around the beam, for the decay background, limit the applicability of such machines as currently envisaged to SUSY exploration.

Concentrating then on the next future of e^+e^- colliders and a machine with CM energy up to around 1 TeV, it is clear from for example searches at LEP2, that pair-production of superpartners can be explored up to the kinematic limit largely independently of their particular decay characteristics. In particular, given the large integrated luminosities and the hermetic detectors, superpartners can even be identified if their decay leads to a negligible amount of visible energy as outlined for example in studies of the AMSB model [31]. In summary, a LC is the machine of choice for superpartners that are kinematically accessible.

If SUSY does describe nature in some way, then we expect experiments in the next few years, Run II at the Tevatron and the LHC, to uncover a light Higgs particle. The stage will then be set for a thorough understanding of the Higgs sector by a LC and hopefully a fruitful collaboration between the LHC and a LC on unscrambling the nature of the new supersymmetric world.

We now review the individual contributions in the working group studying specific aspects of SUSY exploration at a LC.

Yu. Gershtein contributed a study [32] on the ability to measure slepton and neutralino masses in the models of Slope B using a 500 GeV LC. This model line was included as a sort of a challenge, since the sparticle mass differences are much smaller than in typical mSUGRA models which have been studied in the past. It was shown that good precision can be obtained for each of the slepton masses and the lighter two neutralino masses, provided that they are kinematically accessible. Gershtein also proposed a novel way of determining the stau mass, which poses a unique problem in that they always include neutrinos from the tau decay. The method is based on selecting taus with the largest visible mass among the hadronic decay products. This same method can be used for other signals involving particles decaying predominantly to taus.

A complementary study of Slope B was performed by H. Neal [33]. This included an analysis of chargino ($\chi_1^\pm$) production and decay through $e^+e^- \to \chi_1^+\chi_1^- \to qq\chi_1^0 + \ell\nu\chi_1^0$ events at a 500 GeV LC. The analysis demonstrates the effectiveness of the two currently considered detector designs to deal with the lost W mass constraint, low energy tracks and high backgrounds. In addition, a unique modification of the energy end-point technique is used to extract the masses of the $\chi_1^\pm$ and χ_1^0.

Baer, Balazs and Mizukoshi have contributed a study [34] of the complementary role of the LHC and LC in discovering SUSY. They considered an SO(10) model which is based on mSUGRA but contains additional D-term contributions to scalar masses; this model has the attractive theoretical feature that it allows Yukawa coupling unification. The LHC should be able to measure mass differences including $m_{\chi_2^0} - m_{\chi_1^0}$, $m_{\tilde{b}_1} - m_{\chi_1^0}$, and $m_{\tilde{g}} - m_{\chi_1^0}$, and with global fits should be able to distinguish their model from an ordinary mSUGRA one. However, the LHC alone cannot uniquely distinguish the nature of supersymmetry breaking, nor single out the essential SO(10) features of the model. To measure the complete SUSY spectrum, both the LHC and an LC are necessary. This study nicely illustrates some of the pitfalls of relying on global fits, which can be very powerful and precise within a given model framework, but become much less useful if the model framework is relaxed. Of course, the data will not come with a neat label as to which model framework it should be analyzed in.

One interesting question is to consider the most pessimistic case that no charged superpartners are kinematically accessible at a LC; then there remains only the highly problematic possibility of searching for $e^+e^- \to \chi_1^0\chi_1^0\gamma$. Baer and Belyaev [35] contributed a study of this possibility, and demonstrated that unfortunately it does not seem possible under realistic assumptions. There is a huge background from $e^+e^- \to \nu\bar{\nu}\gamma$. This can be reduced by using polarized beams, and if perfect 100% beam polarization were obtainable, it might be feasible. However, they showed that using more realistic beam polarizations (even 95%) the signal-to-background ratio is simply too small.

The reconstruction of MSSM parameters in the neutralino sector with a linear collider was studied by Kalinowski and Moortgat-Pick in the contribution [36]. It is assumed in this study that the SU(2) gaugino parameter M_2, the higgsino mass parameter μ and $\tan\beta$ can be determined from the chargino sector. The remaining fundamental SUSY parameters in the gaugino/higgsino sector of the MSSM, the U(1) gaugino mass M_1 in CP–invariant theories, and its phase in CP–non-invariant theories, can be determined from the neutralino system. They demonstrated strategies for deriving the parameters in CP–invariant as well as in CP–non-invariant theories even if only the light neutralinos were accessible, by looking at the threshold behavior of cross-sections for neutralino and chargino production. The CP-properties of the neutralino system are characterized by 'unitarity quadrangles'. With the evaluation of these formulae and the application of the sum rules, the underlying SUSY model as well as the closure of the neutralino system can be tested.

Kalinowski also contributed a study [37] of the possibility of supersymmetric lepton flavor violation at laboratory energies, e.g., through $\tilde{\nu}_\mu \leftrightarrow \tilde{\nu}_\tau$ mixing, perhaps observable at e^+e^- linear colliders through distinct final state $\tau\mu + jets + \not{E}_T$ can be expected. He argued that in addition to the pair production of sneutrinos or charged sleptons, the production of charginos can make an important contribution to this process and has to be taken into account in quantitative analyses.

Because the lightest squark is likely to be a superpartner of the top, studies of the top squark sector at a linear collider are particularly interesting. If the top squark(s) are kinematically accessible, their study can give information about $\tilde{t}_L$-$\tilde{t}_R$ mixing, and therefore provide a unique window for measuring scalar cubic couplings. In the contribution [38], Nowak and Sopczak have investigated how well one can do with a 180 GeV top squark at a 500 GeV LC with TESLA characteristics using $\mathcal{L} = 500$ fb^{-1}. Beam polarization allows a simultaneous determination of the top squark mass and mixing angle with good precision. The study includes e^+ polarization, which improves the sensitivity. It would be interesting to see this sort of study extended to higher energy machines and heavier top squarks.

Ghosh, Moretti and Wilson [39] looked into the observability of single-electron + $\not{E}_T$ signals from first generation slepton production in the AMSB model of slope G at an 800 GeV LC using beam polarisation to decipher the Wino nature of the LSP and chargino. The study shows that independently of how or even whether the chargino is detected, reasonable signals over the Standard Model backgrounds can already be found at the inclusive level. Work is continuing on evaluating how well the individual slepton processes and branching ratios can be determined.

6. Summary and outlook

A recurring element of the discussions in the Snowmass study is that there is a need and opportunity for improved theoretical tools in preparation for the discovery of SUSY. In order to be competitive with mass measurements at the LHC and a LC, predictions of sparticle and Higgs masses from given model parameters need to be improved by an order of magnitude in some cases. There is also room for growth and improvement in (Monte Carlo) SUSY event generators.

It seems injudicious to discuss priorities in the field of direct SUSY detection independently of having established directly the existence and mass of the Higgs since it is the particle that led to the founding of SUSY models. But under the hypothesis that a light Higgs exists with mass compatible with SUSY, then we should discuss such priorities.

As outlined in section III in the context of the flavor-respecting MSSM, there is no fundamental symmetry to tie, e.g., squark masses to slepton masses, or the gluino mass to the chargino mass or the chargino mass to the neutralino mass. However, models such as mSUGRA do lead to such relationships and LHC studies show that the heaviest super-partners, the squarks and the gluino should be observable for masses up to about 2.5 TeV at the LHC in such models. Depending on the actual decay chains, some other superpartners may be identifiable in the cascade decays of the squarks and the gluino.

On the other hand a LC with CM energy of 1 TeV could comprehensively explore and discover superpartners with masses less than 0.5 TeV largely independently of their nature (neutral, charged, strong, electroweak) and decay modes. In most supersymmetric models, the chargino and neutralino and often the sleptons are much lighter than the squarks and gluino.

A VLHC could extend the mass reach for squarks and the gluino but would not necessarily add much value if these had already been seen at the LHC.

In summary, it would appear that if SUSY is accessible at near future accelerators, the most promising new direction for understanding its nature is a LC with sufficient CM energy.

Acknowledgments

The work of SPM was supported in part by the National Science Foundation grant number PHY-9970691. SM would like to thank The Royal Society (London, UK) for financial support in the form of a Conference Grant.

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