The LHC / LC Study Group
and the Snowmass Points and Slopes

GEORG WEIGLEIN[*]

Institute for Particle Physics Phenomenology
University of Durham, Durham DH1 3LE, U.K.

Abstract

The "LHC / LC Study Group" investigates how analyses at the LHC could profit from results obtained at a future Linear Collider and vice versa. Some of the activities of this recently formed working group are briefly summarised. The LHC / LC Study Group home page is `www.ippp.dur.ac.uk/∼georg/lhclc`. The "Snowmass Points and Slopes" (SPS) are a set of benchmark points and parameter lines in the MSSM parameter space corresponding to different scenarios in the search for Supersymmetry at present and future experiments. This set of benchmarks was agreed upon at the 2001 "Snowmass Workshop on the Future of Particle Physics" as a consensus based on different existing proposals. Further information about the SPS can be found under `www.ippp.dur.ac.uk/∼georg/sps`.

*email: Georg.Weiglein@durham.ac.uk

1 The LHC / LC Study Group

The aim of the LHC / LC Study Group is to investigate a possible cross-talk between the LHC and a future Linear Collider (LC) and to study in how far analyses carried out at one of the machines could profit from results obtained at the other machine. Mutual benefits could occur both at the level of a combined interpretation of Hadron Collider and Linear Collider data and at the level of combined analyses of the data, where results obtained at one machine could directly influence the way analyses are carried out the other machine.

Topics under study comprise the physics of weak and strong electroweak symmetry breaking, Supersymmetric models, new gauge theories, models with extra dimensions, and electroweak and QCD precision physics. For these studies it is assumed that the LC comes into operation about half a decade after the start of the LHC. During simultaneous running of both machines there is obviously the highest flexibility for adapting analyses carried out at one machine according to the results obtained at the other machine. The LC results could in this context also serve as an input for a second phase of LHC running concerning different possible upgrade options.

To mention just one example of studies carried out in the working group, the determination of masses of Supersymmetric particles at the LHC could profit from the precise measurement of the lightest Supersymmetric particle (LSP) at the LC. As a trivial illustration of the possible benefits of a precise measurement of the LSP mass at the LC, Fig. 1 shows the relative accuracy of the determination of the mass of the next-to-lightest neutralino at the LHC, which is highly correlated with the accuracy of the LSP mass determination [1]. The prospective accuracy of the LSP mass measurement at the LC is indicated by a narrow band, which obviously leads to a drastic improvement of the mass determination of the next-to-lightest neutralino at the LHC.

The LHC / LC Study Group has been forming over the last months and is still further expanding. Currently there are about 140 working group members (members of ATLAS, CMS, LC working groups, a Tevatron contact person, and theorists). Further information about the working group can be obtained from `rohini.godbole@cern.ch`, `paige@bnl.gov`, `Georg.Weiglein@durham.ac.uk` or from the LHC / LC Study Group web page `www.ippp.dur.ac.uk/~georg/lhclc`.

2 The Snowmass Points and Slopes (SPS)

In the unconstrained version of the Minimal Supersymmetric extension of the Standard Model (MSSM) no particular Supersymmetry (SUSY) breaking mechanism is assumed, but rather a parameterisation of all possible soft SUSY breaking terms is used. This leads to more than a hundred parameters (masses, mixing angles, phases) in this model in addition to the ones of the Standard Model. For performing detailed simulations of experimental signatures within detectors of high-energy physics experiments it is clearly not practicable to scan over a multi-dimensional parameter space. One thus often concentrates on certain "typical" benchmark scenarios.

The Snowmass Points and Slopes (SPS) [2] are a set of benchmark scenarios in the MSSM parameter space which was agreed upon at the 2001 "Snowmass Workshop on the
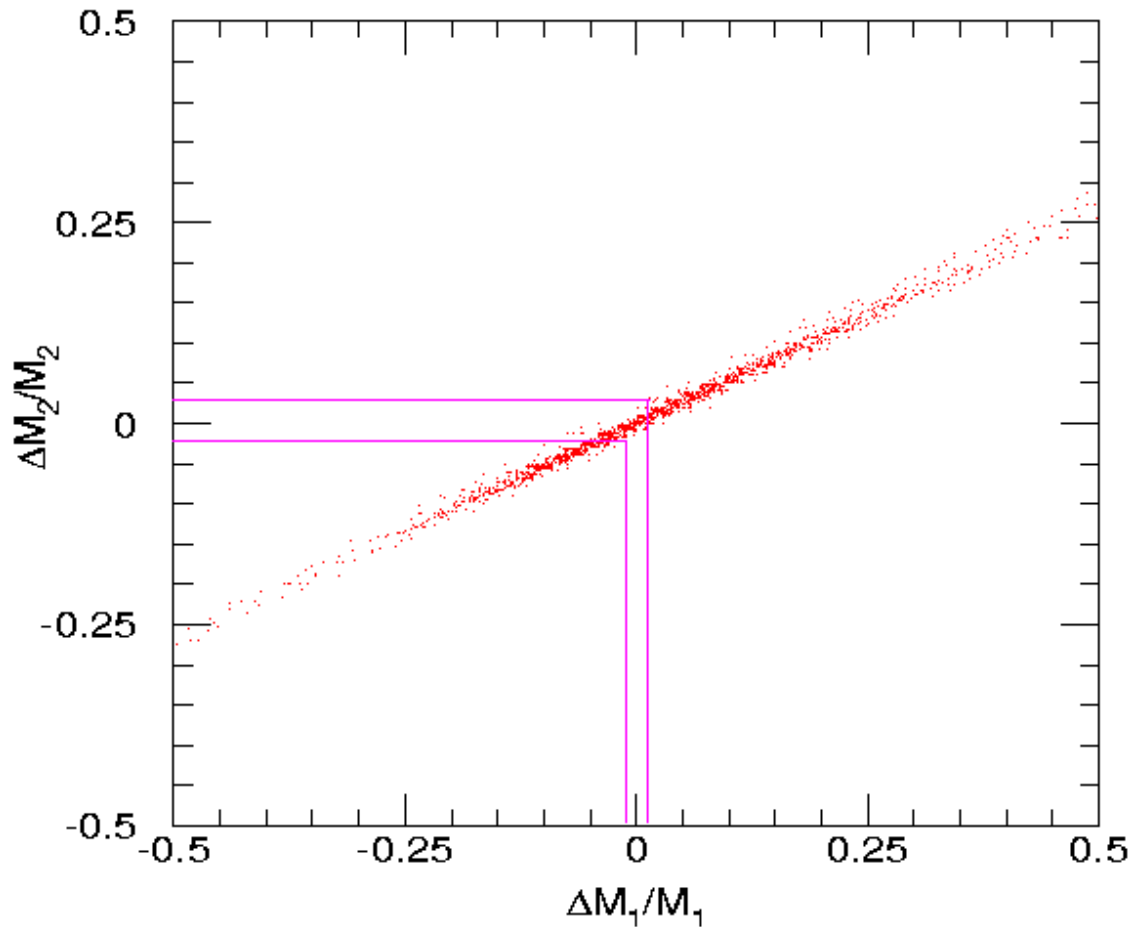
Figure 1: The relative accuracy in the determination of the masses of the lightest and the next-to-lightest neutralino at the LHC, taken from Ref. [1]. The narrow band overlayed in the plot shows the improvement in the mass determination of the next-to-lightest neutralino at the LHC if the measurement of the LSP mass at the LC is used as input.

Future of Particle Physics" as a consensus based on different existing proposals [3]. The SPS consist of model lines ("slopes"), i.e. continuous sets of parameters depending on one dimensionful parameter and specific benchmark points, where each model line goes through one of the benchmark points. The SPS should be regarded as a recommendation for future studies of SUSY phenomenology, but of course are not meant as an exclusive and for all purposes sufficient collection of SUSY models. They mainly focus on "typical" scenarios within the three currently most prominent SUSY-breaking mechanisms, i.e. minimal supergravity (mSUGRA) [4], gauge-mediated SUSY breaking (GMSB) [5], and anomaly-mediated SUSY breaking (AMSB) [6]. Furthermore they contain examples of "more extreme" scenarios, e.g. a "focus point" scenario [7] with a rather heavy SUSY spectrum, indicating in this way different possibilities for SUSY phenomenology that can be realised within the most commonly used SUSY breaking scenarios.

The SPS comprise ten benchmark points, from which six correspond to an mSUGRA scenario, one is an mSUGRA-like scenario with non-unified gaugino masses, two refer to the GMSB scenario, and one to the AMSB scenario. Seven of these benchmark points are attached to model lines, while the remaining three are supplied as isolated points. In studying the benchmark scenarios the model lines should prove useful in performing more general analyses of typical SUSY signatures, while the specific points indicated on the lines are proposed to be chosen as the first sample points for very detailed (and thus time-consuming) analyses. The concept of a model line means of course that more than just one point should be studied on each line. Results along the model lines can often then be roughly estimated by interpolation.

The SUSY-breaking scenarios mentioned above are characterised by a few input parameters (in the mSUGRA scenario, for instance, these are the scalar mass parameter m_0, the gaugino mass parameter $m_{1/2}$, the trilinear coupling A_0, the ratio of the Higgs vacuum expectation values, $\tan\beta$, and the sign of the Supersymmetric Higgs mass parameter, μ). The mass spectra of the SUSY particles in the mSUGRA, GMSB and AMSB scenarios are obtained via renormalisation group running from the scale of the high-energy parameters of the SUSY-breaking scenario to the weak scale. The low-energy parameters obtained in this way are then used as input for calculating the predictions for the production cross sections and for the decay branching ratios of the SUSY particles.

An important aspect in the philosophy behind the benchmark scenarios is that the low-energy MSSM parameters are defined to be the actual benchmark rather than the high-energy input parameters m_0, $m_{1/2}$, etc. A specification of the benchmark scenarios in terms of the latter parameters is merely understood as an abbreviation for the low-energy phenomenology (it also depends on the particular program used for relating the high-energy input parameters to the low-energy MSSM parameters).

While certain sets of low-energy MSSM parameters have been fixed as benchmarks in the SPS by definition (which in principle could have been done without resorting at all to scenarios like mSUGRA, GMSB and AMSB), the evaluation of the mass spectra and decay branching ratios from the MSSM benchmark parameters should be carried out with the tools and at the level of sophistication being most appropriate for the particular application one is interested in. If detailed comparisons between different experiments or different colliders are carried out, it would clearly be advantageous to use the same results for the mass spectra and the branching ratios.

The main qualitative difference between the SPS (and also the recent proposals for post-LEP benchmarks in Ref. [3]) and the benchmarks used previously for investigating SUSY searches at the LHC, the Tevatron and a future Linear Collider is that scenarios with small values of $\tan\beta$, i.e. $\tan\beta \lesssim 3$, are disfavoured as a result of the Higgs exclusion bounds obtained at LEP. Consequently, there is more focus now on scenarios with larger values of $\tan\beta$ than in previous studies. Concerning the SUSY phenomenology, intermediate and large values of $\tan\beta$, $\tan\beta \gtrsim 5$, have the important consequence that there is in general a non-negligible mixing between the two staus (and an even more pronounced mixing in the sbottom sector), leading to a significant mass splitting between the two staus so that the lighter stau becomes the lightest slepton. Neutralinos and charginos therefore decay predominantly into staus and taus, which is experimentally more challenging than the dilepton signal resulting for instance from the decay of the second lightest neutralino

into the lightest neutralino and a pair of leptons of the first or the second generation.

Large values of $\tan\beta$ can furthermore have important consequences for the phenomenology in the Higgs sector, as the couplings of the heavy Higgs bosons H, A to down-type fermions are in general enhanced. For sizable values of μ and $m_{\tilde{g}}$ the $hb\bar{b}$ coupling receives large radiative corrections from gluino loop corrections, which in particular affect the branching ratio $\mathrm{BR}(h \to \tau^+\tau^-)$.

The main features of the SPS benchmarks are listed in the following:

SPS 1: "typical" mSUGRA scenario

This scenario consists of a "typical" mSUGRA point with an intermediate value of $\tan\beta$ and a model line attached to it (SPS 1a) and of a "typical" mSUGRA point with relatively high $\tan\beta$ (SPS 1b). The two-points lie in the "bulk" of the cosmological region where the lightest SUSY particle (LSP) gives rise to an acceptable dark matter density. For the collider phenomenology in particular the τ-rich neutralino and chargino decays are important.

SPS 2: "focus point" scenario in mSUGRA

The benchmark point chosen for SPS 2 lies in the "focus point" region, where a too large relic abundance is avoided by an enhanced annihilation cross section of the LSP due to a sizable higgsino component. This scenario features relatively heavy squarks and sleptons, while the charginos and the neutralinos are fairly light and the gluino is lighter than the squarks.

SPS 3: model line into "coannihilation region" in mSUGRA

The model line of this scenario is directed into the "coannihilation region", where a sufficiently low relic abundance can arise from a rapid coannihilation between the LSP and the (almost mass degenerate) next-to-lightest SUSY particle (NLSP), which is usually the lighter $\tilde{\tau}$. Accordingly, an important feature in the collider phenomenology of this scenario is the very small slepton–neutralino mass difference.

SPS 4: mSUGRA scenario with large $\tan\beta$

The large value of $\tan\beta$ in this scenario has an important impact on the phenomenology in the Higgs sector. The couplings of A, H to $b\bar{b}$ and $\tau^+\tau^-$ as well as the $H^\pm t\bar{b}$ couplings are significantly enhanced in this scenario, resulting in particular in large associated production cross sections for the heavy Higgs bosons.

SPS 5: mSUGRA scenario with relatively light scalar top quark

This scenario is characterised by a large negative value of A_0, which allows consistency of the relatively low value of $\tan\beta$ with the constraints from the Higgs search at LEP, see Ref. [8].

SPS 6: mSUGRA-like scenario with non-unified gaugino masses

In this scenario, the bino mass parameter M_1 is larger than in the usual mSUGRA models by a factor of 1.6. While a bino-like neutralino is still the LSP, the mass

difference between the lightest chargino and the lightest two neutralinos and the sleptons is significantly reduced compared to the typical mSUGRA case. Neutralino, chargino and slepton decays will feature less-energetic jets and leptons as a consequence.

SPS 7: GMSB scenario with $\tilde{\tau}$ NLSP

The NLSP in this GMSB scenario is the lighter stau, with allowed three body decays of right-handed selectrons and smuons into it. The decay of the NLSP into the Gravitino and the τ in this scenario can be chosen to be prompt, delayed or quasi-stable.

SPS 8: GMSB scenario with neutralino NLSP

The NLSP in this scenario is the lightest neutralino. The second lightest neutralino has a significant branching ratio into h when kinematically allowed. The decay of the NLSP into the Gravitino (and a photon or a Z boson) in this scenario can be chosen to be prompt, delayed or quasi-stable.

SPS 9: AMSB scenario

This scenario features a very small neutralino–chargino mass difference, which is typical for AMSB scenarios. Accordingly, the LSP is a neutral wino and the NLSP a nearly degenerate charged wino. The NLSP decays to the LSP and a soft pion with a macroscopic decay length, as much as 10 cm.

As an example, below the benchmark values (i.e. the low-energy MSSM parameters) are given for the benchmark point of SPS 1a. All mass parameters are given in GeV. The value of the top-quark mass for all SPS benchmarks is chosen to be $m_{\mathrm{t}} = 175$ GeV.

All mass parameters for the benchmark point of SPS 1a are to be understood as defined in the $\overline{\mathrm{DR}}$ scheme at the scale $Q = 453.6$ GeV.

The gluino mass $M_{\tilde{\mathrm{g}}}$, the Supersymmetric Higgs mass parameter μ, the mass of the $\mathcal{CP}$-odd Higgs boson M_{A}, the ratio of the vacuum expectation values of the two Higgs doublets $\tan\beta$, and the electroweak gaugino mass parameters M_1 and M_2 have the following values:

$$M_{\tilde{\mathrm{g}}} = 595.2, \quad \mu = 352.4, \quad M_{\mathrm{A}} = 393.6, \quad \tan\beta = 10, \quad M_1 = 99.1, \quad M_2 = 192.7. \quad (1)$$

The soft SUSY-breaking parameters in the diagonal entries of the squark and slepton mass matrices have been chosen to be the same for the first and second generation. They have the following values (these parameters are approximately equal to the sfermion masses; the off-diagonal entries have been neglected for the first two generations; the index i in $M_{\tilde{q}i_L}$ refers to the generation):

$$M_{\tilde{q}1_L} = M_{\tilde{q}2_L} = 539.9, \quad M_{\tilde{d}_R} = 519.5, \quad M_{\tilde{u}_R} = 521.7, \quad M_{\tilde{e}_L} = 196.6, \quad M_{\tilde{e}_R} = 136.2. \quad (2)$$

The soft SUSY-breaking parameters in the diagonal entries of the squark and slepton mass matrices of the third generation have the following values,

$$M_{\tilde{q}3_L} = 495.9, \quad M_{\tilde{b}_R} = 516.9, \quad M_{\tilde{t}_R} = 424.8, \quad M_{\tilde{\tau}_L} = 195.8, \quad M_{\tilde{\tau}_R} = 133.6, \quad (3)$$
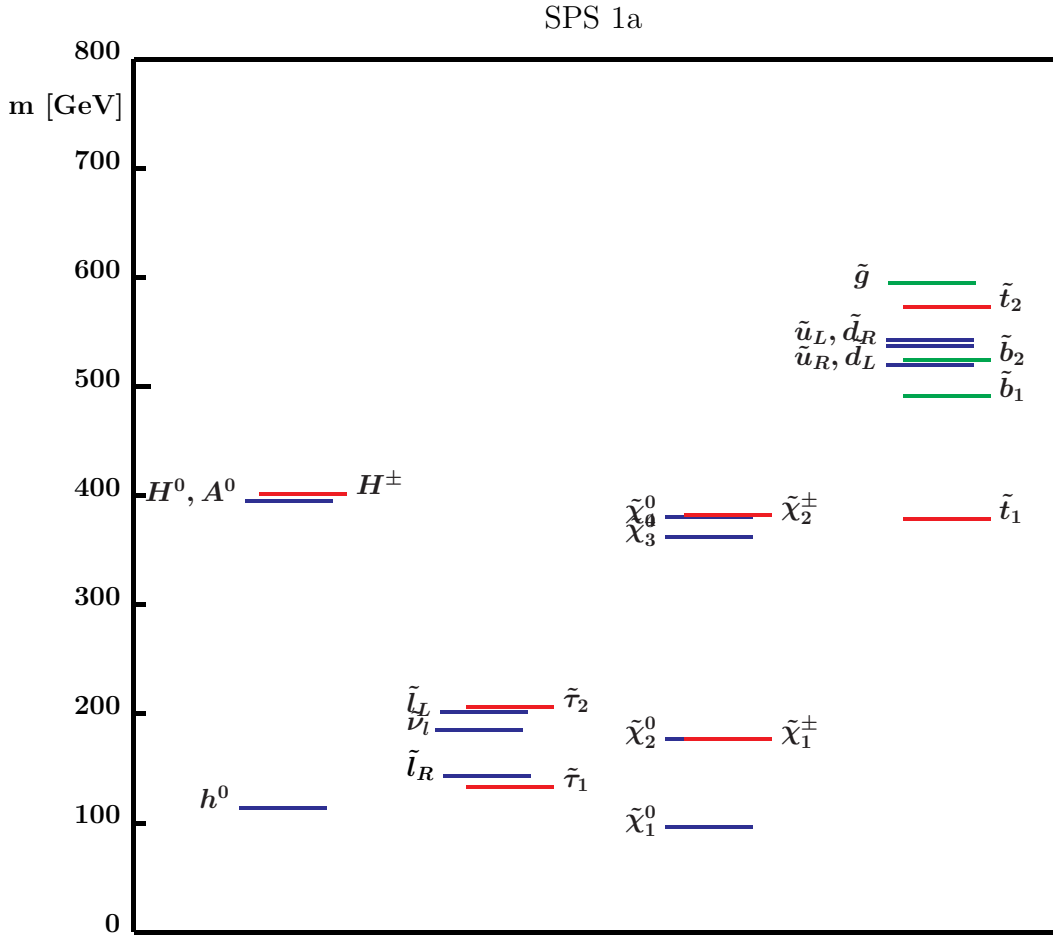
Figure 2: The SUSY particle spectrum for the benchmark point corresponding to SPS 1a (see Refs. [2, 10]).

while the trilinear couplings of the third generation read

$$A_t = -510.0, \quad A_b = -772.7, \quad A_\tau = -254.2. \tag{4}$$

The corresponding SUSY particle spectrum as obtained with *ISAJET 7.58* [9] is shown in Fig. 2.

The benchmark values for the other SPS can be found at `www.ippp.dur.ac.uk/∼georg/sps`, see also Ref. [10].

Acknowledgements

References

[1] ATLAS Collaboration, *Detector and Physics Performance Technical Design Report*, CERN/LHCC/99-15 (1999), see:
`atlasinfo.cern.ch/Atlas/GROUPS/PHYSICS/TDR/access.html` .

[2] B.C. Allanach *et al.*, *Eur. Phys. J.* **C 25** (2002) 113, hep-ph/0202233.

[3] M. Battaglia, A. De Roeck, J. Ellis, F. Gianotti, K.T. Matchev, K.A. Olive, L. Pape, and G.W. Wilson, *Eur. Phys. J.* **C 22**, 535 (2001), hep-ph/0106204; Snowmass P3-47, hep-ph/0112013;
A. Djouadi *et al.*, GDR SUSY Workshop Aix-la-Chapelle 2001, see `www.desy.de/∼heinemey/LesPointsdAix.html`;
S.P. Martin, `http://zippy.physics.niu.edu/modellines.html`;
S.P. Martin, S. Moretti, J. Qian, and G.W. Wilson, Snowmass P3-46.

[4] H.P. Nilles, *Phys. Lett.* **B 115** (1982) 193; *Nucl. Phys.* **B 217** (1983) 366.
A.H. Chamseddine, R. Arnowitt and P. Nath, *Phys. Rev. Lett.* **49** (1982) 970;
R. Barbieri, S. Ferrara and C.A. Savoy, *Phys. Lett.* **B 119** (1982) 343.

[5] For a review, see G.F. Giudice and R. Rattazzi, *Phys. Rep.* **322** (1999) 419, hep-ph/9801271.

[6] L. Randall and R. Sundrum, *Nucl. Phys.* **B 557** (1999) 79, hep-th/9810155;
G.F. Giudice, M.A. Luty, H. Murayama, and R. Rattazzi, *JHEP* **9812** (1998) 027, hep-ph/9810442.

[7] J.L. Feng and T. Moroi, *Phys. Rev.* **D 61** (2000) 095004, hep-ph/9907319;
J.L. Feng, K.T. Matchev, and T. Moroi, *Phys. Rev. Lett.* **84** (2000) 2322, hep-ph/9908309; *Phys. Rev.* **D 61** (2000) 075005, hep-ph/9909334.

[8] A. Djouadi, M. Drees, and J.L. Kneur, *JHEP* **0108** (2001) 055, hep-ph/0107316.

[9] H. Baer, F.E. Paige, S.D. Protopopescu, and X. Tata, hep-ph/9305342, hep-ph/0001086.

[10] N. Ghodbane and H.-U. Martyn, LC Note LC-TH-2001-079, hep-ph/0201233.