A Quick Guide to SUSY Tools*

Peter Z. Skands†

Theoretical Physics, Fermi National Accelerator Laboratory, Batavia, IL, USA

Abstract

The last decade has seen the emergence of a wide range of automated calculations for supersymmetric extensions of the Standard Model. This guide contains a brief summary of these, with the main focus on hadron collider phenomenology, as well as a brief introduction to the so-called SUSY Les Houches Accord. See also the Les Houches Web Repository for BSM Tools:
`http://www.ippp.dur.ac.uk/montecarlo/BSM/`

1 Introduction

Among the most enticing possibilities for observable New Physics both at the Tevatron and at the Large Hadron Collider is supersymmetry (SUSY); for reviews, see e.g. [1–3]. At the most fundamental level, imposing supersymmetry on a quantum field theory represents the most general (and only) possible way of extending the Poincaré group of space–time symmetries [4, 5], at the same time as it furnishes a desirable relation between the bosonic and fermionic degrees of freedom. Empirically, however, supersymmetry can at most be a broken symmetry if it exists in Nature, due to the non-observation of a mass-degenerate (or lighter) spin-partner for each of the Standard Model (SM) particles.

However, even a softly broken supersymmetry can have quite amazing properties, as long as the mass splittings introduced by the breaking are smaller than a TeV or so. Among the most well-known consequences of such a type of supersymmetry are radiative breaking of electroweak symmetry, an elegant solution to the so-called hierarchy problem, a natural weakly interacting dark matter candidate (in theories with conserved R-parity), and unification of the strong, weak, and electromagnetic gauge couplings at a (very) high energy scale.

For collider phenomenology, the most immediately relevant consequences are 1) an extension of the Standard Model Higgs sector to (at least) 2 doublets, 2) promotion of each of the Standard Model fields (plus the extra Higgs content) to superfields, resulting in a spin-partner for each SM particle, with mass splittings inside each boson-fermion doublet $\lesssim 1$ TeV, and 3) the special properties which accompany a conserved R-parity, namely production of the new states only by the pair, followed by individual cascade decays down to the Lightest Supersymmetric Particle (LSP) which is stable and (usually) escapes detection.

The large interest in ($N = 1$) supersymmetric extensions of the SM and their phenomenological consequences has carried with it the need for automated tools to calculate supersymmetric mass and coupling spectra, cross sections, decay rates, dark matter relic densities, event rates, precision observables, etc. To handle the cross-communication between the many tools, the so-called SUSY Les Houches Accord [6–8] (SLHA) is now in widespread use. Section 2 contains a brief introduction to this Accord. Next, in Section 3, an overview of the presently available state-of-the-art tools is given, divided into four main categories. A more extensive collection of tools for BSM physics as well as an online repository can be found in [9]. Another recent and comprehensive tools review is the Les Houches Guidebook to MC Generators [10].

*FERMILAB-CONF-06-004-T. Prepared for the TeV4LHC Physics Landscapes Summary Report.

†skands@fnal.gov

2 The SUSY Les Houches Accord

Given the long history of the subject, it is not surprising that several different conventions for defining supersymmetric theories have been proposed over the years, many of which are in active use by different groups. While this is not a problem per se (unique translations can always be constructed), it does entail a few practical problems, in particular when the results of one group are compared to (or used for) the calculations of a different group.

In addition, even when the theoretical conventions are identical, there remains the purely technical issue that each program has its own native way of inputting and outputting parameters, each of which is unintelligible to most other programs.

The SLHA was proposed to solve both these problems. Due to the large parameter space of unconstrained supersymmetric models, the SLHA in its present form [6] (SLHA1) is limited to the MSSM, with conservation of R-parity, CP, and flavour. Extensions to more general models are underway [8] (SLHA2).

Technically, the Accord is structured into 3 ASCII files (or strings): 1) model definition and measured SM parameters, 2) SUSY mass and coupling spectrum, and 3) decay tables. Though admittedly not elegant, the ASCII format was chosen for its robustness across platforms and compilers. In general, all input parameters used for a calculation are copied to the output, so that any subsequent calculation also has access to the exact input parameters used for the previous one.

2.1 The SLHA Conventions

The backbone of the Accord is a unique set of conventions for defining the supersymmetric parameters, fields, and couplings. These conventions, which have also been adapted for the so-called SPA project [11], largely resemble the widely used Gunion-Haber conventions [12], with a few differences as noted explicitly in [6]. Simply stated, to define a SUSY model, one needs the field content, the Superpotential, the SUSY breaking terms, and the gauge couplings. For the field content, the SLHA assumes that of the MSSM, while SLHA2 will include extensions for the NMSSM.

The MSSM Superpotential is specified by the measured SM particle masses (giving the Yukawa couplings) and by the μ term. At present, only the third generation Yukawas are included. The gauge couplings are specified in terms of M_{Z}, G_F, $\alpha_s(M_{\mathrm{Z}})^{\overline{\mathrm{MS}}}$, and the fine structure constant at zero momentum transfer. All of these are the standard SM ones that one can get from a review text, i.e. no SUSY corrections should be included here. SLHA2 will include masses for all 3 generations, as well as the CKM matrix.

The SUSY breaking terms can either be specified by giving the parameters for a minimal version of a particular SUSY breaking model (SUGRA, GMSB, or AMSB), or individually, either by starting from a minimal model and successively adding non-universal terms or by simply giving all terms explicitly. For higher-order calculations, these parameters are interpreted as given in the modified dimensional reduction ($\overline{\mathrm{DR}}$) scheme [13–15], either at the (derived) unification scale or at a user-specifiable scale. As mentioned, CP, R-parity, and flavour are assumed conserved in SLHA1.

In the spectrum output, three kinds of parameters are given: 1) pole masses of all (s)particles, 2) mixing matrices, and 3) Lagrangian parameters. While the precise definition of the mixing matrix elements are left up to each spectrum calculator, the Lagrangian parameters are defined as $\overline{\mathrm{DR}}$ ones at one or several user-specifiable scales Q.

2.2 The SLHA Decay Tables

A somewhat separate and self-contained aspect of the SLHA is the possibility to pass total widths and partial branching ratios via a file structure similar to that of the rest of the Accord. A common use for this is to improve or extend the width calculations of an event generator by the numbers calculated with a specialised package.

Note! An important potential pitfall when using these files is on-shell intermediate resonances in final states with more than 2 particles. If not treated properly, large problems both with double-counting and with incorrect population of phase space can occur. Please see [6] for an explicit description of the correct procedure to adopt in these cases.

3 Computing SUSY

This Section contains an overview of SUSY calculational tools, divided into 1) spectrum calculators, 2) observables calculators, 3) matrix element and event generators, and 4) fitting programs. For links and references, the reader should consult the recently constructed online repository for BSM tools [9].

3.1 Spectra

Given assumptions about the underlying supersymmetric theory (field content, superpotential, supersymmetry breaking terms) and a set of measured parameters (SM particle masses, gauge couplings, electroweak symmetry breaking), the masses and couplings of all particles in the spectrum can be computed. This is the task of spectrum calculators, also called RGE packages.

The most commonly used all-purpose spectrum calculators are Isajet [16], SoftSusy [17], SPheno [18], and SuSpect [19], all compatible with SLHA. In general, the codes agree with each other to within a percent or so, though larger discrepancies can occur in particular at large $\tan\beta$. For mSUGRA, a useful online tool for comparison between them (and different versions of them) exists [20]. Recent detailed comparison studies can be found in [21–23]. Though Pythia also contains an internal spectrum calculator [24], the resulting spectrum is very approximate and should not be used for serious studies.

There are also a few spectrum calculators with more specialised areas of application, here CPSuperH [25], FeynHiggs [26], and NMHDecay [27]. NMHDecay computes the entire mass spectrum in the NMSSM (and has a limit which is equivalent to the MSSM), but couplings and decay widths are so far only calculated for the Higgs sector, though improvements are underway. NMHDecay is compatible with an extension of the SLHA [8]. The program FeynHiggs deals with the Higgs sector of the MSSM, for which it contains higher precision calculations than the general-purpose programs mentioned above. It is also able to handle both minimal flavour violation (MFV) and CP violation, and is compatible with the SLHA, hence can e.g. be used to provide a final adjustment to the Higgs sector of a general spectrum calculated by one of the other codes. Finally, CPSuperH deals with the Higgs sector in the MSSM with explicit CP violation and contains a number of refinements which makes it interesting also in the CP conserving case.

3.2 Observables

Programs that calculate one or more of the following: cross sections, decay partial widths, dark matter relic density, and indirect/precision observables. Note that we here focus on calculations relevant for hadron colliders and that matrix element and event generators, which also calculate many of these things, are treated separately below.

For hadron collider cross sections, Prospino [28] can be used to calculate inclusive SUSY-NLO cross sections, both total and differential. It also calculates the LO cross section and gives the corresponding K-factor.

For decay partial widths, several specialised packages exist. For the MSSM, SPheno calculates tree-level decays of all (s)particles (soon to include RPV[1]), SDecay [29] computes sparticle decay widths including NLO SUSY-QCD effects, and both FeynHiggs [26] and HDecay [30] compute Higgs partial widths with higher-order corrections. NMHDecay [27] computes partial widths for all Higgs bosons in the NMSSM.

For the density of dark matter, DarkSUSY [31], IsaTools [32], and MicrOMEGAs [33] represent the publically available state-of-the-art tools. All of these work for the MSSM, though a special effort has been put into MicrOMEGAs to make it easily extendable [34], recently resulting in an implementation of the NMSSM [35], and work on CP violation is in progress.

For precision observables, micrOMEGAs includes calculations of $(g-2)_\mu$, $\mathrm{b}\to\mathrm{s}\gamma$, $\mathrm{B_s}\to\mu^+\mu^-$, and

[1]RPV in SPheno is not yet public, but a private version is available from the author

cross-sections for neutralino annihilation at v∼0, relevant for indirect detection of neutralinos. NMHDecay includes a check against LEP Higgs searches, $b \to s\gamma$, and can be interfaced to MicrOMEGAs for the relic density. Isajet/IsaTools include calculations of $b \to s\gamma$, $(g-2)_\mu$, $B_s \to \mu^+\mu^-$, $B_d \to \tau^+\tau^-$, and neutralino-nucleon scattering cross sections. SPheno includes $b \to s\gamma$, $(g-2)_\mu$, as well as the SUSY contributions to the ρ parameter due to sfermions. FeynHiggs also evaluates the contribution to electroweak precision observables via $\Delta\rho$ as well as $(g-2)_\mu$ (with two-loop corrections). Finally, SuSpect also includes a calculation of $b \to s\gamma$.

3.3 Matrix Element and Event Generators

By a matrix element generator, we here understand a program that, given a set of fields and a Lagrangian, is able to generate Feynman diagrams for any process and square them. Note, however, that many of the codes are able to do quite a bit more than that. An event generator is a program that, given a matrix element, is able to generate a series of random exclusive events in phase space, often including resonance decays, parton showers, underlying event, hadronisation, and hadron decays.

The automated tools for generating matrix elements for SUSY are Amegic++ [36], CalcHEP [37], CompHEP [38], Grace-SUSY [39], SUSY-MadGraph [40], and O'Mega [41]. All of these work at Leading Order, except Grace, and all currently only deal with the MSSM, except CalcHEP which contains an NMSSM implementation.

CalcHEP and CompHEP provide internal event generators, while the event generator Sherpa [42] is built on Amegic++, Gr@ppa [43] builds on Grace, MadEvent [44] builds on MadGraph (work is in progress to extend this to SUSY-MadGraph), and Whizard [45] builds on O'Mega. Of these, most are matrix-element-level event generators, that is they provide events consisting of just a few partons and their four-momenta, corresponding to the given matrix element convoluted with phase space. These events must then be externally interfaced [46] e.g. to Pythia or Herwig for resonance decays, parton showering, underlying event, and hadronisation. The exception is Sherpa, which contains its own parton showers and underlying-event models (similar to the Pythia ones), and for which a cluster-based hadronisation model is being developed.

In addition, both Herwig [47] and Pythia [48] contain a large number of internal hardcoded leading order matrix elements, including R-parity violating (RPV) decays in both cases [49–53], and RPV single sparticle production in Herwig [49]. In Pythia, the parton shower off SUSY resonance decays is merged to the real NLO jet emission matrix elements [54], an interface to CalcHEP and NMHDecay exists for the NMSSM [55], and an implementation of the hadronisation of R-hadrons is available [56, 57].

Two other event generators should be mentioned. Isajet [16] also contains a large amount of SUSY phenomenology, but its parton shower and hadronisation machinery are much less sophisticated than those of Herwig, Pythia, and Sherpa. The active development of Susygen [58] (which among other things includes RPV single sparticle production) is currently at a standstill, though basic maintenance is still being carried out.

3.4 Fitters

Roughly speaking, the tools described above all have one thing in common: given a set of fundamental parameters (themselves not directly observable) they calculate the (observable) phenomenological and experimental consequences. However, if SUSY is at some point discovered, a somewhat complementary game will ensue: given a set of observed masses, cross sections, and branching ratios, how much can we say about the fundamental parameters?

The fitting programs Fittino [59] and Sfitter [60] attempt to address this question. In a spirit similar to codes like Zfitter [61], they combine the above tools in an automated statistical analysis, taking as input a set of measured observables and yielding as output a set of fundamental parameters.

Obviously, the main difficulty does not lie in determining the actual central values of the parameters, although this can require significant computing resources in itself; by far the most important aspect of these tools is the error analysis. Statistical uncertainties can be treated rigorously, and are included in both programs. Theoretical and systematic uncertainties are more tricky. In a conventional analysis, these uncertainties are evaluated by careful consideration of both the experimental setup, and of the particular theoretical calculations involved. In an automated analysis, which has to deal simultaneously with the entire parameter space of supersymmetry, a 'correct' evaluation of these errors poses a truly formidable challenge, one that cannot be considered fully dealt with yet.

Acknowledgments

The TeV4LHC series of workshops have been highly enjoyable, and I am thankful for all the hard work put in by the organisers. Thanks also to S. Mrenna, W. Porod, S. Kraml, and S. Heinemeyer for useful comments on the draft. This work was supported by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy.

References

[1] S. P. Martin, (1997), hep-ph/9709356.

[2] X. Tata, (1997), hep-ph/9706307.

[3] D. J. H. Chung et al., Phys. Rept. **407**, 1 (2005).

[4] S. Coleman, J. Mandula, Phys. Rev. **159**, 1251 (1967).

[5] R. Haag, J. T. Lopuszanski, M. Sohnius, Nucl. Phys. **B**, 257 (1975).

[6] P. Skands et al., JHEP **07**, 036 (2004), (see `http://home.fnal.gov/~skands/slha/`).

[7] Beyond the Standard Model Working Group, B. C. Allanach et al., (2004), hep-ph/0402295.

[8] B. C. Allanach et al., Status of the SUSY Les Houches Accord II Project, FERMILAB-CONF-05-517-T. In Les Houches 'Physics at TeV Colliders 2005' BSM Working Group: Summary report, hep-ph/0602198.

[9] P. Skands et al., A repository for beyond-the-standard-model tools, FERMILAB-CONF-05-521-T. In Les Houches 'Physics at TeV Colliders 2005' BSM Working Group: Summary report, hep-ph/0602198. See also: `http://www.ippp.dur.ac.uk/montecarlo/BSM/`.

[10] M. A. Dobbs et al., (2004), in Les Houches 'Physics at Tev Colliders 2003' QCD/SM Working Group: Summary Report (hep-ph/0403100). hep-ph/0403045.

[11] J. A. Aguilar-Saavedra et al., (2005), hep-ph/0511344.

[12] J. F. Gunion, H. E. Haber, Nucl. Phys. **B272**, 1 (1986), [Erratum-ibid. **B402**, 567 (1993)].

[13] W. Siegel, Phys. Lett. **B84**, 193 (1979).

[14] D. M. Capper, D. R. T. Jones, P. van Nieuwenhuizen, Nucl. Phys. **B167**, 479 (1980).

[15] I. Jack, D. R. T. Jones, S. P. Martin, M. T. Vaughn, Y. Yamada, Phys. Rev. **D50**, 5481 (1994).

[16] H. Baer et al., (1993), hep-ph/9305342.

[17] B. C. Allanach, Comput. Phys. Commun. **143**, 305 (2002).

[18] W. Porod, Comput. Phys. Commun. **153**, 275 (2003).

[19] A. Djouadi, J.-L. Kneur, G. Moultaka, (2002), hep-ph/0211331.

[20] S. Kraml, `http://cern.ch/kraml/comparison/`.

[21] B. C. Allanach, S. Kraml, W. Porod, JHEP **03**, 016 (2003).

[22] B. C. Allanach et al., JHEP **09**, 044 (2004).

[23] G. Bélanger, S. Kraml, A. Pukhov, Phys. Rev. **D72**, 015003 (2005).

[24] S. Mrenna, Comput. Phys. Commun. **101**, 232 (1997).

[25] J. S. Lee et al., Comput. Phys. Commun. **156**, 283 (2004).

[26] S. Heinemeyer, W. Hollik, G. Weiglein, Comput. Phys. Commun. **124**, 76 (2000), see `http://www.feynhiggs.de`.

[27] U. Ellwanger, J. F. Gunion, C. Hugonie, JHEP **02**, 066 (2005).

[28] W. Beenakker, R. Hopker, M. Spira, (1996), hep-ph/9611232. See `http://pheno.physics.wisc.edu/~plehn/`.

[29] M. Mühlleitner, A. Djouadi, Y. Mambrini, (2003), hep-ph/0311167.

[30] A. Djouadi, J. Kalinowski, M. Spira, Comput. Phys. Commun. **108**, 56 (1998).

[31] P. Gondolo et al., JCAP **0407**, 008 (2004).

[32] H. Baer, C. Balazs, A. Belyaev, J. O'Farrill, JCAP **0309**, 007 (2003), see `http://www.phy.bnl.gov/~isajet/`.

[33] G. Bélanger, F. Boudjema, A. Pukhov, A. Semenov, Comput. Phys. Commun. **149**, 103 (2002).

[34] G. Bélanger, F. Boudjema, A. Pukhov, A. Semenov, micrOMEGAS2.0 and the relic density of dark matter in a generic model, In Les Houches 'Physics at TeV Colliders 2005' BSM Working Group: Summary report, hep-ph/0602198.

[35] G. Bélanger et al., JCAP **0509**, 001 (2005), [hep-ph/0505142].

[36] F. Krauss, R. Kuhn, G. Soff, JHEP **02**, 044 (2002).

[37] A. Pukhov, (2004), [hep-ph/0412191].

[38] A. Pukhov et al., (1999), [hep-ph/9908288].

[39] Minami-Tateya collaboration, H. Tanaka, M. Kuroda, T. Kaneko, M. Jimbo, T. Kon, Nucl. Instrum. Meth. **A389**, 295 (1997).

[40] G. C. Cho et al., (2006), [hep-ph/0601063].

[41] M. Moretti, T. Ohl, J. Reuter, (2001), [hep-ph/0102195].

[42] T. Gleisberg et al., JHEP **02**, 056 (2004).

[43] S. Tsuno, (2005), [hep-ph/0501174].

[44] F. Maltoni, T. Stelzer, JHEP **02**, 044 (2002).

[45] W. Kilian, LC-TOOL-2001-039.

[46] E. Boos et al., (2001), hep-ph/0109068.

[47] G. Corcella et al., JHEP **01**, 010 (2001).

[48] T. Sjöstrand et al., Comput. Phys. Commun. **135**, 238 (2001), (see also the manual, hep-ph/0308153).

[49] H. K. Dreiner, P. Richardson, M. H. Seymour, JHEP **04**, 008 (2000).

[50] P. Richardson, (2000), [hep-ph/0101105].

[51] P. Z. Skands, Eur. Phys. J. **C23**, 173 (2002).

[52] P. Z. Skands, (2002), [hep-ph/0209199].

[53] T. Sjöstrand, P. Z. Skands, Nucl. Phys. **B659**, 243 (2003).

[54] E. Norrbin, T. Sjöstrand, Nucl. Phys. **B603**, 297 (2001).

[55] A. Pukhov, P. Skands, Les Houches squared event generator for the NMSSM, FERMILAB-CONF-05-520-T. In Les Houches 'Physics at TeV Colliders 2005' BSM Working Group: Summary report, hep-ph/0602198.

[56] A. C. Kraan, Eur. Phys. J. **C37**, 91 (2004).

[57] A. C. Kraan, J. B. Hansen, P. Nevski, (2005), (see `http://www.thep.lu.se/~torbjorn/Pythia.html`), [hep-ex/0511014].

[58] N. Ghodbane, S. Katsanevas, P. Morawitz, E.Perez, (1999), [hep-ph/9909499].

[59] P. Bechtle, K. Desch, P. Wienemann, (2004), hep-ph/0412012.

[60] R. Lafaye, T. Plehn, D. Zerwas, (2004), hep-ph/0404282.

[61] D. Y. Bardin et al., Comput. Phys. Commun. **133**, 229 (2001).