SUSY Calculation Tools

Abdelhak DJOUADI[+]

Laboratoire de Physique Mathématique et Théorique, UMR5825–CNRS
Université de Montpellier II, F–34095 Montpellier Cedex 5, France

Abstract

I discuss the various available tools for the study of the properties of the new particles predicted in the Minimal Supersymmetric extension of the Standard Model. Emphasis will be put on the codes for the determination of the sparticle and Higgs boson spectrum. Codes for the calculation of production cross sections, decay widths and branching ratios, Dark Matter relic density and detection rates, as well as codes for automatic analytical calculations and Monte-Carlo event generators for Supersymmetric processes will be briefly discussed.

1. Introduction

It is a well–known fact that in broken supersymmetric theories, it is a rather tedious task to deal in an exhaustive way with all the basic parameters of the Lagrangian, to derive their relationship with the physical parameters, the particle masses and couplings, and to make detailed and complete phenomenological analyses and comparisons with the outcome or expectations from experiments. This is mainly due to the fact that, even in the Minimal Supersymmetric Standard Model (MSSM) [1, 2], with a:

– minimal gauge group, the Standard Model $\mathrm{SU(3)_C \times SU(2)_L \times U(1)_Y}$ one,
– minimal particle content: three generations of "chiral" sfermions $\tilde{f}^i_{L,R}$ [no right–handed sneutrinos] and two doublets of Higgs fields H_1 and H_2,
– minimal set of couplings imposed by R–parity conservation to enforce baryon and lepton number conservation in a simple way,
– minimal set of soft SUSY–breaking parameters: gaugino mass terms M_i, scalar mass terms m_{H_i} and $m_{\tilde{f}_i}$, a bilinear term B and trilinear sfermion couplings A_i,

there are more than hundred new parameters [3] in the general case of arbitrary complex phases, intergenerational mixing and non-diagonal sfermion mass and coupling matrices. Even if one constrains the model to have a viable phenomenology, assuming for instance no intergenerational mixing, no large new source of CP violation, universality of first and second generation sfermions [a model that we will call [2] phenomenological or pMSSM], there are still more than 20 free parameters left to cope with.

[+]Present address: TH Division, CERN, CH–1211 Geneva 23, Switzerland.

This large number of inputs enters in the evaluation of the masses of $\mathcal{O}(30)$ SUSY particles and Higgs bosons as well as their complicated couplings, which involve several non–trivial aspects, such as the mixing between different states, the Majorana nature of some particles and, if one aims to be rather precise, the higher order corrections which for the calculation of a single parameter need the knowledge of a large part of the remaining spectrum. One has then to calculate in some accurate way, i.e. including higher order corrections, the rates for the many possible decay modes and production processes at the various possible machines and eventually the implications for Dark Matter searches.

Fortunately, there are well motivated theoretical models where the soft SUSY–breaking parameters obey a number of universal boundary conditions at a high (unification) scale, leading to only a handful set of basic parameters. This is the case for instance of the minimal Supergravity model (mSUGRA) [4], where the entire sparticle and Higgs spectrum is determined by the values of only five free parameters [a common gaugino mass $m_{1/2} = M_i$, universal scalar mass $m_0 = m_{\tilde{f}} = m_{H_i}$ and trilinear coupling $A_0 = A_i$ at the GUT scale, the sign of the higgsino parameter μ and $\tan\beta$, the ratios of vevs of the two–Higgs doublets of the MSSM], making comprehensive scans of the parameter space and detailed studies of the spectrum feasible. However, there are also similarly constrained and highly predictive models, such as anomaly (AMSB) [5] and gauge (GMSB) [6] mediated SUSY-breaking model, string inspired models or models with right–handed neutrinos, to name a few, which can serve as benchmarks [7] to be investigated. We then have to trade a complicated situation where we have one general model with many input parameters, with a not less complicated situation where we have many constrained models with a small number of basic parameters.

In addition, in these unified models, the low–energy parameters are derived from the high–energy (GUT and/or possibly some intermediate scale) input parameters through Renormalization Group Equations (RGE) and they should also necessarily involve radiative electroweak symmetry breaking (EWSB), which sets additional constraints. The implementation of the RG evolution and EWSB mechanism poses numerous non–trivial technical problems if they have to be done accurately, i.e. including higher order effects. This complication is to be added to the still present one stemming from the accurate calculation of the particle masses and couplings, decay and production rates, etc...

Therefore, to deal with the supersymmetric spectrum in all possible cases, one needs very sophisticated programs to encode all the information and, eventually, to pass it to Monte–Carlo event generators to simulate the physical properties of the new particles. These programs should have a high degree of flexibility in the choice of the model and/or the input parameters and an adequate level of approximation at different stages, for instance in the incorporation of the RGEs, the handling of the EWSB and the inclusion of the radiative corrections to (s)particle masses, which in many cases can be very important. They should also be reliable, quite fast to allow for rapid comprehensive scans of the parameter space and simple enough to be linked with other spectra programs or Monte–Carlo event generators. There are several public codes which deal with this topic and I will briefly discuss them here[1].

[1] There are also several private codes, dealing with one topic or another, which I will not discuss here. However, I will mention a few still private codes which will be made public in a rather near future.

2. Codes for Spectra calculations

There are four main public codes which make rather detailed calculations of the Supersymmetric particle spectrum in the pMSSM or in constrained scenarii (mSUGRA, etc..):

- `ISASUSY` [8], which is available since the early 90s and is implemented in the Monte–Carlo generator `ISAJET`; it is the most widely used for simulations in the MSSM.
- `SuSpect` [9], a new version has been released very recently but a preliminary version of the program exists since 1998 and was described in Ref. [2].
- `SOFTSUSY` [10], a code written in C++ and has been release a year ago.
- `SPHENO` [11], which is under development and will appear soon.

The codes have different features in general, but they all incorporate the four main ingredients or requirements for any complete calculation of the SUSY spectrum:

i) RG evolution of parameters back and forth between the low energy scale, such as M_Z and the electroweak symmetry breaking scale, and the high–energy scale, such as the GUT scale or the messenger scale in GMSB models. This is the case for the SM gauge and Yukawa couplings and for the soft SUSY–breaking terms: scalar and gaugino masses, bilinear and trilinear couplings, the higgsino parameter μ and $\tan\beta$, the ratios of vevs of the two–Higgs doublets of the MSSM. This procedure has to be iterated several times to include SUSY threshold effects or radiative corrections due SUSY particles.

ii) The implementation of radiative EWSB and the calculation of the bilinear term B and the absolute value of the higgsino parameter $|\mu|$ from the minimization of the full one–loop effective scalar potential [i.e. including all standard and SUSY particle loop contributions] at the EWSB scale which provides two additional constraints. The procedure has to be iterated until a convergent value for these parameters is obtained.

iii) Calculation of the pole masses of the Higgs bosons and all the supersymmetric particles, including the possible mixing between the current states and the radiative corrections when they are important. An iteration, similar to the one for the RGEs, is also needed here to obtain the precise mass values.

iv) The possibility of performing some checks of important theoretical features, such as the absence of tachyonic particles, non desired charge and color breaking (CCB) minima, a potential unbounded from below (UFB) and possibly large fine–tuning in the EWSB conditions and also some experimental constraints from negative searches of sparticles and Higgs bosons at colliders or from high precision measurements.

The general algorithm depicted in Figure 1, includes the various important steps: the choice of SM inputs parameters at low energy [the gauge coupling constant and the pole masses of the third generation fermions], the calculation of the running couplings including radiative corrections in the modified Dimensional Reduction scheme $\overline{\rm DR}$ [which preserves SUSY] and their RG running back and forth between low and high scales, with the possibility of imposing the unification of the gauge couplings and the inclusion of SUSY thresholds in some cases, the RG evolution of the soft–SUSY breaking parameters from the high scale to the EWSB scale, the minimization of the one-loop effective potential and the determination of some important parameters, and finally the calculation of the particle masses including the diagonalization of the mass matrices and the radiative corrections.

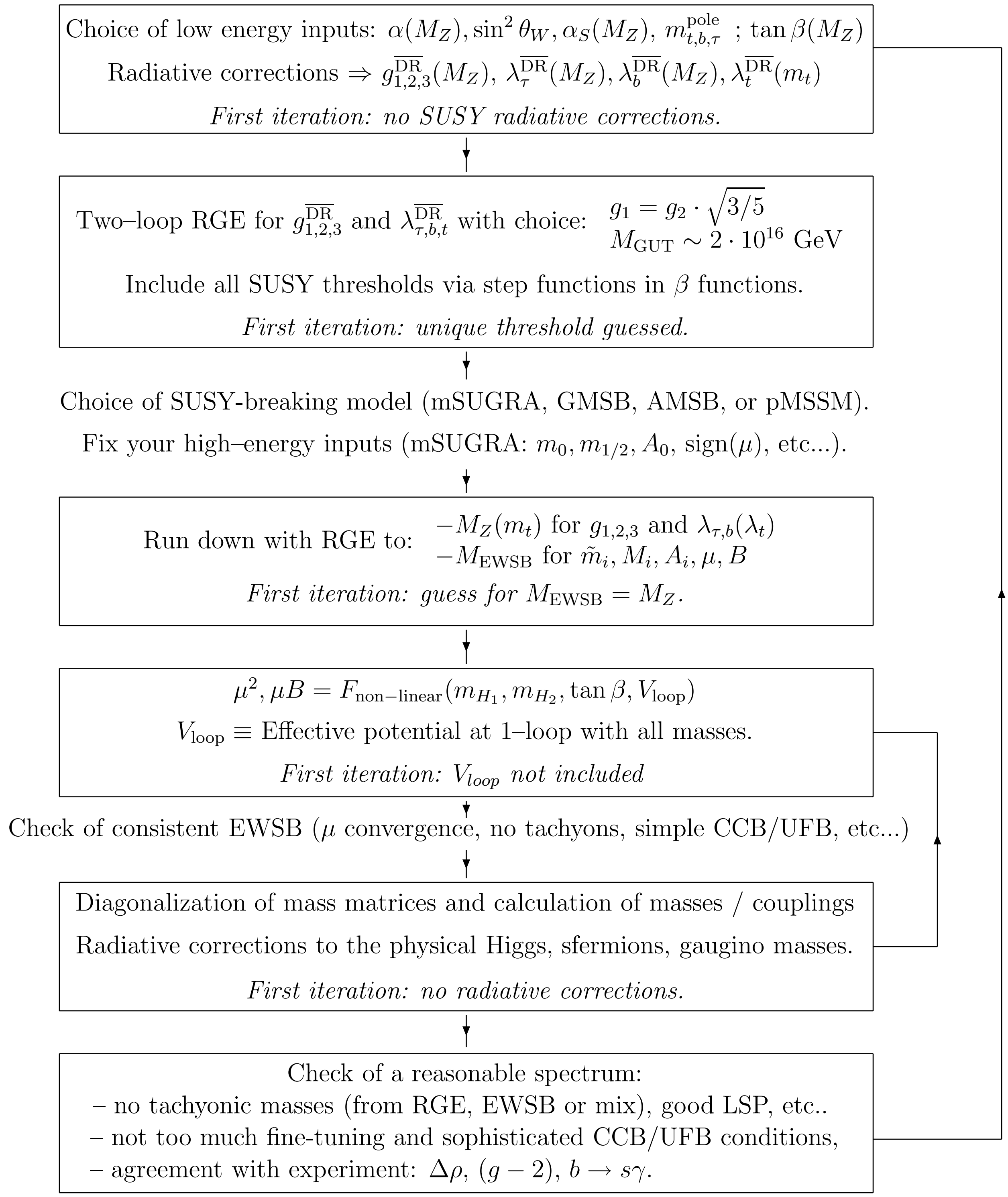

Figure 1: Iterative algorithm for the calculation of the SUSY particle spectrum from the choice of inputs to the check of the spectrum. The small iteration on μ is performed until $\mu_i - \mu_{i-1} \leq \epsilon$ while the long RG/RC iteration needs to be performed at least 3 to 4 times. In the first iteration, no radiative corrections are included and the SUSY thresholds as well as the EWSB and GUT scales are guessed.

For the various aspects of the calculation, the previous four codes have different features in general [which is very useful for performing cross–checks]: some are written in Fortran and some in C++, some are interfaced with event generators or other programs, they have different options for models and input parameters (flexibility) and they use different approximations in the calculation (for instance in the inclusion of the higher order radiative corrections, the RGE running, the EWSB mechanism, etc..). In Table 1, the various features of the four programs are summarized. As can be seen, they all deal with the most studied theoretical models [mS, AM and GM stand, respectively, for mSUGRA, AMSB and GMSB], use sometimes different approximations [although not in very important sectors such as the gauge and Yukawa couplings] and many calculate additional items and/or are interfaced with other programs.

Item/Code	ISASUSY	SuSpect	SOFTSUSY	SPHENO
Language	Fortran	Fortran	C++	Fortran
Models	mS,AM,GM	mS,AM,GM	mS,AM,GM	mS,AM,GM
	pMSSM(25)	pMSSM(22)	–	–
	$\tilde{\nu}_R$, strings	–	–	string sc.
RGEs	2–loop g_i, λ_i	2–loop g_i, λ_i	2–loop g_i, λ_i	2–loop g_i, λ_i
	2 loop soft	1–loop soft	1–loop soft	2–loop soft
EWSB	$\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$	flexible	$\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$	$\sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$
$V_{\rm loop}$/tad.	$t, b, \tilde{t}, \tilde{b}$	1–loop	1–loop	1–loop
Thresholds	Steps	Steps	in RC	in RC
RC SM	leading	lead/full	lead/full	full
RC SUSY	approx.	$\sim$ PBMZ	$\sim$ PBMZ	full
RC Higgs	1Loop EP	SUBH/FHF/HHH	FHF	BDSZ
Checks	–	CCB,UFB,FT	FineTuning	CCB,UFB
	–	EW,a_μ,$bs\gamma$	–	EW,a_μ, $bs\gamma$
Decays	Yes	HDECAY/SDECAY*	–	Yes
Production	pp and e^+e^-	ee SUSYGEN, pp^*	–	e^+e^-
DM calc.	–	μMegas/DarkSUSY	μMegas	–

*Table 1: The various important items implemented in the four RGE codes for the calculation of the (s)particle spectra. The * means that the item is under implementation.*

One important ingredient in these calculations is the radiative corrections to (s)particle masses. These corrections, in particular those stemming from QCD and third generation (s)fermions because of the strong couplings, can be large. In the SUSY sector, they can alter the experimental search strategies at colliders since large corrections may change constraints on the MSSM parameter space and may allow or not some new decay modes. Moreover, the mass difference between the lightest neutralino [which is in general the LSP] and the other sparticles plays a major role, since it gives the amount of missing energy [which is the typical signature of SUSY processes at colliders] and enters Dark Matter relic density calculations [co–annihilation]. In most of the codes above, these radiative corrections are implemented *à la* Pierce, Bagger, Matchev and Zhang (PBMZ) [12].

The radiative corrections are particularly important, as is well known, in the Higgs sector where one– and two–loop contributions of third generation (s)fermions can shift the upper limit on the mass of the lightest Higgs boson from M_Z by up to 40 GeV, dramatically changing the reach of the LEP2 collider for instance. In fact, this is the most delicate quantity to calculate. RGE codes such as `ISASUSY` and `SuSpect` have their own approximate calculations, but they are also linked with routines which do a more sophisticated job. The main available routines for the Higgs sector are:

– `Subhpole` (SUBH) [13]: which calculates the leading radiative corrections in the effective potential approach with a two–loop RG improvement. It includes the leading λ_t^2 corrections as well as the leading part of the SUSY–QCD corrections.

– `HMSUSY` (HHH) [14]: calculates the one–loop corrections in the effective potential approach and includes the leading two–loop standard QCD and EW corrections.

– `FeynHiggsFast` (FFH) [15]: calculates the corrections in the Feynman diagrammatic approach with the one and two–loop QCD corrections at zero momentum transfer [the version `FeynHiggs` [16] has the full one–loop corrections and is slower].

– `BDSZ` [17] gives the leading one–loop corrections from the third generation (s)fermion sector as well as the full $\alpha_s\lambda_t^2, \lambda_t^4$ and $\alpha_s\lambda_b^2$ corrections at zero–momentum transfer.

Detailed comparisons of these codes have been performed. The main conclusion is that despite of the different ways the various items discussed above are implemented, they in general agree at the percent level in large parts of the MSSM parameter space. Several more important differences occur however in some areas of the parameter space, in particular in the high $\tan\beta$ and/or focus point regions with large m_0 values, where the Yukawa couplings of top and bottom quarks play an important role[2].

Once the spectrum is calculated, one has the possibility of linking the previous programs with other routines which determine some properties of the SUSY particles, imposing theoretical and experimental constraints and making scans on the parameter space to constrain the various models or to delineate regions of the parameter space where SUSY signals can be expected in colliders or DM searches. This is exemplified in Fig. 2 from Ref. [19], where in the mSUGRA model a scan in the $(m_0, m_{1/2})$ plane has been performed [for given values of the other parameters $\tan\beta, A_0$ and sign(μ)] including theoretical constraints [proper EWSB, no CCB/UFB/tachyons, χ_1^0 LSP] as well as experimental constraints [bounds on sparticle and Higgs masses and precision measurement from LEP and the Tevatron, the decay $b \to s\gamma$] and possibly some additional requirements [such as the 2σ evidence for a 115 GeV SM Higgs at LEP, a 3 σ contribution to the $(g-2)_\mu$ and a χ_1^0 LSP being a solution for the DM problem i.e. with the relevant relic density].

[2]For a comparison of the four codes, see the talk of Sabine Kraml at this conference [18]. Note that the comparison with the program `SuSpect` made there was with an earlier version which had only a very approximate determination of the Higgs boson masses. The new version, since it is linked to several Higgs routines, gives a much better determination of these parameters.

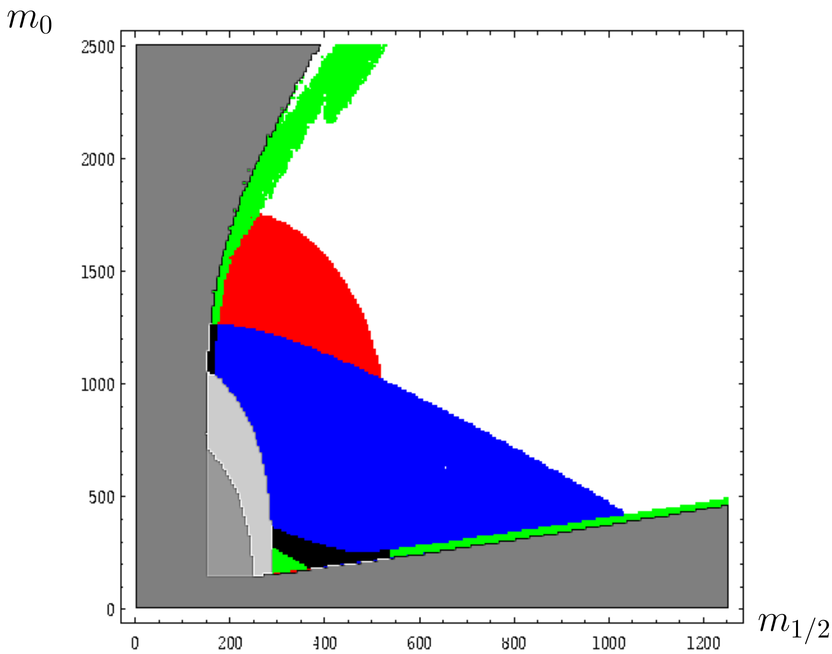

Figure 2: *Constraints on the* $(m_{1/2}, m_0)$ *mSUGRA plane for* $\tan\beta = 40$*,* $A_0 = 0$ *and sign*$(\mu) > 0$*. The gray areas are those excluded by the requirement of EWSB and limits on SUSY particle masses (darker gray), BR(*$b \to s\gamma$*) (medium Rey) and* $M_h > 113$ *GeV (light and dark Frey). The colors are for the possible "evidence" for the LEP2 Higgs boson (red), the* $(g_\mu - 2)$ *excess (blue) and the LSP being the Dark Matter (green).*

3. Codes for Production, Decay and Dark Matter calculations

3.1 NLO Higgs and SUSY particle production calculations

The incorporation of next–to–leading order (NLO) corrections is very important for Higgs boson and SUSY particle production at high–energy colliders. In particular, the QCD corrections at hadron machines LHC or Tevatron, can be rather significant with K–factors as large as two [20]. In turn, radiative corrections in e^+e^- collisions processes are in general much smaller but they can be measurable [21]. Here is a non–exhaustive list of available public codes for Higgs and sparticle production at NLO or including higher order effects:

- NLO MSSM Higgs boson production at hadron colliders [20]:
  - `HIGLU`: for the loop induced Higgs production $pp \to gg \to h, H, A$ (NLO).
  - `VV2H/V2HV`: for production with gauge bosons $qq \to h, H + qq$ and W, Z (NLO).
  - `HQQ`: for radiation off top quark $pp \to q\bar{q}, gg \to h, H, A + Q\bar{Q}$ (LO, NLO to come).
  - `HPAIR`: for Higgs pair production $pp \to q\bar{q}, gg \to hh, HH, hA, HA, AA$ (partly NLO).
- NLO SUSY particle production at hadron colliders [20]:
  - `PROSPINO`: for squark and gluino production $pp \to \tilde{q}\tilde{q}^*, \tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ at NLO.
  - The pair and associated production of gauginos at NLO is under preparation.
- Production of Higgs and SUSY particles at e^+e^- colliders:
  - `SUSYGEN` [22] for Higgs and sparticle production, also a MC generator (see later).
  - `HZHA` [23]: the most used Monte Carlo generator for Higgs production at LEP2.
  - Many four or six fermion production processes at e^+e^- colliders....

3.2 Decays of Higgs and SUSY particles

The decays of SUSY and Higgs particles can be rather complicated and it is important to determine them with a good accuracy. There can be a large number of decay modes for some particles: simple two–body decays in which it is important sometimes to include higher order corrections [as is the case for Higgs bosons and strongly interacting sparticles], and rather complicated many–body decay modes such as the three or four body decays of charginos, neutralinos and top squarks or important loop–induced decay modes. There are several available codes, doing this job with a different level of sophistication:

– `ISASUSY` [8]: only tree–level two–body Higgs and SUSY decays (3 body for gauginos).
– `HDECAY` [24]: SM and MSSM Higgs decays with higher order effects.
– `SDECAY` [25]: sparticle decays including higher order effects (RC and multi–body).
– `SPHENO` [11]: discussed above and has 2 and 3–body SUSY particle decays.

Some decay routines are also included in the Monte–Carlo event generators `SUSYGEN` [22], `HZHA` [23], `PYTHIA` [26] and `HERWIG` [27] with possible links to the programs mentioned above. Some development in this subject is expected in the near future.

3.3 Dark Matter Codes

Several experiments for cold Dark Matter searches are in progress or are planed for a near future. The MSSM has a very good candidate, the LSP neutralino χ_1^0, which is electrically neutral, weakly interacting, massive, absolutely stable and which can have the proper cosmological relic density [28]. An intensive phenomenological activity is happening in this field and numerous analyses in the (un)constrained MSSM are performed for:

– the relic density of the LSP: $\sigma(\chi_1^0\chi_1^0 + \chi_1^0\tilde{P} + \tilde{P}\tilde{P} \to \text{anything})$,
– the rate for the direct detection of the LSPs: $\chi_1^0 N \to \chi_1^0 N$,
– the rate for indirect detection: $\chi_1^0\chi_1^0 \to \gamma\gamma, \gamma Z$ and $\bar{p}, e^+, \nu + X$.

For the calculation of the relic density, one needs the sparticle and Higgs spectra and couplings, the annihilation and co–annihilation cross sections, pair production thresholds, effects of resonances, etc... For the detection, one also needs the modelling of the halo, the hadronization, the nuclear matrix elements, the particle flux, interaction and propagation, etc... There are two main multi–purpose codes which include all these[3]:

– `DarkSUSY` [30]: which has its own pMSSM spectra calculation but can be be linked to `SuSpect`. The hadronization and SM particle decays are taken from `PYTHIA`. The program is widely used, in particular for the indirect detection rates.
– `NeutDriver` [31]: which has only implemented the unconstrained MSSM with 69 parameters and the obtained spectrum seems to be problematic. To my knowledge, there was no recent upgrade of the program.

There is also a new code `micrOMEGAs` [32], which calculates the relic density in the constrained or pMSSM. The (co–)annihilation calculation with all channels included is based on `CompHEP` [33] and includes links to `ISASUSY, SuSpect, HDECAY` for the calculation of the spectra. A number of private codes for one or all of these items also exist[4].

[3]See the talk of Emmanuel Nezri in the parallel sessions [29].

[4]In particular the codes by A. Arnowitt et al. and K. Olive et al. on which some recent MSSM Dark Matter analyses discussed at this conference are based upon.

4. Automatic Matrix Element Generators

Processes in which there are many particles in the final state are very important for pp and e^+e^- physics. For instance, the pp or $e^+e^- \to Ht\bar{t} \to$ process, which allows to measure the top Yukawa coupling, leads to 8 or 10 final fermions depending on whether the Higgs decays into $b\bar{b}$ or WW pairs. The full processes have very large matrix elements and in many cases, they need to be calculated automatically and interfaced to MC event generators for a full simulation. There are several codes available on the market for SUSY and SM processes [the latter being needed for the calculation of the backgrounds]:

- `CompHEP` [33]: is one of the major codes for matrix elements calculations. It uses trace techniques for the algebra, Vegas for phase-space integration and calculates its own SUSY Feynman rules and spectra. It has an easy interface with MC generators à la "Les Houches accord" [34] and the program is developing quite rapidly.
- `GRACE--SUSY` [35]: it has for the moment only e^+e^- production processes, only selected processes and needs model files for the others. It uses Form and Reduce for trace calculations. There was no recent major SUSY development but it has been recently used to calculate the $\mathcal{O}(\alpha)$ corrections to $e^+e^- \to \nu\bar{\nu}H$ in the SM [36].
- `FeynCalc` [37]: together with `FeynArts` for the drawing of the Feynman diagrams is mostly used for loop calculations in the SM and the MSSM.
- `AMEGIC++` [38]: is a C++ program for multi–particle production (no calculation of loops yet). It is now implementing SUSY processes in e^+e^- collisions.

There exist other codes multi–particle production codes, such as `O'MEGA/WHIZARD` [39] and `MadGraph` [40] for instance, but they do not include SUSY processes yet.

5. Monte–Carlo event generators

These are big mastodons which are not specific to SUSY and which perform all analyses from the production of the (new) particles to the hadron decays and simulate the signals and the various backgrounds. They in general include five main phases in the simulation process: 1) the hard production processes, 2) the parton showering, 3) the heavy particle decays, 4) the hadronization process and 5) the hadron decays. In the following, I will briefly discuss only the parts on the production (1) and decays (3) of SUSY/Higgs particles; the rest of the simulation is as in the Standard Model. There are three plus one multipurpose Monte–Carlo event generators[5]:

- `ISAJET` [8]: this is the oldest and most used of all generators dealing with SUSY processes. It has all SUSY production channels (including some $\not{R}_p$ violating processes) and is linked with `ISASUSY` which is built in for the spectrum and decay branching ratios calculation. The known drawback is that it has not a very satisfactory description of the standard processes (steps 2, 4 and 5).
- `(S)PYTHIA` [26]: it is known to give one of the best description of SM physics. It has its own calculation of the 2–body decay rates of SUSY and Higgs particles and has implemented a wide range of production processes (including $\not{R}_p$ processes). But it has not a very precise determination of the Higgs and SUSY particle spectrum since it is based on analytical formulae which are rough approximations.

[5]Thanks to Peter Richardson for his advice in this section.

- HERWIG [27]: which is very good to describe the SM and QCD aspects but the SUSY aspect of the program is developing very rapidly. It has many production channels, a good treatment of $\not{R}_p$,includes the spin correlations in most processes and allows for the polarization of the initial beams in e^+e^- collisions. There is built–in code for spectra or decay calculation but has an interface with ISAJET, and in a near future SuSpect and HDECAY/SDECAY.
- SUSYGEN [22]: which is specialized in e^+e^- collisions (in particular it was used to describe LEP physics) but includes now some processes in pp and ep collisions. The spectrum calculation is performed by SuSpect and for the decay widths and branching ratios it is linked to HDECAY for the Higgs sector while it has its own calculation for the SUSY sector. It has full spin correlations and includes most $\not{R}_p$ processes. It is interfaced with PYTHIA for parton shower and hadronization since it cannot simulate the SM backgrounds.

6. Conclusions

In the recent years, more and more programs for phenomenological and experimental analyses became available and the tendency to make them public is growing rather fast. This is very useful for the reliability of these tools since many checks and comparisons can be then performed, thus minimizing the number of errors, bugs and inconsistencies. It also generates a healthy competition between the various codes which are more often upgraded to take into account new developments. The programs are becoming more and more sophisticated but at the same time, efforts are devoted to make them more clear, user friendly and with the adequate documentation.

Due to the complexity of the subject, most programs deal with only one or a few aspects of the theoretical, phenomenological or experimental facets of SUSY. This calls for complementarity between the various programs for spectra determination, higher order corrections, matrix elements calculations, Dark Matter analyses, Monte–Carlo event generators, etc... A large "communication" effort is made: many workshops devoted to tools are organized [GDR–Supersymétrie, and many discussions to complement and interface the various programs are taking place [see for instance the "accord" [34] obtained during the Les Houches Workshop]. This leads to more interplay between theory and experiment which is very useful for the field.

To summarize, there is a very rapid development of the field. In addition to the fact that many new codes have appeared and many developments in the major spectra codes and Monte–Carlo generators have occurred in the recent years, the trend is to make them much faster, more efficient, user–friendly and as complete as possible. Many programs are moving to C++, although there is still a lack of a complete consensus whether it is mandatory [probably a reflection of the conflict between generations..]. Therefore, we will be certainly ready to analyse the data for the next round of experiment. The hope is that SUSY is also ready to be discovered!

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