



FlexibleSUSY — a *meta* spectrum generator for supersymmetric models

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Abstract

FlexibleSUSY is a software package that takes as input descriptions of (non-)minimal supersymmetric models written in Wolfram/Mathematica and generates a set of spectrum generator libraries and executables, with the aid of SARAH. The design goals are precision, reliability, modularity, speed, and readability of the code. The boundary conditions are independent C++ objects that are plugged into the boundary value problem solver together with the model objects. This clean separation makes it easy to adapt the generated code for individual projects. The current status of the interface and implementation is sketched.

Keywords: sparticle, supersymmetry, Higgs, renormalization group equations

In a generic supersymmetric extension of the Standard Model (SM), there are many couplings and mass parameters that can be sources of flavour-changing neutral currents and/or *CP*-violation in addition to the standard Cabibbo-Kobayashi-Maskawa quark mixing matrix. Unless controlled in a particular way, those extra sources might cause excesses in flavour/*CP*-violating observables that are large enough easily to kill the theory. A popular strategy to circumvent this phenomenological danger is to view the supersymmetric standard model (SSM) as an effective field theory (EFT) imagining that an underlying theory has given rise to a reasonable pattern of the parameter values via a certain mechanism that mediates supersymmetry breaking in a hidden sector to the visible world. A typical example of such a pattern consists of universal scalar masses and trilinear couplings proportional to the corresponding Yukawa couplings as well as real gaugino and supersymmetric masses.

It is unknown at which scale the underlying physics decouples giving way to a SSM. One could only speculate based on circumstantial evidences such as gauge

coupling unification which suggests that the reasonable parameter pattern emerges at or above the unification scale. Neither is it clear how many stages of decoupling there are. It is not unreasonable to consider e.g. a sequence of transitions like superstring theory → supergravity → supersymmetric grand unified theory (GUT) → SSM. In a more complicated scenario, each of these stages might further consist of multiple EFTs. A prime example would be to insert a right-handed neutrino threshold (or multiple thresholds depending on the mass hierarchy) between the GUT scale and the low scale. Other variations enjoying growing interests due to the ever rising lower bounds on the sparticle masses from the Large Hadron Collider (LHC), are high scale supersymmetry and split supersymmetry which would be best described by additional non-supersymmetric EFTs laid below the SSM.

Within the above chain, the large scale differences among the thresholds naturally call for treatment of the renormalization group (RG) evolution of the parameters. In this kind of setup, the primary task of a spectrum generator (SG) is to find the low-energy particle spectrum that meets a set of boundary conditions (BCs).

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Most typical BCs are those imposed on the parameters at a high scale, M_X , enforcing the aforementioned reasonable pattern. In addition, one requires successful electroweak symmetry breaking (EWSB) as well as matching with the low-energy data, i.e. α_{em} , α_s , M_Z , M_W , quark and lepton masses. If there are multiple EFTs between M_X and the low scale, one further imposes a matching condition between each pair of adjacent EFTs. The SG is then to solve the boundary value problem (BVP), consisting of the RG equations (RGEs) and the BCs at multiple scales. After finding a solution, the SG calculates the pole masses and mixing of the particles.

There are already several publicly available SGs. Most of them have been developed for the minimal SSM (MSSM). The second best supported model is the next-to-MSSM (NMSSM). For the other models, no dedicated SG has been published although there are codes in private use. This is an unsatisfactory status given the wide variety of supersymmetric models. As the sparticle searches at the LHC keep ruling out the bulk of the “natural” parameter volume of the MSSM, studies of non-minimal SSMs are becoming more and more important. This motivation is reinforced by the measurement of the Higgs boson mass, which is rather high for “natural” accommodation within the minimal model.

FlexibleSUSY [1], a spectrum generator generator, is the result from an attempt to extrapolate this narrow spectrum of spectrum generators. It is a system of codes which accepts the description of a model and generates a SG tailored for it. Its major components are: GNU-style configuration and build system, FlexibleSUSY meta-code written in Wolfram/Mathematica, FlexibleSUSY core library, SG code templates, predefined model files, bundled codes from external sources, programming examples and documentation. It is intended to be precise, reliable, modular, easy to build on, fast, capable of EFT towers, and open to alternative BVP solving methods. The generated SG code is written in C++, one of the most popular programming languages. This should make the SG code comfortably accessible to a large number of postdocs and postgraduates. Being an object-oriented language, C++ allows one naturally to organize the code in a clean modular structure that is designed directly after the physical picture in a postdoc’s mind.

FlexibleSUSY is not the first SG generator. There has been already a Mathematica package called SARAH [2, 3], which can also generate a SG for a user-defined model. It should be worthwhile to clarify major differences and relationship between FlexibleSUSY and SARAH. SARAH generates the SG code in FOR-

TRAN. A SARAH-generated SG is linked against SPheno, whereas a FlexibleSUSY-generated SG includes parts of Softsusy [4]. SARAH can produce useful physics objects for the given model such as the interaction vertices, β -functions, self-energies, and tadpoles, as well as the EWSB equations. FlexibleSUSY launches SARAH to obtain these results which FlexibleSUSY processes subsequently to generate a C++ class library for the model.

For this reason, FlexibleSUSY combines two pieces of input for each model: an input file to it, and a set of model files to SARAH. The SARAH model files specify the superfield content, superpotential, gauge symmetries, and field mixing. The FlexibleSUSY input file contains the rest of the instructions to the meta-code on how to generate the SG. They can be roughly grouped into two categories: BCs on the model parameters, and switches that control the behaviours of the SG.

The model definitions bundled in the package are: the MSSM, the Z_3 -symmetric and the Z_3 -violating NMSSM, the USSM, the non-universal-Higgs-mass (NUHM) E_6 SSM, the right-handed neutrino extended MSSM, the NUHM-MSSM, and the R -symmetric MSSM.

A typical workflow of a postdoc/postgraduate using FlexibleSUSY would be as follows: (1) install FlexibleSUSY and SARAH; (2) pick out a model specification from the predefined collection or prepare one if not already available; (3) create a directory for the model under the FlexibleSUSY root; (4) tune the FlexibleSUSY input file as needed; (5) configure the build process; (6) run `make` to build the SG executable; (7) play with the SG, varying the input parameters through the SUSY Les Houches Accord (SLHA) file fed to it; (8) pass the SLHA output on to other physics analysis tools; (9) exploit the generated C++ class library for a more advanced study.

To formulate a new BC, one would need to introduce a different set of input parameters. For instance, the constrained MSSM (CMSSM) BC can be expressed in terms of $\{m_0, m_{1/2}, \tan\beta, \text{sign}(\mu), A_0\}$, which the MINPAR block accommodates in the SLHA format. In addition to these, a NUHM BC depends on two more parameters which determine the high-scale soft Higgs masses. If one declares these extra parameters in the model file, FlexibleSUSY automatically takes care of them and generates a C++ code which understands their settings listed in the EXTPAR block in an SLHA input file.

Based on the input files, the FlexibleSUSY meta-code produces a model-specific C++ class library including the physics building blocks such as interaction vertices, two-loop β -functions with the full flavour structure of

couplings and masses retained, self-energies, and tadpoles, as well as the procedures that calculate the $\overline{\text{DR}}$ and the pole masses and mixing. For a generic model, the pole masses include one-loop corrections. For a couple of popular models, the MSSM and the NMSSM, one can opt to add leading two-loop corrections to the neutral Higgs pole masses, by setting the corresponding switches in the input file. In addition, the library contains the BC classes as described in the input file. The low-energy BC class implements the standard one-loop threshold corrections to the gauge and the third-family fermion Yukawa couplings, plus the two-loop QCD correction to the top quark Yukawa. The EWSB class includes the one-loop tadpoles by default. For the (N)MSSM, one can choose to add the two-loop tadpole corrections. The driver template is then instantiated to the given model which forms the `main()` function of the SG program. Finally, FlexibleSUSY links the driver and the model library against the core library and external dependencies to produce the SG executable.

The operation of the program is like other SGs: (1) read the input parameters from a file; (2) make an initial guess of the model parameters; (3) enter the fixed-point iteration loop in which the low-scale, the high-scale, and the SUSY-scale BCs are enforced in the cyclic order after bringing the model parameters to each scale by integrating the RGEs; (4) after the model parameters converge to a fixed-point, compute the pole mass spectrum; (5) produce the output.

The model-specific β -functions and the BCs, implemented as C++ classes, belong to each model library. In a SG program, objects of these RGEs and BCs are plugged into the BVP solver object whose implementation is located in the core library. In fact, this solver is already ready to accept multiple models, even though the current version of FlexibleSUSY auto-generates a SG only for a single model configuration. Given handwritten matching condition classes, it is straightforward to author a SG for a tower of EFTs as mentioned in the early part of the article. The FlexibleSUSY package comes with such an example which realizes the type-I see-saw mechanism by stacking the MSSM plus three heavy right-handed neutrinos on top of the MSSM including the dimension-5 operator.

We take great care in the validation of FlexibleSUSY. Various stages of its operation have been and are being tested thoroughly against Softsusy [4] and Next-to-Minimal Softsusy [5]. The tested components include: the (N)MSSM β -functions, self-energies and tadpoles, tree-level masses and mixing, pole masses, EWSB conditions at the tree-level and loop-levels, as well as the core routines such as the Runge-Kutta differential equa-

tion integrator, the Passarino-Veltman functions, and the linear algebra procedures. An automatic system carries out an extensive suite of tests every night on the source code snapshot fetched from the repository hosted at github.com. Thanks to these regular tests, there has been a notable case where we could spot a Heisenbug due to a race condition caused by a thread-unsafe subroutine for evaluating two-loop Higgs mass corrections.

For an efficient research activity of a human being, the responsiveness of a system is an important factor. Even a delay of half a minute between the input action and the output could easily lead the researcher to a distraction such as web surfing. Fast execution per each input point would also greatly aid a scan or global fit in multidimensional parameter space. In this respect, FlexibleSUSY aims to be a competitive choice. With the flavour-off-diagonal sfermion self-energies ignored in the pole mass calculation, FlexibleSUSY is faster by a factor of 1.4–1.7 than SPheno 3.2.4, and by a factor of 2–2.5 than Softsusy 3.4.0. With the full 6×6 sfermion mass matrices taken into account, FlexibleSUSY is faster by a factor of 2.8–5 than a SARAH-generated SPheno-like SG. FlexibleSUSY can be further accelerated on a platform with multiple CPU cores thanks to its multi-threaded pole mass computation.

There are already exciting studies making use of FlexibleSUSY [6, 7]. More features are coming. Stay tuned.

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