FlexibleSUSY: Precise automated calculations in any BSM theory

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FlexibleSUSY is a software package for various calculations in any model of physics beyond the standard model (not just any supersymmetric model). FlexibleSUSY can solve boundary value problems and uses this to find $\overline{DR}/\overline{MS}$ parameters and calculate the Higgs and BSM particle masses, as well as other observables. FlexibleSUSY is designed to be adaptable, fast, precise and reliable. We describe FlexibleSUSY with particular emphasis on recent developments and the state of the art Higgs mass calculations it can perform. We also show some applications to illustrate how it can be used to obtain interesting physics results with the highest precision possible and with remarkable speed.

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1. **FlexibleSUSY**

A major difficulty in investigating the phenomenology of a novel extension of the standard model is that for meaningful predictions of observables one must perform many dedicated calculations, often at the 1- or 2-loop level and implement these calculations in a programming language so that the parameter space can be explored. Therefore automation of these steps can be extremely useful for phenomenology. `FlexibleSUSY` [1, 2, 3] is an easy-to-use software package which generates a C++ spectrum generator and C++ calculations of observables, for any BSM model. Here we will describe `FlexibleSUSY` and many of its uses. `FlexibleSUSY` uses `SARAH` [4] to obtain a number of model-specific expressions and corrections. Analytic expressions obtained in Mathematica are then translated to C++ and implemented in a code for spectrum generator[1] and observable calculations which is fast, adaptable and reliable. For any of the many distributed model files, the user can immediately create a spectrum generator with three simple commands, e.g.

```
$ ./createmodel --name=MRSSM
$ ./configure --with-models=MRSSM
$ make
```

The `FlexibleSUSY` spectrum generator may then be run with the following:

```
$ cd models/MRSSM
$ ./run_MRSSM.x --slha-input-file=LesHouches.in.MRSSM
```

In the MSSM and NMSSM `FlexibleSUSY` can output SLHA [8] and SLHA2 [9] files for interfacing with other codes. In other models a similar SLHA-like interface can be used if the other codes have also been setup to work with that model by using `SARAH`, with the same `SARAH` model files as `FlexibleSUSY`. For example `FlexibleSUSY` linked to `microOMEGAs` [10] can be used to investigate dark matter [11], with the parameter space sampled efficiently by also interfacing to `MultiNest` [13]. `FlexibleSUSY` can also be used in the global fitting tool `GAMBIT` [14] where it is interfaced with a huge array of observable calculators and samplers.

2-loop RGEs, and full 1-loop self-energy and tadpole corrections are obtained using model-specific analytical expressions that are generated using `SARAH`. In addition `FlexibleSUSY` also implements its own corrections that are also applied to all models. These include a 1-loop calculation of threshold corrections for extracting $\alpha_s(m_Z)$ and $\alpha_e(m_Z)$ in the considered extension of the SM, a new (partial 2-loop) calculation of the weak mixing angle $\sin\theta_W$ which allows us to obtain the $SU(2)_W$ and $U(1)_Y$ gauge couplings, g and g' respectively, and pure QCD 2-loop corrections to the running top and bottom Yukawa couplings. With these precision corrections `FlexibleSUSY` provides state-of-the-art predictions of the mass spectra in any novel extension of the SM chosen by the user.

However in addition to the calculations applicable to any model, `FlexibleSUSY` contains many model specific corrections where there have been recent improvements. Therefore `FlexibleSUSY` includes: 3-loop RGEs in the SM and MSSM; 2-loop (SUSY) QCD corrections to top, bottom

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[1]This spectrum generator contains some numerical routines from `SOFTSUSY` [6].

Yukawas in SM and MSSM [16]; 2-loop (SUSY) QCD corrections to strong gauge coupling in SM, MSSM [16]; 2-loop fixed order Higgs mass corrections SM, MSSM, NMSSM; 3-loop fixed order Higgs mass corrections SM, MSSM (via `Himalaya` [17]); and 3-loop Higgs mass corrections in Split-MSSM [18]. Thus `FlexibleSUSY` also provides state-of-the-art calculation in well-studied models like the MSSM, NMSSM.

Since the Higgs boson mass has been measured with an uncertainty is that is already significantly smaller than the theoretical uncertainty, `FlexibleSUSY` has a number of very sophisticated Higgs mass calculations. For all models `FlexibleSUSY` implements the `Flexible-EFTHiggs` [2] algorithm, which resums logarithms at NLL precision ensuring precise predictions when the new physics scale is high, while matching the 1-loop precision[2] of the fixed-order calculations when the new physics appears at the electroweak scale[3]. We therefore recommend users employ this approach in all cases unless there is a more precise model-specific EFT or fixed-order calculation (depending on the new physics scale) available. For specific models we have additional fixed order corrections mentioned above, allowing an improved prediction of the Higgs mass, for example at the 3-loop level in the MSSM via `Himalaya` [17]. We also provide special model files where matching conditions between the specific high scale and low scale model are implemented. The `FlexibleSUSY` spectrum generators created from these specific model files then perform precise Higgs mass calculations with resummed logs. Currently `FlexibleSUSY` has:

- `HSSUSY` [20]: MSSM calculation assuming a SM EFT, predicts M_h at full NLO with full NLL ressumation + NNLO with NNLL ressumation at $\mathscr{O}(\alpha_t(\alpha_s + \alpha_t) + (\alpha_t + \alpha_b)^2 + \alpha_\tau\alpha_b + \alpha_\tau^2)$ + (very recent) N³LO corrections with N³LL at $\mathscr{O}(\alpha_t\alpha_s^2)$ resummation[4].

- `SplitMSSM`: MSSM calculation assuming a SplitSUSY EFT, predicts M_h at full NLO + NNLO $\mathscr{O}(\alpha_t\alpha_s)$ with full NLL resummation.

- `THDMIIMSSMBCFull`: MSSM calculation assuming a THDMII EFT, predicts M_h at full NLO (+ partial NNLO $\mathscr{O}(\alpha_t\alpha_s)$) with full NLL resummation.

- `HTHDMIIMSSMBC`: MSSM calculation assuming an EFT with THDMII + light Higgsinos states, predicts M_h at full NLO (+ partial NNLO $\mathscr{O}(\alpha_t\alpha_s)$) with full NLL resummation.

- `HGTHDMIIMSSMBCFull`: MSSM calculation assuming an EFT with THDMII + light Higgsino + light gaugino states, predicts M_h at full NLO (+ partial NNLO $\mathscr{O}(\alpha_t\alpha_s)$) with full NLL resummation.

As well as the spectrum and Higgs mass calculations, `FlexibleSUSY` has also implemented additional observable calculations. `FlexibleSUSY` includes a `FlexibleAMU` calculation of the anomalous magnetic moment of the muon at 1-loop, including fermions and scalars in the loops. Additional 2-loop contributions and vector contributions will be included in a future update. `FlexibleSUSY` also includes a 1-loop calculation of lepton EDMs which can provide important constraints when the parameters include complex phases. The new extraction of $\sin\theta_W$ also

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[2]A 2-loop fixed order calculation for any model, using a `SARAH` extension [19] is currently under development.

[3]A version of this procedure with 2-loop matching to provide NNLL resummation is currently under development.

[4]With these recent corrections [21] this C++ Higgs mass calculator is the most precise EFT calculation of the Higgs mass available for the MSSM, with a higher precision than the next-best competitor `SusyHD` [22].

allows us to predict the mass of the W boson, instead of using it as an input to obtain $\sin\theta_W$. `FlexibleSUSY` can also provide the effective vertices for $h \to \gamma\gamma$ and $h \to gg$ decays (where h can be the SM Higgs or any neutral scalar in the SM extension). A full loop-level calculation of Higgs decays and decays of BSM states is under development, with a release anticipated soon.

2. Conclusions

`FlexibleSUSY` is a software package for calculating mass spectra and a growing set of observables in a fast, flexible, precise and robust manner. `FlexibleSUSY` is easy to use and can be readily interfaced with other codes to do detailed phenomenological investigations, and even global fits in both novel and well-known extensions of the standard model.

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