

Addendum: Improved MSSM Higgs mass calculation using the 3-loop FlexibleEFTHiggs approach including x_t -resummation

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ABSTRACT: In this addendum we present the stand-alone C++ program `MSSMEFTHiggs3L`, which implements the 3-loop FlexibleEFTHiggs approach to calculate the lightest CP -even Higgs boson pole mass in the real MSSM at N³LL and N³LO with x_q resummation, presented in ref. [1].

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1 Introduction

We present the C++ program `MSSMEFTHiggs3L`, which implements the 3-loop FlexibleEFTHiggs state-of-the-art calculation of M_h in the real MSSM at $N^3\text{LL}$ and $N^3\text{LO}$ with x_q resummation. The program is based on the `FlexibleSUSY` model `NUHMSSMNoFVHimalaya` and implements the matching and running described in our original publication, thus reproducing the results presented there. The program provides an easy-to-use SLHA interface for the MSSM input parameters and prints the value of M_h as a single number to `stdout`.

We have structured the addendum as follows. In section 2 we describe the technical details relevant for building the program. In section 3 we discuss the user interface and relevant configuration options. Finally, we comment on the upcoming integration of the refined FlexibleEFTHiggs approach with full-model parametrization into the general `FlexibleSUSY` package.

2 Installation and usage of the stand-alone code

The `MSSMEFTHiggs3L` program can be downloaded as compressed package from

<https://flexiblesusy.hepforge.org/downloads/FlexibleEFTHiggs/MSSMEFTHiggs3L.tar.gz>

To build `MSSMEFTHiggs3L`, the boost C++ library, the Eigen3 library, the GNU Scientific Library and the Himalaya library [2] (version 4.0.0 or higher) are required. For installation instructions of the Himalaya library see e. g. ref. [2].

After the package has been extracted, it can be configured and compiled by running the following commands:

```
$ ./configure --enable-himalaya --enable-fflite \
  --with-himalaya-incdir=${HIMALAYA_DIR}/include \
  --with-himalaya-libdir=${HIMALAYA_DIR}/build \
  --with-models=NUHMSSMNoFVHimalaya
$ make
```

The variable `HIMALAYA_DIR` contains the path to Himalaya root directory, required for the 3-loop pole-mass matching. Due to an improved numerical robustness, we recommend the configuration with the shipped 1-loop integral library `FFLite`. For more options see `./configure -h`. After the compilation has finished, the program can be run with the shipped SLHA input file as follows:

```
$ SLHA_INPUT=models/NUHMSSMNoFVHimalaya/LesHouches.in.NUHMSSMNoFVHimalaya
$ models/NUHMSSMNoFVHimalaya/run_NUHMSSMNoFV_fefthiggs.x \
  --slha-input-file=$SLHA_INPUT
```

Running the program with the shipped SLHA input file yields the following output for the lightest CP -even Higgs pole mass M_h on command line:

```
123.522878
```

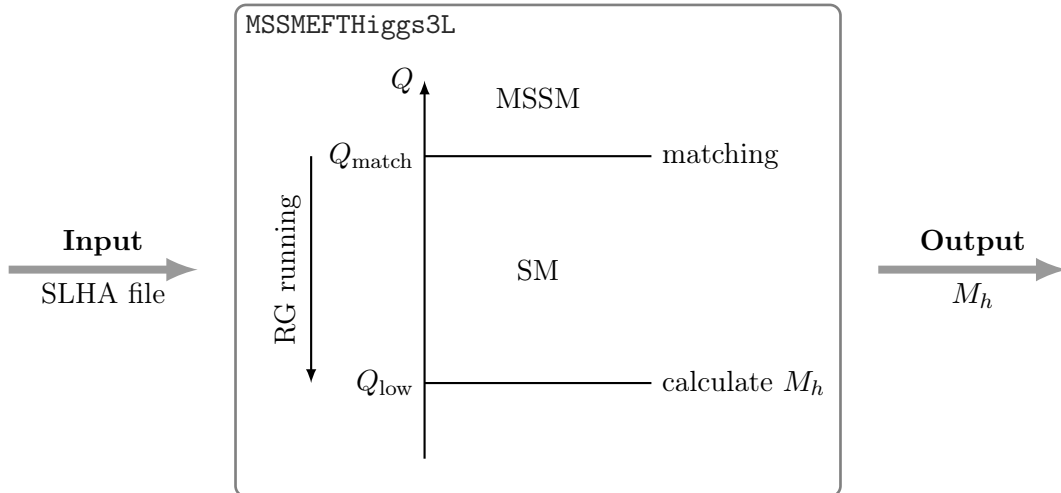


Figure 1: Interface of the stand-alone code

3 Interface and configuration options

The MSSMEFTHiggs3L program expects the MSSM input parameters in SLHA-1 format, see figure 1. It calculates the lightest CP -even Higgs boson pole mass M_h in the real MSSM with fermion and sfermion flavour conservation and with the non-universal Higgs mass parameters $m_{H_u}^2$ and $m_{H_d}^2$ fixed by the electroweak symmetry breaking conditions, as described in the original publication. When the calculation has finished successfully, the program writes the decimal floating-point value of the M_h to `stdout`.

The multi-loop contributions entering the Higgs mass calculation are controlled by the configuration options in the `FlexibleSUSY` block of the SLHA input. A detailed documentation of the flags is given in ref. [3]. Here, we discuss the relevant options in the `FlexibleSUSY` block of the SLHA input, which controls the individual corrections of the Higgs pole mass calculation. Depending on the desired precision of the Higgs pole mass calculation, we present two configurations.

Default 3-loop precision (i.e. M_h at N³LO, N³LL and with x_q -resummation): For a consistent FlexibleEFTHiggs calculation at this order, the following relevant flags have to be set in the SLHA input:

```
Block FlexibleSUSY
4 3 # pole mass loop order
5 3 # EWSB loop order
6 4 # beta-functions loop order
7 3 # threshold corrections loop order
8 1 # Higgs 2-loop corrections 0(alpha_t alpha_s)
9 1 # Higgs 2-loop corrections 0(alpha_b alpha_s)
10 1 # Higgs 2-loop 0((alpha_t + alpha_b)^2)
11 1 # Higgs 2-loop corrections 0(alpha_tau^2)
13 2 # Top pole mass QCD corrections (1 = 2L, 2 = 3L)
18 0 # pole mass scale in the EFT (0 = Mt)
```

```

19  0           # EFT matching scale (0 = SUSY scale)
20  2           # EFT loop order for yt matching
21  3           # EFT loop order for lambda matching
24  124111321  # individual threshold correction loop orders
26  1           # Higgs 3-loop corrections O(alpha_t alpha_s^2)
27  0           # Higgs 3-loop corrections O(alpha_b alpha_s^2)
28  0           # Higgs 3-loop corrections O(alpha_t^2 alpha_s)
29  0           # Higgs 3-loop corrections O(alpha_t^3)
30  0           # Higgs 4-loop corrections O(alpha_t alpha_s^3)

```

The meaning of each flag is described in the associated comment. The user should be aware that deviations from the displayed flag configuration usually result in a reduced precision of the calculation. In the following we briefly describe a selection of adjustments:

- **Flag 18** This flag can be used to set the renormalization scale Q_{pole} (in GeV), at which the Higgs pole mass M_h is calculated in the SM. Possible values are $Q_{\text{pole}} = 0$, which corresponds to $Q_{\text{pole}} = M_t$, or any positive value $Q_{\text{pole}} > 0$. This flag can be used to vary the renormalization scale in order to estimate the low-scale uncertainty as described in sec. 8.3.2.
- **Flag 19** This flag can be used to set the matching scale Q_{match} (in GeV) at which λ is determined. Possible values are $Q_{\text{match}} = 0$, which corresponds to $Q_{\text{match}} = M_S$, or any positive value $Q_{\text{match}} > 0$. This flag can be used to vary the matching scale in order to estimate the high-scale uncertainty as described in the vicinity of eq. (8.11).
- **Flag 20** This flag has a different meaning than described in the documentation in ref. [56], where it controls the loop order of the upwards matching from the SM to the full model. Our calculation does not require any upwards matching and we use it to control the downwards matching of SM-like gauge and Yukawa couplings. Possible values are 0 (tree-level), 1 (1-loop) and 2 (2-loop). For a calculation of M_h at N³LO and N³LL, the flag must be set to 2. Reducing the value to 1 or 0 reduces the large-log resummation to NNLL or LL, respectively.
- **Flag 21** This flag controls the loop order for the calculation of λ and specifies the contributions in eq. (4.28a). Possible values are 0 (tree-level), 1 (1-loop), 2 (2-loop) and 3 (3-loop). For a calculation of M_h at N³LO and N³LL, the flag must be set to 3. If numerical instabilities occur, it may be beneficial to reduce the loop order of the calculation of λ to 2-loop (gauge-less limit) and therefore restrict the precision to NNLL and NNLO.

Minimal 2-loop precision (i. e. M_h at NNLO, NNLL and with x_q -resummation):

The minimal flag configuration to achieve a FlexibleEFTHiggs calculation at this precision requires the following configuration settings in the SLHA input:

```

Block FlexibleSUSY
4   2           # pole mass loop order
5   2           # EWSB loop order

```

```
6 3 # beta-functions loop order
7 2 # threshold corrections loop order
8 1 # Higgs 2-loop corrections O(alpha_t alpha_s)
9 1 # Higgs 2-loop corrections O(alpha_b alpha_s)
10 1 # Higgs 2-loop O((alpha_t + alpha_b)^2)
11 1 # Higgs 2-loop corrections O(alpha_tau^2)
13 1 # Top pole mass QCD corrections (1 = 2L, 2 = 3L)
18 0 # pole mass scale in the EFT (0 = Mt)
19 0 # EFT matching scale (0 = SUSY scale)
20 1 # EFT loop order for yt matching
21 2 # EFT loop order for lambda matching
24 112111111 # individual threshold correction loop orders
26 0 # Higgs 3-loop corrections O(alpha_t alpha_s^2)
27 0 # Higgs 3-loop corrections O(alpha_b alpha_s^2)
28 0 # Higgs 3-loop corrections O(alpha_t^2 alpha_s)
29 0 # Higgs 3-loop corrections O(alpha_t^3)
30 0 # Higgs 4-loop corrections O(alpha_t alpha_s^3)
```

4 Outlook

In this addendum, we have presented the stand-alone program `MSSMEFTHiggs3L`, which has been developed for the Higgs mass calculation presented in the original publication.

We plan to implement the refined `FlexibleEFTHiggs` approach with full-model parametrization into the general `FlexibleSUSY` package. This allows to apply the calculation to models beyond the real MSSM, such as the NMSSM etc. The planned integrated version will also allow access to the full pole-mass spectrum of the model as well as the computation of other observables.

References

- [1] T. Kwasnitza, D. Stöckinger and A. Voigt, *Improved MSSM Higgs mass calculation using the 3-loop FlexibleEFTHiggs approach including x_t -resummation*, *JHEP* **07** (2020) 197, [2003.04639].
- [2] R. V. Harlander, J. Klappert and A. Voigt, *Higgs mass prediction in the MSSM at three-loop level in a pure DR context*, *Eur. Phys. J.* **C77** (2017) 814, [1708.05720].
- [3] P. Athron, M. Bach, D. Harries, T. Kwasnitza, J.-h. Park, D. Stöckinger et al., *FlexibleSUSY 2.0: Extensions to investigate the phenomenology of SUSY and non-SUSY models*, *Comput. Phys. Commun.* **230** (2018) 145–217, [1710.03760].