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Precision Higgs Masses with FeynHiggs 2.2

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FeynHiggs is a program for computing MSSM Higgs-boson masses and related observables, such as mixing angles, branching ratios, and couplings, including state-of-the-art higher-order contributions. The centerpiece is a Fortran library for use with Fortran and C/C++. Alternatively, FeynHiggs has a command-line, Mathematica, and Web interface. The command-line interface can process, besides its native format, files in SUSY Les Houches Accord format. FeynHiggs is an open-source program and easy to install.

1. Introduction

One of main goals of future colliders is to find a Higgs boson. In order to establish the mechanism of electroweak symmetry breaking it will in addition be necessary to measure the properties of the Higgs boson, hopefully allowing to distinguish between different models. While the LHC will almost certainly take the prize of finding a Higgs \[ h \], if it exists, it will take the International Linear Collider (ILC) to nail down many of the properties \[ m_h \] to the desired level of accuracy.

Unlike in the Standard Model (SM), where the Higgs mass is only rather loosely constrained by higher-order effects, the Higgs couplings in the Minimal Supersymmetric Standard Model (MSSM) are directly related, through supersymmetry, to the gauge couplings. This implies that the lightest Higgs-boson mass \( M_h \) can be predicted in terms of the other model parameters. The mass measurement at the ILC is estimated to \( \delta M_h^{\exp} \approx 0.05 \text{ GeV} \), thus \( M_h \) will become a precision observable.

Together, these two issues mandate precise calculations of observables on the theory side in a variety of models, but in particular in supersymmetric ones, where \( M_h \) is a prediction. The FeynHiggs package provides masses, couplings, branching ratios, etc. in the real, complex, and non-minimal flavour-violating MSSM including state-of-the-art radiative corrections.

2. The MSSM Higgs sector

The MSSM contains two Higgs doublets,

\[
H_1 = \left( v_1 + \frac{1}{\sqrt{2}} (\phi_1 + i \chi_1) \right), \quad H_2 = e^{i \xi} \left( v_2 + \frac{1}{\sqrt{2}} (\phi_2 + i \chi_2) \right),
\]

where a possible CP-violating phase \( \xi \) has been indicated. The Higgs potential is given by

\[
V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\varepsilon_{\alpha \beta} H_1^\alpha H_2^\beta + \text{h.c.}) + \frac{g_1^2 + g_2^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g_3^2}{2} |H_1 \bar{H}_2|^2.
\]

The only non-trivial CP-violating phase (besides \( \xi \)) is contained here in \( m_{12} \). At tree level all CP phases can be rotated away, giving five physical states of distinct CP parity: \( h^0, H^0 \) (CP-even), \( A^0 \) (CP-odd), and \( H^\pm \).
The quartic Higgs couplings are completely determined by the gauge couplings $g_1$ and $g_2$ and this leads to the well-known tree-level prediction $M_h < M_Z$, which stands in conflict with measurements since LEP. Fortunately (for the MSSM), significant quantum loop contributions push the upper bound on $M_h$ up to about 140 GeV for a top mass of 178 GeV. But the quantum effects lead also to qualitative changes. In the presence of CP-violating phases, all three neutral Higgs bosons mix and CP is no longer conserved,

$$
\begin{pmatrix}
  h_1 \\
  h_2 \\
  h_3 
\end{pmatrix} =
\begin{pmatrix}
  U_{11} & U_{12} & U_{13} \\
  U_{21} & U_{22} & U_{23} \\
  U_{31} & U_{32} & U_{33}
\end{pmatrix}
\begin{pmatrix}
  h^0 \\
  H^0 \\
  A^0
\end{pmatrix}.
$$

The three mass eigenstates are denoted as $h_i$, $i = 1, 2, 3$, and ordered as $m_{h_1} \leq m_{h_2} \leq m_{h_3}$.

3. FeynHiggs

3.1. Download and Installation

Installing FeynHiggs is simple and fast. Version 2.2 requires no prerequisites (e.g. LoopTools) as before.

- Get the latest FeynHiggs tar file from http://www.feynhiggs.de.
- Unpack, configure, and build:
  ```
  tar xzf FeynHiggs-2.2.N.tar.gz 
  cd FeynHiggs-2.2.N 
  ./configure 
  make 
  ```
  To build also the Mathematica part, replace “make” by “make all”.
- (Optional:) Type “make install” to install the files and “make clean” to remove intermediate files.

3.2. Modes of Operation

FeynHiggs operates in one of four basic modes:

- Library Mode: The FeynHiggs routines are invoked from a Fortran or C/C++ program linked against the FeynHiggs library.
- Command-line Mode: Parameter files in FeynHiggs’ native format or in SUSY Les Houches Accord (SLHA) format are processed at the command line with the standalone executable FeynHiggs.
- WWW Mode: The user interactively chooses parameters at the FeynHiggs User Control Center (FHUCC) and obtains the results on-line at http://www.feynhiggs.de/fhucc.
- Mathematica Mode: The FeynHiggs routines can be used in Mathematica via the MathLink executable MFeynHiggs.

3.3. Application Programming Interface

The FeynHiggs library libFH.a is a static Fortran 77 library. Its global symbols are prefixed with a unique identifier to minimize symbol collisions. The library contains only subroutines (no functions), so that no include files are needed (except for the couplings) and the invocation from C/C++ is hassle-free. Detailed debugging output can be turned on at run time. All routines are described in detail in the API guide and on man-pages, so only a brief overview is needed here:

- FHSetFlags sets the flags of the calculation.
- `FHSetPara` sets the MSSM input parameters directly.
- `FHSetSLHA` extracts the input parameters from an SLHA data structure.
- `FHSetDebug` sets the debugging level.
- `FHGetPara` retrieves (some of) the derived parameters.
- `FHHiggsCorr` evaluates the Higgs masses and mixings, \( M_{h_1, h_2, h_3, H^\pm} \), \( \alpha_{\text{eff}} \) (the effective mixing angle in the CP-conserving case), \( U_{ij} \), featuring:
  - In the neutral Higgs sector, the following propagator matrix is diagonalized,
    \[
    \begin{pmatrix}
    q^2 - M_h^2 + \hat{\Sigma}_{hh}^{2}\hat{\Sigma}_{hh}^{3}
    & \hat{\Sigma}_{hh}^{2}\hat{\Sigma}_{HH}^{3}
    & \hat{\Sigma}_{hh}^{2}\hat{\Sigma}_{HH}^{3}
    \\
    \hat{\Sigma}_{hh}^{2}\hat{\Sigma}_{HH}^{3}
    & q^2 - M_H^2 + \hat{\Sigma}_{HH}^{2}\hat{\Sigma}_{HH}^{3}
    & \hat{\Sigma}_{HH}^{2}\hat{\Sigma}_{HH}^{3}
    \\
    \hat{\Sigma}_{hh}^{2}\hat{\Sigma}_{HH}^{3}
    & \hat{\Sigma}_{hh}^{2}\hat{\Sigma}_{HH}^{3}
    & q^2 - M_A^2 + \hat{\Sigma}_{AA}^{2}\hat{\Sigma}_{AA}^{3}
    \end{pmatrix},
    \]
    where the self-energies include the following terms as indicated,
    ① the most up-to-date leading \( O(\alpha_s\alpha_t, \alpha_s^2) \) \[12, 13\] and subleading \( O(\alpha_s\alpha_b, \alpha_t\alpha_b, \alpha_b^2) \) \[14, 15\] two-loop corrections in the rMSSM (complex effects are taken into account only partially in the two-loop part at present),
    ② full one-loop evaluation (all phases included),
    ③ complete \( q^2 \) dependence.
  - Full one-loop corrections for the charged Higgs sector \[16\].
  - Mixed DR/OS renormalization for the one-loop result \[17\].
  - \( \Delta m_h^\pm \) corrections = leading \( O(\alpha_s\alpha_b) \) and \( O(\alpha_t\alpha_b) \) terms for Higgs masses, couplings, etc. \[18\].
  - Non-minimal flavour-violating effects (e.g. \( \tilde{e}^{-}\tilde{\tau} \) mixing) \[19\].
- `FHUncertainties` estimates the uncertainties of the Higgs masses and mixings. The total uncertainty is the sum of deviations from the central value, \( \Delta X = \sum_{i=1}^{3} |X_i - X| \) with \( X = \{ M_{h_1, h_2, h_3, H^\pm, \alpha_{\text{eff}}, U_{ij}} \} \), where
  - \( X_1 \) is obtained by varying the renormalization scale (entering via the DR renormalization) within \( \frac{1}{2} m_t \leq \mu \leq 2 m_t \),
  - \( X_2 \) is obtained by using \( m_t^{\text{pole}} \) instead of the running \( m_t \) in the two-loop corrections,
  - \( X_3 \) is obtained by using an unresummed bottom Yukawa coupling, \( y_b \), i.e. an \( y_b \) including the leading \( O(\alpha_s\alpha_t) \) corrections, but not resummed to all orders.
- `FHCouplings` computes the Higgs couplings, decay widths, and BRs in the MSSM and also for an SM Higgs boson with mass \( M_{h_1} \) (denoted as \( h_{1,2,3}^{\text{SM}} \)) for comparison:
  \[
  \begin{align*}
  h_{1,2,3} & \rightarrow f \bar{f}, \gamma\gamma, ZZ^*, WW^*, gg, \\
  h_iZ^*, h_ih_j, H^+H^- & \rightarrow h_iW^{\pm*}, \\
  f_i\bar{f}_j, \tilde{f}_i\tilde{f}_j, \tilde{\chi}_i\tilde{\chi}_j, \tilde{\chi}_i\chi_j, \chi_i\chi_j & \rightarrow \tilde{f}_i\tilde{f}_j, \tilde{\chi}_i\tilde{\chi}_j, \chi_i\chi_j,
  \end{align*}
  \]
  \[5\]
- \( \Delta \rho \) at \( O(\alpha, \alpha_s) \) \[21, 22\]. Too large values of \( \Delta \rho \) indicate experimentally disfavoured \( \tilde{t}/\tilde{b} \) masses.
- \( (g_{\mu}-2)_{\text{SUSY}} \) including full one-loop and leading/subleading two-loop SUSY corrections \[23, 24\].
- (Preliminary:) The electric dipole moments of Th, N, and Hg. This part is not yet fully tested.
4. Command-line Modes

The FeynHiggs command-line frontend, FeynHiggs, reads input files both in its own and in SLHA format. The FeynHiggs format simply lists the parameters and their values, for example:

MT 178  
MB 4.7  
MW 80.450 
MZ 91.1875 
TB 50  
MA0 200 
MSusy 975  
...

More sophisticated variants are possible, e.g. “TB 5 50 2.5” declares a loop over $\tan\beta$ from 5 to 50 in steps of 2.5. This input file, e.g. fh.in, is run through FeynHiggs by

FeynHiggs fh.in

Optionally, the flags can be given behind the filename as a string of digits, as in

FeynHiggs fh.in 40020211

The output is listed on stdout in a human-readable form, for example

-------------------- HIGGS MASSES --------------------
| Mh0   = 117.186672 |
| MHH   = 194.268239  |
| MA0   = 200.000000  |
| MHp   = 212.662071  |
| S\text{Aeff}   = -0.36496659 |
| UHiggs = 0.99589960 0.09046538 0.00000000 \ 
|       = -0.09046538 0.99589960 0.00000000 \ 
|       = 0.00000000 0.00000000 1.00000000 |
-------------------- ESTIMATED UNCERTAINTIES --------------------
| DeltaMh0 = 0.919435 |
| DeltaMHH = 0.728304 |
| DeltaMA0 = 0.000000 |
| DeltaMHp = 1.929728 |
...

The listing can become quite lengthy, and although FeynHiggs automatically spawns a pager for easier viewing, one would sometimes like to mask off the details. Such lines contain a % character, thus

FeynHiggs fh.in | grep -v %

turns off the details.

To convert the human-readable into a machine-readable form, the table utility is used. For example, the following line produces a file fh.out with two columns, TB and Mh0,

FeynHiggs fh.in | table TB Mh0 > fh.out

The SLHA mode works similarly, only that the output is not listed on screen, but saved in a file (input filename plus \“.fh\”), again in SLHA format. This way, FeynHiggs can act as a filter in a chain of commands operating on an SLHA file. FeynHiggs tries to read each input file in SLHA format first and if that fails, falls back into its native format. FeynHiggs’ SLHA interface uses the SLHA Library \cite{10.1063/1.5250072}.  

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5. Interactive Modes

FeynHiggs can be used interactively in WWW Mode or in Mathematica Mode. In WWW Mode, point your browser to the FeynHiggs User Control Center at http://www.feynhiggs.de/fhucc. The Web interface allows to select one of the Les Houches benchmark scenarios, or choose each parameter directly. Fig. 1 shows a screen shot.

A much more powerful interactive environment is provided by the Mathematica interface of FeynHiggs. The MathLink executable MFeynHiggs must first be loaded with

    Install["MFeynHiggs"]

and makes all FeynHiggs routines (see Sect. 3.3) available as Mathematica functions. Standard Mathematica functions, such as ContourPlot and FindMinimum, then make some sophisticated analyses possible.

6. Summary

The FeynHiggs package computes Higgs masses, mixing angles, branching ratios, couplings, etc. in the MSSM including state-of-the-art radiative corrections. The heart of the program is a static Fortran library which can be accessed either directly (in Fortran or C/C++) or through various frontends (command-line, Mathematica, WWW). FeynHiggs is freely available from http://www.feynhiggs.de and is straightforward to compile and install.

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