Precision Higgs Masses with FeynHiggs 2.2

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Motivation

One of big issues at a future collider is to

- find a Higgs boson and, if it exists,
- measure its properties to distinguish different models.

Necessary on the theory side: precise predictions of

- masses, couplings, branching ratios, ...

in a variety of models

- SM,
- real MSSM,
- complex MSSM,
- non-minimal flavour-violating MSSM,
- NMSSM...

The MSSM Higgs Sector

$$H_1 = \begin{pmatrix} v_1 + \frac{1}{\sqrt{2}}(\phi_1 + \mathrm{i}\chi_1) \\ \phi_1^- \end{pmatrix}, \quad H_2 = \mathrm{e}^{\mathrm{i}\xi} \begin{pmatrix} \phi_2^+ \\ v_2 + \frac{1}{\sqrt{2}}(\phi_2 + \mathrm{i}\chi_2) \end{pmatrix}$$

Higgs Potential:

$$V = M_1^2 H_1 \bar{H}_1 + M_2^2 H_2 \bar{H}_2 - M_{12}^2 (\varepsilon_{\alpha\dot{\beta}} H_1^\alpha H_2^{\dot{\beta}} + \mathrm{h.c.}) + \frac{g_1^2 + g_2^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g_2^2}{2} |H_1 \bar{H}_2|^2$$

- **Five physical states,** h^0, H^0, A^0, $H^\pm$ **(no ~~CP~~ at tree level).**
- **Input parameters:** $\tan\beta = v_1/v_2$, M_{A^0} **or** $M_{H^\pm}$.
- **Unlike SM, MSSM predicts** M_{h^0} **(cf. Gauge Couplings).**
- $M_{h^0} < M_Z$ **at tree level, excluded by LEP searches.**

Radiative Corrections

Significant quantitative and qualitative changes:

- M_{h^0} **receives large radiative corrections, e.g. the dominant one-loop corrections** $\sim G_F\, m_t^4\, \log(M_{\tilde{t}_1} M_{\tilde{t}_2}/m_t^2)$.
- **The MSSM Higgs sector is connected to all others (in particular the scalar top sector) by loop corrections.**
- **~~CP~~ parameters lead to self-energies** $\hat{\Sigma}_{hA}, \hat{\Sigma}_{HA} \neq 0$ **and induce mixing between** h^0, H^0 **and** A^0**:**

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

Real MSSM (rMSSM)

- "Unconstrained (real) MSSM" has
  M_{A^0}, $\tan\beta$, **5 parameters in $\tilde{t}$-$\tilde{b}$ sector**, μ, $m_{\tilde{g}}$, M_2.
- $M_{h^0} \lesssim 140$ GeV **for** $m_t = 178$ GeV.

  Heinemeyer, Hollik, Weiglein 1999
  Degrassi, Heinemeyer, Hollik, Slavich, Weiglein 2002
- **Complete one-loop result + all presumably dominant two-loop corrections known.**
- **Remaining uncertainties:**
  From unknown higher-order corrections: $\Delta M_{h^0} \approx 3$ GeV.
  From input-parameter uncertainties: $\Delta M_{h^0} \approx 4$ GeV **for** $\Delta m_t \approx 4$ GeV.

  Degrassi, Heinemeyer, Hollik, Slavich, Weiglein 2002
  Frank, Heinemeyer, Hollik, Weiglein 2002
  Allanach, Djouadi, Kneur, Porod, Slavich 2004

Complex MSSM (cMSSM)

- Complex parameters enter via loop corrections and can induce ~~CP~~ effects: μ, $M_{1,2}$, $m_{\tilde{g}}$, $A_{t,b,\tau}$.
- Known:
  - ▷ fermion/sfermion one-loop corrections,
  - ▷ some leading logs from remaining sectors,
  - ▷ leading two-loop corrections.

Pilaftsis 1999 – Pilaftsis, Wagner 1999 – Demir 1999 – Choi, Drees, Lee 2000 – Heinemeyer 2001
Carena, Ellis, Pilaftsis, Wagner 2000, 01 – Ibrahim, Nath 2001, 02 – Ham, Kim, Oh, Son, Yoo 2002

- Since FeynHiggs 2.0:
  - ▷ remaining sectors at one loop ($5\ \mathrm{GeV}$ in rMSSM),
  - ▷ q^2 dependence at one loop ($\sim 2\ \mathrm{GeV}$ in rMSSM).
- Much larger uncertainties than in the rMSSM.

Corrections included in FeynHiggs 2.2

$$\begin{pmatrix} q^2 - M_h^2 + \hat{\Sigma}_{hh}^{\bullet\bullet\bullet} & \hat{\Sigma}_{hH}^{\bullet\bullet\bullet} & \hat{\Sigma}_{hA}^{\bullet\bullet} \\ \hat{\Sigma}_{Hh}^{\bullet\bullet\bullet} & q^2 - M_H^2 + \hat{\Sigma}_{HH}^{\bullet\bullet\bullet} & \hat{\Sigma}_{HA}^{\bullet\bullet} \\ \hat{\Sigma}_{Ah}^{\bullet\bullet} & \hat{\Sigma}_{AH}^{\bullet\bullet} & q^2 - M_A^2 + \hat{\Sigma}_{AA}^{\bullet\bullet} \end{pmatrix}$$

- **Most up-to-date leading $\mathcal{O}(\alpha_s\alpha_t, \alpha_t^2)$ + subleading $\mathcal{O}(\alpha_s\alpha_b, \alpha_t\alpha_b, \alpha_b^2)$ two-loop corrections in the rMSSM (complex effects only partially included in two-loop part).**

  Degrassi, Slavich, Zwirner 2001 – Brignole, Degrassi, Slavich, Zwirner 2001, 02
  Dedes, Degrassi, Slavich 2003

- **Full one-loop evaluation (all phases included).**
- **Complete q^2 dependence.**
- **Full one-loop corrections for the charged Higgs sector.**

  Frank, Heinemeyer, Hollik, Weiglein 2002

Additional Features

- **Mixed $\overline{\text{MS}}$/OS renormalization for one-loop result.**

  Frank, Heinemeyer, Hollik, Weiglein 2002

- **"Δm_b" corrections = leading $\mathcal{O}(\alpha_s \alpha_b)$ terms for Higgs masses, couplings, etc.**

  Carena, Garcia, Nierste, Wagner 2000

- **Non-minimal flavour-violating effects (e.g. $\tilde{c}$-$\tilde{t}$ mixing).**

  Heinemeyer, Hollik, Merz, Peñaranda 2004

Output of FeynHiggs 2.2

- `FHHiggsCorr:` **All Higgs-boson masses and mixings:** $M_{h_1}, M_{h_2}, M_{h_3}, M_{H^\pm}, \alpha_{\rm eff}, U_{ij}, \ldots$
- `FHUncertainties:` **Uncertainties of masses and mixings.**
- `FHCouplings:`
  - ▷ **Couplings and Branching Ratios for the channels**

    $h_{1,2,3} \to f\bar{f}, \gamma\gamma, ZZ^*, WW^*, gg$ $\quad H^\pm \to f\bar{f}'$

    $h_i Z^*, h_i h_j, H^+H^-$ $\quad h_i W^{\pm *}$

    $\tilde{f}_i \tilde{f}_j,$ $\quad \tilde{f}_i \tilde{f}'_j,$

    $\tilde{\chi}_i^\pm \tilde{\chi}_j^\pm, \tilde{\chi}_i^0 \tilde{\chi}_j^0$ $\quad \tilde{\chi}_i^0 \tilde{\chi}_j^\pm$
  - ▷ **Branching Ratios of an SM Higgs with mass M_{h_i}:**

    $h_{1,2,3}^{\rm SM} \to f\bar{f}, \gamma\gamma, ZZ^*, WW^*, gg$
- `FHConstraints:` **Additional constraints.**

FHUncertainties

`FHUncertainties` **estimates the theoretical uncertainties** of the Higgs masses and mixings. This is done in three ways:

- by **varying the renormalization scale** as $\frac{1}{2}m_t \leqslant \mu \leqslant 2m_t$,
- by using m_t^{pole} **instead of the running** m_t in the two-loop corrections,
- by using an **unresummed** m_b, i.e. an m_b including the leading $\mathcal{O}(\alpha_s\alpha_b)$ corrections, but not resummed to all orders.

The total uncertainty is the sum of the absolute deviations, i.e.

$$\Delta X = \sum_{i=1}^{3} |X_i - X| \,, \quad X = \{M_h, \alpha_{\text{eff}}, U_{ij}\} \,.$$

FHConstraints

`FHConstraints` **evaluates several electroweak precision observables,** to be used as additional constraints:

- $\Delta\rho$ **at** $\mathcal{O}(\alpha, \alpha\alpha_s)$
  $\Delta\rho \gtrsim 2 \times 10^{-3}$ **indicates exp. disfavoured** $\tilde{t}/\tilde{b}$ **masses.**
- $(g_\mu - 2)_{\mathrm{SUSY}}$
  Full one-, leading/subleading two-loop SUSY corrections.
  Heinemeyer, Stöckinger, Weiglein 2003
- **EDM Th, EDM N, EDM Hg**
  Preliminary (currently not fully tested).

Download and Build

- Get the FeynHiggs tar file from www.feynhiggs.de.
- Unpack and configure:

```
tar xfz FeynHiggs-2.2.7beta.tar.gz
cd FeynHiggs-2.2.7beta
./configure
```

- Type make to build the Fortran/C++ part only.
  Type make all to build also the Mathematica part.
  Takes about 2 min to build on a Pentium IV.
- Type make install to install the package.
- Type make distclean to remove unnecessary files.

Note: no prerequisites (e.g. LoopTools) required as in previous versions.

Usage

Four operation modes:

- **Library Mode:** Invoke the FeynHiggs routines from a **Fortran or C/C++ program** linked with `libFH.a`.
- **Command-line Mode:** Process **parameter files in FeynHiggs or SLHA format** at the shell prompt or in scripts with the standalone executable `FeynHiggs`.
- **WWW Mode:** Interactively choose the parameters at the **FeynHiggs User Control Center (FHUCC)** and obtain the results on-line.
- **Mathematica Mode:** Access the **FeynHiggs routines in Mathematica** via MathLink with `MFeynHiggs`.

All programs and subroutines are documented in man pages.

Library Mode

- Static Fortran 77 library `libFH.a`.
- All global symbols prefixed to prevent symbol collision.
- Uses only subroutines (no functions):
  - ▷ no include files needed (except for couplings),
  - ▷ hassle-free invocation from C/C++.
    C/C++ users include `CFeynHiggs.h` for prototypes.
- Detailed debugging output can be turned on at run time.
- Internal software engineering straightened out compared to older versions, e.g. access to couplings much simplified.

API

Subroutines in the FeynHiggs 2.2 library:

- `FHSetFlags` – set the flags of the calculation,
- `FHSetPara` – set the MSSM input parameters directly,
- `FHSetSLHA` – extract the parameters from SLHA data,
- `FHSetDebug` – set the debugging level,
- `FHGetPara` – retrieve (some of) the derived parameters,
- `FHHiggsCorr` – compute the Higgs masses and mixings,
- `FHUncertainties` – estimate their uncertainties,
- `FHCouplings` – compute the Higgs couplings and BRs,
- `FHConstraints` – evaluate additional constraints.

Command-line Mode

Input File

```
MT          178
MB          4.7
MW          80.450
MZ          91.1875
MSusy       975
MA0         200
Abs(M_2)    332
Abs(MUE)    980
TB          50
Abs(At)     -300
Abs(Ab)     1500
Abs(M_3)    975
```

Command

FeynHiggs *file flags* →

Screen Output

```
------------------- HIGGS MASSES -------------------
| Mh0     =   116.022817
| MHH     =   199.943497
| MA0     =   200.000000
| MHp     =   216.973920
| SAeff   =  -0.02685112
| UHiggs =   0.99999346  -0.00361740   0.00000000 \
|            0.00361740   0.99999346   0.00000000 \
|            0.00000000   0.00000000   1.00000000

-------------- ESTIMATED UNCERTAINTIES -------------
| DeltaMh0  =  1.591957
| DeltaMHH  =  0.004428
| DeltaMA0  =  0.000000
| DeltaMHp  =  0.152519
  ...
```

- Loops over parameter values possible (parameter scans).
- Mask off details with `FeynHiggs` *file flags* `| grep -v %`
- `table` utility converts to machine-readable format, e.g.
  `FeynHiggs` *file flags* `| table TB Mh0 > outfile`

SUSY Les Houches Accord Format

Input File

```
BLOCK MODSEL
    1    1
BLOCK MINPAR
    1   0.100000000E+03  # m0
    2   0.250000000E+03  # m12
    3   0.100000000E+02  # tanb
    4   0.100000000E+01  # Sign(mu)
    5  -0.100000000E+03  # A
BLOCK SMINPUTS
    4   0.911870000E+02  # MZ
    5   0.425000000E+01  # mb(mb)
    6   0.175000000E+03  # t
  ...
```

Command

FeynHiggs *file flags* →

file.fh

```
BLOCK MASS
   25   1.12697840E+02   # Mh0
   35   4.00145460E+02   # MHH
   36   3.99769788E+02   # MA0
   37   4.08050556E+02   # MHp
  ...
BLOCK ALPHA
       -1.10658125E-01   # Alpha
  ...
```

- {Uses / was developed into} the SLHA I/O Library.

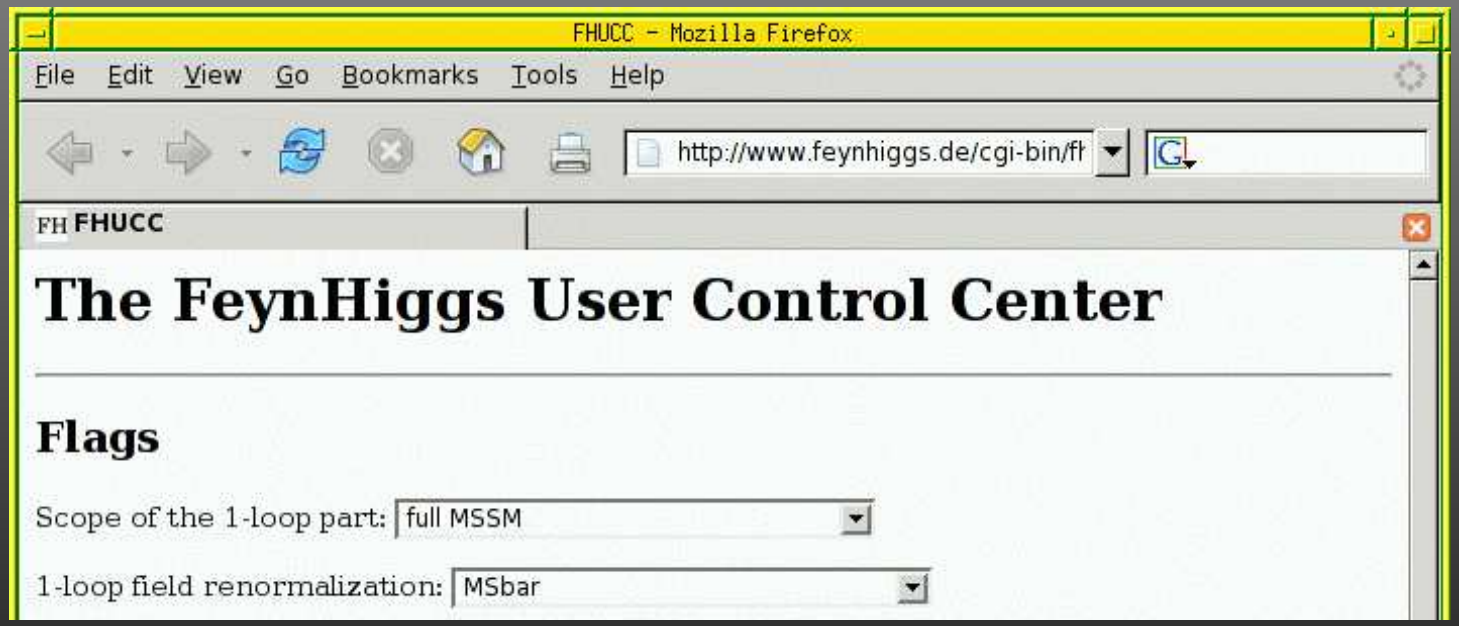
  Hahn 2004

- SLHA can also be used in Library Mode with `FHSetSLHA`.
- FeynHiggs tries to read each file in SLHA format first.
  If that fails, fallback to native format.

WWW Mode

The FeynHiggs User Control Center (FHUCC) is on-line at

http://www.feynhiggs.de/fhucc



FHUCC is a Web interface for the Command-line Frontend. The user gets the results together with the input file for the Command-line Frontend.

Mathematica Mode

Provides the FeynHiggs functions in Mathematica, e.g.

```
In[1]:= Install["MFeynHiggs"];

In[2]:= FHSetFlags[...];

In[3]:= FHSetPara[...];

In[4]:= FHHiggsCorr[]

Out[4]= {MHiggs -> {117.184, 194.268, 200., 212.67},
>         SAeff -> -0.37575,
>         UHiggs -> {{0.994782, 0.102021, 0},
>                    {-0.102021, 0.994782, 0},
>                    {0, 0, 1.}}}
```

- Can use all Mathematica functions on the results (e.g. `ContourPlot`, `FindMinimum`).
- Convenient interactive mode for FeynHiggs 2.2.

Spin-Off: SLHA I/O Library

- The SUSY Les Houches Accord defines a common interface for SUSY tools.

  Skands et al. 2003

- Reading/writing SLHA files not entirely straightforward.
- The SLHA I/O Library fills this gap:
  - ▷ Implemented as **native Fortran 77 Library.**
  - ▷ All data transferred in **one double-precision array.**
  - ▷ This array is **indexed by preprocessor macros,** e.g. `MinPar_TB` instead of `slhadata(20)`.
  - ▷ Main functions: `SLHARead`, `SLHAWrite`.

  Hahn 2004

- Freely available at **http://www.feynarts.de/SLHA.**

Summary

- FeynHiggs 2.2 provides Higgs-boson masses, couplings, branching ratios, etc. in the real or complex MSSM.
- Full one-loop evaluation including q^2 dependence.
- Latest leading and subleading two-loop corrections. Inclusion of complex phases at two loop in preparation.
- Easy to build. Four operating modes: Library, Command-line, WWW, Mathematica Mode.
- Command-line Mode reads files in native or SLHA format.
- Download from http://www.feynhiggs.de. Maintained by S. Heinemeyer and T. Hahn.
- Spin-off: SLHA I/O Library. Download from http://www.feynarts.de/SLHA.