FeynHiggs

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Purpose of FeynHiggs

Calculation of masses, mixings etc. in the MSSM at highest level of accuracy.

- works with real and complex parameters
- written in `Fortran`
- standard tool for masses, couplings and some decays in the LHCHXSWG
- current version: `2.13.0`

FeynHiggs team

HB, Sven Heinemeyer, Thomas Hahn, Wolfgang Hollik, Sebastion Paßehr, Heidi Rzehak, Georg Weiglein

Core of FeynHiggs: Higgs mass calculation

- MSSM includes two Higgs doublets

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ v_1 + \frac{1}{\sqrt{2}}(\phi_1 + i\chi_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ v_2 + \frac{1}{\sqrt{2}}(\phi_2 + i\chi_2) \end{pmatrix}$$

$\rightarrow$ five physical Higgs states: h, H, A, $H^\pm$

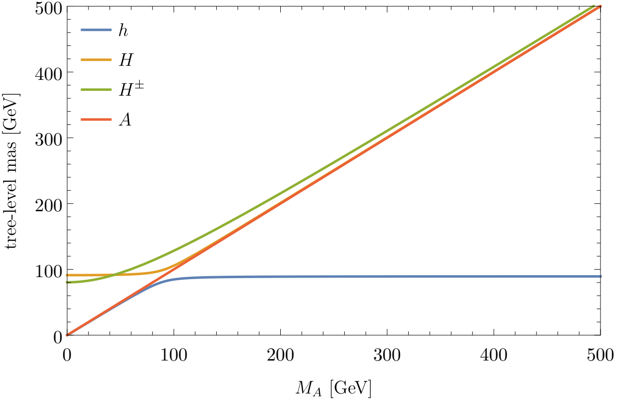
- Higgs potential:

$$V_H = m_1^2 H_{1i}^* H_{1i} + m_2^2 H_{2i}^* H_{2i} - \epsilon^{ij}(m_{12} H_{1i} H_{2j} + m_{12}^* H_{1i}^* H_{2j}^*) + \frac{1}{8}(g^2 + g'^2)(H_{1i}^* H_{1i} - H_{2i}^* H_{2i})^2 + \frac{1}{2} g^2 |H_{1i}^* H_{2i}|^2$$

  - Minimization of potential $\rightarrow$ m_1^2 and m_2^2 eliminated
  - Reexpress m_{12}^2 through mass of A boson

$\rightarrow$ Higgs sector at tree-level determined by only two variables: M_A and $\tan\beta = v_2/v_1$

$\rightarrow$ Mass of SM-like Higgs can be predicted



- tree-level bound on SM-like Higgs boson mass: $M_h^2 \leq M_Z^2$
- at loop level mixing between h, H and A
- loop-corrections can be large (up to 100%)

$\rightarrow$ For precision studies higher order corrections are essential!

Fixed-order calculation

Straightforward approach

Calculate self-energy corrections!

For $M_A^2 \gg M_Z^2$ mixing negligible: Solve $p^2 - \hat{\Sigma}_{hh}(p^2) = 0$!

- Full 1L and partial 2L results included
- Renormalization scheme: OS or $\overline{\text{DR}}$
- Resummation of bottom Yukawa coupling for large $\tan\beta$

Includes all corrections at given order
→ Precise for not too much separated scales ☺
→ For high SUSY scale, large logarithms spoil convergence ☹

e.g. $M_h^2 \overset{\mathcal{O}(\alpha_t)}{\sim} m_h^2 + 12k\frac{M_t^4}{v^2}\left(\ln(M_S^2/M_t^2) + ...\right)$

Code generation

Full 1L and $\mathcal{O}(\alpha_t^2)$ corrections can be generated automatically

- relies on tools `FeynArts`, `FormCalc` and `TwoCalc`
- `bash` scripts run the tools and output compile-ready `Fortran` files

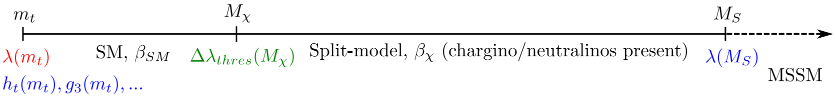
Toolchain for $\mathcal{O}(\alpha_t^2)$ corrections: [Hahn & Paßehr]

1. Generate diagrams with `FeynArts`
2. Prepare for tensor reduction
3. Tensor reduction with `TwoCalc` and `FormCalc`
4. Simplify expressions
5. Calculate renormalization constants with `FeynArts/FormCalc`
6. Combine everything and simplify
7. Generate code

EFT calculation

Alternative approach

If all SUSY particles are heavy, integrate them out!
$\rightarrow M_h^2 = 2\lambda(M_t)v^2$

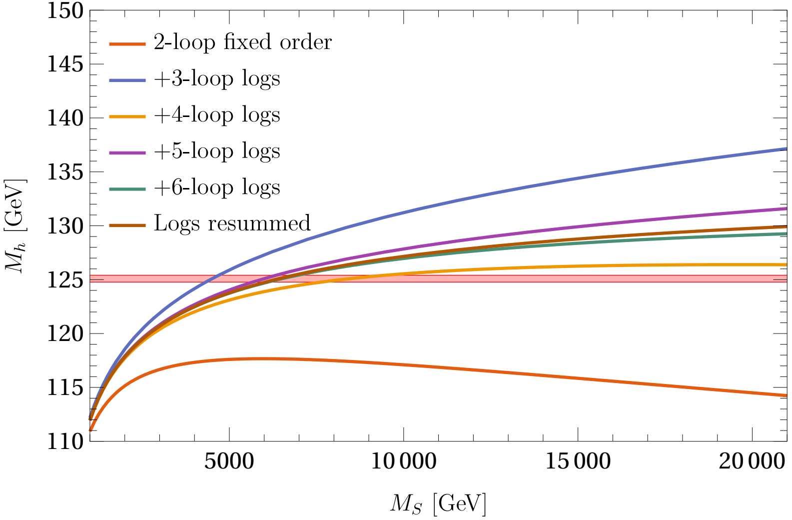


State of the art EFT calculation:

- Full LL+NLL resummation
- $\mathcal{O}(\alpha_s, \alpha_t)$ NNLL resummation
- separate chargino/neutralino threshold

EFT calculation resums large logarithms
$\rightarrow$ precise prediction for high scales ☺
$\rightarrow$ misses however terms suppressed by SUSY scale $\propto v/M_S$ ☹

Effect of resummation



Hybrid approach

Idea

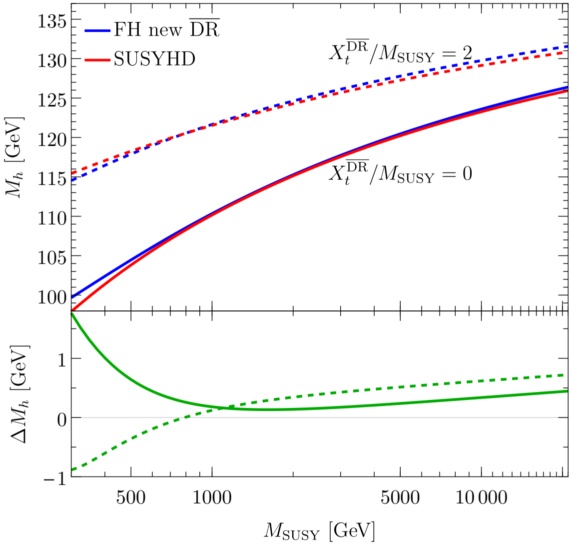
Combine EFT and fixed-order approach to allow for precise prediction for all scales.

$$\hat{\Sigma}_{hh}(m_h^2) \longrightarrow \hat{\Sigma}_{hh}(m_h^2) - \left[2v^2\lambda(M_t)\right]_{\text{log}} - \left[\hat{\Sigma}_{hh}(m_h^2)\right]_{\text{log}} = \\ = \left[\hat{\Sigma}_{hh}(m_h^2)\right]_{\text{nolog}} - \left[2v^2\lambda(M_t)\right]_{\text{log}}$$

- Have to avoid double-counting of 1L and 2L logarithms
- Have to avoid double-counting of non-log terms
- EFT uses $\overline{\text{DR}}$, fixed-order calcalculation can be OS
  $\rightarrow$ parameter conversion needed

Benefits:
$\rightarrow$ precise prediction for all scales ☺☺

Comparison to pure EFT calculation



Summary of available self-energy corrections

Need to find complex poles ($\mathcal{M}^2 = M^2 - iM\Gamma$) of inverse propagator matrix Δ^{-1} :

$$\begin{pmatrix} p^2 - m_h^2 + \Sigma_{hh}^{\color{blue}\bullet\color{red}\bullet\color{green}\bullet\color{orange}\bullet} & \Sigma_{hH}^{\color{blue}\bullet\color{red}\bullet\color{green}\bullet\color{orange}\bullet} & \Sigma_{hA}^{\color{blue}\bullet\color{red}\bullet} \\ \Sigma_{Hh}^{\color{blue}\bullet\color{red}\bullet\color{green}\bullet\color{orange}\bullet} & p^2 - m_H^2 + \Sigma_{HH}^{\color{blue}\bullet\color{red}\bullet\color{green}\bullet\color{orange}\bullet} & \Sigma_{HA}^{\color{blue}\bullet\color{red}\bullet} \\ \Sigma_{Ah}^{\color{blue}\bullet\color{red}\bullet} & \Sigma_{AH}^{\color{blue}\bullet\color{red}\bullet} & p^2 - m_A^2 + \Sigma_{AA}^{\color{blue}\bullet\color{red}\bullet} \end{pmatrix}$$

and $\Sigma_{H^\pm H^\pm}^{\color{blue}\bullet\color{red}\bullet}$, $\qquad (\Sigma = \Sigma(p^2))$

- $\color{blue}\bullet$: full one-loop corrections (all phases, p^2 dependence, NMFV)
- $\color{red}\bullet$: $\mathcal{O}(\alpha_s\alpha_t)$ corrections (all phases, p^2 dependence), $\mathcal{O}(\alpha_t^2)$ corrections (all phases, $p^2 = 0$)
- $\color{green}\bullet$: $\mathcal{O}(\alpha_t\alpha_b, \alpha_b^2)$ corrections (phases interpolated, $p^2 = 0$)
- $\color{orange}\bullet$: resummed logarithms using EFT

Numerical determination of the poles?

For $M_A \gg M_Z$,

$$M_h^2 = m_h^2 - \hat{\Sigma}_{hh}^{(1)}(m_h^2) - \hat{\Sigma}_{hh}^{(2)}(m_h^2) + \hat{\Sigma}_{hh}^{(1)\prime}(m_h^2)\hat{\Sigma}_{hh}^{(1)}(m_h^2) + ...$$

- Non-SM contributions to $\hat{\Sigma}_{hh}^{(1)\prime}(m_h^2)\hat{\Sigma}_{hh}^{(1)}(m_h^2)$ are cancelled by subloop-renormalization in $\hat{\Sigma}_{hh}^{(2)}(m_h^2) \to$ vev-CT
- holds generally at 2L (probably also at higher orders)
- but `FH` includes $\hat{\Sigma}_{hh}^{(2)}$ only for vanishing electroweak couplings $\to$ incomplete cancellation

$$\Downarrow$$

Numerical determination of poles spoils calculation!

$\to$ Solution easy for $M_A \gg M_Z$, but what to do for $M_A \sim M_Z$?

Procedure for general M_A

At 1L level $M_h^2 = m_h^2 - \hat{\Sigma}_{hh}^{(1)}(m_h^2) \to$ expand around 1L solution

$\Rightarrow$ determine poles of

$$\Delta_{hh}^{-1}(p^2) = p^2 - m_h^2 \quad + \hat{\Sigma}_{hh}^{(1)}(m_h^2) \quad + \hat{\Sigma}_{hh}^{(2)}(0) \quad - \left[\hat{\Sigma}_{hh}^{(1)\prime}(m_h^2) \hat{\Sigma}_{hh}^{(1)}(m_h^2) \right]_{g=g_Y=0}$$

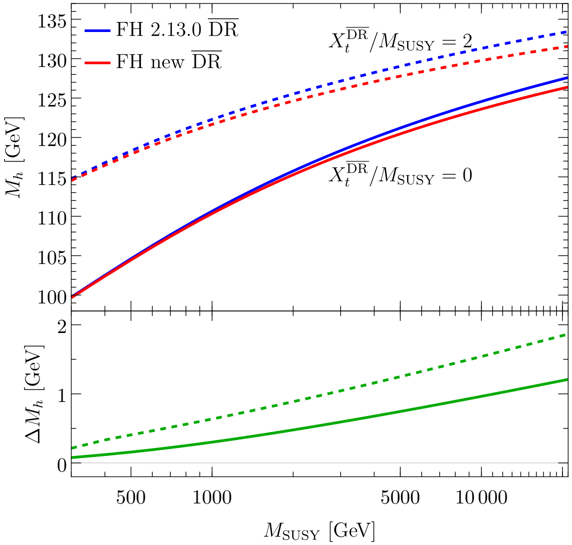
$$\Delta_{hH}^{-1}(p^2) = \quad + \hat{\Sigma}_{hH}^{(1)}(m_h^2) \quad + \hat{\Sigma}_{hH}^{(2)}(0) \quad - \left[\hat{\Sigma}_{hH}^{(1)\prime}(m_h^2) \hat{\Sigma}_{hh}^{(1)}(m_h^2) \right]_{g=g_Y=0}$$

$$\Delta_{HH}^{-1}(p^2) = p^2 - m_H^2 \quad + \hat{\Sigma}_{HH}^{(1)}(m_h^2) \quad + \hat{\Sigma}_{HH}^{(2)}(0) \quad - \left[\hat{\Sigma}_{HH}^{(1)\prime}(m_h^2) \hat{\Sigma}_{hh}^{(1)}(m_h^2) \right]_{g=g_Y=0}$$

For determination of M_H expand around $M_H^2 = m_H^2 - \hat{\Sigma}_{HH}^{(1)}(m_H^2)$

$\to$ will be available in the next release (`FH2.14.0`)

Numerical impact of improved pole determination



Output

Observables

- Higgs masses: M_{h_1}, M_{h_2}, M_{h_3}, $M_{H^\pm}$
- Z_{ij}-factors for calculating processes involving external Higgs bosons
- effective mixing angle α_{eff}

For all observables theory uncertainty is estimated by

- change of renormalization scheme
- scale variation
- switching off the resummation of the bottom Yukawa coupling

Neutral Higgs decays

- total decay width: $\Gamma_{h_i}^{\text{tot}}$, $\Gamma_{H^+}^{\text{tot}}$
- Branching ratios of h_i
  - SM fermions: $h_i \to f\bar{f}$
  - gauge bosons: $h_i \to \gamma\gamma, Z^{(*)}Z^{(*)}, W^{(*)}W^{(*)}, gg$
  - gauge and Higgs boson: $h_i \to Z^{(*)}h_j$
  - two Higgs bosons: $h_i \to h_j h_k$
  - sfermions: $h_i \to \tilde{f}_i\tilde{f}_j$
  - charginos/neutralinos: $h_i \to \tilde{\chi}_j^{\pm}\tilde{\chi}_k^{\mp}, \tilde{\chi}_j^0\tilde{\chi}_k^0$
- For comparison also SM branching ratios are calculated
- Branching ratios of H^+
  - SM fermions: $H^+ \to f^{(*)}\bar{f}'$
  - gauge and Higgs boson: $H^+ \to W^{+(*)}h_i$
  - sfermions: $h_i \to \tilde{f}_i\tilde{f}_j'$
  - chargino and neutralino: $h_i \to \tilde{\chi}_i^0\tilde{\chi}_j^0$

Higgs production

Available cross-sections:

- $\bar{b}b, gg \to h + X$
- $\bar{q}q \to \bar{q}qh + X$
- $\bar{q}q, gg \to \bar{t}th + X$
- $\bar{q}q \to Wh + X$
- $\bar{q}q \to Zh + X$
- $pp \to \tilde{t}_1\tilde{t}_1h + X$
- $gb \to tH^- + X$
- $t \to H^+\bar{b}$ for $M_{H^\pm} \leq M_t$
- For comparison also SM cross-sections are calculated.

EWPO and flavour observables

Electroweak precision observables:

- W boson mass M_W
- effective weak mixing angle $\sin\theta_{\text{eff}}$
- Δr, $\Delta\rho$
- Anomalous magnetic moment of the muon $g_\mu - 2$
- Electric dipole moments of the electron, neutron and mercury

Flavour observables:

- $b \to s\gamma$
- ΔM_s
- $B_s \to \mu^+\mu^-$

Getting and running the code

- Download latest version at `feynhiggs.de`
- Install via: "`./configure, make, make install`"
- 4 ways to run the code
  - Command line
  - Call from `Fortran/C++` code
  - Mathematica interface
  - Web interface `feynhiggs.de/fhucc`

Command line I

Inputfile:

```
MT 173.32
MSusy 2000
MA0 400
TB 10
Abs(At) 500
Arg(At) 0.8
...
```

→ `FeynHiggs file [flags]`

Screen output:

```
...
- HIGGS MASSES -
| Mh0 = 121.50245316
| MHH = 1002.92887238
| MA0 = 1000.00000000
| MHp = 1005.78424242
- ESTIMATED UNC. -
| DeltaMh0 = 1.06229069
| DeltaMHH = 0.40235972
| DeltaMA0 = 0.00000000
| DeltaMHp = 0.24339873
...
```

- Possible to define loops over parameters
- Possible to use interpolation tables
- Alternatively use SLHA files as input

Command line II

Example bash script

```
#! /bin/sh

FeynHiggs - ${4:-4002423110} «- _EOF_ > FH.out
MT 173.32
MSusy $2
Xt $3
TB 10
MA0 1000
MUE 1000
M_2 1000
M_3 1000
_EOF_

cat FH.out | table $1 FH.out 2>/dev/null
```

Call from Fortran/C++ code

- Link static `Fortran` library `FHlib.a`
- For `C/C++` prototype file available: `CFeynHiggs.h`
- Most important routines
  - input
    - `FHSetFlags` - options (accuracy, approximations, ...
    - `FHSetPara` - MSSM input parameters
  - output
    - `FHHiggsCorr` - Higgs masses and mixings
    - `FHUncertainties` - theory uncertainty estimate for Higgs masses and mixings
    - `FHCouplings` - Higgs couplings and BRs
    - `FHHiggsProd` - Higgs production cross-sections
    - `FHEWPO` - electroweak precision observables
    - `FHFlavour` - flavour constraints
    - `FHConstraints` - additional constraints

Call from Mathematica

- `make all` to generate `MathLink` executable
- uses it via:
  - input:

```
Install["MFeynHiggs"];
FHSetFlags[...];
FHSetPara[...];
FHHiggsCorr[]
```

  - output

```
{MHiggs -> {124.495, 999.552, 1000., 1003.24},
SAeff -> -0.101772,
UHiggs -> ..., ZHiggs -> ...}
```

- allows to use `Mathematica` functions (`ContourPlot, ...`)

The FeynHiggs User Control Center (2.13.0)

You can still access older versions: [FH2.10.2] [FH2.9.5] [FH2.8.6] [FH2.7.4] [FH2.5.1] [FH2.3.2]

Flags

Scope of the 1-loop part: full MSSM

1-loop field renormalization: DRbar

1-loop tan(beta) renormalization: DRbar

Mixing in the neutral Higgs sector: 2x2 (h0-HH) mixing = real parameters

Approximation for the 1-loop result: no approx., UHiggs evaluated at p^2 = 0

Higher-order corrections: 2-loop corrections

Inclusion of log resummation: no log resummation

m_t in the 1-/2-loop corrections: running top mass (SM MSbar 2L)

m_b in the 1-/2-loop corrections: resummed MB

complex parameters in the 2-loop corrections: all corrections evaluated in the rMSSM

p^2-dependent terms in the 2-loop corrections: not included

In a hurry? Go straight to the results

Or, choose a predefined scenario: mh_max | no-mixing | small alpha_eff | gluophobic Higgs | CPX

Summary:

- FeynHiggs calculates Higgs masses, mixings, decays, production cross-sections etc. in the MSSM
- Includes combined state-of-the-art fixed-order and EFT calculations
- Allows for precise predictions for low and high SUSY scales

Near future outlook (version 2.14.0):

- Improved pole mass determination
- Optional $\overline{\mathrm{DR}}$ renormalization of stop sector

To come later...

- Complete revamp of 2L corrections
- Improved resummation for low M_A (eff. THDM)
- NMSSM extension