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FeynHiggs: a program for the calculation of the masses of the neutral $\mathcal{CP}$-even Higgs bosons in the MSSM

S. Heinemeyer[1*], W. Hollik[2,3†], G. Weiglein[3‡]

[1] *DESY Theorie, Notkestr. 85, 22603 Hamburg, Germany*

[2] *Theoretical Physics Division, CERN, CH-1211 Geneva 23, Switzerland*

[3] *Institut für Theoretische Physik, Universität Karlsruhe, D–76128 Karlsruhe, Germany*

Abstract

FeynHiggs is a Fortran code for the calculation of the masses of the neutral $\mathcal{CP}$-even Higgs bosons in the MSSM up to two-loop order. It is based on the complete diagrammatic on-shell results at the one-loop level, the leading diagrammatic two-loop QCD contributions and further improvements taking into account leading electroweak two-loop and leading higher-order QCD corrections. The Higgs-boson masses are calculated as functions of the MSSM parameters for general mixing in the scalar top sector and arbitrary choices of the parameters in the Higgs sector of the model.

*email: Sven.Heinemeyer@desy.de
†email: Wolfgang.Hollik@physik.uni-karlsruhe.de
‡email: georg@particle.physik.uni-karlsruhe.de

1 Introduction

A direct and very stringent test of Supersymmetry (SUSY) is provided by the search for the lightest Higgs boson, since the prediction of a relatively light Higgs boson is common to all supersymmetric models whose couplings remain in the perturbative regime up to a very high energy scale [1]. A precise prediction for the mass of the lightest Higgs boson, m_h, in terms of the relevant SUSY parameters is crucial in order to determine the discovery and exclusion potential of LEP2 and the upgraded Tevatron. If the Higgs boson exists, it will be accessible at the LHC and future linear colliders, where then a high-precision measurement of the mass of this particle will become feasible. A precise knowledge of the mass of the heavier $\mathcal{CP}$-even Higgs boson, m_H, is important for resolving the mass splitting between the $\mathcal{CP}$-even and -odd Higgs-boson masses.

In the Minimal Supersymmetric Standard Model (MSSM) [2] the mass of the lightest Higgs boson is restricted at the tree level to be smaller than the Z-boson mass. This bound, however, is strongly affected by the inclusion of radiative corrections, which yield an upper bound of about 130 GeV [3, 4, 5, 6, 7, 8, 9]. Results beyond one-loop order have been obtained in several approaches: a Feynman diagrammatic calculation of the leading QCD corrections has been performed [6, 7]. Also renormalization group (RG) methods have been applied in order to obtain leading logarithmic higher-order contributions [8]. Furthermore the leading two-loop QCD corrections have been calculated in the effective potential method [9]. All these calculations show that the corrections beyond one-loop order lead to a sizable decrease of m_h of up to 20 GeV.

Concerning the calculation of the lighter and heavier neutral $\mathcal{CP}$-even Higgs bosons two different kinds of computer codes have been used for phenomenological analyses so far: they are either based on the RG improved one-loop effective potential approach [8] or on the one-loop diagrammatic on-shell calculation [4, 5]. These approaches differ by $\mathcal{O}(10 \text{ GeV})$.

Here we present a new Fortran program named *FeynHiggs*, which is based on the results of the Feynman-diagrammatic calculations up to $\mathcal{O}(\alpha\alpha_s)$ given in Refs. [5, 6, 7]. It includes the complete diagrammatic on-shell results at the one-loop level, the leading diagrammatic two-loop QCD contributions and further improvements taking into account leading electroweak two-loop and leading higher-order QCD corrections. The calculation of m_h and m_H is performed for arbitrary values of parameters in the $t - \tilde{t}$-sector and the Higgs sector of the MSSM. As a subroutine, *FeynHiggs* can be linked to other programs thus incorporating in an easy way a precise prediction for m_h and m_H. In addition the program provides as an option the calculation of the SUSY contribution to the ρ-parameter in $\mathcal{O}(\alpha\alpha_s)$, based on Refs. [10, 11]. In this way experimentally disfavored combinations of squark masses can automatically be excluded.

The paper is organized as follows: in section 2 we specify our notations and give a brief outline of the calculation of m_h and m_H. In section 3 the program *FeynHiggs* is described in detail. Examples of how to use *FeynHiggs* are shown in section 4. The conclusions are given in section 5.

2 The calculational basis

2.1 The top-squark sector of the MSSM

In order to fix the notation we shortly list our conventions for the MSSM scalar top sector: the mass matrix in the basis of the current eigenstates $\tilde{t}_L$ and $\tilde{t}_R$ is given by

$$\mathcal{M}_{\tilde{t}}^2 = \begin{pmatrix} M_{\tilde{t}_L}^2 + m_t^2 + \cos 2\beta \, (\frac{1}{2} - \frac{2}{3} s_W^2) M_Z^2 & m_t M_t^{LR} \\ m_t M_t^{LR} & M_{\tilde{t}_R}^2 + m_t^2 + \frac{2}{3} \cos 2\beta \, s_W^2 M_Z^2 \end{pmatrix}, \tag{1}$$

where

$$m_t M_t^{LR} = m_t (A_t - \mu \cot\beta \,) \; . \tag{2}$$

Diagonalizing the $\tilde{t}$-mass matrix yields the mass eigenvalues $m_{\tilde{t}_1}, m_{\tilde{t}_2}$ and the $\tilde{t}$ mixing angle $\theta_{\tilde{t}}$, which relates the current eigenstates to the mass eigenstates:

$$\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{t}} & \sin\theta_{\tilde{t}} \\ -\sin\theta_{\tilde{t}} & \cos\theta_{\tilde{t}} \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix} \; . \tag{3}$$

2.2 Calculation of the Higgs-boson masses

Contrary to the Standard Model (SM), in the MSSM two Higgs doublets are required. The Higgs potential [12]

$$\begin{aligned} V &= m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) \\ &\quad + \frac{g'^2 + g^2}{8} \, (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g^2}{2} \, |H_1 \bar{H}_2|^2 \end{aligned} \tag{4}$$

contains m_1, m_2, m_{12} as soft SUSY breaking parameters; g, g' are the $SU(2)$ and $U(1)$ gauge couplings, and $\epsilon_{12} = -1$.

The doublet fields H_1 and H_2 are decomposed in the following way:

$$\begin{aligned} H_1 &= \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1^0 + i\chi_1^0)/\sqrt{2} \\ \phi_1^- \end{pmatrix}, \\ H_2 &= \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2^0 + i\chi_2^0)/\sqrt{2} \end{pmatrix}. \end{aligned} \tag{5}$$

The potential (4) can be described with the help of two independent parameters (besides g and g'): $\tan\beta \, = v_2/v_1$ and $M_A^2 = -m_{12}^2(\tan\beta \, + \cot\beta \,)$, where M_A is the mass of the $\mathcal{CP}$-odd A boson.

In order to obtain the $\mathcal{CP}$-even neutral mass eigenstates, the rotation

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix} \tag{6}$$

is performed, where the mixing angle α is given in terms of $\tan\beta$ and M_A as follows:

$$\tan 2\alpha = \tan 2\beta \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}, \quad -\frac{\pi}{2} < \alpha < 0. \tag{7}$$

At tree level the mass matrix of the neutral $\mathcal{CP}$-even Higgs bosons in the $\phi_1 - \phi_2$ basis can be expressed in terms of M_Z and M_A as follows:

$$\begin{aligned} M_{\text{Higgs}}^{2,\text{tree}} &= \begin{pmatrix} m_{\phi_1}^2 & m_{\phi_1\phi_2}^2 \\ m_{\phi_1\phi_2}^2 & m_{\phi_2}^2 \end{pmatrix} \\ &= \begin{pmatrix} M_A^2 \sin^2\beta \, + M_Z^2 \cos^2\beta & -(M_A^2 + M_Z^2) \sin\beta \, \cos\beta \\ -(M_A^2 + M_Z^2) \sin\beta \, \cos\beta & M_A^2 \cos^2\beta \, + M_Z^2 \sin^2\beta \end{pmatrix}, \end{aligned} \tag{8}$$

which by diagonalization according to eq. (6) yields the tree-level Higgs-boson masses

$$M_{\text{Higgs}}^{2,\text{tree}} \stackrel{\alpha}{\longrightarrow} \begin{pmatrix} m_{H,\text{tree}}^2 & 0 \\ 0 & m_{h,\text{tree}}^2 \end{pmatrix}. \tag{9}$$

In the Feynman-diagrammatic approach the Higgs-boson masses in higher orders are derived by finding the poles of the $h - H$-propagator matrix whose inverse reads:

$$\left(\Delta_{\text{Higgs}}\right)^{-1} = -i \begin{pmatrix} q^2 - m_{H,\text{tree}}^2 + \hat{\Sigma}_H(q^2) & \hat{\Sigma}_{hH}(q^2) \\ \hat{\Sigma}_{hH}(q^2) & q^2 - m_{h,\text{tree}}^2 + \hat{\Sigma}_h(q^2) \end{pmatrix}. \tag{10}$$

The poles are then obtained by solving the equation

$$(q^2 - m_{h,\text{tree}}^2 + \hat{\Sigma}_h(q^2))(q^2 - m_{H,\text{tree}}^2 + \hat{\Sigma}_H(q^2)) - (\hat{\Sigma}_{hH}(q^2))^2 = 0 \,. \tag{11}$$

In the following the $\hat{\Sigma}^{(i)}$ denote the one-loop ($i = 1$) and the two-loop ($i = 2$) contributions to the renormalized self-energies.

In *FeynHiggs* the one-loop results for the Higgs-boson self-energies $\hat{\Sigma}_s^{(1)}(q^2)$ are calculated according to Ref. [5]. They contain the full one-loop contribution obtained via an explicit Feynman-diagrammatic calculation in the on-shell scheme. Here the gaugino parameters M_1 and $M(\equiv M_2)$ enter in the neutralino mass matrix. M_1 is fixed via the GUT relation

$$M_1 = \frac{5}{3} \frac{s_W^2}{c_W^2} M, \tag{12}$$

whereas M is kept as a free input parameter.

The two-loop results for the Higgs-boson self-energies $\hat{\Sigma}_s^{(2)}$ are taken from Refs. [6, 7]. The leading two-loop corrections have been obtained by calculating the $\mathcal{O}(\alpha\alpha_s)$ contribution of the $t-\tilde{t}$-sector to the renormalized Higgs-boson self-energies at zero external momentum from the Yukawa part of the theory. These two-loop QCD corrections are expected to constitute the most sizable part of the full set of two-loop corrections. In Refs. [6, 7] the self-energies have been computed first in the $\phi_1 - \phi_2$ basis and afterwards rotated into the $h - H$ basis according to eq. (6):

$$\begin{aligned}
\hat{\Sigma}^{(2)}_H &= \cos^2\alpha\, \hat{\Sigma}^{(2)}_{\phi_1} + \sin^2\alpha\, \hat{\Sigma}^{(2)}_{\phi_2} + 2\sin\alpha\, \cos\alpha\, \hat{\Sigma}^{(2)}_{\phi_1\phi_2} \\
\hat{\Sigma}^{(2)}_h &= \sin^2\alpha\, \hat{\Sigma}^{(2)}_{\phi_1} + \cos^2\alpha\, \hat{\Sigma}^{(2)}_{\phi_2} - 2\sin\alpha\, \cos\alpha\, \hat{\Sigma}^{(2)}_{\phi_1\phi_2} \\
\hat{\Sigma}^{(2)}_{hH} &= -\sin\alpha\, \cos\alpha \left(\hat{\Sigma}^{(2)}_{\phi_1} - \hat{\Sigma}^{(2)}_{\phi_2}\right) + (\cos^2\alpha\, - \sin^2\alpha\,)\hat{\Sigma}^{(2)}_{\phi_1\phi_2}.
\end{aligned} \tag{13}$$

Thus for our results up to the two-loop level the matrix (10) contains the renormalized Higgs-boson self-energies

$$\hat{\Sigma}_s(q^2) = \hat{\Sigma}^{(1)}_s(q^2) + \hat{\Sigma}^{(2)}_s(0), \quad s = h, H, hH, \tag{14}$$

where the momentum dependence is neglected only in the two-loop contribution. The calculation is performed for arbitrary parameters of the Higgs and the scalar top sector and for arbitrary gluino mass $m_{\tilde{g}}$. Thus the accuracy of the calculation does not depend on how the parameters of the $\tilde{t}$ sector $m_{\tilde{t}_1}, m_{\tilde{t}_2}$ and $\theta_{\tilde{t}}$ are chosen.

In order to take into account the leading electroweak two-loop contribution to the mass of the lightest Higgs boson, we have implemented the leading Yukawa correction of $\mathcal{O}(G_F^2 m_t^6)$, which gives a sizable contribution only for m_h. The formula is taken over from the result obtained by renormalization group methods. It reads [13]

$$\Delta m_h^2 = \frac{9}{16\pi^4} G_F^2 m_t^6 \left[\tilde{X} t + t^2\right] \tag{15}$$

$$\text{with} \quad \tilde{X} = \Bigg[\left(\frac{m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2}{4m_t^2} \sin^2 2\theta_{\tilde{t}}\right)^2 \left(2 - \frac{m_{\tilde{t}_2}^2 + m_{\tilde{t}_1}^2}{m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2} \log\left(\frac{m_{\tilde{t}_2}^2}{m_{\tilde{t}_1}^2}\right)\right) + \frac{m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2}{2m_t^2} \sin^2 2\theta_{\tilde{t}} \log\left(\frac{m_{\tilde{t}_2}^2}{m_{\tilde{t}_1}^2}\right) \Bigg], \tag{16}$$

$$t = \frac{1}{2} \log\left(\frac{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}{m_t^4}\right). \tag{17}$$

The second step of refinement incorporated into *FeynHiggs* concerns leading QCD corrections beyond two-loop order. They are taken into account by using the $\overline{MS}$ top mass

$$\overline{m}_t = \overline{m}_t(m_t) \approx \frac{m_t}{1 + \frac{4}{3\pi}\alpha_s(m_t)} \tag{18}$$

for the two-loop contributions instead of the pole mass, $m_t = 175$ GeV.

The results implemented in *FeynHiggs* have been compared to the calculations using RG methods. Good agreement has been found in the case of no mixing in the $\tilde{t}$ sector, i.e. $M_t^{LR} = 0$ GeV, whereas sizable deviations can occur when mixing in the $\tilde{t}$-sector is taken into account. This has been discussed in detail in Ref. [7].

2.3 Calculation of the ρ-parameter

We have also implemented the calculation of the MSSM contributions to $\Delta\rho$ [10, 11]. Here the corrections arising from $\tilde{t}/\tilde{b}$-loops up to $\mathcal{O}(\alpha\alpha_s)$ have been taken into account. The result is valid for arbitrary parameters in the $\tilde{t}$- and $\tilde{b}$-sector, also taking into account the mixing in the $\tilde{b}$-sector which can have a non-negligible effect in the large $\tan\beta$ scenario [11].

The two-loop result is separated into the pure gluon-exchange contribution, which can be expressed by a very compact formula that allows a very fast evaluation, and the pure gluino-exchange contribution, which is given by a rather lengthy expression. The latter correction goes to zero with increasing gluino mass and can thus be discarded for a heavy gluino[1]. The ρ-parameter can be used as an additional constraint (besides the experimental bounds) on the squark masses. A value of $\Delta\rho$ outside the experimentally preferred region of $\Delta\rho^{\rm SUSY} \approx 10^{-3}$ [15] indicates experimentally disfavored $\tilde{t}$- and $\tilde{b}$-masses.

3 The Fortran program *FeynHiggs*

3.1 The main structure

The complete program *FeynHiggs* consists of about 50.000 lines Fortran code, where the main part belongs to the formulas for the renormalized Higgs self-energies at the two-loop level and the gluino contribution to $\Delta\rho$. The executable file fills about 4 MB disk space. The calculation for one set of parameters, including the $\Delta\rho$ constraint, with the highest accuracy takes less than 2 seconds on a third-generation Alpha 21164 microprocessor (300 MHz processing speed).

There exists a Home page for *FeynHiggs*:
`http://www-itp.physik.uni-karlsruhe.de/feynhiggs` .
Here a uu-encoded version as well as an ASCII version is available, together with a short instruction, information about bug fixes etc.

FeynHiggs consists of several subprograms which are listed in Table 1. We now describe the different subprograms in detail.

- **FeynHiggs.f** is the front-end for the whole program. Here all variables are set, all options are chosen, the subprogram **FeynHiggsSub.f** is called, and the results for the Higgs masses are printed out. For an easy use of *FeynHiggs* this front-end can be manipulated at will, the rest of the program need not to be changed.
- **FeynHiggsSub.f**: Here the actual calculation is carried out. The various results for the renormalized Higgs-boson self-energies (14) are put together. Eq. (11) is solved numerically, the refinement terms (the leading two-loop Yukawa contribution and the leading QCD corrections beyond two-loop order) are incorporated.

[1] An additional contribution to $\Delta\rho$, arising from a shift in the squark masses when the soft SUSY breaking parameters are used as input (due to the $SU(2)$ invariance of these parameters in the squark sector), is not implemented in *FeynHiggs*. This correction is described in detail in Ref. [10].

subprogram	function of the program
FeynHiggs.f	front-end
FeynHiggsSub.f	main part of *FeynHiggs* : calculation of m_h, m_H
Hhmasssr2.f	one-loop self-energies
varcom.h	definition of variables
bc.f	one-loop functions
lamspen.f	further mathematical functions
def2.f	definitions for the MSSM parameters
P1secode.f	Fortran code for $\hat{\Sigma}^{(1)}_{\phi_1}(0)$
P1sesum.f	putting together the different parts of $\hat{\Sigma}^{(1)}_{\phi_1}(0)$
P1sevar.f	definition of variables for $\hat{\Sigma}^{(1)}_{\phi_1}(0)$
P2se[code,sum,var].f	same for $\hat{\Sigma}^{(1)}_{\phi_2}(0)$
P1P2se[code,sum,var].f	same for $\hat{\Sigma}^{(1)}_{\phi_1\phi_2}(0)$
P1setl[code,sum,var].f	same for $\hat{\Sigma}^{(2)}_{\phi_1}(0)$
P2setl[code,sum,var].f	same for $\hat{\Sigma}^{(2)}_{\phi_2}(0)$
P1P2setl[code,sum,var].f	same for $\hat{\Sigma}^{(2)}_{\phi_1\phi_2}(0)$
delrhosub.f	main part for the calculation of $\Delta\rho$
delrhoGluino[code,sum,var].f	subroutines for the gluino-exchange contribution to $\Delta\rho$

Table 1: The subprograms of *FeynHiggs*.

- **Hhmasssr2.f**: The results for the complete one-loop self-energies are evaluated.
- **varcom.h**: The variables needed for the files ***code.f** are defined and grouped in common blocks.
- **bc.f, lamspen.f** contain mathematical functions needed for the one- and two-loop self-energies.
- **def2.f**: The masses of the stops and sbottoms are calculated from the parameters in the squark mass matrices. The opposite way is also possible.
- **P1setlcode.f** contains the complete code for the two-loop contribution to the renor-

malized ϕ_1 self-energy in $\mathcal{O}(\alpha\alpha_s)$. This code was first calculated with the help of *Mathematica* packages (see [6, 7]) and was afterwards transformed automatically into this Fortran code. The complete code has been split up into 13 smaller functions in order not to exceed the maximal number of continuation lines of the Fortran compiler.

- **P1setlsum.f**: The sum of 13 functions for the renormalized ϕ_1 self-energy at the two-loop level, contained in **P1setlcode.f**, is put together.

- **P1setlvar.f** contains the variable definition for the 13 subfunctions described above.

- The above three files exist in an analogous way for the other renormalized Higgs-boson self-energies at the one- and at the two-loop level. The one-loop self-energies in these files are given in the approximation explained in detail in [6, 7] and are only needed internally for consistency checks. For the real calculation of m_h and m_H the complete one-loop self-energies are calculated in **Hhmasssr2.f**.

- **delrhosub.f** is needed for the calculation of the MSSM contribution to $\Delta\rho$. In this program the evaluation of the leading one-loop contribution is performed. In addition also the gluon-exchange correction in $\mathcal{O}(\alpha\alpha_s)$ is calculated. The $\mathcal{O}(\alpha\alpha_s)$ contribution to $\Delta\rho$ is completed by including the gluino-exchange contribution by calling the subprogram **delrhoGluinosum.f**.

- **delrhoGluino[code,sum,var].f**: The code for the gluino exchange contribution to $\Delta\rho$ is implemented in the same way as it is described for the renormalized Higgs-boson self-energies.

3.2 Options and setting of variables

FeynHiggs can be run in several ways, determined by the choice of several options.

- **Depth of calculation** allows to choose to what extent the refinements described in section 2.2 should be applied.

- **Selection of input parameters:** One can either use the physical parameters of the $\tilde{t}$ mass matrix ($m_{\tilde{t}_1}, m_{\tilde{t}_2}$ and $\theta_{\tilde{t}}$) or the soft SUSY breaking parameters ($M_{\tilde{t}_L}, M_{\tilde{t}_R}$ and M_t^{LR}) as input parameters.

- **m_t in the $\tilde{t}$ mass matrix:** If the soft SUSY breaking parameters are used as input parameters, one can choose whether the top pole mass, m_t, or the running top mass, $\overline{m}_t$, should be used in the $\tilde{t}$ mass matrix in order to determine the masses of the eigenstates $m_{\tilde{t}_1}, m_{\tilde{t}_2}$ and $\theta_{\tilde{t}}$.

- **Limit for $\Delta\rho^{\rm SUSY}$:** One can specify the maximally allowed value for the MSSM contribution to $\Delta\rho$. If $\Delta\rho^{\rm SUSY}$ exceeds this limit a warning is printed out.

- **Selection for the one-loop accuracy:** Before the calculation of the Higgs masses starts, one has to specify to what accuracy the one-loop renormalized self-energies should be evaluated. One can either take into account the top sector only, one can choose to use the top *and* the bottom sector, or one can select the option that the complete MSSM should be taken into account.

input for *FeynHiggs*	**expression in the MSSM**	**internal expr. in** *FeynHiggs*
`tan(beta)`	$\tan\beta$	`ttb`
`Msusy_top_L`	$M_{\tilde{t}_L}$	`msusytl`
`Msusy_top_R`	$M_{\tilde{t}_R}$	`msusytr`
	$M_{\tilde{b}_L}$	`msusybl`
	$M_{\tilde{b}_R}$	`msusybr`
`MtLR`	M_t^{LR}	`mtlr`
`MSt2`	$m_{\tilde{t}_2}$	`mst2`
`delmst`	$\Delta m_{\tilde{t}} = m_{\tilde{t}_2} - m_{\tilde{t}_1}$	`delmst`
`sin(theta_stop)`	$\sin\theta_{\tilde{t}}$	`stt`
	$\sin\theta_{\tilde{b}}$	`stb`
`Mtop` or `mt`	m_t	`mmt`
	m_b	`mbb`
`Mgluino`	$m_{\tilde{g}}$	`mgl`
`Mue`	μ	`mmue`
`M`	M	`mmm`
`MA`	M_A	`mma`

Table 2: The meaning of the different MSSM variables which have to be entered into *FeynHiggs*.

In **FeynHiggs.f** the Standard Model (SM) variables are set to their present experimental values. New values for these variables can be implemented by the user into the code of the file **FeynHiggs.f** easily. The MSSM variables can be chosen by the user at will. In addition, since the dependence of the Higgs masses on the top mass is very strong, also m_t can be chosen at will. In Table 2 the meaning of the different parameters *FeynHiggs* asks for is explained[2]. All these variables are transferred to the different subprograms by common blocks.

4 How to use *FeynHiggs*

In this section we will give two examples of how *FeynHiggs* is used. As stated before, the front-end **FeynHiggs.f** can be manipulated by the user at will, whereas the subprogram **FeynHiggsSub.f** and all the other subprograms should not be changed. Concerning a modificaton of the front-end one has to note that all variables have to be defined in the front-end. The Higgs masses are then obtained by calling the subroutine via

$$\texttt{call feynhiggssub}(\texttt{mh1}, \texttt{mh2}, \texttt{mh12}, \texttt{mh22}) \ ,$$

where `mh1` and `mh2` are the one-loop corrected values for m_h and m_H, respectively. `mh12` and `mh22` contain the values for the two-loop corrected Higgs masses, including the refinement terms as it has been specified in the options.

In the following two examples are given, how the application of *FeynHiggs* looks like, using the given front-end of the currently distributed version. The user's input is given in **bold face** letters.

[2]Some MSSM variables exist internally in *FeynHiggs*, but are not input parameters. These variables have no entry in the left column of Table 2.

4.1 Example 1

>FeynHiggs.exe

```
... Introduction ...
---------------------------------------------------

depth of calculation ?
1: full 1-loop + 2-loop QCD
2: same as 1, but in addition with
              mt = 166.5 at 2-loop
3: same as 2, but in addition with
              Yukawa term added for light Higgs
```

1

```
Select input:
1: Msusy, MtLR, ...
2: MSt2, delmst, stt, ...
```

2

```
Limit for Delta rho = 1.3 * 10^ -3 ? (0 = ok)
```

0

```
tan(beta) = ?
```

1.6

```
MSt2 = ?
```

400

```
delmst = ?
```

100

```
sin(theta_stop) = ?
(0: stt = 0 // 1: stt = sin(-Pi/4))
```

1

```
Mtop = 175 ? (0 = ok)
```

173.8

```
Mgluino = 500 ? (0 = ok)
```

300

```
Mue = -200 ? (0 = ok)
```

100

```
M = ? (0: M = 400 // 1: M = Msusy)
```

1

```
MA = ?
```
500

```
Selection: 1 = top only, 2 = top/bottom only, 3 = all
```
3

```
Your parameters:
tb, Msusy(top-left), Msusy(top-right), MtLR
MT, Mgl, Mue, M, MA
1.600000       309.2813       308.0858       200.0000
173.8000       300.0000       100.0000       309.2813       500.0000

-------------------------------------------------
The results:  light Higgs      heavy Higgs

mh-tree :       39.42879        506.7153
mh-1loop:       69.53253        508.7314
mh-2loop:       64.10773        508.3541
-------------------------------------------------
Delta rho 1-loop         :   5.909909368803866E-004
Delta rho 2-loop (gluon) :   6.177715322384914E-005
Delta rho 2-loop (gluino):   4.755834893556049E-006
Delta rho total          :   6.575239249977918E-004
-------------------------------------------------


tan(beta) = ?
...
```

In this example the physical parameters in the $\tilde{t}$-sector have been chosen as input parameters, no refinement term has been included. The selection for M sets $M = M_{\tilde{t}_L}$, where $M_{\tilde{t}_L}$ is calculated from $m_{\tilde{t}_1}$, $m_{\tilde{t}_2}$ and $\sin\theta_{\tilde{t}}$, see eq. (1).

4.2 Example 2

>FeynHiggs.exe

```
... Introduction ...
---------------------------------------------------

depth of calculation ?
1: full 1-loop + 2-loop QCD
2: same as 1, but in addition with
              mt = 166.5 at 2-loop
3: same as 2, but in addition with
              Yukawa term added for light Higgs
```
3

```
mt in the stop mass matrix at 2-loop ?
1: mt = pole mass
2: mt = running mass
```
2

```
Select input:
1: Msusy, MtLR, ...
2: MSt2, delmst, stt, ...
```
1

```
Limit for Delta rho = 1.3 * 10^ -3 ? (0 = ok)
```
0.00001

```
tan(beta) = ?
```
20

```
Msusy_top_L = ?
```
1000
```
Msusy_top_R = ? (0: Msusy_top_R = Msusy_top_L)
```
0
```
Mtop = 175 ? (0 = ok)
```
0
```
Mgluino = 500 ? (0 = ok)
```
0
```
Mue = -200 ? (0 = ok)
```
-100

```
M = ? (0: M = 400 // 1: M = Msusy)
```
300
```
MA = ?
```
400
```
MtLR = ?
```
1000
```
Selection: 1 = top only, 2 = top/bottom only, 3 = all
```
3
```
Your parameters:
tb, Msusy(top-left), Msusy(top-right), MtLR
MT, Mgl, Mue, M, MA
20.00000      1000.000      1000.000      1000.000
175.0000      500.0000     -100.0000      300.0000      400.0000

-------------------------------------------------
The results:  light Higgs     heavy Higgs

mh-tree :      90.70748       400.1090
mh-1loop:      133.6753       400.1799
mh-2loop:      118.8657       400.1770
-------------------------------------------------
using running mt for two-loop contribution:   167.338636349986
... also for mt in Stop mass matrix
mh-2loop:      120.8774       400.1780
-------------------------------------------------
using running mt for two-loop contribution:   167.338636349986
... also for mt in Stop mass matrix
adding Yukawa term for light Higgs
... also with running mt in stop mass matrix
mh-2loop:      122.2504       400.1780
-------------------------------------------------
WARNING: Delta rho > experimental limit
Delta rho 1-loop         :   3.224156596235517E-005
Delta rho 2-loop (gluon) :   3.475299800114144E-006
Delta rho 2-loop (gluino):   2.896993903992095E-005
Delta rho total          :   6.468680480239026E-005
-------------------------------------------------


tan(beta) = ?
...
```

If one selects to include all refinement terms, the front-end automatically calculates the Higgs masses in all three steps of accuracy. The running top mass (in this example `167.338636349986` GeV) is used also in the $\tilde{t}$ mass matrix. In this example only a very small SUSY contribution to $\Delta\rho$ ia allowed and the value of $\Delta\rho^{\rm SUSY}$ for the chosen parameters exceeds the above specified maximal value (a warning is printed out.)

5 Conclusions

FeynHiggs is a Fortran code for the calculation of the masses of the neutral $\mathcal{CP}$-even Higgs bosons of the MSSM. It is based on results which have been obtained using the Feynman-diagrammatic approach. The results consist of the full one-loop and the leading two-loop QCD corrections. Two further steps of refinements have been implemented. The Fortran code for the one-loop contribution has been taken over from a program written by A. Dabelstein. The Fortran code for the two-loop correction has been generated automatically from a *Mathematica* result.

The program is available via the WWW page
`http://www-itp.physik.uni-karlsruhe.de/feynhiggs` .

The code consists of a front-end and a subroutine. The front-end can be manipulated at the user's will. The different parts of the code have been described in detail, and the meaning of the variables used in the code has been explained. We have given two examples of how to use *FeynHiggs*.

The subroutine is self-contained and can be linked as an independent part to other existing programs[3] thus providing a precise prediction for m_h and m_H, which can then be used for further computations.

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