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HDECAY:
a Program for Higgs Boson Decays in the Standard Model and its Supersymmetric Extension

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Abstract

We describe the Fortran code HDECAY[†], which calculates the decay widths and the branching ratios of the Standard Model Higgs boson, and of the neutral and charged Higgs particles of the Minimal Supersymmetric extension of the Standard Model. The program is self-contained (with all subroutines included), easy to run, fast and calculates the decay widths and branching ratios according to the current theoretical knowledge.

[†]The program may be obtained from http://wwwcn.cern.ch/~mspira/ or http://www.lpm.univ-montp2.fr/~djouadi/program.html, or via E-mail from: djouadi@lpm.univ-montp2.fr, kalino@desy.de, spira@cern.ch.

1 Introduction

The experimental observation of scalar Higgs particles is crucial for our present understanding of the mechanism of electroweak symmetry breaking. Thus the search for Higgs bosons is one of the main entries in the LEP2 agenda, and will be one of the major goals of future colliders such as the Large Hadron Collider LHC and the future Linear e^+e^- Collider LC. Once the Higgs boson is found, it will be of utmost importance to perform a detailed investigation of its fundamental properties, a crucial requirement to establish the Higgs mechanism as the basic way to generate the masses of the known particles. To this end, a very precise prediction of the production cross sections and of the branching ratios for the main decay channels is mandatory.

In the Standard Model (SM), one doublet of scalar fields is needed for the electroweak symmetry breaking, leading to the existence of one neutral scalar particle H^0 [1]. Once M_{H^0} is fixed, the profile of the Higgs boson is uniquely determined at tree level: the couplings to fermions and gauge bosons are set by their masses and all production cross sections, decay widths and branching ratios can be calculated unambiguously [2]. Unfortunately, M_{H^0} is a free parameter. From the direct search at LEP1 and LEP2 we know that it should be larger than about 71 GeV [3]. Triviality restricts the Higgs particle to be lighter than about 1 TeV; theoretical arguments based on Grand Unification at a scale $\sim 10^{16}$ GeV suggest however, that the preferred mass region will be 100 GeV $\lesssim M_{H^0} \lesssim$ 200 GeV; for a recent summary, see Ref. [4].

In supersymmetric (SUSY) theories, the Higgs sector is extended to contain at least two isodoublets of scalar fields. In the Minimal Supersymmetric Standard Model (MSSM) this leads to the existence of five physical Higgs particles: two CP-even Higgs bosons h and H, one CP-odd or pseudoscalar Higgs boson A, and two charged Higgs particles $H^\pm$ [1]. Besides the four masses, two additional parameters are needed: the ratio of the two vacuum expectation values, $\mathrm{tg}\beta$, and a mixing angle α in the CP-even sector. However, only two of these parameters are independent: choosing the pseudoscalar mass M_A and $\mathrm{tg}\beta$ as inputs, the structure of the MSSM Higgs sector is entirely determined at lowest order. However, large SUSY radiative corrections [5] affect the Higgs masses and couplings, introducing new [soft SUSY-breaking] parameters in the Higgs sector. If in addition relatively light genuine supersymmetric particles are allowed, the whole set of SUSY parameters will be needed to describe the MSSM Higgs boson properties unambiguously.

In this report we describe the program HDECAY[1], which calculates the decay widths and branching ratios of Higgs bosons in the SM and the MSSM. It includes:

- All decay channels that are kinematically allowed and which have branching ratios larger than 10^{-4}, *y compris* the loop mediated, the most important three body decay modes, and in the MSSM the cascade and the supersymmetric decay channels.

[1] A complete overview over all theoretical details can be found in Ref. [6].

- All relevant higher-order QCD corrections to the decays into quark pairs and to the quark loop mediated decays into gluons are incorporated in the most complete form [7]. The largest part of the corrections to the heavy quark pair decay modes are mapped into running masses which have to be evaluated at the scale of the Higgs mass. The small leading electroweak corrections are also included. They become sizeable only in the large Higgs mass regime due to the enhanced self-interactions of the Higgs bosons.

- Double off-shell decays of the CP-even Higgs bosons into massive gauge bosons which then decay into four massless fermions [8]. These decays are important for masses close to M_W or M_Z. For larger masses, it is a sufficient approximation to switch off these decays [which are CPU time consuming] and to allow for one on-shell gauge boson only.

- All important below-threshold [three-body] decays: with off-shell heavy top quarks $H^0, H, A \to t\bar{t}^* \to t\bar{b}W^-$ and $H^+ \to t^*\bar{b} \to b\bar{b}W^+$; with one off-shell gauge boson $H \to W^{\pm *}H^{\mp}$, $H \to Z^*A$, $A \to Z^*h$ and $H^{\pm} \to W^{\pm *}A, W^{\pm *}h$; as well as the decays of H with one off-shell Higgs boson $H \to hh^*, AA^*$. These three body decays can be rather important, especially in the MSSM [9] (see also [10]).

- In the MSSM, the complete radiative corrections in the effective potential approach with full mixing in the stop and sbottom sectors; it uses the renormalization group improved values of the Higgs masses and couplings, and the relevant leading next-to-leading-order corrections are also implemented [11].

- In the MSSM, all the decays into SUSY particles when they are kinematically allowed. The decays into charginos and neutralinos are included in the most general case, and the decays to sleptons and squark pairs with sfermion mixing in the third generation sector [12].

- In the MSSM, all SUSY particles are included in the loop mediated $\gamma\gamma$ and gg decay channels: charged Higgs bosons, chargino, slepton and squark [including mixing] loops in $h, H \to \gamma\gamma$ decays, chargino loops in $A \to \gamma\gamma$ and squark loops in $h, H \to gg$. In the gluonic decay modes the large QCD corrections for quark [13, 14] and squark loops [15] are also included.

The basic input parameters, fermion and gauge boson masses and their total widths, coupling constants and in the MSSM, soft SUSY-breaking parameters can be chosen from an input file. In this file several flags allow to switch on/off or change some options [*e.g.* choose a particular Higgs boson, include/exclude the multi-body or SUSY decays, or include/exclude specific higher-order QCD corrections]. The results for the many decay branching ratios and the total decay widths are written into several output files with headers indicating the processes and giving the input parameters.

The program is written in FORTRAN and has been tested on several machines: VAX stations under the operating system VMS and work stations running under UNIX. All the necessary subroutines [e.g. for integration] are included. The program is lengthy [more than 5000 FORTRAN lines] but rather fast, especially if some options [as decays into double off-shell gauge bosons] are switched off.

The rest of this report is organized as follows. In the next section we discuss the physical decay processes included in the program. We describe the parameters of the input file in Section 3. In Section 4, we present examples of output files. Some comments and conclusions are given in Section 5.

2 Decay Modes

2.1 Standard Model

a) Decays to quarks and leptons

The Higgs boson partial width for decays to massless quarks, directly coupled to the SM Higgs particle, is calculated including the $\mathcal{O}(\alpha_s^3)$ QCD radiative corrections [16, 17] in the $\overline{\rm MS}$ renormalization scheme. Large logarithms are resummed by using the running quark mass $\overline{m}_Q(M_H)$ and the strong coupling constant $\alpha_s(M_H)$ both defined at the scale of the Higgs boson mass. The quark masses can be neglected in the phase space and in the matrix element except for decays in the threshold region, where the leading order QCD corrections are given in terms of the quark *pole* mass M_Q [16].

The relation between the perturbative *pole* quark mass (M_Q) and the running $\overline{\rm MS}$ mass ($\overline{m}_Q$) at the scale of the pole mass can be expressed as [18]

$$\overline{m}_Q(M_Q) = \frac{M_Q}{1 + \frac{4}{3}\frac{\alpha_s(M_Q)}{\pi} + K_Q\left(\frac{\alpha_s(M_Q)}{\pi}\right)^2} \tag{1}$$

where the numerical values of the NNLO coefficients are given by $K_t \sim 10.9$, $K_b \sim 12.4$ and $K_c \sim 13.4$. Since the relation between the pole mass M_c of the charm quark and the $\overline{\rm MS}$ mass $\overline{m}_c(M_c)$ evaluated at the pole mass is badly convergent [18], the running quark masses $\overline{m}_Q(M_Q)$ are adopted as starting points. The flag NNLO(I) determines whether (I=1) the input running mass is related to the pole mass according to the eq. (1) or (I=0) using the simplified version with the K_Q term neglected [in this case we denote the pole mass by $M_Q^{\rm pt2}$]. The input pole mass values and corresponding running masses are presented in Table 1. The evolution from M_Q upwards to a renormalization scale μ is given by

$$\overline{m}_Q\,(\mu) \;\; = \;\; \overline{m}_Q\,(M_Q)\,\frac{c\,[\alpha_s\,(\mu)/\pi]}{c\,[\alpha_s\,(M_Q)/\pi]} \tag{2}$$

with [20]

$$c(x) \;\; = \;\; \left(\frac{9}{2}\,x\right)^{\frac{4}{9}}\,[1 + 0.895x + 1.371\,x^2] \qquad \text{for } M_s < \mu < M_c$$

Q	$\overline{m}_Q(M_Q)$	$M_Q^{\rm pt2}$	M_Q
c	1.23 GeV	1.41 GeV	1.64 GeV
b	4.23 GeV	4.62 GeV	4.87 GeV
t	167.4 GeV	175.0 GeV	177.1 GeV

Table 1: *Quark mass values for the* $\overline{\rm MS}$ *mass and the two different definitions of the pole masses. The strong coupling has been chosen as* $\alpha_s(M_Z) = 0.118$ *and the bottom and charm mass values are taken from Ref. [19].*

$$
\begin{aligned}
c(x) &= \left(\frac{25}{6}\,x\right)^{\frac{12}{25}} [1 + 1.014x + 1.389\,x^2] && \text{for } M_c < \mu < M_b \\
c(x) &= \left(\frac{23}{6}\,x\right)^{\frac{12}{23}} [1 + 1.175x + 1.501\,x^2] && \text{for } M_b < \mu < M_t \\
c(x) &= \left(\frac{7}{2}\,x\right)^{\frac{4}{7}} [1 + 1.398x + 1.793\,x^2] && \text{for } M_t < \mu
\end{aligned}
$$

For the charm quark mass the evolution is determined by eq. (2) up to the scale $\mu = M_b$, while for scales above the bottom mass the evolution must be restarted at $M_Q = M_b$. The values of the running b, c masses at the scale $\mu = 100$ GeV, characteristic for the Higgs mass, are typically 35% (60%) smaller than the bottom (charm) pole masses $M_b^{\rm pt2}$ ($M_c^{\rm pt2}$).

The program HDECAY includes the full massive NLO corrections close to the thresholds as well as the massless $\mathcal{O}(\alpha_s^3)$ corrections far above the thresholds. The transition between both regions is provided by a linear interpolation as shown in Fig. 1. Thus the result is optimized for the description of the mass effects in the threshold region and for the renormalization group improved large Higgs mass regime.

The electroweak corrections to heavy quark and lepton decays in the intermediate Higgs mass range are small [21] and could thus be neglected, but the bulk of the effect [22] is included in the program. For large Higgs masses the electroweak corrections due to the enhanced self-coupling of the Higgs bosons are included, which however turn out to be small [23].

In the case of $t\bar{t}$ decays of the Standard Higgs boson, the $\mathcal{O}(\alpha_s)$ QCD corrections are included according to [16]. Below-threshold (three-body) decays $H \to t\bar{t}^* \to t\bar{b}W^-$ into off-shell top quarks may be sizeable [9] and thus are implemented.

b) Decays to gluons

The decay of the Higgs boson to gluons is mediated by heavy quark loops in the Standard Model; the partial decay width in lowest order is given in [24]. QCD radiative

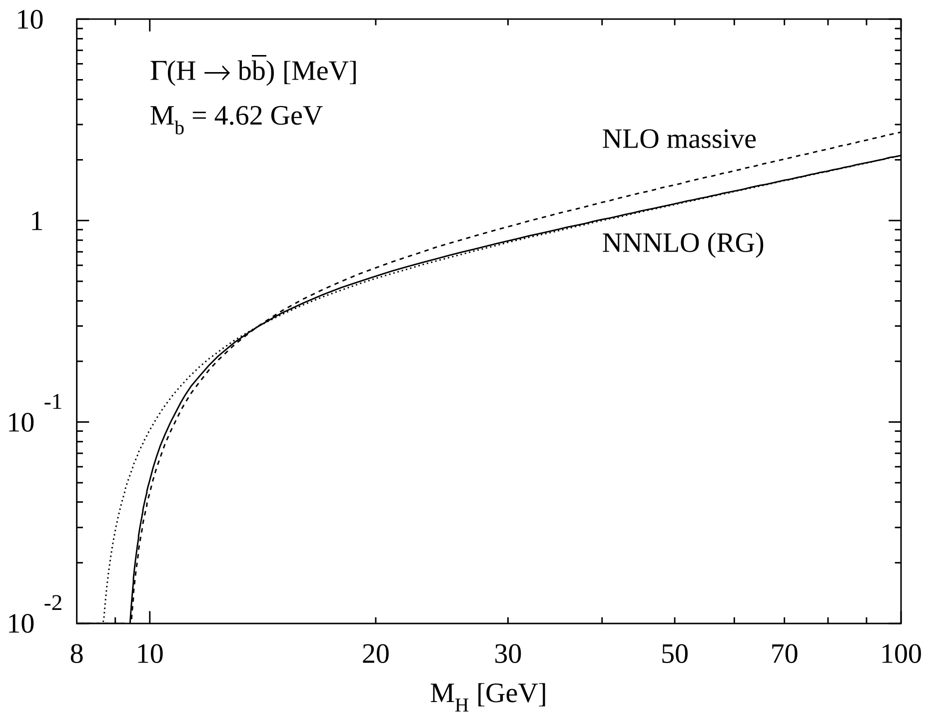

Figure 1: *Interpolation between the full massive NLO expression (dashed line) for the* $b\bar{b}$ *decay width of the Standard Higgs boson and the renormalization group improved NNNLO result (dotted line). The interpolated curve is presented by the full line.*

corrections [13, 14] are built up by the exchange of virtual gluons, gluon radiation from the internal quark loop and the splitting of a gluon into unresolved two gluons or a quark-antiquark pair. The radiative corrections are very large, nearly doubling the partial width. Since b quarks, and eventually c quarks, can in principle be tagged experimentally, it is physically meaningful to include gluon splitting $g^* \to b\bar{b}$ $(c\bar{c})$ in $H \to gg^* \to gb\bar{b}\,(c\bar{c})$ decays to the inclusive decay probabilities $\Gamma(H \to b\bar{b} + \ldots)$ *etc.* [7]. Separating this contribution generates large logarithms, which can be effectively absorbed by defining the number of active flavors in the gluonic decay mode in the input file of HDECAY by specifying the NF-GG parameter. The contributions of the subtracted flavors will automatically be added to the corresponding heavy quark decay modes.

c) Decays to $\gamma\gamma$ and $Z\gamma$

The decay of the Higgs boson to two photons and to a photon and a Z boson, mediated by W and heavy fermion loops, are implemented according to [25]. QCD radiative corrections are rather small [13, 26] and thus neglected in the program.

d) Decays to WW/ZZ bosons

Above the WW and ZZ decay thresholds the partial decay widths into pairs of on-shell massive gauge bosons are given in [27]. Electroweak corrections are small in the intermediate mass range [28] and thus neglected in the program HDECAY. Higher order corrections due to the self-couplings of the Higgs particles are sizeable [29] for $M_H \gtrsim 400$ GeV and are taken into account.

Below the WW/ZZ threshold, the decay modes into off-shell gauge bosons are important. With the input parameter ON-SH-WZ=1 the program includes decays with one on-shell and one off-shell gauge boson [30], while for ON-SH-WZ=0 decays with both off-shell are also calculated [8]. The branching ratios for the latter reach the percent level for Higgs masses above about 100 (110) GeV for both $W(Z)$ boson pairs off-shell. For higher masses, it is sufficient to allow for one off-shell gauge boson only, especially because the two virtual gauge boson option is CPU time consuming.

2.2 The Minimal Supersymmetric Standard Model

The MSSM Higgs sector is implemented in HDECAY including the complete radiative corrections due to top/bottom quark and squark loops within the effective potential approach. Next-to-leading order QCD corrections and the full mixing in the stop and sbottom sectors are incorporated. The Higgs boson mass spectrum, the mixing angles and Higgs boson couplings are calculated using the approximate formulae of M. Carena, M. Quiros and C.E.M. Wagner [11]. The basic parameters describing the effective Higgs potential at higher orders are specified in the input file. The formulae for the decay widths at tree-level have been derived in Ref. [32].

a) Decays to quarks and leptons

The calculation of the partial decay widths of scalar neutral Higgs bosons h and H to fermions in the MSSM is performed using the same approximations and options as in the Standard Model case with properly modified Higgs boson couplings. For massless quarks the QCD corrections for scalar, pseudoscalar and charged Higgs boson decays are implemented analogously to the SM case [16, 17], *i.e.* the Yukawa and QCD couplings are evaluated at the scale of the Higgs boson mass.

In the threshold regions mass effects play a significant role, in particular for the pseudoscalar Higgs boson, which has an S-wave suppression β as compared to β^3 for CP-even Higgs bosons $[\beta = (1 - 4m_f^2/M_\Phi^2)^{1/2}$ is the velocity of the decay fermions]. The QCD corrections to the partial decay width of the CP-odd Higgs boson A into heavy quark pairs are taken from Ref. [16], and for the charged Higgs particles from Ref. [31]. The transition from the threshold region, involving mass effects, to the renormalization group improved large Higgs mass regime is provided by a smooth linear interpolation analogous to the SM case.

Below the $t\bar{t}$ threshold, decays of the neutral Higgs bosons into off-shell top quarks are sizeable, thus modifying the profile of the Higgs particles significantly. Off-shell pseudoscalar branching ratios reach a level of a few percent for masses above about 300 GeV for small tgβ values. Similarly, below the $t\bar{b}$ threshold, off-shell decays $H^+ \to t^*\bar{b} \to b\bar{b}W^+$ are important, reaching the percent level for charged Higgs boson masses above about 100

GeV for small tgβ values. These decays are incorporated according to the expressions from Ref. [9].

b) Decays to gluons

Since the b quark couplings to the Higgs bosons may be strongly enhanced and the t quark couplings suppressed in the MSSM, b loops can contribute significantly to the Higgs-gg couplings so that the approximation $M_Q^2 \gg M_H^2$ cannot be applied any more for $M_\Phi \lesssim 150$ GeV, where this decay mode is important. Nevertheless, it turns out *a posteriori* that this is an excellent approximation for the QCD corrections. The LO width for $h, H \to gg$ is generated by quark and squark loops with the latter contributing significantly for Higgs masses below about 400 GeV [15]. The partial decay widths are calculated according to Ref. [13, 14]. The bottom and charm final states from gluon splitting can be added to the corresponding $b\bar{b}$ and $c\bar{c}$ decay modes, as in the SM case, by defining NF-GG=3 in the input file.

c) Decays into $\gamma\gamma$ and $Z\gamma$

The decays of the neutral Higgs bosons to two photons and a photon plus a Z boson are mediated by W and heavy fermion loops, as in the Standard Model, and in addition by charged Higgs, sfermion and chargino loops; the partial decay widths are calculated according to Ref. [13]. QCD corrections to the quark and squark loop contributions are small [13, 26] and thus neglected in the program.

d) Decays to WW/ZZ gauge bosons

The partial widths of the CP-even neutral MSSM Higgs bosons into W and Z boson pairs are obtained from the SM Higgs decay widths by rescaling with the corresponding MSSM couplings. They are strongly suppressed [due to kinematics in the case of h and reduced couplings for the heavy H], thus not playing a dominant role as in the SM case.

e) Decays to Higgs boson pairs

The heavy CP-even Higgs particle can decay into a pair of light scalars as well to a pair of pseudoscalar Higgs bosons, $H \to hh$ and $H \to AA$. While the former is the dominant decay mode of H in the mass range $2M_h < M_H < 2m_t$ for small values of tgβ, the latter mode occurs only in a marginal area of the MSSM parameter space. For large values of tgβ, these decays occur only if $M_A \sim M_h \lesssim M_H/2$, corresponding to the lower end of the heavy Higgs mass range, and have branching ratios of 50% each. Since the bbH Yukawa coupling is strongly enhanced for large tgβ, below threshold decays $H \to hh^*, AA^*$ with $A, h \to b\bar{b}$ are included [9]. The lightest CP-even Higgs particle h can also decay into pseudoscalar Higgs pairs for values tg$\beta \sim 1$ and $M_h < 50$ GeV; however this area of the parameter space is already ruled out by present data.

f) Decays to W/Z and Higgs bosons

The Higgs bosons can also decay into a gauge boson and a lighter Higgs boson. The branching ratios for the two body decays $A \to hZ$ and $H^+ \to W^+h$ may be sizeable in specific regions of the MSSM parameter space [small values of tgβ and below the tt/tb thresholds for neutral/charged Higgs bosons]. The expressions of the decay widths are given in e.g. Ref. [9].

Below-threshold decays into a Higgs particle and an off-shell gauge boson turned out to be rather important for the heavy Higgs bosons of the MSSM. Off-shell $A \to hZ^*$ decays are important for the pseudoscalar Higgs boson for masses above about 130 GeV for small tgβ. The decay modes $H^\pm \to hW^*, AW^*$ reach branching ratios of several tens of percent and lead to a significant reduction of the dominant branching ratio into $\tau\nu$ final states to a level of 60% to 70% for small tgβ. In addition, three-body $H \to AZ^*$ and $H \to H^+W^{-*}$, which are kinematically forbidden at the two-body level, can be sizeable for small M_A values. The partial decay widths for these three-body decays are calculated according to the formulae given in Ref. [9].

g) Decays to charginos and neutralinos

The lightest charginos and neutralinos are expected to have masses of the order of the Z boson mass. The heavy CP-even, CP-odd and charged Higgs bosons of the MSSM can therefore decay into these states [32]. Present experimental bounds on the SUSY particle masses, do not allow decays for SUSY decay modes of the lightest CP-even Higgs boson h, except maybe for the decays into a pair of the lightest neutralinos. These decays, the partial widths of which can be found in Ref. [12], are included in the program.

The masses of charginos and neutralinos as well as their couplings to the Higgs bosons depend on three extra parameters [in addition to those describing the Higgs sector at the tree-level]: the Higgs-Higgssino mass parameter μ [which also enters the radiative corrections in the Higgs sector], the B-ino and W-ino mass parameters M_1 and M_2. Assuming a common gaugino mass at the unification scale, the parameter M_1 is related to M_2 by the GUT relation $M_1 = \frac{5}{3} M_2 \tan^2\theta_W$.

The chargino and neutralino mass matrices are diagonalized using the analytical expressions given in Ref. [33]. The masses and the couplings to the Higgs bosons are calculated in the subroutine GAUGINO.

h) Decays to sleptons and squarks

The MSSM Higgs bosons can also decay into the SUSY partners of leptons and quarks if the latter are light enough. In particular, if kinematically allowed, decays into third generation sfermions can be dominant due to enhanced couplings [34]. For instance, the couplings of the CP-even Higgs bosons to stop pairs are proportional to m_t^2/M_Z^2 and can lead to very large decay widths.

The sfermions masses and couplings to Higgs bosons will depend on three extra parameters [in addition to tgβ and M_A] for each generation: the left- and right-handed soft SUSY-breaking mass parameters $M_{\tilde{f}_L}$ and $M_{\tilde{f}_R}$ and the trilinear coupling A_f. The trilinear couplings are important only in the case of the third generation sfermions, and only A_t, A_b and A_τ need to be introduced. The latter couplings [at least A_t and A_b] also contribute to the radiative corrections to the Higgs sector. For the SUSY breaking scalar masses, we assumed degeneracy in the first and second generation and treated the third generation separately[2]. While the masses of the left- and right-handed 1st/2nd generation sfermions correspond to the physical sfermion masses, in the third generation mixing between these fields needs to be included to obtain the physical eigenstates [35].

The masses of the sfermions, as well as their couplings to Higgs bosons, including the mixing in the generation are calculated in the subroutine SFERMION. The decay widths are calculated in the main subroutine using the formulae given in Ref. [12]. The QCD corrections to squark decays [in particular stop and sbottom decays] have been calculated in Ref. [37] but are not yet implemented in the program.

3 How to Run HDECAY: Input File

The HDECAY program is self-contained with all necessary subroutines included. In addition to the source code of the program HDECAY, an input file defined as unit 98 is needed from which the program reads the input parameters. The name of this input file can be defined in the first OPEN statement of HDECAY. It should be noted that the input numbers must *not* start before the equality signs in each corresponding line. The input file contains the following parameters [all non-integer parameters are in double precision and the mass parameters as well as the decay widths and the trilinear couplings are in GeV]:

<u>HIGGS:</u> integer, chooses the Higgs boson to be considered
- 0: Standard Model Higgs boson H^0
- 1: light CP-even MSSM Higgs boson h
- 2: heavy CP-even MSSM Higgs boson H
- 3: pseudoscalar Higgs boson A
- 4: charged MSSM Higgs bosons $H^{\pm}$
- 5: all MSSM Higgs bosons

<u>TGBET:</u> ratio of the vacuum expectation values in the MSSM, tgβ, the second basic input of the model; the program is suitable only for values tg$\beta \gtrsim 1$.

<u>MABEG</u>: start value of the Higgs mass in GeV

<u>MAEND</u>: end value of the Higgs mass in GeV

<u>NMA</u>: integer, number of iterations for the input Higgs mass
In the SM, MA$\equiv M_{H^0}$ while in the MSSM case MA is the pseudoscalar Higgs mass M_A, which will be the basic input parameter for the MSSM Higgs sector.

[2] We could have taken the same inputs for the three generations. However, to allow for a comparison with ISAJET [36], we have used different inputs for the SUSY breaking scalar mass of the 1st/2nd and the 3rd generation.

ALS(MZ): strong coupling constant at the scale M_Z: $\alpha_S(M_Z)$

MSBAR(1): $\overline{\rm MS}$ mass of the strange quark at the scale $Q = 1$ GeV

MC: charm quark pole mass

MB: bottom quark pole mass

MT: top quark pole mass

MTAU: τ lepton mass

MMUON: muon mass

1/ALPH: inverse QED coupling constant: $\alpha^{-1}(0)$

GF: Fermi decay constant

GAMW: total decay width of the W boson

GAMZ: total decay width of the Z boson

MZ: Z boson mass

MW: W boson mass

VUS: CKM parameter V_{us}

VCB: CKM parameter V_{cb}

VUB/VCB: ratio of the CKM parameters V_{ub}/V_{cb}.

MU: SUSY breaking Higgs mass parameter μ

M2: SUSY breaking gaugino mass parameter M_2

MSL1: SUSY breaking mass parameter for 1st/2nd generation left-handed sleptons, $M_{\tilde{l}_L}$

MER1: SUSY breaking mass parameter for 1st/2nd generation right-handed charged sleptons, $M_{\tilde{e}_R}$

MSQ1: SUSY breaking mass parameter for 1st/2nd generation left-handed up and down type squarks, $M_{\tilde{q}_L}$

MUR1: SUSY breaking mass parameter for 1st/2nd generation right-handed up-type squarks, $M_{\tilde{u}_R}$

MDR1: SUSY breaking mass parameter for 1st/2nd generation right-handed down-type squarks, $M_{\tilde{d}_R}$

MSL: SUSY breaking mass parameter for 3rd generation left-handed sleptons, $M_{\tilde{L}_L}$

MER: SUSY breaking mass parameter for 3rd generation right-handed sleptons, $M_{\tilde{\tau}_R}$

MSQ: SUSY breaking mass parameter for 3rd generation left-handed up- and down-type squarks, $M_{\tilde{Q}_L}$

MUR: SUSY breaking mass parameter for right-handed stops, $M_{\tilde{t}_R}$

MDR: SUSY breaking mass parameter for right-handed sbottoms, $M_{\tilde{b}_R}$

AL: SUSY breaking trilinear coupling for τ sleptons, A_τ

AU: SUSY breaking trilinear coupling for stops, A_t

AD: SUSY breaking trilinear coupling for sbottoms, A_b

NNLO (M): integer,
=0: use $\mathcal{O}(\alpha_s)$ formula for the quark pole masses $\to$ $\overline{\text{MS}}$ masses
=1: use $\mathcal{O}(\alpha_s^2)$ formula for the quark pole masses $\to$ $\overline{\text{MS}}$ masses

ON-SHELL: integer
=0: include three-body decays with off-shell tops, Higgs and gauge bosons
=1: exclude three-body decays with off-shell tops, Higgs and gauge bosons

ON-SH-WZ: integer
=0: include double off-shell decays to gauge bosons $\Phi \to W^*W^*, Z^*Z^*$
=1: include only single off-shell gauge bosons $\Phi \to W^*W, Z^*Z$

IPOLE: integer
=0: calculate $\overline{\text{MS}}$ masses of the MSSM Higgs particles
=1: calculate pole masses of the MSSM Higgs particles

OFF-SUSY: integer
=0: include decays into and loops of supersymmetric particles
=1: exclude decays into and loops of supersymmetric particles

INDIDEC: integer
=0: write out only the sums of chargino, neutralino and sfermion decays
=1: write out all individual chargino, neutralino and sfermion decays

NF-GG: integer
number of light flavors included in the decays $\Phi \to gg^* \to gq\bar{q}$ (NF-GG=3,4 or 5).

The current values of the SM parameters [fermion masses, gauge boson masses and total widths, coupling constants, CKM angles] are given in Tab. 2, where an example of the input file is displayed. The entire Higgs sector of the MSSM is fixed once the parameters tgβ, M_A, μ, M_2, the masses $M_{\tilde{L}_L}, M_{\tilde{E}_R}, M_{\tilde{U}_L}, M_{\tilde{U}_R}, M_{\tilde{D}_R}$ and the trilinear couplings A_τ, A_t and A_b are specified. Some examples for these values are shown in Tab. 2.

```
HIGGS     = 0
TGBET     = 1.5D0
MABEG     = 100.D0
MAEND     = 500.D0
NMA       = 5
ALS(MZ)   = 0.118D0
MSBAR(1)  = 0.190D0
MC        = 1.42D0
MB        = 4.62D0
MT        = 175.D0
MTAU      = 1.7771D0
MMUON     = 0.105658389D0
1/ALPHA   = 137.0359895D0
GF        = 1.16639D-5
GAMW      = 2.080D0
GAMZ      = 2.490D0
MZ        = 91.187D0
MW        = 80.33D0
VUS       = 0.2205D0
VCB       = 0.04D0
VUB/VCB   = 0.08D0
MU        = 300.D0
M2        = 200.D0
MSL1      = 500.D0
MER1      = 500.D0
MQL1      = 500.D0
MUR1      = 500.D0
MDR1      = 500.D0
MSL       = 500.D0
MER       = 500.D0
MSQ       = 500.D0
MUR       = 500.D0
MDR       = 500.D0
AL        = 1500.D0
AU        = 1500.D0
AD        = 1500.D0
NNLO (M)  = 0
ON-SHELL  = 0
ON-SH-WZ  = 0
IPOLE     = 0
OFF-SUSY  = 1
INDIDEC   = 0
NF-GG     = 5
```

Table 2: *Example of the input file.*

4 Results of Test Run: Output Files

The output is written to several files. Only the output files of the chosen HIGGS boson(s) are printed, and they contain all decay branching ratios and the total decay width, except for the decays to SUSY particles [if OFF-SUSY=0] where only the sums of the branching ratios into charginos, neutralinos, sleptons and squarks are printed if the flag INDIDEC=0; only for INDIDEC=1 all individual branching ratios are printed in additional output files. For convenience, an output file br.input is printed in which the input parameters are given. Below we will describe the output files in the SM and the MSSM [also with the option for SUSY decays switched on] and list all the decay channels which we have considered for the various Higgs bosons.

4.1 Standard Model Higgs boson

For the SM Higgs boson, in addition to the file br.input for the input parameters, two output files areprinted in which the total decay width and the following 11 branching ratios are given [notice that we have put the decays into fermions and gauge bosons into two different files]

br.sm1 : M_{H^0} , $BR(b\bar{b})$, $BR(\tau^+\tau^-)$, $BR(\mu^+\mu^-)$, $BR(s\bar{s})$, $BR(c\bar{c})$, $BR(t\bar{t})$

br.sm2 : M_{H^0} , $BR(gg)$, $BR(\gamma\gamma)$, $BR(\gamma Z)$, $BR(WW)$, $BR(ZZ)$, $\Gamma_{H^0}^{\rm tot}$

For the example of input file shown in Tab. 2, one obtains the two outputs given in Tab. 3. The various branching ratios and the total decay width are shown in Fig. 2.

```
  MHSM        BB       TAU TAU     MU MU        SS          CC          TT
------------------------------------------------------------------------------

 100.000     0.8119      0.7926E-01 0.2752E-03 0.6048E-03 0.3698E-01     0.
 200.000     0.2596E-02 0.2884E-03 0.1000E-05 0.1928E-05 0.1177E-03     0.
 300.000     0.6082E-03 0.7274E-04 0.2521E-06 0.4513E-06 0.2754E-04 0.5293E-04
 400.000     0.2283E-03 0.2869E-04 0.9940E-07 0.1694E-06 0.1033E-04 0.1376
 500.000     0.1183E-03 0.1542E-04 0.5342E-07 0.8772E-07 0.5347E-05 0.1936

  MHSM         GG      GAM GAM     Z GAM        WW          ZZ        WIDTH
------------------------------------------------------------------------------

 100.000     0.5807E-01 0.1532E-02 0.4654E-04 0.1025E-01 0.1046E-02 0.2598E-02
 200.000     0.8219E-03 0.5241E-04 0.1753E-03 0.7350     0.2609      1.428
 300.000     0.5674E-03 0.1289E-04 0.5670E-04 0.6913     0.3073      8.510
 400.000     0.7532E-03 0.3192E-05 0.1935E-04 0.5872     0.2741      28.89
 500.000     0.5476E-03 0.4897E-06 0.7666E-05 0.5450     0.2607      67.53
```

Table 3: *The two output files in the SM with the inputs of Tab. 2.*

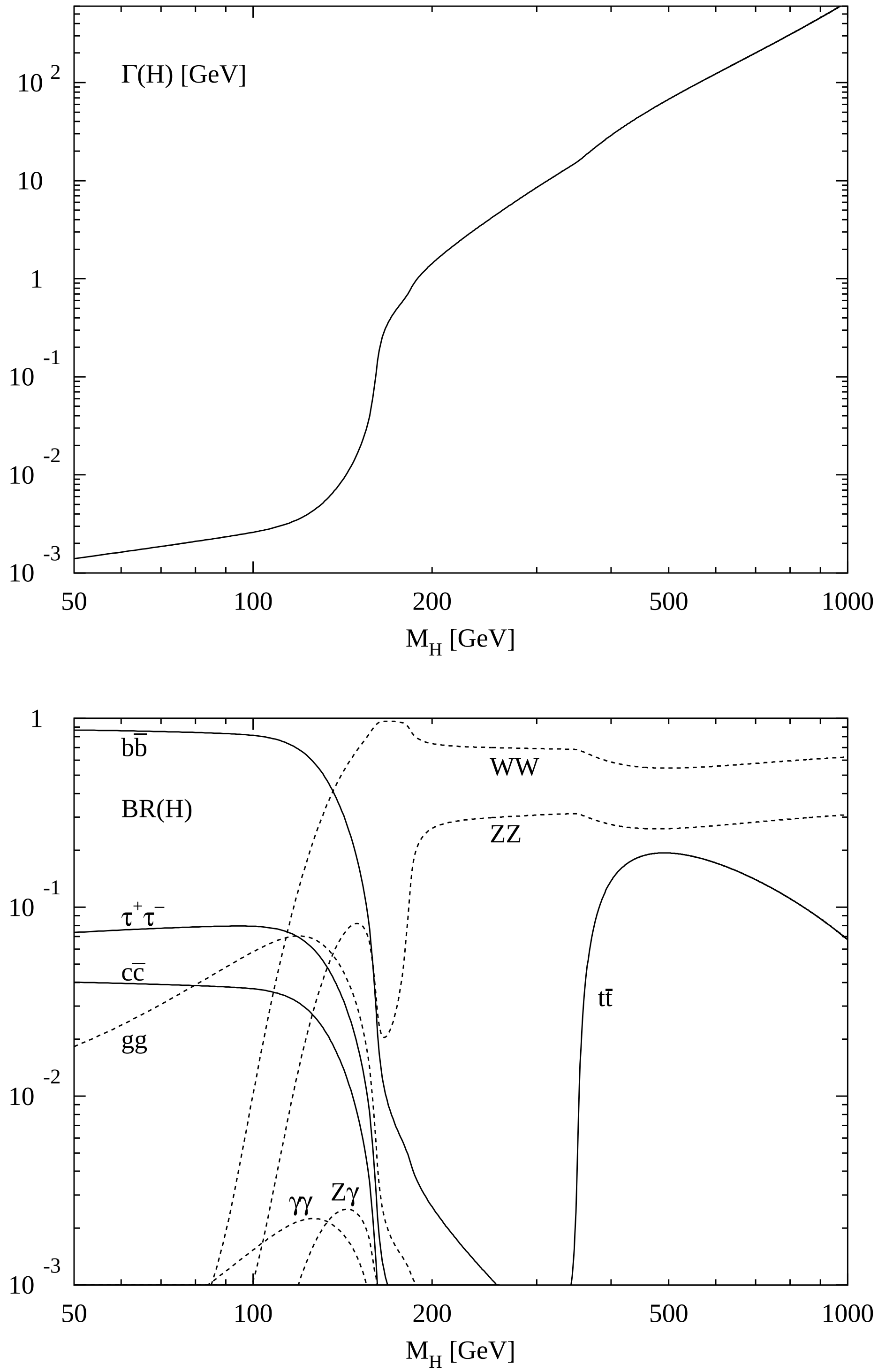

Figure 2: *Total decay width $\Gamma(H)$ in GeV and the main branching ratios $BR(H)$ of the Standard Model Higgs decay channels, using the inputs of Tab. 2.*

4.2 MSSM without SUSY decays

As discussed earlier, the two basic inputs of the program for the MSSM Higgs sector are tgβ and M_A. Once these parameters are fixed, all the other Higgs masses and couplings are determined at tree-level. However, subleading effects due to squark mixing [mainly the parameters $A_{t,b}$ and μ] will alter these values.

For the lightest MSSM Higgs boson h, the decays are the same as in the SM if the SUSY decays are switched off. The two output files contain the following branching ratios

$$\begin{array}{ll} \text{br.l1 :} & M_h \ , \ BR(b\bar{b}) \ , \ BR(\tau^+\tau^-) \ , \ BR(\mu^+\mu^-) \ , \ BR(s\bar{s}) \ , \ BR(c\bar{c}) \ , \ BR(t\bar{t}) \\ \text{br.l2 :} & M_h \ , \ BR(gg) \ , \ BR(\gamma\gamma) \ , \ BR(\gamma Z) \ , \ BR(WW) \ , \ BR(ZZ) \ , \ \Gamma_h^{\rm tot} \end{array}$$

For the heavy CP-even MSSM Higgs boson H, there are more possibilities for the decays due to the larger mass: in addition to the same decay modes as h, cascade decays into two light Higgs bosons or a mixed pair of Higgs and gauge bosons occur. The branching ratios of 15 decay modes are written to the following output files

$$\begin{array}{ll} \text{br.h1 :} & M_H \ , \ BR(b\bar{b}) \ , \ BR(\tau^+\tau^-) \ , \ BR(\mu^+\mu^-) \ , \ BR(s\bar{s}) \ , \ BR(c\bar{c}) \ , \ BR(t\bar{t}) \\ \text{br.h2 :} & M_H \ , \ BR(gg) \ , \ BR(\gamma\gamma) \ , \ BR(\gamma Z) \ , \ BR(WW) \ , \ BR(ZZ) \\ \text{br.h3 :} & M_H \ , \ BR(hh) \ , \ BR(AA) \ , \ BR(AZ) \ , \ BR(W^\pm H^\mp) \ , \ \Gamma_H^{\rm tot} \end{array}$$

For the CP-odd MSSM Higgs boson A, there are less possibilities than for the H boson: due to CP-invariance, the pseudoscalar A does not couple to gauge and Higgs boson pairs. The 10 decay channels are printed in the output files as follows

$$\begin{array}{ll} \text{br.a1 :} & M_A \ , \ BR(b\bar{b}) \ , \ BR(\tau^+\tau^-) \ , \ BR(\mu^+\mu^-) \ , \ BR(s\bar{s}) \ , \ BR(c\bar{c}) \ , \ BR(t\bar{t}) \\ \text{br.a2 :} & M_A \ , \ BR(gg) \ , \ BR(\gamma\gamma) \ , \ BR(\gamma Z) \ , \ BR(hZ) \ , \ \Gamma_A^{\rm tot} \end{array}$$

For the charged MSSM Higgs bosons $H^\pm$, there are 8 decay channels which can exceed the 10^{-4} level; these are written in the two output files

$$\begin{array}{ll} \text{br.c1 :} & M_{H^+} \ , \ BR(c\bar{b}) \ , \ BR(\tau^+\nu_\tau) \ , \ BR(\mu^+\nu_\mu) \ , \ BR(u\bar{s}) \ , \ BR(c\bar{s}) \ , \ BR(t\bar{b}) \\ \text{br.c2 :} & M_{H^+} \ , \ BR(hW^+) \ , \ BR(AW^+) \ , \ \Gamma_{H^+}^{\rm tot} \end{array}$$

Examples of the output files for the four MSSM Higgs bosons excluding the SUSY decays are shown in Tab. 4a–d. The numbers are obtained by using the input file of Tab. 2, with HIGGS=5.

The branching ratios for the main decay channels [those listed in the output files] of h, H, A and H^+ as function of corresponding masses are shown in Fig. 3a–c. The total decay widths $\Gamma(\Phi)$ of the four MSSM Higgs bosons are shown in Fig. 3c.

MHL	BB	TAU TAU	MU MU	SS	CC	TT
70.7080	0.9058	0.8281E-01	0.2938E-03	0.6587E-03	0.5552E-02	0.
85.8094	0.8728	0.8282E-01	0.2935E-03	0.6372E-03	0.2018E-01	0.
89.2134	0.8531	0.8150E-01	0.2888E-03	0.6242E-03	0.2827E-01	0.
90.4005	0.8438	0.8079E-01	0.2863E-03	0.6180E-03	0.3196E-01	0.
90.9499	0.8390	0.8041E-01	0.2849E			

MHL	GG	GAM GAM	Z GAM	WW	ZZ	WIDTH
70.7080	0.4520E-02	0.2694E-03	0.	0.7392E-04	0.2137E-04	0.4399E-02
85.8094	0.2164E-01	0.7488E-03	0.	0.7356E-03	0.1789E-03	0.3241E-02
89.2134	0.3353E-01	0.9854E-03	0.	0.1421E-02	0.3015E-03	0.2778E-02
90.4005	0.3927E-01	0.1090E-02	0.	0.1833E-02	0.3638E-03	0.2607E-02
90.9499	0.4226E-01	0.1143E-02	0.	0.2072E-02	0.3972E-03	0.2528E-02

Table 4a: *The output files br.l1 and br.l2 for the light CP-even h decays without SUSY particles using the inputs in Tab. 2 but with HIGGS=5.*

MHH	BB	TAU TAU	MU MU	SS	CC	TT
145.680	0.3669	0.3930E-01	0.1390E-03	0.2575E-03	0.2475E-01	0.
221.034	0.5570E-01	0.6430E-02	0.2274E-04	0.3953E-04	0.9850E-03	0.
313.454	0.7133E-01	0.8781E-02	0.3105E-04	0.5072E-04	0.8778E-03	0.7003E-02
409.924	0.5451E-02	0.7035E-03	0.2487E-05	0.3878E-05	0.5864E-04	0.9421
507.876	0.2584E-02	0.3460E-03	0.1223E-05	0.1839E-05	0.2610E-04	0.9784

MHH	GG	GAM GAM	Z GAM	WW	ZZ
145.680	0.1001	0.3088E-03	0.9334E-03	0.2607	0.3433E-01
221.034	0.1002E-01	0.1167E-04	0.5215E-04	0.3527	0.1420
313.454	0.2296E-01	0.5107E-04	0.2259E-04	0.2488	0.1116
409.924	0.4751E-02	0.1359E-04	0.3069E-05	0.1211E-01	0.5670E-02
507.876	0.2782E-02	0.8875E-05	0.1970E-05	0.3967E-02	0.1900E-02

MHH	hh	AA	Z A	W+- H-+	WIDTH
145.680	0.1508	0.7363E-06	0.2011E-01	0.1428E-02	0.5795E-02
221.034	0.4320	0.2673E-10	0.3105E-04	0.4103E-06	0.1237
313.454	0.5285	0.2548E-12	0.2991E-05	0.1732E-07	0.1496
409.924	0.2910E-01	0.6195E-15	0.3915E-07	0.1561E-09	2.564
507.876	0.9974E-02	0.2049E-16	0.4845E-08	0.1594E-10	6.600

Table 4b: *The output files br.h1, br.h2 and br.h3 for the heavy CP-even H decays without SUSY particles using the inputs in Tab. 2 but with HIGGS=5.*

MHA	BB	TAU TAU	MU MU	SS	CC	TT
100.000	0.8790	0.8610E-01	0.3046E-03	0.6401E-03	0.7925E-02	0.
200.000	0.4748	0.5313E-01	0.1879E-03	0.3449E-03	0.4270E-02	0.
300.000	0.2582	0.3118E-01	0.1102E-03	0.1874E-03	0.2321E-02	0.1953E-01
400.000	0.2185E-02	0.2777E-03	0.9816E-06	0.1585E-05	0.1964E-04	0.9892
500.000	0.1714E-02	0.2263E-03	0.8001E-06	0.1244E-05	0.1541E-04	0.9926

MHA	GG	GAM GAM	Z GAM	Z HL	WIDTH
100.000	0.2539E-01	0.5914E-04	0.8400E-07	0.5965E-03	0.5413E-02
200.000	0.7001E-01	0.1944E-03	0.2781E-04	0.3970	0.1755E-01
300.000	0.1403	0.4287E-03	0.9264E-04	0.5476	0.4487E-01
400.000	0.4515E-02	0.1468E-04	0.3641E-05	0.3820E-02	6.718
500.000	0.3162E-02	0.1090E-04	0.2810E-05	0.2275E-02	10.30

Table 4c: *The output files br.a1 and br.a2 for the CP-odd A decays without SUSY particles using the inputs in Tab. 2 but with HIGGS=5.*

MHC	BC	TAU NU	MU NU	SU	CS	TB
126.847	0.9519E-02	0.6288	0.2224E-02	0.2059E-03	0.5637E-01	0.5893E-01
214.686	0.2091E-04	0.1521E-02	0.5378E-05	0.4520E-06	0.1237E-03	0.9654
309.984	0.4888E-05	0.3800E-03	0.1343E-05	0.1057E-06	0.2892E-04	0.9914
407.542	0.3382E-05	0.2755E-03	0.9740E-06	0.7309E-07	0.2001E-04	0.9955
506.054	0.2899E-05	0.2448E-03	0.8654E-06	0.6265E-07	0.1715E-04	0.9971

MHC	hW	hA	WIDTH
126.847	0.2142	0.2965E-01	0.9404E-03
214.686	0.3296E-01	0.2509E-05	0.6581
309.984	0.8185E-02	0.6596E-07	3.804
407.542	0.4160E-02	0.9100E-08	6.898
506.054	0.2599E-02	0.2187E-08	9.640

Table 4d: *The output files br.c1 and br.c2 for the charged H^+ decays without SUSY particles using the inputs in Tab. 2 but with HIGGS=5.*

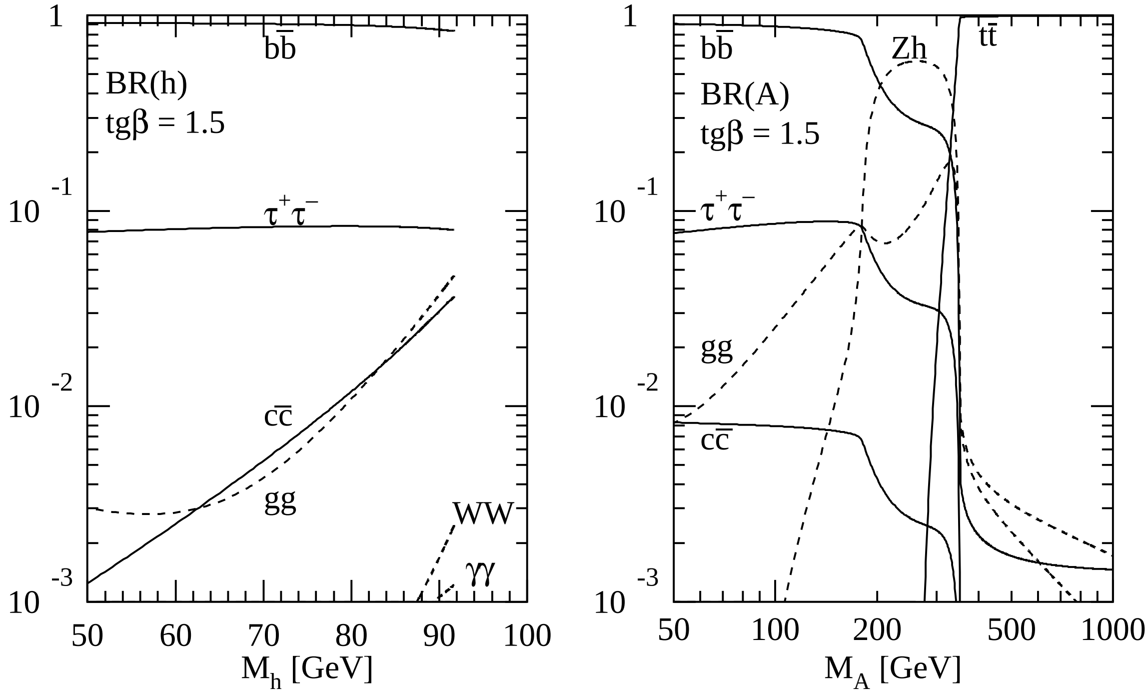

Fig. 3a

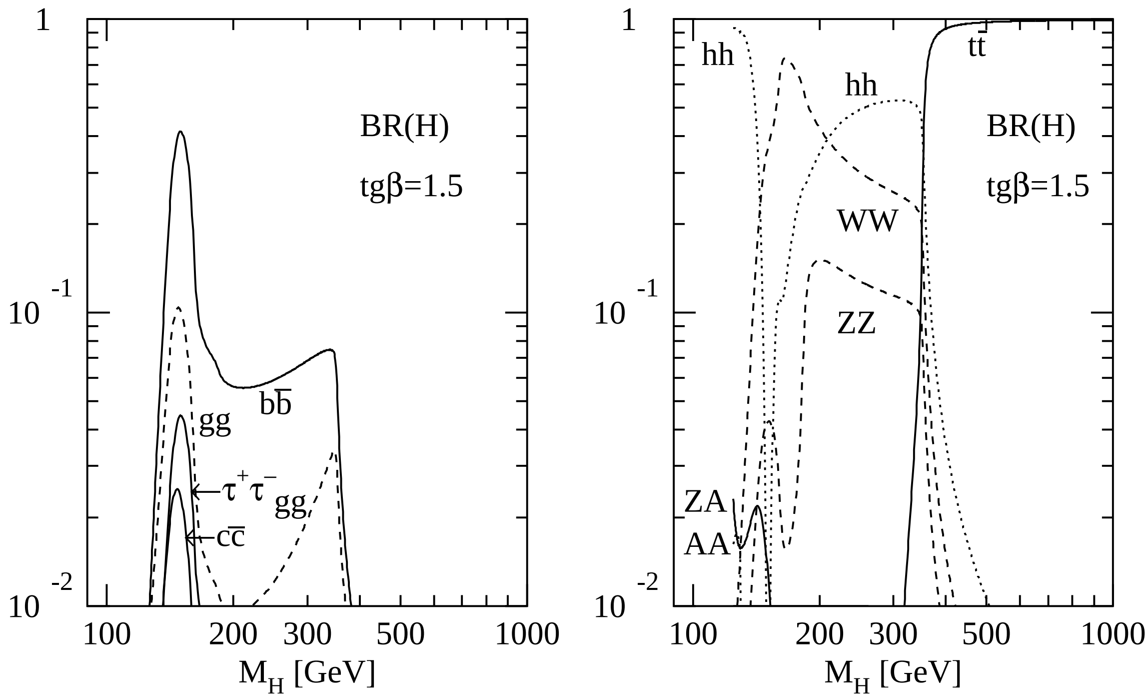

Fig. 3b

Figure 3: *Branching ratios of the MSSM Higgs bosons $h, A(a), H(b), H^{\pm}(c)$ and their total decay widths $\Gamma(\Phi)(c)$, using the inputs of Tab. 2.*

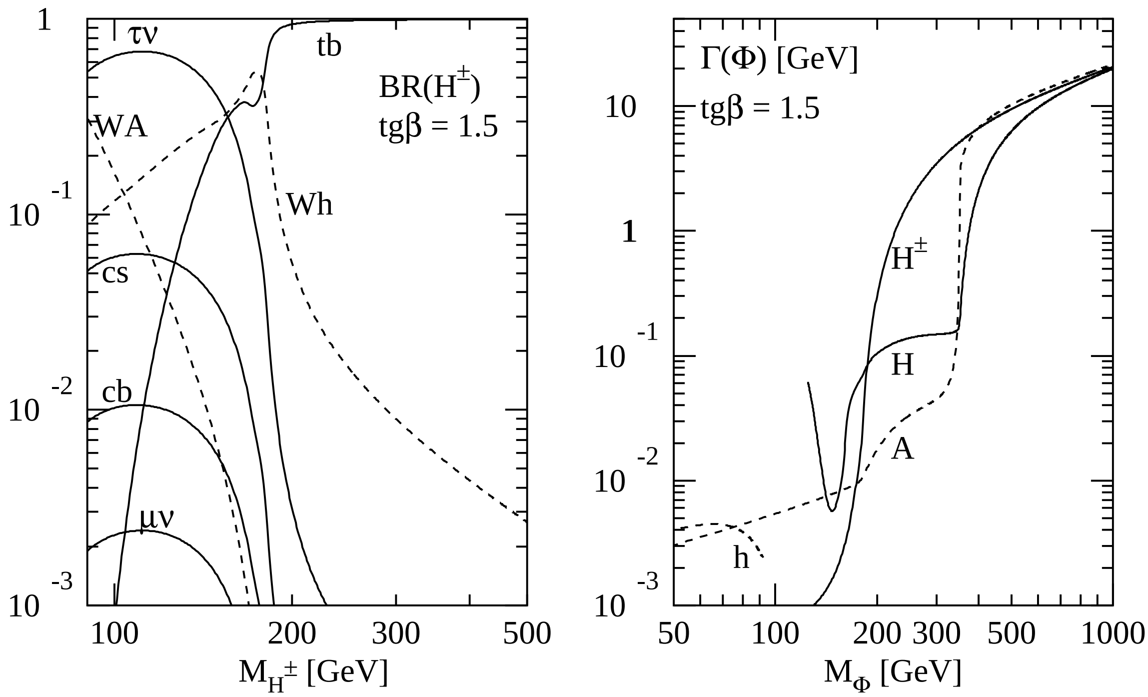

Fig. 3c

Figure 3: *Continued.*

4.3 MSSM with SUSY decays

If the SUSY particles charginos, neutralinos, sleptons and squarks are relatively light, a plethora of new decay channels is available especially for the heavy CP-even, CP-odd and charged Higgs bosons. For the light CP-even Higgs boson h, due to the present experimental bounds on the SUSY particle masses [38], the only decays which could be allowed are decays into the lightest neutralinos, and possibly decays into the lightest charginos, sleptons and stop squarks if M_h is close to its maximum allowed value [for large tgβ and A_t values] and the sparticles masses are close to their experimental bounds.

The pseudoscalar Higgs boson decays into all kinds of charginos and neutralinos, but due to CP-invariance it does not decay into the first and second generation squarks since we neglect their mixing. Therefore we have included only the decays into top and bottom squarks and τ sleptons $A \to \tilde{t}_1\tilde{t}_2, \tilde{b}_1\tilde{b}_2$ and $\tilde{\tau}_1\tilde{\tau}_2$. The heavy CP-even Higgs boson decays into all possible chargino, neutralino, slepton and squark states. Also, the charged Higgs boson will decay into chargino-neutralino pairs, slepton and squark pairs; however, the decays into sfermions will be important only for the third generation.

Because the number of possibilities for decays into SUSY particles is huge we include in the output only the sum of decays into all charginos, neutralinos, sleptons and squarks

$$\text{br.Xs}: \quad M_\Phi \;,\; \sum BR(\chi_j^+\chi_j^-) \;,\; \sum BR(\chi_j^0\chi_j^0) \;,\; \sum BR(\tilde{l}_i\tilde{l}_j) \;,\; \sum BR(\tilde{q}_i\tilde{q}_j)$$

with X = l,h,a and c for $\Phi = h, H, A$ and $H^\pm$ respectively [for sleptons and squarks of the two first generations the combinations $i \neq j$ do not contribute]. However, the main program calls all individual decays, except for the two first generations of squarks and sleptons for which the decays have been summed. For the flag INDIDEC=1 all the branching ratios of the individual channels are written to the output files br.Xsi with $i = 1, \ldots, 5$.

An example of output file for the heavy CP-even, CP-odd and charged Higgs boson decays into SUSY particles is shown in Tab. 5a–c [no SUSY decay channel is allowed for the lightest CP-even Higgs boson]. The numbers are obtained by using the input file of Tab. 2, with HIGGS=5 and OFF-SUSY=0. For convenience, the input SUSY parameters and the resulting masses for the various SUSY particles are also printed. One has to check, that with the choice of input parameters the current experimental lower bounds on the SUSY particle masses are satisfied [we do not include any experimental constraint since these bounds will probably vary in the near future].

```
TB= 1.50000      M2= 200.000      MU= 300.000      MSQ= 500.000
C1=157.197 C2= 343.795 N1= 85.367 N2=162.619 N3= 300.696 N4= 348.902
MST1= 244.202      MST2= 703.413      MSUL= 498.877      MSUR= 499.522
MSB1= 497.816      MSB2= 503.780      MSDL= 501.358      MSDR= 500.239
TAU1= 498.934 TAU2= 502.663 EL= 500.882 ER= 500.716 NL= 498.398
   MHH        CHARGINOS  NEUTRALS   SLEPTONS   SQUARKS
--------------------------------------------------------------------
 145.680          0.          0.          0.          0.
 221.034          0.      0.2379E-02     0.          0.
 313.454          0.      0.3335E-01     0.          0.
 409.924     0.6221E-02 0.6506E-01     0.          0.
 507.876     0.2204E-01 0.3325E-01     0.      0.7003
```

Table 5a: *The output file br.hs for the heavy CP-even H decays into SUSY particles with the inputs in Tab. 2 with HIGGS=5, OFF-SUSY=0.*

```
TB= 1.50000      M2= 200.000      MU= 300.000      MSQ= 500.000
C1=157.197 C2= 343.795 N1= 85.367 N2=162.619 N3= 300.696 N4= 348.902
MST1= 244.202      MST2= 703.413      MSUL= 498.877      MSUR= 499.522
MSB1= 497.816      MSB2= 503.780      MSDL= 501.358      MSDR= 500.239
TAU1= 498.934 TAU2= 502.663 EL= 500.882 ER= 500.716 NL= 498.398
   MHA        CHARGINOS  NEUTRALS   SLEPTONS   SQUARKS
------------------------------------------------------------------------------
 100.000          0.          0.          0.          0.
 200.000          0.      0.5923         0.          0.
 300.000          0.      0.8161         0.          0.
 400.000     0.9247E-01 0.6735E-01     0.          0.
 500.000     0.9382E-01 0.7468E-01     0.          0.
```

Table 5b: *The output file br.as for the heavy CP-odd A decays into SUSY particles with the inputs in Tab. 2 with HIGGS=5, OFF-SUSY=0.*

```
TB= 1.50000     M2= 200.000     MU= 300.000     MSQ= 500.000
C1=157.197 C2= 343.795 N1= 85.367 N2=162.619 N3= 300.696 N4= 348.902
MST1= 244.202     MST2= 703.413     MSUL= 498.877     MSUR= 499.522
MSB1= 497.816     MSB2= 503.780     MSDL= 501.358     MSDR= 500.239
TAU1= 498.934 TAU2= 502.663 EL= 500.882 ER= 500.716 NL= 498.398
   MHC        CHARG/NEU  SLEPTONS   SQUARKS
-----------------------------------------------------------------------------
 126.847         0.         0.         0.
 214.686         0.         0.         0.
 309.984    0.2895E-01     0.         0.
 407.542    0.3083E-01     0.         0.
 506.054    0.8753E-01     0.         0.
```

Table 5c: *The output file br.cs for the heavy charged H^+ decays into SUSY particles with the inputs in Tab. 2 with HIGGS=5, OFF-SUSY=0.*

Note finally, the numbers included in the standard decay files for the gg, $\gamma\gamma$ and $Z\gamma$ decay channels will now include (OFF-SUSY=0) the contribution of the SUSY loops. Furthermore, the total width which is quoted at the end includes of course the partial decay widths into SUSY particles.

5 Summary and Outlook

We have described the Fortran code HDECAY which calculates the total widths and the branching fractions of the decays of the Higgs bosons in the Standard Model as well as in its minimal supersymmetric extension. In the SM, all decay modes are included; the QCD corrections to the hadronic decays as well as the possibility of virtual intermediate states have been incorporated according to the present state of the art. In the MSSM, the complete radiative corrections in the Higgs sector have been implemented in the effective potential approach. The QCD corrections to the hadronic decays, the main three-body decay channels as well as the decays into charginos, neutralinos, squarks and sleptons and the SUSY contributions to the standard decay modes have been implemented.

The program, although lengthy, is fast, and has been tested on several machines; it can be easily used. The basic SM and MSSM input parameters can be chosen from an input file which contains several flags to switch on/off some options as e.g. multi-body decays, SUSY particle decays or higher-order radiative corrections. Examples for the output files for the decay branching ratios with some options have been given.

While for the case of the SM the program is rather complete, in the case of the MSSM the present version of the program can be extended/improved in several aspects:

- In the present version, the total widths and branching ratios are calculated as a function of the Higgs boson mass with other parameters kept fixed. In the MSSM, it would be useful to vary other parameters such as μ, M_2, *etc.*.

- The QCD corrections to the decays of the heavy MSSM Higgs bosons into squark pairs have been calculated recently and found to be rather large [37]. These corrections are not yet implemented in the program.

- There are some three-body decays for heavy Higgs bosons which can reach the percent level and which are not yet included. Examples of such decays are $H^0 \to WWZ, t\bar{t}Z$ and $t\bar{b}W$ in the SM [39] and $H, A \to t\bar{t}Z$ and $t\bar{b}W$ in the MSSM.

- We have restricted ourselves to the scenario where the lightest neutralino is the lightest SUSY particle. Models where the LSP is the gravitino have been discussed and in this case the Higgs decays into gravitinos can be very important [40] and should be included.

These extensions and improvements will be made in the next version of the program.

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