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Benchmark Scenarios for MSSM Higgs-Boson Searches at the LHC

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Abstract

A number of benchmark scenarios for MSSM Higgs-boson searches at the LHC have been proposed in recent years, and some of them are already in use by the ATLAS and CMS collaborations for the interpretation of their results from Run 2. The LHC Higgs Working Group provides a set of `ROOT` files that contain the numerical predictions for masses, branching ratios and production cross sections in these scenarios, relying on state-of-the art calculations implemented in public codes. In this document we first summarize the theory setup and the definitions of the scenarios, and then discuss the technical details of the `ROOT` files. A C++ interface to access these data is presented as well.

1 Introduction

The Minimal Supersymmetric Standard Model (MSSM) is the simplest and most intensively studied supersymmetric extension of the Standard Model (SM). Its Higgs sector consists of two SU(2) doublets, H_1 and H_2, whose relative contribution to electroweak symmetry breaking (EWSB) is determined by the ratio of vacuum expectation values (vevs) of their neutral components, $\tan\beta \equiv v_2/v_1$. At the tree level, $\mathcal{CP}$ is conserved in the Higgs sector of the MSSM, and the spectrum of physical Higgs bosons consists of two neutral $\mathcal{CP}$-even scalars, of which we denote the lighter as h and the heavier as H, one $\mathcal{CP}$-odd scalar, A, and a charged-scalar pair, $H^\pm$. Supersymmetry (SUSY) imposes relations between the quartic Higgs couplings and the gauge couplings, ensuring that the tree-level masses of all Higgs bosons can be expressed in terms of the gauge-boson masses, M_Z and M_W, plus two additional parameters which can be chosen as the $\mathcal{CP}$-odd scalar mass, M_A (or alternatively the charged Higgs boson mass, $M_{H^\pm}$), and $\tan\beta$. In particular, the tree-level mass of the lighter $\mathcal{CP}$-even scalar h is bounded from above by $M_Z\,|\cos 2\beta|$. However, radiative corrections – especially those involving top and bottom quarks and their scalar partners, the stops and the sbottoms – can significantly alter the tree-level predictions for the Higgs masses, allowing for $M_h \approx 125$ GeV but bringing along a dependence on many free parameters of the MSSM. Moreover, for specific choices of those parameters, radiative corrections to the mixing between the scalars can also allow for scenarios in which the heavier mass eigenstate, H, is the one with $M_H \approx 125$ GeV and roughly SM-like couplings. In the presence of complex parameters in the MSSM Lagrangian, radiative corrections can break $\mathcal{CP}$ in the Higgs sector and induce a mixing among the two $\mathcal{CP}$-even scalars, h and H, and the $\mathcal{CP}$-odd scalar, A, such that beyond tree-level they combine into three neutral mass eigenstates which we denote as h_a (with $a = 1, 2, 3$).

The large number of free parameters complicates the task of interpreting within the MSSM both the properties of the observed Higgs boson and the results of the ongoing searches for additional, non-standard Higgs bosons. Complete scans of the MSSM parameter space would be highly impractical for experimental analyses. Therefore, a number of *benchmark scenarios* have been proposed over the years, in which two parameters in the Higgs sector are varied – typically, one of them is $\tan\beta$ and the other is either M_A, for the $\mathcal{CP}$-conserving case, or $M_{H^\pm}$, for the $\mathcal{CP}$-violating case – while the remaining parameters (such as the soft-SUSY-breaking masses and mixing terms for the sfermions, as well as the masses of gauginos and higgsinos) are fixed to values that are chosen to illustrate certain aspects of MSSM Higgs phenomenology.

In 2013, Ref. [1] proposed seven $\mathcal{CP}$-conserving benchmark scenarios that, over a wide range of values of the two free parameters, featured a Higgs boson whose properties were compatible with those measured during Run 1 of the LHC. The LHC-HWG produced a set of `ROOT` files [2,3] providing, for each of the benchmark scenarios of Ref. [1], what were then state-of-the-art predictions for the masses, branching ratios (BRs) and production cross sections of the three neutral Higgs bosons of the MSSM, over a grid of values of M_A and $\tan\beta$ (except for one scenario in which the free parameters were $\tan\beta$ and the Higgs/higgsino superpotential mass μ). Those predictions were subsequently used by both the ATLAS and CMS collaborations to interpret the results of their searches for additional scalars in the context of the MSSM.

Important developments in the years following the publication of Ref. [1] motivated a re-assessment of the benchmark scenarios presented there. On the one hand, the full analysis of Run-1 LHC data at center-of-mass energies of 7 and 8 TeV, as well as the available analyses of Run-2 data at 13 TeV, tightened the experimental constraints on masses and couplings of both the observed Higgs boson and any still-unobserved BSM particles. On the other hand, the theoretical predictions for the MSSM Higgs-boson masses evolved significantly (see Ref. [4] for a recent review). In particular, the renewed interest in SUSY scenarios with heavy superpartners (i.e., with masses larger than a few TeV) stimulated new calculations based on the effective field theory (EFT) approach, aiming at the resummation of potentially large corrections enhanced by logarithms of the ratio between the SUSY scale and the EWSB scale. The versions of the code `FeynHiggs` [5–12] used both to devise the scenarios of Ref. [1] and in the production of the corresponding `ROOT` files had relied on a fixed-order (FO) calculation of the MSSM Higgs masses. The subsequent implementation in `FeynHiggs` of the resummation of the large logarithmic corrections required modifications that, even for the stop masses around one TeV featured in the scenarios of Ref. [1], could lower the prediction for M_h by $1-2$ GeV.

In 2018, in the context of the LHC-HWG activities, Ref. [13] proposed six new benchmark scenarios for MSSM Higgs searches that were designed to be compatible with the available Run-2 results for the Higgs-boson properties and the bounds on masses and couplings of new particles. These scenarios also relied on improved calculations of the masses and couplings of the neutral Higgs bosons, including the effects of the resummation of large logarithmic corrections. The first scenario is characterized by relatively heavy superparticles, so the Higgs phenomenology at the LHC resembles that of a two-Higgs-doublet model (2HDM) with MSSM-inspired Higgs couplings. The second and third scenario are characterized by some of the superparticles (staus or charginos/neutralinos) being lighter than the others and affecting the Higgs decays. The fourth and fifth scenario are characterized by the phenomenon of "alignment without decoupling" [14–16], in which one of the two neutral $\mathcal{CP}$-even Higgs scalars has SM-like couplings independently of the mass spectrum of the remaining Higgs bosons (in particular, the SM-like scalar with mass around 125 GeV is h in the fourth scenario and H in the fifth). Finally, the sixth scenario incorporates $\mathcal{CP}$ violation in the Higgs sector, giving rise to a strong admixture of the two heavier neutral states and leading to significant interference effects in their production and decay. In 2020, Ref. [17] proposed three additional benchmark scenarios in which the MSSM parameters are set as in the first scenario of Ref. [13], with the exception of μ which takes negative values. This results in an enhancement at large $\tan\beta$ of the couplings of the heavier Higgs bosons to bottom quarks, due to non-decoupling radiative corrections involving SUSY particles (the so-called Δ_b terms [18–24]).

The region of the MSSM parameter space with small to moderate values of $\tan\beta$, say $\tan\beta \lesssim 10$, requires a dedicated study. On the one hand, the decays of the heavier $\mathcal{CP}$-even scalar to ZZ, WW and hh pairs, as well as the decay $A \to hZ$, may have significant BRs. On the other hand, the tree-level MSSM prediction for M_h goes to zero as $\tan\beta$ approaches unity, thus, at very low $\tan\beta$, stop masses much larger than a few TeV are needed to obtain $M_h \approx 125$ GeV through radiative corrections. In the benchmark scenarios of Refs. [1, 13, 17], where all of the SUSY masses are fixed to values around the TeV scale, the low-$\tan\beta$ region is ruled out by an excessively low prediction for the mass of the SM-like Higgs boson. A benchmark scenario meant to cover the region with low $\tan\beta$ and very heavy SUSY was first considered by the LHC-HWG in 2015, see Ref. [25]. In this so-called "low-tb-high" scenario the parameters that determine the stop masses were adjusted point-by-point in such a way that `FeynHiggs` returned a prediction of $M_h \approx 125$ GeV for each of the considered values of $\tan\beta$ and M_A. An alternative route to the interpretation of the Higgs searches in the MSSM with low $\tan\beta$ is the so-called "hMSSM approach" [26–29], in which a number of simplifying assumptions on the MSSM parameters allow for approximate predictions for the mass of the heavier $\mathcal{CP}$-even scalar and for the Higgs couplings. The advantage of this approach is that its approximate predictions depend only on $\tan\beta$, M_A and M_h, with the latter treated as an input parameter rather than an output of the calculation. As described in Ref. [25], the LHC-HWG produced `ROOT` files for both the "low-tb-high" scenario and the hMSSM.

In 2019, Ref. [30] proposed two new benchmark scenarios for the MSSM with low $\tan\beta$, in which the parameters that determine the stop masses are adjusted in such a way that $M_h \approx 125$ GeV for each of the considered values of $\tan\beta$ and M_A. In the first of these scenarios the chargino and neutralino mass parameters are taken around 1 TeV, while in the second they are taken around 200 GeV, opening up the possibility of SUSY decays for the heavier Higgs bosons. The Higgs masses and couplings in these scenarios are computed with `FeynHiggs`, which includes a proper resummation of large logarithmic corrections via an EFT approach where the theory valid below the SUSY scale is a 2HDM supplemented with gauginos and higgsinos. These scenarios supersede the "low-tb-high" scenario of Ref. [25], in which the resummation of the logarithmic corrections was perfomed within an EFT where only the combination of Higgs doublets that corresponds to the SM-like doublet is light.

As of 2021, the LHC-HWG provides and maintains `ROOT` files that contain the predictions for the masses, BRs and production cross sections of all of the (neutral and charged) Higgs bosons of the MSSM, in the eleven benchmarks scenarios proposed in Refs. [13, 17, 30], as well as in the hMSSM approach of Refs. [26–29]. The files are made available for download from the CERN-hosted Zenodo database via the record *"LHCHWG MSSM ROOT files"* [31]. In section 2 of this note we recall the definitions of the eleven benchmark scenarios and of the hMSSM approach; in section 3 we describe the theoretical calculations of the MSSM Higgs masses, BRs and cross sections that were used in the production of the `ROOT` files; finally, in section 4 we describe the structure of the `ROOT` files, and in section 5 we describe an interface meant to simplify the access to their content.

2 Definition of the benchmark scenarios

In this section we define the eleven benchmark scenarios for MSSM Higgs searches at the LHC proposed in Refs. [13, 17, 30], and we briefly summarize the hMSSM approach of Refs. [26–29]. All scenarios include a scalar with mass around 125 GeV and SM-like properties over large parts of the defined parameter space. In each scenario two of the input parameters are left free, such that searches for additional Higgs bosons can be presented in two-dimensional planes: one of the free parameters is always $\tan\beta$, while the other is either M_A or $M_{H^\pm}$. All scenarios were designed in such a way that a significant region of the considered plane is still allowed by the searches for additional Higgs bosons at the LHC.

2.1 SM input parameters

We follow the recommendation of the LHC-HWG in Ref. [3] and make use of the following SM input parameters:

$$m_t^{\rm pole} = 172.5\ \text{GeV}, \quad m_b^{\overline{\rm MS}}(m_b) = 4.18\ \text{GeV}, \quad m_c^{\overline{\rm MS}}(3\,\text{GeV}) = 0.986\ \text{GeV},$$

$$\alpha_s(M_Z) = 0.118, \quad G_F = 1.16637 \cdot 10^{-5}\ \text{GeV}^{-2}, \quad M_Z = 91.1876\ \text{GeV}, \quad M_W = 80.385\ \text{GeV}\,. \tag{1}$$

The dependence of the Higgs-boson properties on other quark and lepton masses is not very pronounced, and we stick to the default values of the code FeynHiggs.

2.2 SUSY input parameters

In principle, the definition of an MSSM scenario would require choices for about a hundred parameters in the soft-SUSY-breaking Lagrangian. However, in studies focused on Higgs-boson phenomenology it is convenient to neglect possible new sources of flavor violation in the soft-SUSY-breaking terms. In that case, the precise values of the soft-SUSY-breaking mass and interaction terms for the first- and second-generation sfermions have only a limited effect on the predictions for the Higgs masses and mixing. The scenarios of Refs. [13, 17, 30] thus consider a common soft-SUSY-breaking mass $M_{\tilde f}$ for the first- and second-generation sfermions, and set the corresponding Higgs–sfermion interaction terms A_f to zero. The remaining soft-SUSY-breaking parameters that define the scenarios are: the third-generation squark mass parameters M_{Q_3}, M_{U_3} and M_{D_3}; the third-generation slepton mass parameters M_{L_3} and M_{E_3}; the third-generation Higgs–sfermion interaction terms A_t, A_b and A_τ; the gaugino masses M_1, M_2 and M_3. We recall that the Higgs/higgsino superpotential mass μ is an additional input parameter. Some of the scenarios do not fix an input value for A_t, but rather for the combination $X_t = A_t - \mu \cot\beta$ which enters the left–right mixing term in the stop mass matrix and determines the correction to the mass of a SM-like Higgs boson. All SUSY input parameters are considered to be real, except in the scenario that exhibits $\mathcal{CP}$ violation where a non-zero phase for A_t is introduced.

2.3 Scenarios with TeV-scale SUSY

The benchmark scenarios of Refs. [13, 17] are characterized by SUSY particles with masses around the TeV scale (or possibly below, in the case of charginos and neutralinos). In the following we list the choices of MSSM parameters that define these scenarios, including the ranges in which the free parameters (typically M_A and $\tan\beta$) are varied in the ROOT files. In all of these scenarios the common mass of the first- and second-generation sfermions is set to $M_{\tilde f} = 2$ TeV. We remark that some choices of the free parameters are already ruled out by the measured properties of the SM-like Higgs boson (e.g., the region with very low $\tan\beta$) or by the direct searches for additional Higgs bosons (e.g., the region with large $\tan\beta$ and low M_A).

2.3.1 M_h^{125} scenario

In this scenario all superparticles are chosen to be heavy enough that production and decays of the MSSM Higgs bosons are only mildly affected by their presence. In particular, the loop-induced SUSY contributions to the couplings of the lighter $\mathcal{CP}$-even scalar are small, and the heavy Higgs bosons with masses up to 2 TeV decay only to SM particles. Therefore, the phenomenology of this scenario at the LHC resembles that of a type-II 2HDM with MSSM-like Higgs couplings. The SUSY input parameters are fixed as

$$M_{Q_3} = M_{U_3} = M_{D_3} = 1.5 \text{ TeV}, \quad M_{L_3} = M_{E_3} = 2 \text{ TeV},$$

$$\mu = 1 \text{ TeV}, \quad M_1 = 1 \text{ TeV}, \quad M_2 = 1 \text{ TeV}, \quad M_3 = 2.5 \text{ TeV},$$

$$X_t = 2.8 \text{ TeV}, \quad A_b = A_\tau = A_t\,, \tag{2}$$

and the free parameters in the `ROOT` file are varied within the ranges [1]

$$70 \text{ GeV} \leq M_A \leq 2.6 \text{ TeV}, \qquad 0.5 \leq \tan\beta \leq 60\ . \tag{3}$$

A detailed discussion of the properties of the M_h^{125} scenario is given in section 3.4 of Ref. [13].

2.3.2 $M_h^{125\,\mu_i-}$ scenarios

In these scenarios the MSSM parameters are fixed as in the M_h^{125} scenario, see eqs. (2) and (3), with the exception of the Higgs/higgsino superpotential mass parameter μ, which can take one among three negative values μ_i $(i = 1, 2, 3)$:

$$\mu_i = (-1 \text{ TeV},\ -2 \text{ TeV},\ -3 \text{ TeV})\ . \tag{4}$$

As a consequence of the negative and relatively large values of μ, the non-decoupling SUSY corrections to the relation between the bottom quark mass and the bottom Yukawa coupling (the so-called Δ_b terms [18–23]) have the effect of enhancing the couplings of the heavier Higgs bosons to bottom quark pairs at large values of $\tan\beta$. A detailed discussion of the properties of the three $M_h^{125\,\mu_i-}$ scenarios is given in section 2 of Ref. [17].

2.3.3 $M_h^{125}(\tilde{\tau})$ scenario

In this scenario the supersymmetric partners of the tau leptons, the staus, have masses of a few hundred GeV. This opens up the possibility of the heavier Higgs bosons decaying into stau (or, for the charged Higgs boson, stau-sneutrino) pairs, and of non-negligible contributions from stau loops to the decay of the SM-like Higgs boson into photons. The electroweak (EW)

[1] The upper bound on M_A stems from the fact that the heavy-SUSY expansion adopted in the two-loop contributions to the gluon-fusion production process, see section 3.3, fails above the stop-pair threshold.

gauginos are also chosen to be relatively light, to ensure that the lighter stau is not the lightest SUSY particle (LSP) in most of the parameter space. The SUSY input parameters are fixed as

$$M_{Q_3} = M_{U_3} = M_{D_3} = 1.5 \text{ TeV}, \quad M_{L_3} = M_{E_3} = 350 \text{ GeV},$$

$$\mu = 1 \text{ TeV}, \quad M_1 = 180 \text{ GeV}, \quad M_2 = 300 \text{ GeV}, \quad M_3 = 2.5 \text{ TeV},$$

$$X_t = 2.8 \text{ TeV}, \quad A_b = A_t, \quad A_\tau = 800 \text{ GeV}\,, \tag{5}$$

and the free parameters in the `ROOT` file are varied within the ranges:

$$70 \text{ GeV} \le M_A \le 2.6 \text{ TeV}, \qquad 0.5 \le \tan\beta \le 60\ . \tag{6}$$

A detailed discussion of the properties of the $M_h^{125}(\tilde{\tau})$ scenario is given in section 3.5.1 of Ref. [13].

2.3.4 $M_h^{125}(\tilde{\chi})$ scenario

In this scenario all charginos and neutralinos (collectively denoted as EW-inos) have masses smaller than about 200 GeV. This opens up the possibility of the heavier Higgs bosons decaying into EW-ino pairs, and of non-negligible contributions from chargino loops to the decay of the SM-like Higgs boson into photons. The SUSY input parameters are fixed as

$$M_{Q_3} = M_{U_3} = M_{D_3} = 1.5 \text{ TeV}, \quad M_{L_3} = M_{E_3} = 2 \text{ TeV},$$

$$\mu = 180 \text{ GeV}, \quad M_1 = 160 \text{ GeV}, \quad M_2 = 180 \text{ GeV}, \quad M_3 = 2.5 \text{ TeV},$$

$$X_t = 2.5 \text{ TeV}, \quad A_b = A_\tau = A_t\,. \tag{7}$$

and the free parameters in the `ROOT` file are varied within the ranges:

$$70 \text{ GeV} \le M_A \le 2.6 \text{ TeV}, \qquad 0.5 \le \tan\beta \le 60\ . \tag{8}$$

A detailed discussion of the properties of the $M_h^{125}(\tilde{\chi})$ scenario is given in section 3.5.2 of Ref. [13].

2.3.5 M_h^{125}(alignment) scenario

This scenario is characterized by the phenomenon of *alignment without decoupling* [14–16], in which the term in the mass matrix for the neutral $\mathcal{CP}$-even scalars that mixes the field aligned with the SM Higgs vev with the field orthogonal to it vanishes. As a result, one of the $\mathcal{CP}$-even scalars – which in this particular scenario is the lighter one, h – has SM-like couplings to gauge bosons and matter fermions, irrespective of the masses of the other Higgs bosons. In the MSSM, alignment without decoupling can arise only for specific choices of parameters that lead to large radiative corrections to the relevant matrix element. The SUSY input parameters in the M_h^{125}(alignment) scenario are fixed as

$$M_{Q_3} = M_{U_3} = M_{D_3} = 2.5 \text{ TeV}, \quad M_{L_3} = M_{E_3} = 2 \text{ TeV},$$

$$\mu = 7.5 \text{ TeV}, \quad M_1 = 500 \text{ GeV}, \quad M_2 = 1 \text{ TeV}, \quad M_3 = 2.5 \text{ TeV},$$

$$A_t = A_b = A_\tau = 6.25 \text{ TeV}\,. \tag{9}$$

Compared with the previous scenarios, the free parameters in the `ROOT` file are varied within a reduced range around the region with $\tan\beta \approx 7$ where the alignment occurs:

$$120 \text{ GeV} \leq M_A \leq 1 \text{ TeV}, \qquad 1 \leq \tan\beta \leq 20\ . \tag{10}$$

A detailed discussion of the properties of the M_h^{125}(alignment) scenario is given in section 3.6.1 of Ref. [13].

2.3.6 M_H^{125} scenario

Like the previous one, this scenario is characterized by alignment without decoupling. However, the $\mathcal{CP}$-even scalar playing the role of the SM-like Higgs boson is the heavier one, H. Since all of the Higgs states have masses below 200 GeV, the scenario is already strongly constrained by the searches of additional Higgs bosons at the LHC. However, the region with relatively low $\tan\beta$ and $M_{H^\pm} \approx m_t$, where the decay $H^\pm \to W^\pm h$ may become dominant if it is kinematically open, is not fully excluded by the searches for $A \to \tau\tau$ and $H^\pm \to \tau\nu_\tau$, and requires a dedicated study. Obtaining alignment without decoupling in this region requires rather specific adjustments of the MSSM parameters. In the M_H^{125} scenario the parameters that determine the sfermion and EW-ino masses are varied as a function of $M_{H^\pm}$, which is treated as a free parameter together with $\tan\beta$:

$$M_{Q_3} = M_{U_3} = 750\,\text{GeV} - 2\,(M_{H^\pm} - 150\,\text{GeV})\ ,$$

$$\mu = [5800\,\text{GeV} + 20\,(M_{H^\pm} - 150\,\text{GeV})]\ M_{Q_3}/(750\,\text{GeV})\ ,$$

$$A_t = A_b = A_\tau = 0.65\,M_{Q_3}, \quad M_{D_3} = M_{L_3} = M_{E_3} = 2 \text{ TeV}\ ,$$

$$M_1 = M_{Q_3} - 75\,\text{GeV}, \quad M_2 = 1\,\text{TeV}, \quad M_3 = 2.5\,\text{TeV}\ . \tag{11}$$

The free parameters in the `ROOT` file are varied only in a narrow range around the region of interest:

$$150 \text{ GeV} \leq M_{H^\pm} \leq 200 \text{ GeV}, \qquad 5 \leq \tan\beta \leq 6\ . \tag{12}$$

A detailed discussion of the properties of the M_H^{125} scenario is given in section 3.6.2 of Ref. [13].

2.3.7 $M_{h_1}^{125}$(CPV) scenario

This scenario is characterized by $\mathcal{CP}$ violation in the Higgs sector, induced by a non-zero phase for the soft SUSY-breaking Higgs-stop coupling A_t. The role of the SM-like Higgs boson is played by the lightest neutral state h_1, and a strong admixture of the two heavier neutral states h_2 and h_3 leads to negative interference effects in their production and decay, weakening the exclusion bounds from $\tau^+\tau^-$ searches in the region of the parameter space where the interference is maximal. The SUSY input parameters in the $M_{h_1}^{125}$(CPV) scenario are fixed as

$$M_{Q_3} = M_{U_3} = M_{D_3} = M_{L_3} = M_{E_3} = 2 \text{ TeV},$$

$$\mu = 1.65 \text{ TeV}, \quad M_1 = M_2 = 1 \text{ TeV}, \quad M_3 = 2.5 \text{ TeV},$$

$$|A_t| = \mu \cot\beta + 2.8 \text{ TeV}, \quad \phi_{A_t} = \tfrac{2\pi}{15}, \quad A_b = A_\tau = |A_t| \; . \tag{13}$$

Since the $\mathcal{CP}$-odd state A is not a mass eigenstate in the presence of $\mathcal{CP}$ violation, the mass of the charged Higgs boson is treated as a free parameter together with $\tan\beta$. They are varied in the ranges

$$130 \text{ GeV} \leq M_{H^\pm} \leq 1.5 \text{ TeV}, \qquad 1 \leq \tan\beta \leq 20 \; . \tag{14}$$

A detailed discussion of the properties of the $M_{h_1}^{125}$(CPV) scenario is given in section 3.7 of Ref. [13].[2]

2.4 Scenarios with heavy sfermions

The two scenarios described in this section were developed in Ref. [30] to cover the low-$\tan\beta$ region of the MSSM, in which stop masses above the TeV scale are required to obtain a prediction for M_h compatible with the measured value. In these scenarios all of the sfermion masses, including those of the first two generations, are set equal to a common SUSY scale M_S, which is adjusted[3] for each of the considered values of M_A and $\tan\beta$ in such a way that $M_h \approx 125$ GeV. In the predictions for the Higgs masses and couplings, the resummation of the large logarithmic corrections relies on an EFT approach in which the theory valid below the scale M_S is a 2HDM supplemented with gauginos and higgsinos. These scenarios supersede the "low-tb-high" scenario of Ref. [25], in which the resummation of the logarithmic corrections was performed within an EFT with only one light Higgs doublet.

2.4.1 $M_{h,\mathrm{EFT}}^{125}$ scenario

In this scenario the masses of gauginos and higgsinos are set to values at or above the TeV scale. Consequently, the presence of SUSY fermions does not directly affect the LHC phenomenology of the Higgs sector, which corresponds to the one of a type-II 2HDM with SUSY-inspired

[2] See also the note added at the end of Ref. [13] for a discussion of the implications of the ACME bound [32] on the electric dipole moment of the electron.

[3] The lists of the values of M_S used in the two scenarios for each point of the $(M_A\,, \tan\beta)$ plane are provided as ancillary files to Ref. [30], see `https://arxiv.org/src/1901.05933v2/anc` .

couplings. In this sense, the $M_{h,\mathrm{EFT}}^{125}$ scenario of Ref. [30] can be viewed as a low-$\tan\beta$ extension of the M_h^{125} scenario of Ref. [13], see section 2.3.1. The SUSY input parameters are fixed as

$$M_{\tilde{f}} = M_{Q_3} = M_{U_3} = M_{D_3} = M_{L_3} = M_{E_3} \equiv M_S, \quad A_t = A_b = A_\tau = 0\,,$$
$$\mu = 1\ \mathrm{TeV}, \quad M_1 = 1\ \mathrm{TeV}, \quad M_2 = 1\ \mathrm{TeV}, \quad M_3 = 2.5\ \mathrm{TeV}, \tag{15}$$

and the free parameters in the `ROOT` file are varied within the ranges:

$$70\ \mathrm{GeV} \leq M_A \leq 3\ \mathrm{TeV}, \qquad 1 \leq \tan\beta \leq 10\ . \tag{16}$$

A detailed discussion of the properties of the $M_{h,\mathrm{EFT}}^{125}$ scenario is given in section 4.2 of Ref. [30].

2.4.2 $M_{h,\mathrm{EFT}}^{125}(\tilde{\chi})$ scenario

In this scenario the masses of the EW gauginos and of the higgsinos are set to values below 200 GeV. The presence of light charginos and neutralinos affects the LHC phenomenology of the Higgs sector, opening up the possibility of the heavier Higgs bosons decaying into EW-ino pairs, and of non-negligible contributions from chargino loops to the decay of the SM-like Higgs boson into photons. In this sense, the $M_{h,\mathrm{EFT}}^{125}(\tilde{\chi})$ scenario of Ref. [30] can be viewed as a low-$\tan\beta$ extension of the $M_h^{125}(\tilde{\chi})$ scenario of Ref. [13], see section 2.3.4. The SUSY input parameters are fixed as

$$M_{\tilde{f}} = M_{Q_3} = M_{U_3} = M_{D_3} = M_{L_3} = M_{E_3} \equiv M_S, \quad A_t = A_b = A_\tau = 0\,,$$
$$\mu = 180\ \mathrm{GeV}, \quad M_1 = 160\ \mathrm{GeV}, \quad M_2 = 180\ \mathrm{GeV}, \quad M_3 = 2.5\ \mathrm{TeV}, \tag{17}$$

and the free parameters in the `ROOT` file are varied within the ranges:

$$70\ \mathrm{GeV} \leq M_A \leq 3\ \mathrm{TeV}, \qquad 1 \leq \tan\beta \leq 10\ . \tag{18}$$

A detailed discussion of the properties of the $M_{h,\mathrm{EFT}}^{125}(\tilde{\chi})$ scenario is given in section 4.3 of Ref. [30].

2.5 The hMSSM approach

As an alternative to interpreting Higgs searches at the LHC in specific MSSM scenarios, a simplifying approach, the so-called "hMSSM", was proposed in 2013 [26–29]. This approximation assumes that: *i*) the Higgs sector of the MSSM is $\mathcal{CP}$-conserving; *ii*) all SUSY particles are too heavy to affect Higgs production and decays; *iii*) any non-decoupling SUSY corrections to the Higgs couplings (e.g., the Δ_b corrections to the bottom Yukawa coupling) are negligible; *iv*) the radiative corrections to the elements other than (2,2) in the mass matrix of the neutral $\mathcal{CP}$-even components of H_1 and H_2 are also negligible, i.e. $\Delta\mathcal{M}_{1j}^2 \approx 0$ for $j = 1, 2$. In this case, the remaining radiative correction $\Delta\mathcal{M}_{22}^2$ can be expressed in terms of the parameters that determine the tree-level mass matrix (i.e. $\tan\beta$, M_Z and M_A) plus the smaller eigenvalue M_h, which is treated as an input and identified with the mass of the observed Higgs boson:

$$\Delta\mathcal{M}^2_{22} \;=\; \frac{M_h^2\,(M_A^2+M_Z^2-M_h^2) - M_A^2\,M_Z^2\,\cos^2 2\beta}{M_Z^2\,\cos^2\beta + M_A^2\sin^2\beta - M_h^2}\;, \tag{19}$$

Consequently, the larger eigenvalue M_H and the angle α that diagonalizes the $\mathcal{CP}$-even mass matrix can in turn be expressed in terms of just those four input parameters, of which only M_A and $\tan\beta$ are unknown:

$$M_H^2 \;=\; \frac{(M_A^2+M_Z^2-M_h^2)(M_Z^2\,\cos^2\beta + M_A^2\sin^2\beta) - M_A^2\,M_Z^2\,\cos^2 2\beta}{M_Z^2\,\cos^2\beta + M_A^2\sin^2\beta - M_h^2}\;, \tag{20}$$

$$\tan\alpha \;=\; -\frac{(M_Z^2+M_A^2)\,\cos\beta\,\sin\beta}{M_Z^2\,\cos^2\beta + M_A^2\sin^2\beta - M_h^2}\;. \tag{21}$$

In this approximation the mass of the charged scalar coincides with its tree-level value within the MSSM. The couplings of the Higgs bosons to fermions and to gauge bosons are fixed to their tree-level form, but they are expressed in terms of the effective (i.e., loop-corrected) angle α obtained in eq. (21). In contrast, the trilinear and quartic Higgs self-couplings receive additional contributions. For example, the effective trilinear self-coupling of the lighter scalar in the hMSSM reads

$$\lambda_{hhh} \;=\; \lambda_{hhh,\text{tree}} \;+\; \frac{3\,\cos^3\alpha}{v\,\sin\beta}\left(\Delta\mathcal{M}^2_{22} - \frac{m_t^4}{\pi^2\,v^2\,\sin^2\beta}\right), \tag{22}$$

where the tree-level coupling is also expressed in terms of the effective α, the EWSB parameter $v \approx 246$ GeV is defined by $v^2 \equiv v_1^2 + v_2^2$, and the correction $\Delta\mathcal{M}^2_{22}$ is given in eq. (19). The second term within parentheses in eq. (22) is an additional correction arising from top-quark loops [33], which had not been included in the original hMSSM proposal of Refs. [26–29] and was introduced in 2018 in Ref. [34].

In the `ROOT` file for the hMSSM the free parameters M_A and $\tan\beta$ are varied in the ranges

$$130\ \text{GeV} \le M_A \le 2\ \text{TeV}, \qquad 0.8 \le \tan\beta \le 60\;. \tag{23}$$

We recall however that the hMSSM approach was originally introduced to describe the low-$\tan\beta$ region of the MSSM. At large values of $\tan\beta$, there are regions of the MSSM parameter space in which some of the underlying assumptions of the hMSSM approach – namely the irrelevance of the Δ_b corrections and the condition $\Delta\mathcal{M}^2_{12} \ll \mathcal{M}^2_{12,\text{tree}}$ – are not satisfied.

3 Theory setup

In this section we provide details on the predictions for the Higgs-boson masses, BRs and production cross sections that were used in the production of the `ROOT` files for the benchmark scenarios defined in section 2. We also define the interference factors relevant to Higgs production and decay in the MSSM with $\mathcal{CP}$ violation. For general reviews of these calculations and complete lists of references we point the reader to Ref. [4] (for the masses) and Ref. [35] (for production and decays).

3.1 Higgs-boson masses and mixing

In the production of the ROOT files for the MSSM benchmark scenarios of sections 2.3 and 2.4, the code FeynHiggs [5–12] is used to compute the Higgs-boson masses as well as the so-called "Z-factors", i.e. wave-function normalization factors that encode the effect of scalar mixing at the same loop level as in the Higgs-mass calculation, and are used in the computation of the decay widths and of the production cross sections. Further details on the versions of the code used for the different benchmark scenarios are provided below.

To account for the theory uncertainty of the Higgs-mass calculation – namely, the uncertainty stemming from uncomputed higher-order corrections – the prediction for the SM-like Higgs mass obtained with FeynHiggs is considered compatible with the data if it lies in an interval of ±3 GeV around the experimental measurement.[4] However, this criterion complicates the comparison of the MSSM predictions for the cross sections and branching ratios of the SM-like Higgs boson with the data, because these quantities depend in turn on the Higgs mass, and their measurements at the LHC are now sufficiently precise to be sensitive to the mass dependence even in the considered ±3 GeV interval. On the other hand, the mass dependence of the signal strength modifiers – defined as $\mu^I \equiv \sigma^I/\sigma^I_{\rm SM}$ for each production process $I \to h$ and $\mu^F \equiv {\rm BR}^F/{\rm BR}^F_{\rm SM}$ for each decay $h \to F$ – is much milder. It is therefore preferable to compare with the data the MSSM predictions for the signal strength modifiers. In order to allow the users to follow this prescription, the ROOT files include, for each point of a given MSSM scenario, the SM predictions for cross sections and branching ratios of a Higgs boson $H_{\rm SM}$ with mass equal to the predicted mass $m_h^{\rm pred}$ of the SM-like Higgs boson of the MSSM. To avoid the inclusion of spurious effects in the signal strength modifiers, the MSSM and SM predictions should be computed at the same level of accuracy in the relevant couplings (in practice, they are computed using the same codes). We note that this approach is equivalent to computing the MSSM cross sections and branching ratios at the observed Higgs mass $m_h^{\rm obs}$ by rescaling the SM predictions as

$$\sigma^{\rm MSSM}(m_h^{\rm obs}) \;=\; \frac{\sigma^{\rm MSSM}(m_h^{\rm pred})}{\sigma^{\rm SM}(m_h^{\rm pred})} \times \sigma^{\rm SM}(m_h^{\rm obs})\,, \tag{24}$$

$${\rm BR}^{\rm MSSM}(m_h^{\rm obs}) \;=\; \frac{{\rm BR}^{\rm MSSM}(m_h^{\rm pred})}{{\rm BR}^{\rm SM}(m_h^{\rm pred})} \times {\rm BR}^{\rm SM}(m_h^{\rm obs})\,. \tag{25}$$

Finally, in contrast to the case of the MSSM benchmark scenarios of sections 2.3 and 2.4, in the production of the ROOT file for the hMSSM approach of section 2.5 there is no need for a code to compute the Higgs masses and mixing: the values of M_h and M_A are treated as input parameters, the charged-Higgs mass is computed at tree level, and the values of M_H and of the effective mixing angle α are obtained from eqs. (20) and (21), respectively.

TeV-scale sfermions: In the ROOT files for the six scenarios with TeV-scale sfermions and positive μ defined in Ref. [13] the calculation of the Higgs-boson masses employs version 2.14.3

[4] See section 6.2 of Ref. [4] for a discussion of this criterion.

of `FeynHiggs`, whereas in the `ROOT` files for the three scenarios with TeV-scale sfermions and negative μ defined in Ref. [17], namely the $M_h^{125\,\mu_i-}$ scenarios in section 2.3.2, the calculation employs version `2.14.4` of the code. In both cases the Higgs masses and mixing are computed following the "hybrid" approach developed in Refs. [9–11]. In particular, a FO calculation which includes full one-loop corrections [8] plus two-loop corrections in the limits of vanishing momentum and vanishing EW gauge couplings [6,36–39] is combined with a full next-to-leading logarithmic (NLL) and partial next-to-next-to leading logarithmic (NNLL) resummation of the corrections involving logarithms of the ratio between the SUSY scale and the EWSB scale.

For the calculation of the Higgs masses and mixing in the scenario with complex parameters, namely the $M_{h_1}^{125}$(CPV) scenario in section 2.3.7, `FeynHiggs 2.14.3` includes the full one-loop corrections of Ref. [8] and the dominant two-loop corrections involving the top Yukawa coupling from Refs. [40–43]. Additional two-loop corrections involving the bottom Yukawa coupling, as well as the resummation of higher-order logarithmic effects, are approximated by interpolation of the corresponding corrections computed in the MSSM with real parameters.

For future reference, we list here the values of the input flags of `FeynHiggs 2.14.3` used in the production of the `ROOT` files for the six scenarios of Ref. [13] (see the online manual of the code [44] for more details):

$$\text{mssmpart} = 4, \quad \text{higgsmix} = 2, \quad \text{p2approx} = 4, \quad \text{looplevel} = 2,$$
$$\text{loglevel} = 3, \quad \text{runningMT} = 1, \quad \text{botResum} = 1, \quad \text{tlCplxApprox} = 0.$$

For the three scenarios of Ref. [17], `FeynHiggs 2.14.14` is run with the same flags as listed above, with the exception of botResum = 2. This change affects the calculation of the BRs for the Higgs decays (see section 3.2 below) but it does not affect the calculation of the masses.

Heavy sfermions: In the `ROOT` files for the two scenarios with low $\tan\beta$ and heavy sfermions defined in Ref. [30], the calculation of the Higgs masses and mixing relied on a private version of `FeynHiggs`, following the hybrid approach developed in Ref. [45]. In particular, a FO calculation including the full one-loop corrections of Ref. [8] is combined with an EFT calculation in which the theory valid below the sfermion mass scale is a 2HDM supplemented with higgsinos and gauginos. This ensures a NLL resummation of the corrections involving logarithms of the ratio between the SUSY scale and the EWSB scale.

3.2 Branching ratios

The BRs for the decays of the Higgs bosons provided in the `ROOT` files for most of the scenarios with TeV-scale sfermions, see section 2.3, are obtained from a combination of results of `FeynHiggs` [5–12] and of `HDECAY` [46, 47]. The exceptions are the M_H^{125} and $M_{h_1}^{125}$(CPV) scenarios, for which only `FeynHiggs` is used. In the `ROOT` files for the two scenarios with heavy sfermions, see section 2.4, the BRs are computed entirely with the private version of `FeynHiggs` used for the Higgs-mass calculation. Finally, in the `ROOT` file for the hMSSM approach the BRs are computed entirely with `HDECAY`.

The combination of results from `FeynHiggs` and `HDECAY` in the $\mathcal{CP}$-conserving scenarios with TeV-scale sfermions follows the prescription of the LHC-HWG [2,3,48]. In particular, the total decay widths for the neutral Higgs bosons are

$$\begin{aligned}\Gamma_\phi &= \Gamma^{\rm FH}_{\phi\to\tau^+\tau^-} + \Gamma^{\rm FH}_{\phi\to\mu^+\mu^-} + \Gamma^{\rm FH}_{\phi\to W^{(*)}W^{(*)}} + \Gamma^{\rm FH}_{\phi\to Z^{(*)}Z^{(*)}} \\ &\quad + \Gamma^{\rm HD}_{\phi\to b\bar b} + \Gamma^{\rm HD}_{\phi\to t\bar t} + \Gamma^{\rm HD}_{\phi\to c\bar c} + \Gamma^{\rm HD}_{\phi\to gg} + \Gamma^{\rm HD}_{\phi\to\gamma\gamma} + \Gamma^{\rm HD}_{\phi\to Z\gamma} \\ &\quad + \Gamma_{\phi\to\rm Higgs} + \Gamma^{\rm FH}_{\phi\to\rm SUSY}\,, \end{aligned} \tag{26}$$

where $\phi = (h, H, A)$, the superscripts “FH” and “HD” stand for the code with which the corresponding decay widths are computed, namely `FeynHiggs` and `HDECAY`, respectively, and we omitted the tiny contributions of the decays to electrons and to light quarks. The partial decay widths $\Gamma_{\phi\to\rm Higgs}$, corresponding to decays with Higgs bosons in the final state, are defined as

$$\Gamma_{h\to\rm Higgs} = 0\,, \tag{27}$$

$$\Gamma_{H\to\rm Higgs} = \Gamma^{\rm FH}_{H\to hh} + \Gamma^{\rm FH}_{H\to AA} + \Gamma^{\rm FH}_{H\to ZA} + \Gamma^{\rm HD}_{H\to H^\pm W^\mp}\,, \tag{28}$$

$$\Gamma_{A\to\rm Higgs} = \Gamma^{\rm FH}_{A\to Zh} + \Gamma^{\rm FH}_{A\to ZH}\,, \tag{29}$$

where of course some of the decay channels might not be kinematically open, in which case the corresponding widths are set to zero. The last term $\Gamma^{\rm FH}_{\phi\to\rm SUSY}$ in eq. (26) represents collectively the decays to SUSY particles that are kinematically open in a given point of the parameter space. The same prescription, for the relevant channels, is used for the SM Higgs boson $H_{\rm SM}$ as well. In the case of the $\mathcal{CP}$-violating scenario the partial widths are computed using only `FeynHiggs` and the total width is defined as in eq. (26), with $\phi = (h_1, h_2, h_3)$ and with

$$\Gamma_{h_1\to\rm Higgs} = 0\,, \tag{30}$$

$$\Gamma_{h_2\to\rm Higgs} = \Gamma^{\rm FH}_{h_2\to h_1h_1} + \Gamma^{\rm FH}_{h_2\to Zh_1} + \Gamma^{\rm FH}_{h_2\to H^\pm W^\mp}\,, \tag{31}$$

$$\Gamma_{h_3\to\rm Higgs} = \Gamma^{\rm FH}_{h_3\to h_1h_1} + \Gamma^{\rm FH}_{h_3\to h_1h_2} + \Gamma^{\rm FH}_{h_3\to h_2h_2} + \Gamma^{\rm FH}_{h_3\to Zh_1} + \Gamma^{\rm FH}_{h_3\to Zh_2} + \Gamma^{\rm FH}_{h_3\to H^\pm W^\mp}\,. \tag{32}$$

The total decay width for the charged Higgs boson in the $\mathcal{CP}$-conserving case is instead

$$\begin{aligned}\Gamma_{H^\pm} &= \Gamma^{\rm FH}_{H^\pm\to\tau\nu_\tau} + \Gamma^{\rm FH}_{H^\pm\to\mu\nu_\mu} + \Gamma^{\rm FH}_{H^\pm\to hW^\pm} + \Gamma^{\rm FH}_{H^\pm\to HW^\pm} + \Gamma^{\rm FH}_{H^\pm\to AW^\pm} \\ &\quad + \Gamma^{\rm HD}_{H^\pm\to tb} + \Gamma^{\rm HD}_{H^\pm\to ts} + \Gamma^{\rm HD}_{H^\pm\to td} + \Gamma^{\rm HD}_{H^\pm\to cb} + \Gamma^{\rm HD}_{H^\pm\to cs} + \Gamma^{\rm HD}_{H^\pm\to cd} \\ &\quad + \Gamma^{\rm HD}_{H^\pm\to ub} + \Gamma^{\rm FH}_{H^\pm\to\rm SUSY}\,, \end{aligned} \tag{33}$$

and the corresponding expression for the $\mathcal{CP}$-violating case is obtained via the replacement in the first line of h, H and A with h_1, h_2 and h_3.

We now summarize the accuracy of the calculations of decay widths implemented in the codes `FeynHiggs` and `HDECAY`.

Decay widths from `FeynHiggs`**:** The decays to quark and lepton pairs are evaluated at the full one-loop level, supplemented with two-loop contributions from the "Z-factors" that ensure the OS properties of the external Higgs particles. The decays to bottom pairs also include a resummation of the $\tan\beta$-enhanced SUSY corrections, using one-loop formulae from Ref. [49] for the so-called Δ_b terms. For the three $M_h^{125\,\mu_i-}$ scenarios, where the effect of the Δ_b terms is particularly relevant, the two-loop contributions from Refs. [50–52] are also included. The decays to gluons or photons are computed at the lowest order (i.e., one loop), supplemented with the NLO-QCD contributions in the heavy-top limit from diagrams involving gluons. For the decays to massive gauge bosons, `FeynHiggs` approximates the MSSM results by reweighting the SM results of the code `Prophecy4F` [53, 54] with the appropriate Higgs–gauge-boson couplings. For the decays to Higgs bosons `FeynHiggs` implements a full one-loop calculation within the (complex) MSSM [55, 56], improved with the resummation of potentially large logarithmic corrections. Finally, the decays to SUSY particles are computed at the tree level.

A light charged Higgs boson can be produced in the decay of a top quark (this is relevant mainly for the M_H^{125} scenario). `FeynHiggs` computes the total width of the top quark and the BR of the decay $t \to H^+ b$, relying on the tree-level results plus one-loop $\mathcal{O}(\alpha_s)$ corrections from Refs. [22, 57], supplemented by the appropriate coupling rescaling factors from Ref. [22] in order to include the Δ_b corrections.

Decay widths from `HDECAY`**:** We describe here the computation of the decay widths that in the `ROOT` files are obtained from `HDECAY`. For several decay channels, the public version of the code implements EW corrections (beyond those included in the Δ_b terms) in the SM case but not in the MSSM case. Therefore, to avoid introducing spurious effects in the rescaling factors of eq. (25), the EW corrections are disabled when computing the branching ratios of $H_{\rm SM}$.

The decays of the neutral Higgs bosons to quark pairs include the QCD corrections up to N^{4}LO following Refs. [58–70]. For a heavier neutral scalar with mass below the $t\bar{t}$ threshold, the decays to off-shell top pairs are included following Ref. [71, 72]. The decays of the charged Higgs boson to quark pairs include QCD corrections up to N^{4}LO from Refs. [73–75] in the case of light quarks, and the NLO QCD corrections from Ref. [75] in the case of heavy quarks (an interpolation between the two limits is implemented in the code). The one-loop SUSY-QCD corrections to the neutral Higgs decays to bottom quarks are included following Refs. [24, 76, 77].

The resummation of the $\tan\beta$-enhanced SUSY corrections to both neutral and charged Higgs decays relies on Refs. [24, 50, 51, 78] for the evaluation of the Δ_b terms up to two loops. The decays to lepton pairs are obtained from `HDECAY` only in the hMSSM case, for which they are computed at the tree level.

The decays of the neutral Higgs bosons to a gluon pair include the (non-SUSY) NLO-QCD contributions with full quark-mass dependence from Ref. [79], plus higher-order contributions in the limit of heavy top quarks, up to the N^{3}LO in QCD for the neutral scalars [80] and up to the NNLO for the pseudoscalar [81]. The contributions from squark loops are included up to the NLO in QCD as in Ref. [82], neglecting the two-loop diagrams that involve gluinos or quartic squark couplings. The decays of the neutral Higgs bosons to a photon pair include the full one-loop contributions, plus, at two loops, the QCD corrections from Ref. [79]. The decays of the neutral Higgs bosons to a photon and a Z boson are computed at one loop following

Ref. [79, 83–85].

Finally, the decays of the Higgs bosons to pairs of massive gauge bosons and to final states that involve Higgs bosons are obtained from HDECAY only within the ROOT file for the hMSSM. In this case the decay widths are computed at the tree level, but the Higgs self-couplings entering the tree-level formulas are replaced by loop-corrected effective couplings analogous to the one given in eq. (22).

3.3 Production cross sections

In the ROOT files for the scenarios with TeV-scale sfermions, the cross sections for Higgs-boson production via gluon fusion and bottom-quark annihilation are calculated with SusHi 1.7.0 [86, 87] and with its extension to the MSSM with complex parameters, SusHiMi [88]. A link to FeynHiggs provides both the loop-corrected Higgs-boson masses and the matrix of Z-factors.

For both the top- and bottom-quark contributions to gluon fusion, SusHi includes the full next-to-leading order (NLO) results [79, 89]. In addition, SusHi includes the next-to-NLO (NNLO) top-quark contributions in the heavy-quark effective theory [90–94] and even, for the SM-like scalar only, the next-to-NNLO ($\mathrm{N^3LO}$) contributions in a threshold expansion [95–97]. In the MSSM with real parameters, squark and gluino contributions to gluon fusion are taken into account at NLO following Refs. [98–100], which rely on an expansion in inverse powers of the superparticle masses. In the MSSM with complex parameters these NLO contributions are interpolated, while the leading-order contribution incorporates the full phase dependence, see Ref. [88]. The $\tan\beta$-enhanced SUSY contributions to the Higgs–bottom couplings are resummed using the one-loop Δ_b terms from Ref. [49], as provided by FeynHiggs (for the $M_h^{125\,\mu_i-}$ scenarios the two-loop contributions from Refs. [50–52] are also included). The two-loop EW corrections mediated by light quarks are included by reweighting the SM results of Refs. [101, 102] with the appropriate Z-factors. The central renormalization and factorization scales are chosen to be $\mu_\mathrm{R} = \mu_\mathrm{F} = m_\phi/2$ (where ϕ is the produced Higgs boson). For the parton distribution functions (PDFs) the central sets of PDF4LHC15_nlo_mc and PDF4LHC15_nnlo_mc [103] are used for the NLO and the NNLO/$\mathrm{N^3LO}$ contributions, respectively.

For Higgs-boson production in bottom-quark annihilation, the LHC-HWG provides cross sections for the SM Higgs boson as a function of its mass, based on soft-collinear effective theory [104,105] (these coincide with the results of the so-called "fixed order plus next-to-leading log" (FONLL) approach [106, 107]). The pure bottom-Yukawa contribution and the loop-induced top-bottom interference contribution are separately reweighted with effective Higgs couplings, using an effective mixing angle (or, in the case of $\mathcal{CP}$ violation, the matrix of Z-factors) in the scalar sector, and taking into account the resummation of $\tan\beta$-enhanced SUSY contributions as in the gluon-fusion case. In principle, the cross section for the production of a $\mathcal{CP}$-odd scalar in bottom-quark annihilation differs from the one of a $\mathcal{CP}$-even scalar, but this difference is negligible for $\mathcal{CP}$-odd-scalar masses beyond 100 GeV. Therefore, the SM cross section is also used to obtain a reweighted cross section for the $\mathcal{CP}$-odd scalar.

The cross sections for Higgs production through vector-boson fusion, Higgs-strahlung and associated production with top quarks are computed with `FeynHiggs`, which reweights the SM predictions provided by the LHC-HWG with the appropriate MSSM/SM ratios of the couplings involved. Finally, the cross section for charged-Higgs production via $gg \to tbH^{\pm}$ is read from a $(M_{H^{\pm}}, \tan\beta)$ grid for the type-II 2HDM provided by the LHC-HWG – relying on the calculations of Refs. [108–112] – and then reweighted with the Δ_b corrections to the Higgs–bottom couplings provided by `FeynHiggs`.

In the `ROOT` files for the scenarios with heavy sfermions and for the hMSSM the cross sections for Higgs-boson production are computed as described above, with the exception that all SUSY contributions are removed.

Uncertainty estimates: The `ROOT` files contain also estimates of the theoretical uncertainties for the dominant Higgs-production cross sections. For the production of a $\mathcal{CP}$-even scalar via gluon fusion in the MSSM, the relative PDF+α_s uncertainties are assumed to coincide with those for the production of a SM Higgs boson of the same mass, which can be determined from the above-mentioned `PDF4LHC15` sets following the prescriptions of Ref. [103]. For the production of a $\mathcal{CP}$-odd scalar via gluon fusion, a separate set of relative PDF+α_s uncertainties is generated, assuming the field content of a 2HDM (in the scenario with $\mathcal{CP}$ violation, however, the SM-inspired estimate is applied to to all three neutral scalars). The second source of uncertainty taken into account for gluon fusion is the renormalization-scale dependence, which is estimated using the analytic approach described in Ref. [87]. For this purpose, the minimal and maximal values of the cross section for 100 equidistant scale choices between $\mu_{\rm R} = m_\phi/4$ and $\mu_{\rm R} = m_\phi$ are determined, and their difference is used as a symmetric uncertainty. The factorization-scale dependence, on the other hand, is known to be subdominant [113] and is not further considered. Finally, the renormalization-scale uncertainty and the PDF+α_s uncertainty are added in quadrature.

For bottom-quark annihilation the uncertainty estimate relies on the absolute uncertainties provided by the LHC-HWG for the SM Higgs boson, as a function of its mass and of the center-of-mass energy. Those include symmetric renormalization- and factorization-scale uncertainties, symmetric uncertainties related to the bottom-quark mass value and to the bottom-quark matching scale, and asymmetric PDF+α_s uncertainties. All downward (upward) shifts are added in quadrature, and the result is transformed into a total relative downward (upward) uncertainty. This relative uncertainty is applied to the production of all MSSM Higgs bosons, independently of the $\mathcal{CP}$ nature of the scalar under consideration.

For charged-Higgs production the uncertainties are read from the $(M_{H^{\pm}}, \tan\beta)$ grid for the type-II 2HDM provided by the LHC-HWG. However, an additional $\pm 10\%$ uncertainty is included for $\tan\beta < 10$. This accounts for the omission of the SUSY-QCD corrections to the contributions induced by the top Yukawa coupling, which are most relevant at low $\tan\beta$.

3.4 Interference effects in Higgs production and decay

If two or more admixed Higgs bosons are nearly mass-degenerate and their Breit-Wigner propagators overlap, large interference effects occur in processes that involve these Higgs bosons in the s-channel. Rather than calculating the full process $I \to \sum_a h_a \to F$, involving the initial state I, the final state F and the exchange of all three of the Higgs mass eigenstates, in Refs. [114–116] an approximation was developed that combines the separate predictions for the production and decay of each mass eigenstate h_a with the respective interference contributions:

$$\sigma\,(I \to \textstyle\sum_a h_a \to F) \;\simeq\; \textstyle\sum_a \sigma(I \to h_a)\,(1+\eta_a^{IF})\,\mathrm{BR}(h_a \to F)\,. \tag{34}$$

The calculation of the interference factors $\eta_a^{IF} \equiv \eta(I \to h_a \to F)$ is carried out at leading order only, however it takes into account the radiatively corrected Higgs masses, their total widths Γ_{h_a} and the Z-factors (the latter affect the internal Higgs-boson propagators). The advantage of this procedure is that higher-order corrections to the production and decay processes can be taken into account separately. This factorization is well justified if the total widths of the involved Higgs bosons are not too broad compared to the masses, and only neglects loop diagrams that connect initial and final states (and possible effects of signal-background interference). For a more detailed explanation of this approximation we point the reader to Refs. [114–116].

In the so-called “decoupling limit”, realized in $\mathcal{CP}$-violating scenarios when $M_{H^\pm} \gg M_Z$, the lightest scalar h_1 hardly mixes with the two heavier scalars due to the large mass splitting, and thus remains almost purely $\mathcal{CP}$-even. In contrast, h_2 and h_3 become approximately mass-degenerate and can reach a sizable admixture, resulting in a large destructive interference effect in processes involving $h_{2,3}$ in the s-channel. Focusing on the h_2–h_3 interference, the interference factors are defined as

$$\eta_2^{IF} = \eta_3^{IF} \;\equiv\; \eta(I \to h_{2,3} \to F) \;=\; \frac{\sigma_{\rm coh}}{\sigma_{\rm incoh}} - 1\,, \tag{35}$$

where we distinguish the coherent cross section $\sigma_{\rm coh} = \sigma(|h_2{+}h_3|^2)$ that sums up the amplitudes involving h_2 and h_3 from the incoherent cross section $\sigma_{\rm incoh} = \sigma(|h_2|^2){+}\sigma(|h_3|^2)$. The calculation of the interference factors is implemented in `SusHi` for the initial states $I \in \{gg,\ b\bar{b}\}$ and the final states $F \in \{\tau\tau,\ b\bar{b},\ t\bar{t}\}$. The Higgs-boson propagators are numerically integrated for the invariant mass of the final state, m^F, within $m^F_{\rm min,max} = (m_{h_2} + m_{h_3})/2 \mp 5(\Gamma_{h_2} + \Gamma_{h_3})/2$. The interference factors produced by `SusHi` for the $\tau\tau$ final state, with every combination of initial state and intermediate Higgs boson, are stored in the `ROOT` file for the $M_{h_1}^{125}$(CPV) scenario. They can be used to obtain the correct rates for the processes $gg, b\bar{b} \to h_{2,3} \to \tau\tau$ according to eq. (34).

4 Structure of the `ROOT` files

For each of the scenarios described in section 2 we provide three `ROOT` files, corresponding to cross sections computed with hadronic center-of-mass energies of 8, 13 and 14 TeV. The format of the `ROOT` files is schematically presented in Fig. 1. In each of the files we provide:

- The masses of the neutral and charged Higgs bosons of the MSSM.
- The prediction for the total widths and the branching ratios of the neutral and charged Higgs bosons of the MSSM, computed as described in section 3.2; the histograms for these

quantities are named following the scheme br_<ϕ>_<ij>, where <ϕ>=h,H,A,Hp and <ij> is the final state of the decay channel, and as width_<ϕ> for the total widths. In the case of the $M_{h_1}^{125}$(CPV) scenario, the possible values for <ϕ> are H1,H2,H3,Hp.

- The prediction for the total width of the top quark (width_t) and for the branching ratio of the decay $t \to H^+ b$ (br_t_Hpb).

- The cross sections for the production of the neutral Higgs bosons in gluon fusion, bottom-associated production, VBF, Higgs-strahlung and top-associated production, computed as described in section 3.3; the histograms for the central values of the neutral Higgs cross sections are named following the scheme xs_gg_<ϕ>, xs_bb_<ϕ>, xs_vbf_<ϕ>, xs_hs_Z<ϕ>, xs_hs_W<ϕ>, xs_tth_<ϕ> for the channels listed above, with <ϕ>=h,H,A (for the neutral Higgs bosons in the $M_{h_1}^{125}$(CPV) scenario, <ϕ>=H1,H2,H3 is used instead). Separate histograms for the upper and lower limit of the envelope of scale and PDF+α_s uncertainties are available for the gluon fusion channel, while for the bottom-associated production process we provide only two histograms, with the upper and lower limits of the combined uncertainties; no uncertainties are provided for the other channels.

- The total width, branching ratios and cross sections for a SM Higgs boson of equal mass to the SM-like Higgs boson of the MSSM, following the same histogram naming scheme of the corresponding MSSM quantities but using <ϕ>=HSM instead. Note that we do not provide the cross section uncertainty bands for the SM case.

- The cross section for charged-Higgs production in association with a top, with the corresponding uncertainties, computed as described in section 3.3. The uncertainties are represented by two histograms providing the upper and lower limit of their envelope.

- In the case of the $\mathcal{CP}$-conserving scenarios, the effective mixing angle α, which diagonalizes the radiatively corrected 2×2 mass matrix for the $\mathcal{CP}$-even scalars at zero external momenta. In the case of the $M_{h_1}^{125}$(CPV) scenario, we provide instead the tree-level value of α, as well as the elements of the 3×3 matrix (named Hmix in the files) that rotates the eigenstates (h, H, A) of the tree-level mass matrices for the $\mathcal{CP}$-even and $\mathcal{CP}$-odd scalars into the eigenstates (h_1, h_2, h_3) of the radiatively corrected 3×3 mass matrix for the neutral scalars at zero external momenta.

- In the case of the $\mathcal{CP}$-conserving scenarios, the rescaling factors for the top and bottom Yukawa couplings for all of the three neutral Higgs bosons.

- For all of the scenarios, the real and imaginary parts of Δ_b.

- The effective trilinear coupling of the SM-like Higgs boson of the MSSM, which we call λ_{hhh} (λ_{HHH}) in the $\mathcal{CP}$-conserving scenarios and $\lambda_{h_1h_1h_1}$ in the $\mathcal{CP}$-violating one. We also provide the corresponding coupling computed for a Higgs boson of equal mass in the SM, both at the tree level and at the same level of accuracy as the MSSM one. In the case of the hMSSM the coupling is computed with HDECAY according to eq. (22), whereas for the remaining scenarios it is computed with FeynHiggs, following an approach introduced in

Scenario	Range	Binning (min-max:bin width)
M_h^{125} $M_h^{125}(\tilde{\tau})$ $M_h^{125}(\tilde{\chi})$ $M_h^{125\,\mu_i-}$	$M_A \in [70, 2600]$ GeV $\tan\beta \in [0.5, 60]$	70-200:1, 200-320:5, 320-370:1, 370-2600:5 0.5-1:0.1, 1-10:0.5,10-60:1
M_h^{125}(alignment)	$M_A \in [120, 1000]$ GeV $\tan\beta \in [1, 20]$	120-600:1, 600-1000:5 1-20:0.25
M_H^{125}	$M_{H^\pm} \in [150, 200]$ $\tan\beta \in [5, 6]$	150-200:0.2 5-6:0.01
$M_{h_1}^{125}$(CPV)	$M_{H^\pm} \in [130, 1500]$ $\tan\beta \in [1, 20]$	130-200:1, 200-320:5,320-370:1, 370:1500:5 1-20:0.25
$M_{h,\mathrm{EFT}}^{125}$ $M_{h,\mathrm{EFT}}^{125}(\tilde{\chi})$	$M_A \in [70, 3000]$ $\tan\beta \in [1, 10]$	70-200:1, 200-320:5,320-370:1, 370:3000:5 1-10:0.25
hMSSM	$M_A \in [130, 2000]$ $\tan\beta \in [1, 10]$	130-2000:5 0.5-6:0.1, 6-60:1

Table 1: Range and binning of the 2D histograms provided in the `ROOT` files.

Ref. [25]. In particular, `FeynHiggs` employs a formula analogous to eq. (22), but $\Delta\mathcal{M}^2_{22}$ and the effective mixing angle α are not obtained from eqs. (19) and (21), respectively, and include instead the explicit MSSM results for the one- and two-loop corrections and for the resummation of higher-order logarithmic effects.

- In the case of the $M_{h_1}^{125}$(CPV) scenario, the interference factors for gluon-fusion and bottom-associated Higgs production with the $\tau\tau$ final state, named `int_<in>_tautau_<`ϕ`>` with `<in> = gg,bb` and `<`ϕ`> = H1,H2,H3`.

All of the information is provided in the form of 2D histograms in either the $(M_A, \tan\beta)$ plane or the $(M_{H^\pm}, \tan\beta)$ plane – depending on which mass is treated as input in the considered scenario – implemented using the `TH2F` class provided by `ROOT`. The range of the histograms depends on the scenarios as described in section 2. The binning of the histograms is not uniform, and it was chosen to provide an adequate resolution across the parameter plane in light of the Higgs-sector phenomenology. Predictions with a finer granularity are available upon request. We summarize the binning information in Table 1.

The `ROOT` files are made available via the Zenodo record *"LHCHWG MSSM ROOT files"* [31]. Subsequent updates will be released via the same record. A unique DOI is associated to each new release, allowing for the tracking of the exact version of the `ROOT` files used in a given study. The `ROOT` files were generated with `ROOT` version `6.24`. Accessing these files with older versions of `ROOT` may not be possible.

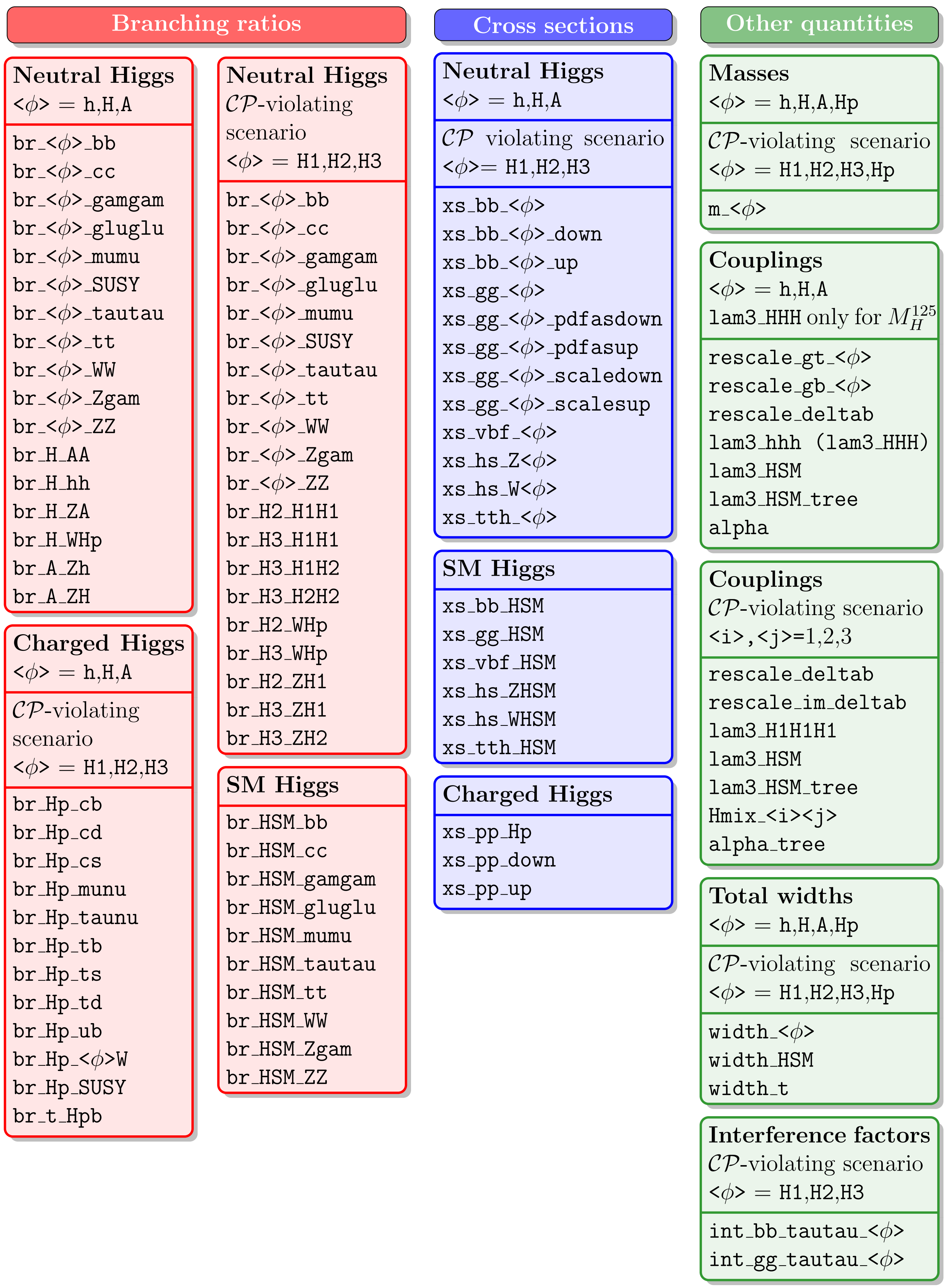

Figure 1: Schematic representation of the format used in the ROOT files. Every item is stored as a TH2F object.

5 The ROOT file access tool

The histograms in the ROOT files can be directly accessed by the users through their own code. However, as a matter of convenience, we provide a standard interface and we make it available in our gitlab repository [117] and on the Twiki page of the MSSM working group. Below we provide a description of the most important aspects of the access tool, as it stands in version 2.4.

The access tool consists of the following files:

- mssm_xs_tools.h and mssm_xs_tools.C are the definition and the implementation of the mssm_xs_tools C++ class, which constitutes our interface to the ROOT files;
- mssm_xs_tools.py is a Python wrapper for the C++ class mssm_xs_tools.

It is possible to use the interface interactively by directly loading the class in the ROOT interpreter. For this purpose, the following commands should be executed

```
> root
root[0] .L mssm_xs_tools.C
```

Once this is done, if for instance the predictions for the M_h^{125} scenario with cross sections computed at 13 TeV are required, the corresponding ROOT file can be loaded via the following set of commands

```
root[1] mssm=mssm_xs_tools("mh125_13.root",true,0)
root[2] MA=1300
root[3] mssm.mass("h",MA,3)
root[4] mssm.width("H",MA,3)
root[5] mssm.br("H->tautau",MA,3)
root[6] mssm.xsec("gg->H",MA,3)
```

A similar syntax would be used in a C++ source file within a compiled program.

In order to use the Python wrapper, the ROOT module has to be compiled into a library using the '++' syntax of ROOT

```
> root
root[0] .L mssm_xs_tools.C++
```

Then the interface can be accessed via ctypes (or equivalent framework), as shown in the example script mssm_xs_tools.py.

5.1 Structure of the mssm_xs_tools class

The structure of the mssm_xs_tools class is the following.

```
mssm_xs_tools(const char* filename="", bool kINTERPLOTATION=false,
              unsigned verbosity=0)
```

The constructor takes three variables as arguments: a pointer to a `char`, `filename`, which provides the name of the `ROOT` file to be opened; a boolean variable, `kINTERPLOTATION`, which enables or disables the linear interpolation of the histograms between the grid nodes; an unsigned `int`, `verbosity`, which when set to 0 suppresses the output, and when set to `3` or `100` makes the interface print more information.

```
TH2F* hist(std::string name);
```

The `public` function `hist` returns a pointer to a `TH2F` instance corresponding to the histogram specified via the `std::string` given as argument. On the first call, the histogram is loaded from the `ROOT` file that was given to the constructor; on subsequent calls, the address to the already loaded object is returned. Part of the histogram information is cached after the first call. If the histogram does not exist and it is impossible to load it from the input file, the call returns `NULL`.

```
double  mass(const char* boson, double mphi, double tanb);
double width(const char* boson, double mphi, double tanb);
```

These `public` functions return the mass and the width of the Higgs boson specified by the string pointed by `boson` (its possible values being `h, H, A, H1, H2, H3, Hp`), for the parameter space point specified by the two `double` arguments `mphi` and `tanb`. In these functions, and elsewhere in our interface, `mphi` is M_A or $M_{H^\pm}$ depending on the definition of the scenario.

```
double       br(const char* decay, double mphi, double tanb);
double     xsec(const char*  mode, double mphi, double tanb);
double coupling(const char* boson, double mphi, double tanb);
```

These `public` functions return the value of branching ratios, cross sections and couplings for the point in the parameter space specified by the arguments `mphi` and `tanb`.

To specify the decay channel when calling the function `br`, the argument `decay` should be of the form "`<boson>-><decay>`", where `<boson>` can assume the same values as as the ones used for the functions `mass` and `width` described above, and `<decay> = tautau, mumu, ...` selects the final state.

In addition, the function `br` can also be used to retrieve the value of the branching ratio of the top to H^+b, using the string "`t->Hpb`" for the argument `decay`.

When retrieving a cross section with the function `xsec`, the argument `mode` should be of the form "`<channel>-><boson>`", where `<channel> = gg, bb, vbf, hs_Z, hs_W, tth`. Cross-section uncertainties are accessed by appending a tag to the string, i.e. "`<channel>-><boson>::<tag>`" where `<tag> = scaleup, scaledown, pdfasdown, pdfasup, down, up`. The possible values for `<boson>` are the same as the ones recognized by the function `br`.

Calling `coupling` requires "`boson`" to be of the form "`<coupling>_<boson>`", where `<coupling>` = `gt, gb`, or to be "`lam3hhh`", "`lam3HHH`", "`lamh31h1h1`", "`lam3HSM`", "`lam3HSMtree`".

To improve the user-friendliness of the interface, we also provide a complementary set of `public` functions that do not require any specification of the requested quantities with a formatted string. Due to their number, below we present only an illustrative subset of them. The complete set of definitions can be found in `mssm_xs_tools.h`.

```
double mh(double mphi, double tanb);
double mH(double mphi, double tanb);
[...]
```

These functions return the mass of a specific Higgs boson in the parameter space point determined by the arguments `mphi` and `tanb`;

```
double width_h(double mphi, double tanb);
double width_H(double mphi, double tanb);
[...]
```

These functions return the total width of a specific Higgs boson in the parameter space point determined by the arguments `mphi` and `tanb`;

```
double gtA(double mphi, double tanb);
[...]
```

These functions return the value of one of the coupling modifiers for a specific Higgs boson in the parameter space point determined by the arguments `mphi` and `tanb`;

```
double re_deltab(double mphi, double tanb);
double im_deltab(double mphi, double tanb);
```

These functions return the real and imaginary parts of Δ_b in the parameter space point determined by the arguments `mphi` and `tanb`;

```
double br_htt(double mphi, double tanb);
[...]
```

These functions return the value of a specific branching ratio in the parameter space point determined by the arguments **mphi** and **tanb**;

```
double ggH_A(double mphi, double tanb);
[...]
```

These functions return the value of a specific cross section in the parameter space point determined by the arguments **mphi** and **tanb**;

```
double ggH_A_scale(double mphi, double tanb, const bool kUP);
double ggH_A_uncboundaries(double mphi, double tanb,
                           const bool kUP);
[...]
```

These functions return the uncertainty range for a specific cross section in the parameter space point determined by the arguments **mphi** and **tanb**;

```
double interference_bb_tautau_H3(double mphi, double tanb);
[...]
```

These functions return the interference factors for a specific process in the $M_{h_1}^{125}$(CPV) scenario.

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