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MSSM Higgs Boson Searches at the LHC: Benchmark Scenarios after the Discovery of a Higgs-like Particle

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Abstract

A Higgs-like particle with a mass of ~ 125.7 GeV has been discovered at the LHC. Within the experimental uncertainties this new state is compatible with the Higgs boson of the Standard Model (SM). On the oher hand, it is also compatible with the predictions of the Higgs sector of the Minimal Supersymmetric Standard Model (MSSM), interpreting the new state either as the light or the heavy $\mathcal{CP}$-even Higgs boson. At the same time, the searches for the additional Higgs bosons of the MSSM place important constraints on the parameter space. We suggest new MSSM benchmark scenarios that are in agreement with the discovery of the new state at ~ 125.7 GeV and at the same time exhibit the general features of the rest of the MSSM Higgs spectrum. In particular, we propose a modified $m_h^{\max}$ scenario, in which the light $\mathcal{CP}$-even Higgs boson is in the range between 123 GeV and 127 GeV over large parts of the M_A-$\tan\beta$ plane and behaves SM-like. Similarly we define a scenario in which the heavy $\mathcal{CP}$-even Higgs is interpreted as the newly discovered state and behaves SM-like. Finally we define a variant of the "small $\alpha_{\rm eff}$" scenario in which the light Higgs has suppressed couplings to bottom-like fermions. We suggest that the base scenarios are supplemented with a variation of the μ parameter. This affects only slightly the search channels for a SM-like Higgs boson, while having a major impact on the searches for non-standard MSSM Higgs bosons.

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1 Introduction

Disentangling the mechanism that controls electroweak symmetry breaking is one of the main tasks of the LHC. The spectacular discovery of a Higgs-like particle with a mass around $M_H \simeq 125.7$ GeV, which has just been announced by ATLAS and CMS [?], marks a milestone of an effort that has been ongoing for almost half a century and opens a new era of particle physics. Both ATLAS and CMS reported a clear excess around ~ 125.7 GeV in the two photon channel as well as in the $ZZ^{(*)}$ channel, whereas the analyses in other channels have a lower mass resolution and at present are less mature. The combined sensitivity in each of the experiments reaches about $\sim 5\sigma$. The observed rate in the $\gamma\gamma$ channel turns out to be considerably above the expectation for a SM Higgs both for ATLAS and CMS. While the statistical significance of this possible deviation from the SM prediction is not sufficient at present to draw a definite conclusion, if confirmed in the future it could be a first indication of a non-SM nature of the new state.

Among the most studied candidates for EWSB in the literature are the Higgs mechanism within the Standard Model (SM) or within the Minimal Supersymmetric Standard Model (MSSM). Contrary to the SM, two Higgs doublets are required in the MSSM, resulting in five physical Higgs boson degrees of freedom. In the absence of explicit $\mathcal{CP}$-violation in the soft supersymmetry-breaking terms these are the light and heavy $\mathcal{CP}$-even Higgs bosons, h and H, the $\mathcal{CP}$-odd Higgs boson, A, and the charged Higgs boson, $H^\pm$. The Higgs sector of the MSSM can be specified at lowest order in terms of M_Z, M_A, and $\tan\beta \equiv v_2/v_1$, the ratio of the two Higgs vacuum expectation values. The masses of the $\mathcal{CP}$-even neutral Higgs bosons and the charged Higgs boson can be calculated, including higher-order corrections, in terms of the other MSSM parameters [?]. An upper bound of ~ 135 GeV for the mass of the lightest MSSM Higgs boson mass was obtained [32]. The theoretical uncertainty in the calculation of M_h was estimated to be at the level of $\sim 2 - 3$ GeV [32].

The measurements of the production cross sections times branching ratios of the new state around ~ 125.7 GeV show, within the experimental uncertainties, a SM-like behavior. However, since the experimental uncertainties are still rather large, also a Higgs particle with couplings (substantially) deviating from the SM prediction can fit the data. It was shown that in particular that the interpretation of the new state as the light $\mathcal{CP}$-even Higgs boson of the MSSM is a viable possibility [?]. On the other hand, it was also pointed out that the heavy $\mathcal{CP}$-even Higgs boson can have a mass around ~ 125.7 GeV, while maintining (within the uncertainties) a SM-like behavior.

At the same time the search for "the other" MSSM Higgs bosons at the LHC continued. In the case of the light $\mathcal{CP}$-even Higgs at ~ 125.7 GeV the search for the heavy Higgs bosons was pursued mainly via the channels ($\phi = h, H, A$):

$$b\bar{b}\phi, \phi \to b\bar{b} \tag{1}$$

$$p\bar{p} \to \phi \to \tau^+\tau^- \text{ (inclusive)}, \tag{2}$$

$$p\bar{p} \to t\bar{t} \to H^\pm W^\mp b\bar{b}, H^\pm \to \tau\nu_\tau \ . \tag{3}$$

The non-observation of any additional state puts by now stringent constaints on the MSSM parameter space. Similarly, the non-observation of SUSY particles puts constraints on the masses of, in particular, the first and second generation of scalar quarks as well as of the gluino.

Due to the large number of free parameters, a complete scan of the MSSM parameter space is too involved. Therefore the search results at LEP have been interpreted [2] in several benchmark scenarios [3,4]. In these scenarios only the two parameters that enter the Higgs sector tree-level predictions, M_A and $\tan\beta$ are varied (i.e. the results are shown in the M_A-$\tan\beta$ plane), whereas the other SUSY parameters, entering via radiative corrections, are fixed in a particular way. The $m_h^{\max}$ scenario has been used to obtain conservative bounds on $\tan\beta$ for fixed values of the top-quark mass and the scale of the supersymmetric particles [5]. Besides the $m_h^{\max}$ scenario and the no-mixing scenario, where a vanishing mixing in the stop sector is assumed, the "small $\alpha_{\rm eff}$" scenario and the "gluophobic Higgs scenario" have been investigated [2]. While the latter one exhibits a strong suppression of the ggh coupling over large parts of the M_A–$\tan\beta$ parameter space, the small $\alpha_{\rm eff}$ scenario has strongly reduced couplings of the light $\mathcal{CP}$-even Higgs boson to bottom-type fermions up to $M_A \lesssim 350$ GeV. These scenarios were conceived to study particular cases of challenging and interesting phenomenology in the searches for the SM-like Higgs boson, i.e. mostly the light $\mathcal{CP}$-even Higgs boson. Subsequent analyses at the Tevatron and at the LHC also have been performed in the scenarios proposed in Refs. [3,4]. However, in the search for the heavier MSSM Higgs bosons it was noted that via the inclusion of the Δ_b corrections (see below), in particular, a dependence on the Higgs mixing parameter μ enters the investigations [**?**]. Consequently, it was proposed to augment the traditional $m_h^{\max}$ and no-mixing scenario with a variation of μ [**?**].

The "traditional" benchmark scenarios are strongly constrained by the observation of a Higgs-like state at ~ 125.7 GeV. The $m_h^{\max}$ scenario is in agreement with the interpretation of the light $\mathcal{CP}$-even Higgs boson at $M_h \sim 125.7$ GeV in a small strip at lower $\tan\beta$. The no-mixing scenario has $M_h \lesssim 122$ GeV and is thus not in agreement with the recent discovery. Also the other two scenarios, small $\alpha_{\rm eff}$ and gluophobic Higgs, are not in agreement with $M_h \sim 125.7$ GeV. The scenarios discussed here are designed specifically to produce a Higgs boson with a mass around ~ 125.7 GeV (taking into account the theoretical uncertainties). They are defined to study the MSSM Higgs sector and to explore its possibilities especially for the searches of the "other" MSSM Higgs bosons while having a neutral Higgs around ~ 125.7 GeV. On the other hand, we do not assume any particular soft supersymmetry-breaking scenario and taking into account constraints only from the Higgs boson sector itself. In particular, constraints from requiring the correct cold dark matter density, BR$(b \to s\gamma)$, BR$(B_s \to \mu^+\mu^-)$ or $(g-2)_\mu$, which depend on other parameters of the theory, are not crucial in defining the Higgs boson sector, and may be avoided.

The paper is organized as follows: Section 2 gives a summary of the most relevant supersymmetric sectors and parameters. We briefly review the radiative corrections to the relevevant Higgs boson production cross section and decay widths. In section 3 we propose new MSSM benchmark scenarios taking into account the recent "constraints" from the LHC Higgs searches, including the discovery around ~ 125.7 GeV. The conclusions are presented in section 4.

2 Theoretical basis

2.1 Notation

The tree-level values for the $\mathcal{CP}$-even Higgs bosons of the MSSM, m_h and m_H, are determined by $\tan\beta$, the $\mathcal{CP}$-odd Higgs-boson mass M_A, and the Z boson mass M_Z. The mass of the charged Higgs boson, $M_{H^\pm}$, is given in terms of M_A and the W boson mass, M_W. Beyond the tree-level, the main correction to the Higgs boson masses stems from the $t/\tilde{t}$ sector, and for large values of $\tan\beta$ also from the $b/\tilde{b}$ sector, see Ref. [?] for reviews.

In order to fix our notations, we list the conventions for the inputs from the scalar top and scalar bottom sector of the MSSM: the mass matrices in the basis of the current eigenstates $\tilde{t}_L, \tilde{t}_R$ and $\tilde{b}_L, \tilde{b}_R$ are given by

$$\mathcal{M}^2_{\tilde{t}} = \begin{pmatrix} M^2_{\tilde{t}_L} + m_t^2 + \cos 2\beta(\frac{1}{2} - \frac{2}{3}s_\mathrm{w}^2)M_Z^2 & m_t X_t \\ m_t X_t & M^2_{\tilde{t}_R} + m_t^2 + \frac{2}{3}\cos 2\beta s_\mathrm{w}^2 M_Z^2 \end{pmatrix}, \tag{4}$$

$$\mathcal{M}^2_{\tilde{b}} = \begin{pmatrix} M^2_{\tilde{b}_L} + m_b^2 + \cos 2\beta(-\frac{1}{2} + \frac{1}{3}s_\mathrm{w}^2)M_Z^2 & m_b X_b \\ m_b X_b & M^2_{\tilde{b}_R} + m_b^2 - \frac{1}{3}\cos 2\beta s_\mathrm{w}^2 M_Z^2 \end{pmatrix}, \tag{5}$$

where

$$m_t X_t = m_t(A_t - \mu\cot\beta), \quad m_b\, X_b = m_b\,(A_b - \mu\tan\beta). \tag{6}$$

Here A_t denotes the trilinear Higgs–stop coupling, A_b denotes the Higgs–sbottom coupling, and μ is the higgsino mass parameter.

SU(2) gauge invariance leads to the relation

$$M_{\tilde{t}_L} = M_{\tilde{b}_L}. \tag{7}$$

For the numerical evaluation, a convenient choice is

$$M_{\tilde{t}_L} = M_{\tilde{b}_L} = M_{\tilde{t}_R} = M_{\tilde{b}_R} =: M_\mathrm{SUSY}. \tag{8}$$

Concerning analyses for the case where $M_{\tilde{t}_R} \neq M_{\tilde{t}_L} \neq M_{\tilde{b}_R}$, see e.g. Refs. [11, 12]. Accordingly, the most important parameters for the corrections in the Higgs sector are m_t, M_SUSY, X_t, and X_b.

The corresponding soft SUSY-breaking parameters in the scalar tau/neutrino sector are denoted as $M_{\tilde{l}_3}$, where we assume the diagonal entries to be equal as in the $\tilde{t}/\tilde{b}$ sector, and A_τ. For the squarks and sleptons of the first and second generation we also assume "unification" of the diagonal soft SUSY-breaking parameters, denoted as $M_{\tilde{q}_{1,2}}$ and $M_{\tilde{l}_{1,2}}$, respectively. The off-diagonal A-terms are always multiplied with the corresponding fermion mass and can be set to zero without any loss of generality.

The Higgs sector observables furthermore depend on the SU(2) gaugino mass parameter, M_2. The other gaugino mass parameter, M_1, is usually fixed via the GUT relation

$$M_1 = \frac{5}{3}\frac{s_\mathrm{w}^2}{c_\mathrm{w}^2} M_2. \tag{9}$$

At the two-loop level also the gluino mass, $m_{\tilde{g}}$, enters the predictions for the Higgs-boson masses.

2.2 Calculations in the OS and the $\overline{\rm DR}$ scheme

Corrections to the MSSM Higgs boson sector have been evaluated in several approaches, see Refs. [?, ?] for reviews. The remaining theoretical uncertainty on the light $\mathcal{CP}$-even Higgs boson mass has been estimated to be below ~ 2 GeV [32,33]. The existing calculations have been implemented into public codes. The program `FeynHiggs` [?, 12, 32, 34] is based on the results obtained in the Feynman-diagrammatic (FD) approach. The code `CPsuperH` [38] is based on the renormalization group (RG) improved effective potential approach [18, 19, 39]. For the MSSM with real parameters the two codes can differ by up to ~ 4 GeV for the light $\mathcal{CP}$-even Higgs boson mass, mostly due to formally subleading two-loop corrections that are included only in `FeynHiggs`. Both codes are missing the subleading two-loop contributions evaluated in Ref. [?], which are not available in a readily usable code format. They are furthermore missing the existing 3-loop corrections as evaluated in Refs. [?, ?], which are not available in a format to be added straight forwardly to the existing calculations (see, however, Ref. [?].)

It should be noted in this context that the FD result has been obtained in the on-shell (OS) renormalization scheme, whereas the RG result has been calculated using the $\overline{\rm MS}$ scheme; see Refs. [39, 44] for a detailed comparison. Owing to the different schemes used in the FD and the RG approach for the renormalization in the scalar top sector, the parameters X_t and $M_{\rm SUSY}$ are also scheme-dependent in the two approaches. This difference between the corresponding parameters has to be taken into account when comparing the results of the two approaches. In a simple approximation the relation between the parameters in the different schemes is at $\mathcal{O}(\alpha_s)$ given by [39]

$$M_S^{2,\overline{\rm MS}} \approx M_S^{2,{\rm OS}} - \frac{8}{3}\frac{\alpha_s}{\pi}M_S^2, \tag{10}$$

$$X_t^{\overline{\rm MS}} \approx X_t^{\rm OS} + \frac{\alpha_s}{3\pi}M_S\left(8 + 4\frac{X_t}{M_S} - 3\frac{X_t}{M_S}\log\left(\frac{m_t^2}{M_S^2}\right)\right), \tag{11}$$

where in the terms proportional to α_s it is not necessary to distinguish between $\overline{\rm MS}$ and on-shell quantities, since the difference is of higher order. While the resulting shift in the parameter $M_{\rm SUSY}$ turns out to be relatively small in general, sizable differences can occur between the numerical values of X_t in the two schemes, see Refs. [12, 39]. For this reason we specify below different values for X_t within the two approaches.

2.3 Leading effects from the bottom/sbottom sector

The relation between the bottom-quark mass and the Yukawa coupling h_b, which controls also the interaction between the Higgs fields and the sbottom quarks, reads at lowest order $m_b = h_b v_1$. This relation is affected at one-loop order by large radiative corrections [28–30, 45], proportional to $h_b v_2$, in general giving rise to $\tan\beta$-enhanced contributions. These terms proportional to v_2, often called threshold corrections to the bottom mass, are generated either by gluino–sbottom one-loop diagrams (resulting in $\mathcal{O}(\alpha_b\alpha_s)$ corrections to the Higgs masses), or by chargino–stop loops (giving $\mathcal{O}(\alpha_b\alpha_t)$ corrections). Because the $\tan\beta$-enhanced contributions can be numerically relevant, an accurate determination of h_b

from the experimental value of the bottom mass requires a resummation of such effects to all orders in the perturbative expansion, as described in Refs. [29, 30].

The leading effects are included in the effective Lagrangian formalism developed in Ref. [29]. Numerically this is by far the dominant part of the contributions from the sbottom sector (see also Refs. [26, 27, 31]). The dominant contributions arise from the loop-induced coupling of H_u (the Higgs field that couples at the tree-level to up-type fermions only) to the down-type fermions. The effective Lagrangian is given by

$$\mathcal{L} = \frac{g}{2M_W}\frac{\overline{m}_b}{1+\Delta_b}\Bigg[\tan\beta\, A\, i\, \bar{b}\gamma_5 b + \sqrt{2}\, V_{tb}\, \tan\beta\, H^+ \bar{t}_L b_R + \left(\frac{\sin\alpha}{\cos\beta} - \Delta_b \frac{\cos\alpha}{\sin\beta}\right) h \bar{b}_L b_R - \left(\frac{\cos\alpha}{\cos\beta} + \Delta_b \frac{\sin\alpha}{\sin\beta}\right) H \bar{b}_L b_R \Bigg] + \text{h.c.}\ . \tag{12}$$

Here $\overline{m}_b$ denotes the running bottom quark mass including SM QCD corrections. In the numerical evaluations obtained with `FeynHiggs` below we choose $\overline{m}_b = \overline{m}_b(m_t) \approx 2.97$ GeV. The prefactor $1/(1+\Delta_b)$ in Eq. (12) arises from the resummation of the leading corrections to all orders. The additional terms $\sim \Delta_b$ in the $h\bar{b}b$ and $H\bar{b}b$ couplings arise from the mixing and coupling of the "other" Higgs boson, H and h, respectively, to the b quarks.

As explained above, the function Δ_b consists of two main contributions, an $\mathcal{O}(\alpha_s)$ correction from a sbottom–gluino loop and an $\mathcal{O}(\alpha_t)$ correction from a stop–higgsino loop.[1] The explicit form of Δ_b in the limit of $M_S \gg m_t$ and $\tan\beta \gg 1$ reads [28]

$$\Delta_b = \frac{2\alpha_s}{3\,\pi}\, m_{\tilde{g}}\, \mu\, \tan\beta\, \times\, I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) + \frac{\alpha_t}{4\,\pi}\, A_t\, \mu\, \tan\beta\, \times\, I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu)\ . \tag{13}$$

The function I is given by

$$\begin{aligned} I(a,b,c) &= \frac{1}{(a^2-b^2)(b^2-c^2)(a^2-c^2)} \left(a^2 b^2 \log\frac{a^2}{b^2} + b^2 c^2 \log\frac{b^2}{c^2} + c^2 a^2 \log\frac{c^2}{a^2} \right) \\ &\sim \frac{1}{\max(a^2, b^2, c^2)}\ . \end{aligned} \tag{14}$$

The large $\tilde{b}-\tilde{g}$ loops are resummed to all orders of $(\alpha_s \tan\beta)^n$ via the inclusion of Δ_b [28–30]. The leading electroweak contributions are taken into account via the second term in Eq. (13).

For large values of $\tan\beta$ and the ratios of $\mu m_{\tilde{g}}/M^2_{\text{SUSY}}$ and $\mu A_t/M^2_{\text{SUSY}}$, the Δ_b correction can become very important. Considering positve values of A_t and $m_{\tilde{g}}$, the sign of the Δ_b term is governed by the sign of μ. Cancellations can occur if A_t and $m_{\tilde{g}}$ have opposite signs. For $\mu, m_{\tilde{g}}, A_t > 0$ the Δ_b correction is positive, leading to a suppression of the bottom Yukawa coupling. On the other hand, for negative values of Δ_b, the bottom Yukawa coupling may be strongly enhanced and can even acquire non-perturbative values when $\Delta_b \to -1$. The inclusion of Δ_b into the MSSM Higgs sector

[1] The evaluation in `FeynHiggs` contains the full one-loop contributions to Δ_b as given in Ref. [?]. Furthermore the leading QCD two-loop corrections to Δ_b are available [?], which stabilize the scale dependence of Δ_b substantially.

In Ref. [?] the impact of the Δ_b corrections on the searches for, in particular, the heavy MSSM Higgs bosons was analyzed. It was shown that the exclusion bounds in the channels

$$b\bar{b}\phi, \phi \to b\bar{b} \quad (\phi = h, H, A) \tag{15}$$

$$p\bar{p} \to t\bar{t} \to H^{\pm}W^{\mp}\, b\bar{b}, H^{\pm} \to \tau\nu_{\tau} \tag{16}$$

depend strongly on the sign and size of Δ_b, whereas the channel

$$p\bar{p} \to \phi \to \tau^+\tau^- \quad (\phi = h, H, A) \tag{17}$$

shows a weaker dependence on Δ_b. It was recommended in Ref. [?] to augment the 'traditional benchmark scenarios', such as the $m_h^{\max}$ and the no-mixing scenario [4] with a variation of μ in the range -1000 GeV to $+1000$ GeV to explore the full phenomenology of the MSSM Higgs sector.

3 Benchmark Scenarios

The benchmark scenarios defined in Ref. [4], which were mainly designed for the search for the light $\mathcal{CP}$-even Higgs boson h in the $\mathcal{CP}$-conserving case, are also useful in the search for the heavy MSSM Higgs bosons H, A and $H^{\pm}$. In order to take into account the discovery of a Higgs-like state at ~ 125.7 GeV we suggest several scenarios in the following subsections.

Concerning the parameters that have a minor impact on the MSSM Higgs sector predictions we recommend the following values:

$$M_{\tilde{q}_{1,2}} = 1500 \text{ GeV} , \tag{18}$$

$$M_{\tilde{l}_{1,2}} = 500 \text{ GeV} . \tag{19}$$

$$\tag{20}$$

Motivated by the analysis in Ref. [?] we suggest to investigate the following values of μ in addition to the value given in the following subsections:

$$\mu = \pm 200, \pm 500, \pm 1000 \text{ GeV} , \tag{21}$$

allowing both an enhancement and a suppression of the bottom Yukawa coupling and taking into account the limits from direct searches for charginos at LEP [69].

The value of the top-quark mass in Refs. [?, 4] was chosen according to the experimental central value at that time. We propose to substitute this value with the most up-to-date experimental central value for m_t, see below.

3.1 The $m_h^{\max}$ scenario

The $m_h^{\max}$ scenario was defined to give conservative exclusion bounds on $\tan\beta$ in the LEP Higgs searches. The scenario can provide conservative lower bounds on M_A, $M_{H^\pm}$ and $\tan\beta$ if the light $\mathcal{CP}$-even Higgs is interpreted as the newly discovered state at ~ 125.7 GeV [?]. In Fig. 1 we show the MA-$\tan\beta$ plane (left) and the $M_{H^\pm}$-$\tan\beta$ plane (right) in the $m_h^{\max}$ scenario (as updated from Ref. [?]). The blue areas are excluded by LEP Higgs searches, the brown areas by the LHC searchses for heavy Higgs bosons (both evaluated with `HiggsBounds` [?]. The two green shades correspond to to $M_h = 125.7 \pm 2(3)$ GeV. New conservative lower bounds are obtained in the $m_h^{\max}$ scenario as the lowest values in the green bands (see Ref. [?] for details). These bounds will improve in the future by a more precise experimental determination of M_h, by a more precise theory evaluation of M_h and by extended exclusion regions from the LHC heavy MSSM Higgs boson searches.

The (updated) $m_h^{\max}$ scenario is defined as (with the remaining values defined in Eq. (20))
$\underline{m_h^{\max}:}$

$$
\begin{aligned}
m_t &= 173.2 \text{ GeV}, \\
M_{\rm SUSY} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\rm OS} &= 2\, M_{\rm SUSY} \text{ (FD calculation)}, \\
X_t^{\overline{\rm MS}} &= \sqrt{6}\, M_{\rm SUSY} \text{ (RG calculation)}, \\
A_b &= A_\tau = A_t, \\
m_{\tilde g} &= 800 \text{ GeV}, \\
M_{\tilde l_3} &= 1000 \text{ GeV} \;.
\end{aligned}
\tag{22}
$$

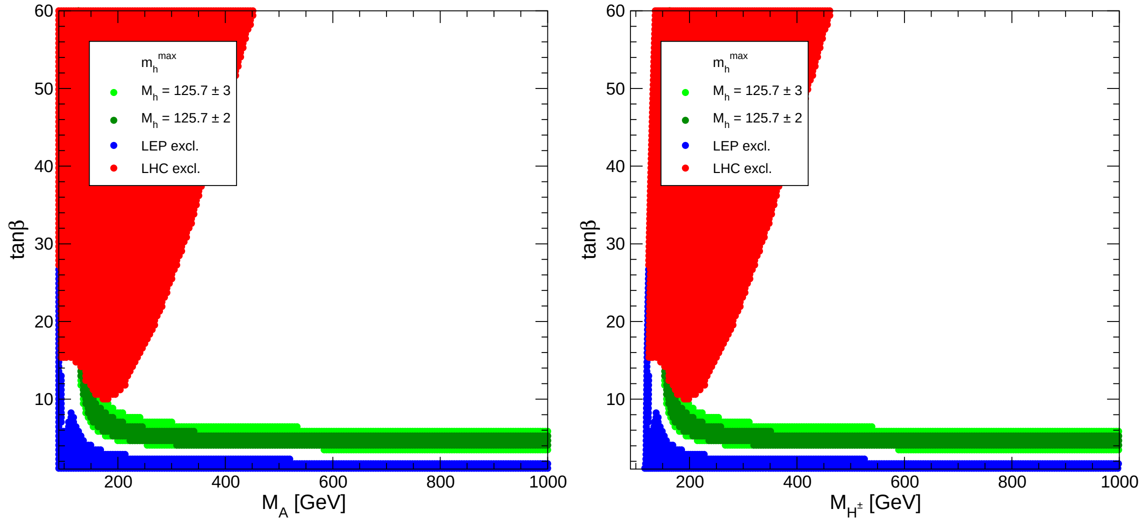

Figure 1: The MA-$\tan\beta$ plane (left) and the $M_{H^\pm}$-$\tan\beta$ plane (right) are shown in the $m_h^{\rm max}$ scenario (as updated from Ref. [?]). The blue areas are excluded by LEP Higgs searches, the brown areas by the LHC searchses for heavy Higgs bosons. The two green shades correspond to to $M_h = 125.7 \pm 2(3)$ GeV.

3.2 The $m_h^{\rm mod}$ scenario

As visible in Fig. 1 the light $\mathcal{CP}$-even Higgs is in agreement with the discovery of a Higgs-like state only in a small strip in the M_A-$\tan\beta$ plane at relatively low $\tan\beta$. By a variation to lower values of either $M_{\rm SUSY}$ or $X_t/M_{\rm SUSY}$ the corresponding M_h values are lowered. In order to arrive at $M_h = 125.7 \pm 3$ GeV the change in the stop sector parameters can be compensated by a change in $\tan\beta$, and larger $\tan\beta$ values are in agreement with the lightest $\mathcal{CP}$-even Higgs mass interpreted as the newly discovered state. Consequently, we define the $m_h^{\rm mod}$ scenario with a lower value of $X_t/M_{\rm SUSY}$. This scenario is in agreement with the recent discovery over nearly the whole M_A-$\tan\beta$ plane, as can be seen in Fig. 2.

We split the definition into two scenarios, the $m_h^{\rm mod+}$ and the $m_h^{\rm mod-}$ scenario with differ by the sign and the size of $X_t/M_{\rm SUSY}$. While the positive sign of the product $(\mu\, M_2)$ results in general in better agreement with the $(g-2)_\mu$ experimental results, the negative sign of the product $(\mu\, A_t)$ yields in general (assuming minimal flavor violation) better agreement with the BR$(b \to s\gamma)$ measurements.

$\underline{m_h^{\rm mod+}}$:

$$
\begin{aligned}
m_t &= 173.2 \text{ GeV}, \\
M_{\rm SUSY} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\rm OS} &= 1.5\, M_{\rm SUSY} \text{ (FD calculation)}, \\
X_t^{\overline{\rm MS}} &= 1.9\, M_{\rm SUSY} \text{ (RG calculation)}, \\
A_b &= A_\tau = A_t,
\end{aligned}
$$

$$
\begin{aligned}
m_{\tilde{g}} &= 1500 \text{ GeV}, \\
M_{\tilde{l}_3} &= 1000 \text{ GeV} \ .
\end{aligned} \tag{23}
$$

$\underline{m_h^{\text{mod}-}:}$

$$
\begin{aligned}
m_t &= 173.2 \text{ GeV}, \\
M_{\text{SUSY}} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\text{OS}} &= -1.9\, M_{\text{SUSY}} \text{ (FD calculation)}, \\
X_t^{\overline{\text{MS}}} &= -2.2\, M_{\text{SUSY}} \text{ (RG calculation)}, \\
A_b &= A_\tau = A_t, \\
m_{\tilde{g}} &= 1500 \text{ GeV}, \\
M_{\tilde{l}_3} &= 1000 \text{ GeV} \ .
\end{aligned} \tag{24}
$$

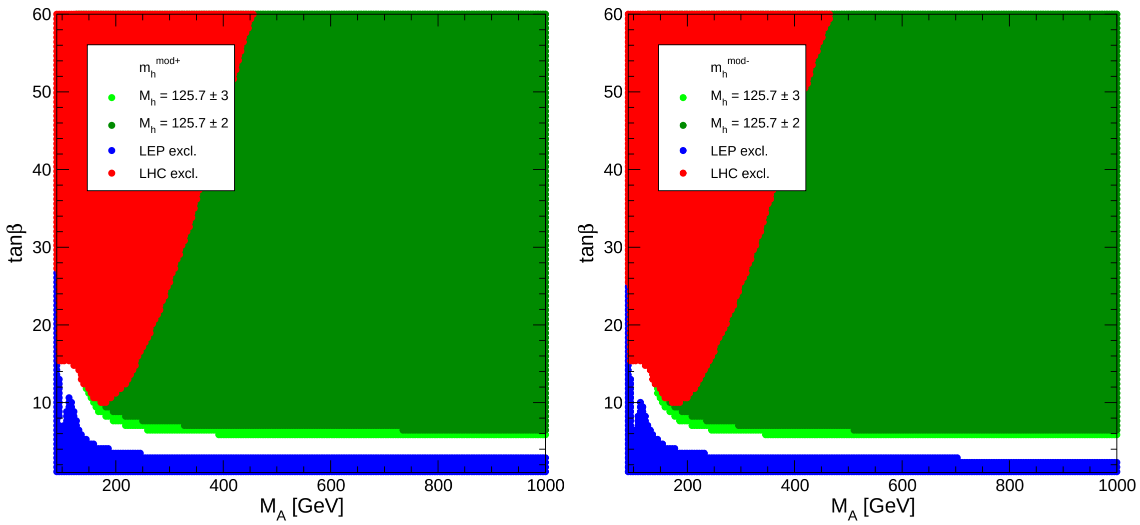

Figure 2: The MA-$\tan\beta$ plane in the $m_h^{\text{mod}+}$ (left) and the $m_h^{\text{mod}-}$ scenario (right). The color coding is as in Fig. 1.

3.3 The low-M_H scenario

As it was shown in Refs. [?, ?] it is also possible to identify the heavy $\mathcal{CP}$-even Higgs with the Higgs-like state at ~ 125.7 GeV. The heavy Higgs behaves SM-like and the scenario can fulfill the experimental constraints from low-energy and B-physics. We define the "low-M_H" scenario in which large parts of the M_A-tb plane are in agreement with $M_H \sim 125.7$ GeV, as can be seen in Fig. 3.

low-M_H:

$$\begin{aligned}
m_t &= 173.2 \text{ GeV}, \\
M_{\text{SUSY}} &= 1000 \text{ GeV}, \\
\mu &= 2300 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\text{OS}} &= 1\, M_{\text{SUSY}} \text{ (FD calculation)}, \\
X_t^{\overline{\text{MS}}} &= 1.2\, M_{\text{SUSY}} \text{ (RG calculation)}, \\
A_b &= A_\tau = A_t, \\
m_{\tilde{g}} &= 1500 \text{ GeV}, \\
M_{\tilde{l}_3} &= 1000 \text{ GeV} .
\end{aligned} \tag{25}$$

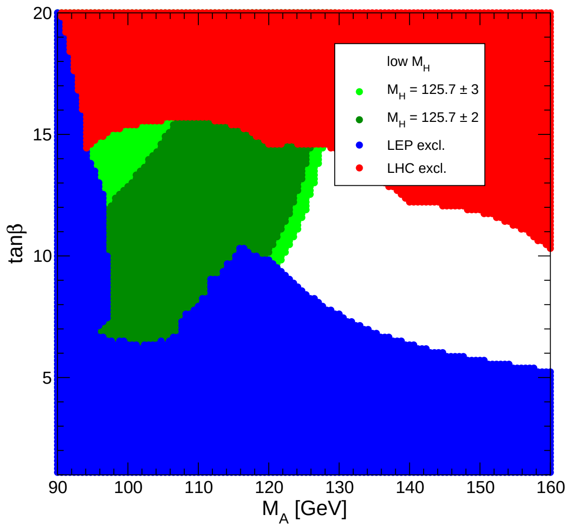

Figure 3: The MA-$\tan\beta$ plane in the low-M_H scenario. The blue areas are excluded by LEP Higgs searches, the brown areas by the LHC searchses for heavy Higgs bosons. The two green shades correspond to to $M_H = 125.7 \pm 2(3)$ GeV.

3.4 The light stop scenario

Various differences in the production and decay modes of the light (or heavy) $\mathcal{CP}$-even Higgs can be realized in the MSSM with respect to the SM Higgs properties. Here we propose a new scenario that contains relatively light scalar top and bottom quarks that can have an impact, e.g., on $\sigma(gg \to h)$. The parameters are

light stop:

$$\begin{aligned} m_t &= 173.2 \text{ GeV}, \\ M_{\text{SUSY}} &= 500 \text{ GeV}, \\ \mu &= 200 \text{ GeV}, \\ M_2 &= 200 \text{ GeV}, \\ X_t^{\text{OS}} &= 2.0\, M_{\text{SUSY}} \text{ (FD calculation)}, \\ X_t^{\overline{\text{MS}}} &= \sqrt{6}\, M_{\text{SUSY}} \text{ (RG calculation)}, \\ A_b &= A_t = A_\tau, \\ m_{\tilde{g}} &= 1500 \text{ GeV}, \\ M_{\tilde{l}_3} &= 1000 \text{ GeV} . \end{aligned} \tag{26}$$

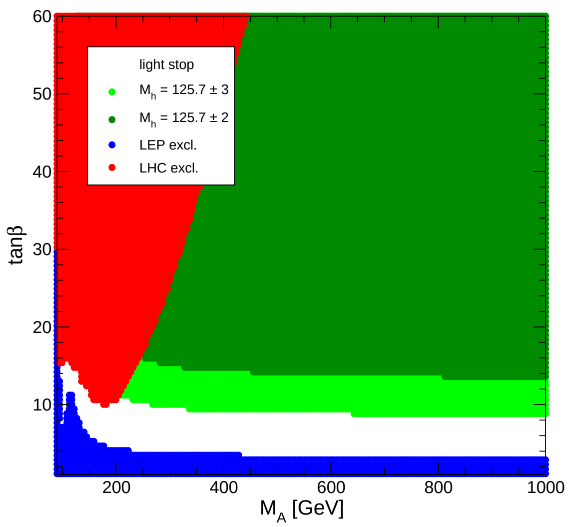

Figure 4: The MA-$\tan\beta$ plane in the light stop scenario. The color coding is as in Fig. 1

$\to$ add figure with $\sigma(gg \to h)_{M_{\text{SUSY}}=500}/\sigma(gg \to h)_{M_{\text{SUSY}}=1000}$?

3.5 The light stau scenario

Light SUSY particles can also have an impact on the Higgs decay rates. In particular it was shown that light scalar taus can modify $\Gamma(h \to \gamma\gamma)$ []. Here we propose a new scenario that contains such light scalar taus,

light stau:

$$\begin{aligned} m_t &= 173.2 \text{ GeV}, \\ M_{\text{SUSY}} &= 1000 \text{ GeV}, \\ \mu &= 500 \text{ GeV}, \\ M_2 &= 100 \text{ GeV}, \\ X_t^{\text{OS}} &= 1.7\, M_{\text{SUSY}} \text{ (FD calculation)}, \\ X_t^{\overline{\text{MS}}} &= 2.2\, M_{\text{SUSY}} \text{ (RG calculation)}, \\ A_b &= A_t\ , \\ m_{\tilde{g}} &= 1500 \text{ GeV}, \\ M_{\tilde{l}_3} &= 300 \text{ GeV} \\ A_\tau &= \pm 1000 \text{ GeV}\ . \end{aligned} \tag{27}$$

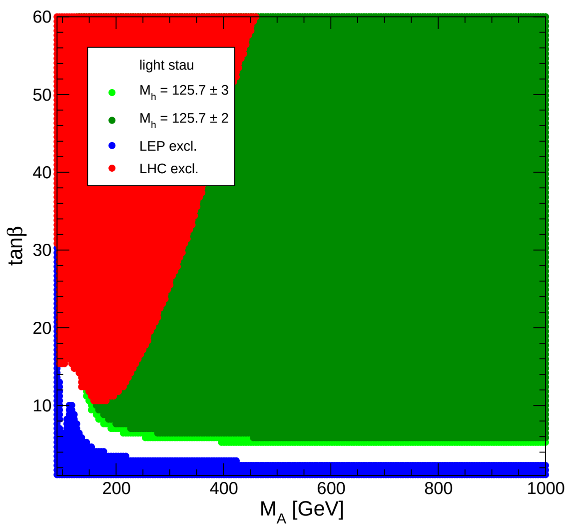

Figure 5: The MA-tan β plane in the light stau scenario. The color coding is as in Fig. 1

$\to$ add figure with $\Gamma(h \to \gamma\gamma)_{M_{\tilde{l}_3}=300}/\Gamma(h \to \gamma\gamma)_{M_{\tilde{l}_3}=1000}$?

3.6 The modified couplings scenario

Higher-order corrections can influence the relative couplings of the Higgs bosons to SM fermions. This can lead to modified rates to $b\bar{b}$ and $\tau^+\tau^-$ final states via corrections to the mixing angle $\alpha_{\rm eff}$ (see Ref. [51] for details), similar to the "small $\alpha_{\rm eff}$" scenario proposed in Ref. [4]. The parameters are,

modified couplings:

$$\begin{aligned} m_t &= 173.2 \text{ GeV}, \\ M_{\rm SUSY} &= 1500 \text{ GeV}, \\ \mu &= 2000 \text{ GeV}, \\ M_2 &= 200 \text{ GeV}, \\ X_t^{\rm OS} &= 3650 \text{ GeV (FD calculation)}, \\ X_t^{\overline{\rm MS}} &= 3000 \text{ GeV (RG calculation)}, \\ A_b &= A_\tau = A_t \ , \\ m_{\tilde{g}} &= 1500 \text{ GeV}, \\ M_{\tilde{l}_3} &= 500 \text{ GeV} \ . \end{aligned} \tag{28}$$

4 Conclusions

In this paper we have proposed new benchmark scenarios for MSSM Higgs boson searches at the LHC. The scenarios take into account the recent discovery of a Higgs-like state at ~ 125.7 GeV.

The first scenario is a small modification to the previously defined $m_h^{\rm max}$ scenario. The only proposed change is in the sfermion masses of the first and second generation. The values are set to values high enough to escape the exclusion bounds from the LHC. The scenario allows for conservative lower bounds on M_A, $M_{H^\pm}$ and $\tan\beta$ via the interpretation of the light $\mathcal{CP}$-even Higgs as the newly observed state at ~ 125.7 GeV (including theoretical uncertainties).

The second scenario is a modification of the $m_h^{\rm max}$ scenario, called the $m_h^{\rm mod}$ scenario. Here $X_t/M_{\rm SUSY}$ is lowered such that $M_h \sim 125.7$ GeV is realized in large parts of the M_A-$\tan\beta$ plane. We propose two versions, one with positive X_t, the other one with negative X_t (and a small variation of $|X_t|/M_{\rm SUSY}$). These scenarios are in agreement with recent results from LHC Higgs searches. They can be used for the future interpretations of the searches of the heavy MSSM Higgs bosons.

The third scenario, "low-M_H", interprets the *heavy* $\mathcal{CP}$-even Higgs boson as the newly discovered state at ~ 125.7 GeV. The parameters are tuned in a way that large parts of the M_A-$\tan\beta$ parameter space have M_H around the desired value.

The final scenario is the "modified couplings scenario". It exemplifies two features: light staus can enhance the $\gamma\gamma$ rate. Higher-order corrections to the mixing angle in the $\mathcal{CP}$-even Higgs sector, $\alpha_{\rm eff}$, can lower the rates into $b\bar{b}$ and $\tau^+\tau^-$ final states.

For all scenarios we propose a change in Δ_b, which can have a non-negligible impact on the heavy Higgs searches.

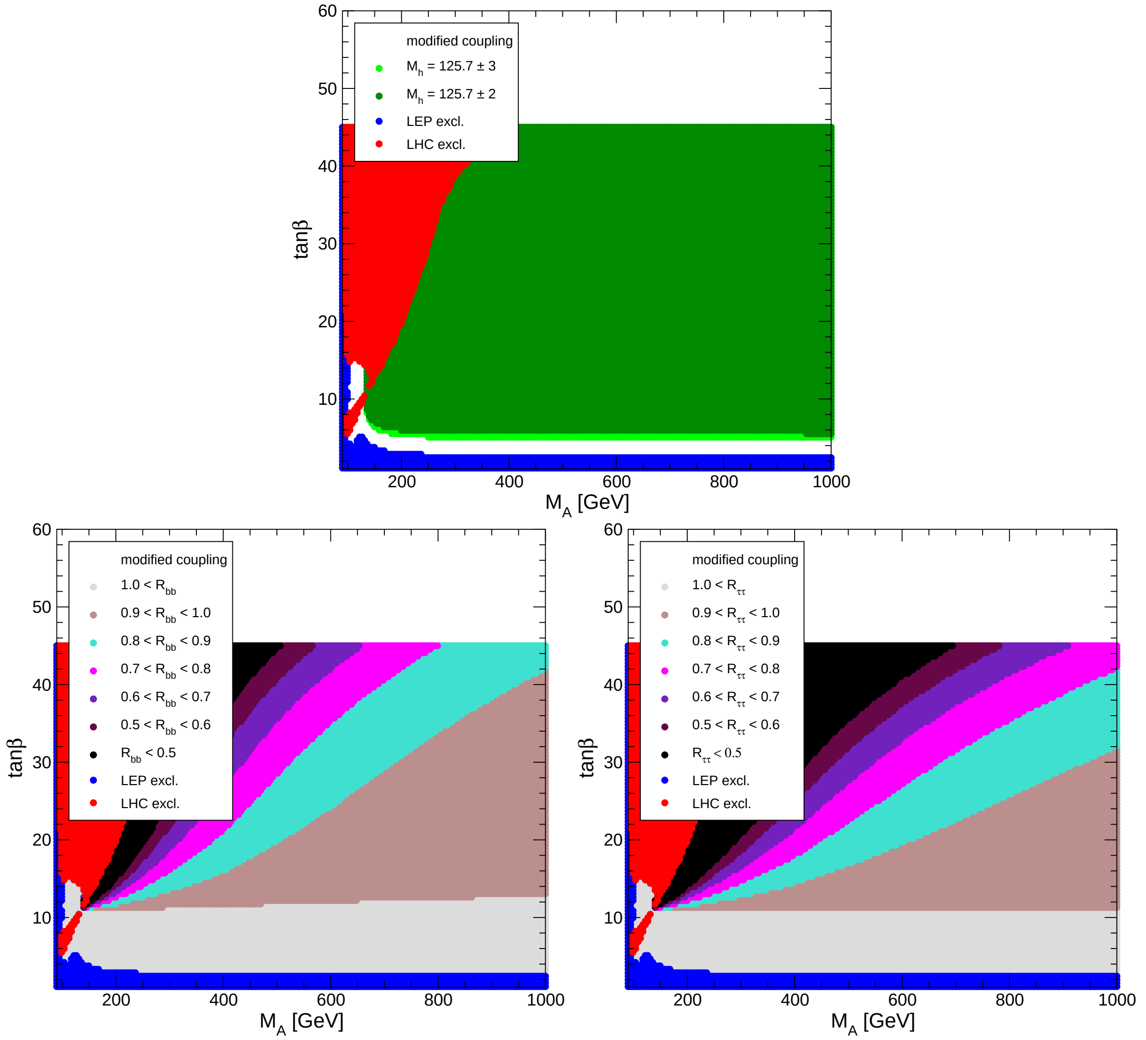

Figure 6: The MA-$\tan\beta$ plane in the "modified coupling" scenario. The color coding in the upper plot is as in Fig. 1. The lower plots show the potential suppression of R^h_{bb} (left) and $R^h_{\tau\tau}$ (right).

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