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Benchmark Scenario for low $\tan\beta$ in the MSSM: First preliminary interim recommendation/suggestion

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Abstract

Within the MSSM we define a benchmark scenario that yields $M_h \sim 125$ GeV at low $\tan\beta$ and low M_A.

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1 Introduction

We interpret the new particle found at the LHC [1, 2] as the lightest Higgs boson in the Minimal Supersymmetric Standard Model (MSSM) [3–5]. The Higgs sector of the MSSM with two scalar doublets accommodates five physical Higgs bosons. In lowest order these are the light and heavy $\mathcal{CP}$-even h and H, the $\mathcal{CP}$-odd A, and the charged Higgs bosons $H^\pm$. At the tree-level the Higgs sector is described by two parameters, conventionally chosen as the mass of the $\mathcal{CP}$-odd Higgs boson, M_A, and the ratio of the two vacuum expectation values, $\tan\beta \equiv v_2/v_1$.

In the MSSM the mass of the light $\mathcal{CP}$-even Higgs boson, M_h, can directly be predicted from the other parameters of the model, where higher-order corrections play a crucial role. Within the "LHC Higgs Cross Section Working Group" (LHCHXSWG) the code `FeynHiggs` [6–10] has been used as the default code for the evaluation of Higgs boson masses, mixings and couplings within the MSSM (so far restricted to real parameters). Within this code the remaining theoretical uncertainty in the calculation of M_h, from unknown higher-order corrections, was estimated to be up to 3 GeV [9, 11], depending on the parameter region. However, in view of the now known mass of the particle and recent newly evaluated corrections to M_h a re-evaluation of this uncertainty is required. Lacking a more thorough analysis, an interval of

$$M_h = 125 \pm 3 \text{ GeV} \tag{1}$$

can be considered as being in agreement with experimental data.

Of special interest in the search for the heavy MSSM Higgs bosons are decays that involve the light Higgs boson with a mass in the range of Eq. (1). In particular the decays

$$H \to hh, \qquad A \to Zh \tag{2}$$

have been searched for. These decays have a large BR for low values of $\tan\beta$ and not too high values of M_A (below the $t\bar{t}$ threshold). However, benchmark scenarios so far, see Ref. [12, 13], only permit values of $\tan\beta > 4$, mainly driven by the requirement in Eq. (1) and the scale of the scalar top masses which is set to ~ 1 TeV in the "old" benchmarks [12, 13]. The idea of this note is to define a scenario that yield a Higgs boson mass value in the range of Eq. (1) also for values in the range $0.5 \leq \tan\beta \leq 4$.

2 Notation

In the description of our notation we are including only the relevant SUSY parameters. The tree-level masses of the $\mathcal{CP}$-even MSSM Higgs bosons, M_h^{tree} and M_H^{tree}, are determined by $\tan\beta$, the $\mathcal{CP}$-odd Higgs boson mass, M_A, and the Z boson mass, M_Z. The main radiative corrections to the Higgs boson masses arise from the $t/\tilde{t}$ sector, and for large values of $\tan\beta$ also from the $b/\tilde{b}$ and sector.

The mass matrices for the stop and sbottom sectors of the MSSM, in the basis of the current eigenstates $\tilde{t}_L, \tilde{t}_R$ and $\tilde{b}_L, \tilde{b}_R$, are given by

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

$$\mathcal{M}_{\tilde{b}}^2 = \begin{pmatrix} M_{\tilde{b}_L}^2 + m_b^2 + \cos 2\beta(-\frac{1}{2} + \frac{1}{3}s_\mathrm{w}^2)M_Z^2 & m_b X_b \\ m_b X_b & M_{\tilde{b}_R}^2 + m_b^2 - \frac{1}{3}\cos 2\beta s_\mathrm{w}^2 M_Z^2 \end{pmatrix}, \qquad (4)$$

where

$$m_t X_t = m_t(A_t - \mu \cot\beta), \quad m_b\, X_b = m_b\,(A_b - \mu \tan\beta). \qquad (5)$$

Here A_t denotes the trilinear Higgs–stop coupling, A_b denotes the Higgs–sbottom coupling, and μ is the higgsino mass parameter. We furthermore use the notation $s_\mathrm{w} = \sqrt{1 - c_\mathrm{w}^2}$, with $c_\mathrm{w} = M_W/M_Z$, and M_W denotes the W boson mass. The mass eigenvalues of the two matrices are denoted as $m_{\tilde{t}_1}$, $m_{\tilde{t}_2}$, $m_{\tilde{b}_1}$, $m_{\tilde{b}_2}$.

SU(2) gauge invariance leads to the relation

$$M_{\tilde{t}_L} = M_{\tilde{b}_L}. \qquad (6)$$

The Higgs sector depends also on the gaugino masses. For instance, at the two-loop level the gluino mass, $m_{\tilde{g}}$, enters the predictions for the Higgs boson masses. The Higgs sector observables furthermore depend on the SU(2) and U(1) gaugino mass parameters, M_2 and M_1, respectively, which are usually assumed to be related via the GUT relation,

$$M_1 = \frac{5}{3}\frac{s_\mathrm{w}^2}{c_\mathrm{w}^2} M_2 \ . \qquad (7)$$

This relation is assumed in the definition of the scenario.

3 The scenario

3.1 The definition of the "low-tb-high" scenario

In order to reach M_h in the interval of Eq. (1) relatively large scalar top masses and large mixing in the stop sector are required. In particular, a resummation of leading logarithms of the form $\log(m_{\tilde{t}}/m_t)$ is required. A first consistent combination of such a resummation with a diagrammatic calculation of corrections to M_h has been included into `FeynHiggs` from version `2.10.0` on [10].

The scenario is called "low-tb-high", indicating that it is defined for low $\tan\beta$ values and does not have charginos or neutralinos in a mass range that have an influence on the Higgs decays.

The parameters for `FeynHiggs` are given in the file `low-tb-high-LHCHXSWG.dat` available at the web page of the BR group of the LHCHXSWG,

`https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWGBRs/low-tb-high-LHCHXSWG.dat`

In this file each row defines one point in the M_A–$\tan\beta$ parameter space in the ranges

$$\begin{aligned} M_A &= 150 \text{ GeV} \ldots 500 \text{ GeV (in steps of 5 GeV)} \ , \\ \tan\beta &= 0.5 \ldots 10 \text{ (in steps of 0.1)} \ . \end{aligned} \qquad (8)$$

Defined are the soft SUSY-breaking parameters, where all soft SUSY-breaking mass parameters of colored particles as well as the soft SUSY-breaking parameters in the slepton sector are set to a common value $M_{\rm SUSY}$. It varies between a few TeV for large M_A and/or $\tan\beta$ up to 100 TeV for small M_A and/or $\tan\beta$. The parameter X_t is varied such that $M_h \sim 125$ GeV is reached over nearly the full parameter space, see Sect. 4. The values are chosen as

$$\begin{aligned} \tan\beta \le 2 &: X_t/M_{\rm SUSY} = 2 \;, \\ 2 < \tan\beta \le 8.6 &: X_t/M_{\rm SUSY} = 0.0375 \tan^2\beta - 0.7 \tan\beta + 3.25 \;, \\ 8.6 < \tan\beta &: X_t/M_{\rm SUSY} = 0 \;. \end{aligned} \tag{9}$$

All other trilinear couplings are set to 2000 GeV, and $\mu = 1500$ GeV and $M_2 = 2000$ GeV. The top quark mass is set to the default value of the LHCHXSWG, $m_t = 172.5$ GeV.

FeynHiggs can be called to produce numbers in this scenario as

```
./Feynhiggs low-tb-high-LHCHXSWG.in 400243110
```

where the input file defines M_A and $\tan\beta$, and the numeric string defines the FeynHiggs flags as they have to be set for the evaluation in this scenario. A possible input file could read

```
MA0     327.5
TB      2.37
table low-tb-high-LHCHXSWG.dat MA0 TB
```

Values for M_A and $\tan\beta$ can be chosen anywhere in the defined intervals, where FeynHiggs interpolates accordingly. More details about the "table mode" of FeynHiggs can be found in Ref. [14][1] .

3.2 Shortcomings

The following shortcomings should be kept in mind.

(i) The application of the log-resummation as implemented in FeynHiggs assumes that *all* SUSY mass scales are at (or above) the scale $M_{\rm SUSY}$. However, in the defintion of the parameters μ, M_2 and M_A are kept at lower values. This applies in particular to M_A, which by definition lies below 500 GeV. Using the log-resummation as implemented in FeynHiggs anyway results in an increased uncertainty in the M_h evaluation (which is not captured by the automatic M_h uncertainty evaluation implemented in FeynHiggs). For effects of μ below the scale $M_{\rm SUSY}$ see Ref. [15]. No evaluations or estimates for low M_A values are available so far.

(ii) Decays of heavy Higgs bosons to charginos and neutralinos are not possible due to the high mass values of the latter. Consequently, the BR's obtained (see Sect. 4) are best-case scenarios.

[1]The parameter table is largern than the so far foreseen table size. This can easily be adjusted in the file src/include/FHRecord.h.in, where in the line

```
parameter (maxcols = FHRecordN, maxrows = 2400)
```

the 2400 has to be changed to 10000.

(iii) It has not been tested whether the production cross sections and branching ratios of the light MSSM Higgs are in full agreement with the latest results of ATLAS and CMS, which indicate a SM-like Higgs boson with uncertainties in the $\mathcal{O}(10-20\%)$ range.

(iv) Related to point (iii), the scenario is not defined as an "alignment decoupling scenario", see, e.g., Ref. [16]. It has not been investigated whether such a scenario can be realized for $\tan\beta \sim 1$, i.e. in the parameter region with large BR's for for Eq. (2).

4 Sample plots

The numbers for the plots have been obtained with `FeynHiggs 2.10.2`, and setting $m_t = 173.2$ GeV. We show the mass of the lightest $\mathcal{CP}$-even Higgs boson in the low-tb-high scenario in Fig. 1. It can be seen that the choices of, in particular, $M_{\rm SUSY}$ and X_t lead to $M_h = 125 \pm 1$ GeV (neglecting theory uncertainties) over nearly the whole M_A–$\tan\beta$ plane.

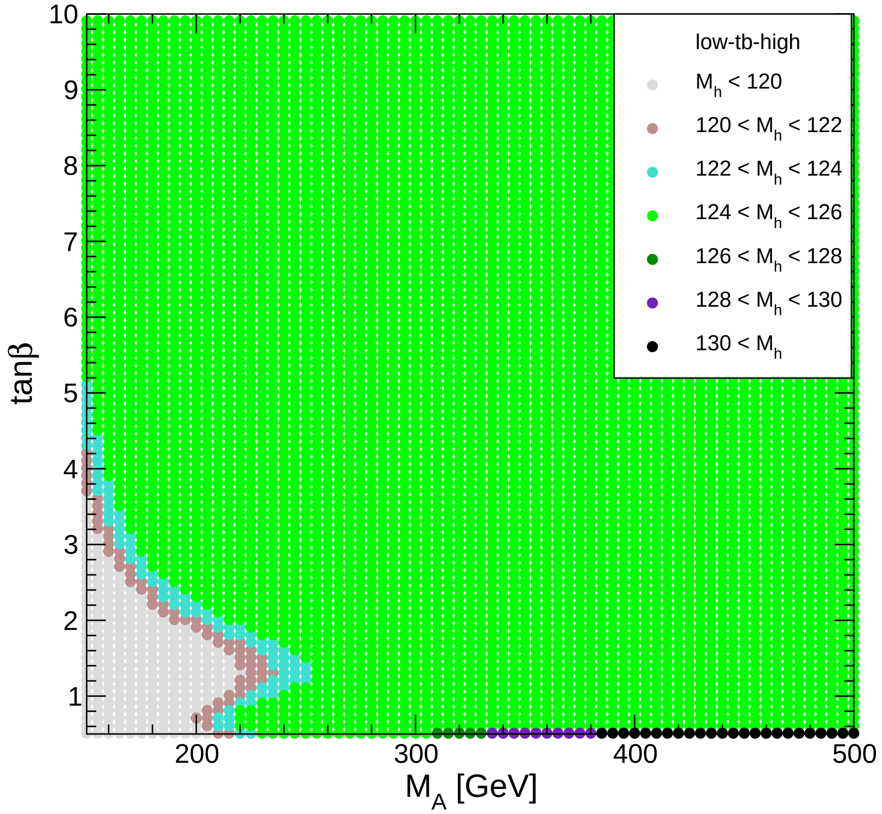
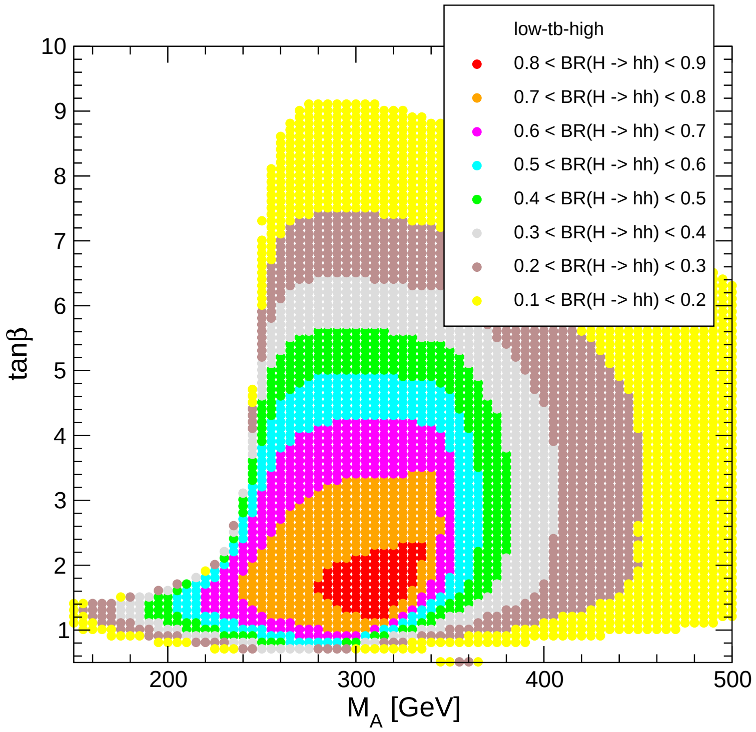


Figure 1: M_h in the M_A–$\tan\beta$ plane evaluated in the "low-tb-high" scenario (see text).

The BR's of the decays in Eq. (2), as evaluated with `FeynHiggs` (i.e. not with the method used by the LHCHXSWG) are shown in Fig. 2. One can see that the highest BR's ar reached for $\tan\beta < 4$. In the case of $\text{BR}(H \to hh)$ non-negligible values can be found up to $\tan\beta \lesssim 9$.



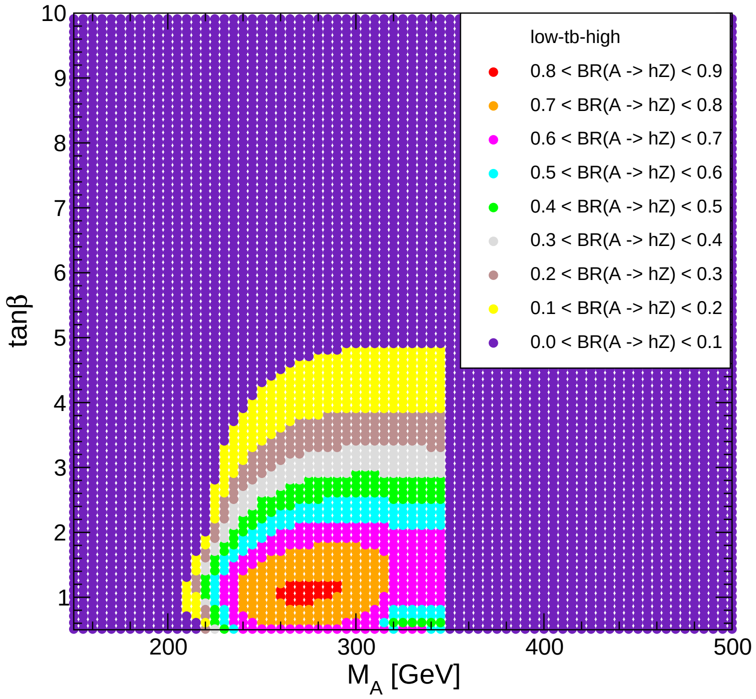


Figure 2: $\mathrm{BR}(H \to hh)$ (upper plot) and $\mathrm{BR}(A \to Zh)$ (lower plot) in the M_A–$\tan\beta$ plane evaluated in the "low-tb-high" scenario (see text).

5 Future improvements

Future improvements should lead to a set of benchmark scenarios at low $\tan\beta$ values and take care of the shortcomings discussed in Sect. 3.2. Consequently, the effects of low values of M_A, μ and M_2 should at least be quantified and included in an uncertainty estimate. The scenario should be defined such that it is ensured that the Higgs signal rates are in agreement with the measurements of ATLAS and CMS.

Further additional scenarios of interest would be

- a scenario with low masses of the charginos and neutralinos, such that

$$H/A \to \tilde{\chi}^0_i \tilde{\chi}^0_j / \tilde{\chi}^\pm_k \tilde{\chi}^\mp_l, \quad (i,j = 1 \ldots 4,\ k,l = 1,2) \tag{10}$$

  is kinematically allowed for $M_A \lesssim 500$ GeV, leading to suppressed BR's for the decays of interest.

- an alignment scenario, where a SM-like Higgs boson is realized up to very low values of M_A around a fixed $\tan\beta$ value (see, e.g., Ref. [16] and references therein).

We leave these investigations for future work. :-)

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