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Higgs branching ratios in constrained minimal and next-to-minimal supersymmetry scenarios surveyed

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ABSTRACT

In the CMSSM the heaviest scalar and pseudo-scalar Higgs bosons decay largely into b-quarks and tau-leptons because of the large $\tan\beta$ values favored by the relic density. In the NMSSM the number of possible decay modes is much richer. In addition to the CMSSM-like scenarios, the decay of the heavy Higgs bosons is preferentially into top quark pairs (if kinematically allowed), lighter Higgs bosons or neutralinos, leading to invisible decays. We provide a scan over the NMSSM parameter space to project the 6D parameter space of the Higgs sector on the 3D space of the Higgs masses to determine the range of branching ratios as function of the Higgs boson mass for all Higgs bosons. Specific LHC benchmark points are proposed, which represent the salient NMSSM features.

1. Introduction

A light Higgs boson below 135 GeV is predicted within Supersymmetry (SUSY) [1–3]. So the discovery of a Higgs-like boson with a mass of 125 GeV [4,5] strongly supports SUSY although no SUSY particles have been found so far. The precise value of the Higgs mass depends on radiative corrections. Within the constrained minimal supersymmetric standard model (CMSSM) [6] the tree level Higgs boson mass is below the Z^0-boson mass M_Z (91 GeV) and to reach the observed mass of 125 GeV the radiative corrections from stop loops have to be large, see e.g. [7–10] and references therein. However, a 125 GeV Higgs boson is easily obtained in the minimal extension of the CMSSM where an additional Higgs singlet is introduced, since then the tree level value of the Higgs boson can be above M_Z. The reason is simple: within the so-called next-to-minimal supersymmetric standard model (NMSSM) [11] the mixing with the additional Higgs singlet increases the Higgs mass at tree level [12–19], so the radiative corrections from the stop loops do not need multi-TeV stop squarks in the NMSSM, thus avoiding the fine-tuning problem [3,2,1]. The addition of a Higgs singlet yields more parameters in the Higgs sector to cope with the interactions between the singlet and the doublets and the singlet self-interaction. Furthermore, the supersymmetric partner of the singlet leads to an additional Higgsino, thus extending the neutralino sector from 4 to 5 neutralinos. These additional particles and their interactions lead to a large parameter space, even if one considers the well-motivated subspace with unified masses and couplings at the GUT scale.

On the other hand, experiments are mostly interested in possible ranges of Higgs masses and branching ratios. With 5 neutral Higgs masses, of which one has to be 125 GeV and two of the heavy neutral Higgses masses are practically mass-degenerate, one is left with a 3-dimensional (3D) space in the Higgs masses in contrast to the 6-dimensional (6D) parameter space of the constrained Z_3-invariant NMSSM Higgs sector. A certain point in the Higgs mass space can be obtained for several combinations of the 6D parameter space, which in turn leads to a range of branching ratios of the Higgs bosons.

In this paper we ventured to project the 6D parameter space on the 3D space of Higgs masses to obtain the expected range of branching ratios as function of the Higgs mass for each Higgs boson. This allows us to look for the distinctive features between the NMSSM and CMSSM. After a short summary of the Higgs and gaugino sectors in the CMSSM and NMSSM we discuss the fit strategy to project the 6D parameter space on the 3D neutral Higgs mass space. We conclude by summarizing the branching ratios of

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both models and selected benchmark points showing the salient features of the NMSSM.

2. NMSSM Higgs sector

We focus on the well-motivated semi-constrained next-to-minimal supersymmetric standard model (NMSSM), as described in Ref. [11] and use the corresponding code NMSSMTools 4.6.0 [20] to calculate the SUSY mass spectrum, Higgs boson masses and branching ratios from the NMSSM parameters.

Within the NMSSM the Higgs fields consist of the two Higgs doublets (H_u, H_d), which appear in the MSSM as well, but together with an additional complex Higgs singlet S. In addition, we have the GUT scale parameters of the CMSSM: m_0, $m_{1/2}$ and A_0, where $m_0(m_{1/2})$ are the common mass scales of the spin 0(1/2) SUSY particles at the GUT scale and A_0 is the trilinear coupling of the CMSSM Higgs sector at the GUT scale. In total the semi-constrained NMSSM has nine free parameters:

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \lambda,\ \kappa,\ A_\lambda,\ A_\kappa,\ \mu_{\text{eff}}. \tag{1}$$

Here $\tan\beta$ corresponds to the ratio of the vevs of the Higgs doublets, i.e. $\tan\beta \equiv v_u/v_d$, λ represents the coupling between the Higgs singlet and doublets ($\lambda S H_u \cdot H_d$), κ the self-coupling of the singlet ($\kappa S^3/3$); A_λ and A_κ are the corresponding trilinear soft breaking terms, μ_{eff} represents an effective Higgs mixing parameter and is related to the vev of the singlet s via the coupling λ, i.e. $\mu_{\text{eff}} \equiv \lambda s$. Therefore, μ_{eff} is naturally of the order of the electroweak scale, thus avoiding the μ-problem [11]. The latter six parameters in Eq. (1) form the 6D parameter space of the NMSSM Higgs sector.

The neutral components from the two Higgs doublets and singlet mix to form three physical CP-even scaler (S) bosons and two physical CP-odd pseudo-scalar (P) bosons.

The elements of the corresponding mass matrices at tree level read [21]:

$$\begin{aligned}
\mathcal{M}^2_{S,11} &= M_A^2 + (M_Z^2 - \lambda^2 v^2)\sin^2 2\beta,\\
\mathcal{M}^2_{S,12} &= -\frac{1}{2}(M_Z^2 - \lambda^2 v^2)\sin 4\beta,\\
\mathcal{M}^2_{S,13} &= -\frac{1}{2}(M_A^2 \sin 2\beta + \frac{2\kappa\mu^2}{\lambda})\frac{\lambda v}{\mu}\cos 2\beta,\\
\mathcal{M}^2_{S,22} &= M_Z^2\cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta,\\
\mathcal{M}^2_{S,23} &= 2\lambda\mu v\left[1 - (\frac{M_A \sin 2\beta}{2\mu})^2 - \frac{\kappa}{2\lambda}\sin 2\beta\right],\\
\mathcal{M}^2_{S,33} &= \frac{1}{4}\lambda^2 v^2 (\frac{M_A \sin 2\beta}{\mu})^2 + \frac{\kappa\mu}{\lambda}(A_\kappa + \frac{4\kappa\mu}{\lambda})\\
&\quad - \frac{1}{2}\lambda\kappa v^2 \sin 2\beta,
\end{aligned} \tag{2}$$

$$\begin{aligned}
\mathcal{M}^2_{P,11} &= \frac{\mu(\sqrt{2}A_\lambda + \kappa\frac{\mu}{\lambda})}{\sin 2\beta} = M_A^2,\\
\mathcal{M}^2_{P,12} &= \frac{1}{\sqrt{2}}\left(M_A^2\sin 2\beta - 3\frac{\kappa}{\lambda}\mu^2\right)\frac{v\lambda}{\mu},\\
\mathcal{M}^2_{P,22} &= \frac{1}{2}\left(M_A^2\sin 2\beta + 3\frac{\kappa}{\lambda}\mu^2\right)\frac{v^2}{\mu^2}\lambda^2\sin 2\beta - \frac{3}{\sqrt{2}\frac{\kappa}{\lambda}\mu A_\kappa}.
\end{aligned} \tag{3}$$

One observes that the element $\mathcal{M}^2_{S,22}$, which corresponds to the tree-level term of the lightest CMSSM Higgs boson, can be above M_Z^2 because of the $\lambda^2 v^2 \sin^2 2\beta$ term. The diagonal element $\mathcal{M}^2_{P,11}$ at tree level corresponds to the pseudo-scalar Higgs bosons in the MSSM limit of small λ, so it is called M_A. $M^2_{S,33}$ and $M^2_{P,22}$ correspond to the diagonal terms for the additional scalar and pseudo-scalar Higgs boson not present in the MSSM. The mass of the heaviest scalar and pseudo-scalar Higgs bosons are usually close to each other, since the dominant term at tree level is in both cases M_A^2, as can be seen from a comparison of $\mathcal{M}^2_{S,11}$ and $\mathcal{M}^2_{P,11}$. The mass eigenstate of the charged Higgs fields reads:

$$M^2_{H^\pm} = M_A^2 + M_W^2 - \frac{1}{2}(\lambda v)^2. \tag{4}$$

Note that the heavy charged and heavy neutral Higgs masses are all of the order of M_A and largely independent of the SUSY masses.

3. CMSSM and NMSSM gaugino sector

Within the NMSSM the singlino, the superpartner of the Higgs singlet, mixes with the gauginos and Higgsinos, leading to an additional fifth neutralino. The resulting mixing matrix reads [11,22]:

$$\mathcal{M}_0 = \begin{pmatrix}
M_1 & 0 & -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_1 v_u}{\sqrt{2}} & 0\\
0 & M_2 & \frac{g_2 v_d}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & 0\\
-\frac{g_1 v_d}{\sqrt{2}} & \frac{g_2 v_d}{\sqrt{2}} & 0 & -\mu_{\text{eff}} & -\lambda v_u\\
\frac{g_1 v_u}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & -\mu_{\text{eff}} & 0 & -\lambda v_d\\
0 & 0 & -\lambda v_u & -\lambda v_d & 2\kappa s
\end{pmatrix} \tag{5}$$

with the gaugino masses M_1, M_2, the gauge couplings g_1, g_2 and the Higgs mixing parameter μ_{eff} as parameters. Furthermore, the vacuum expectation values of the two Higgs doublets v_d, v_u, the singlet s and the Higgs couplings λ–κ enter the neutralino mass matrix. The upper 4×4 submatrix of the neutralino mixing matrix corresponds to the MSSM neutralino mass matrix, see e.g. Ref. [3]. Since the additional Higgs singlino affects only the neutral gaugino sector, the mixing matrix for the charginos in the NMSSM and CMSSM are identical:

$$\mathcal{M}_\pm = \begin{pmatrix} M_2 & g_2 v_u \\ g_2 v_d & \mu_{\text{eff}} \end{pmatrix}. \tag{6}$$

To obtain the mass eigenstates the mass matrices have to be diagonalized. Typically the diagonal elements in Eq. (5) and (6) dominate over the off-diagonal terms, so the neutralino masses are of the order of M_1, M_2, the Higgs mixing parameter μ_{eff} and in case of the NMSSM $2\kappa/\lambda\mu_{\text{eff}}$. The chargino masses are of the order of M_2 and μ_{eff}.

Since we use GUT scale input parameters and the mass spectrum at the low mass SUSY scales is calculated via the renormalization group equations (RGEs), the masses are correlated. The gaugino masses are proportional to $m_{1/2}$ [3,1,2]:

$$M_1 \approx 0.4 m_{1/2},\ M_2 \approx 0.8 m_{1/2},\ M_3 \approx M_{\tilde{g}} \approx 2.7 m_{1/2}. \tag{7}$$

This leads to bino-like light neutralinos and wino-like light charginos in the CMSSM, since μ is typically much larger than $m_{1/2}$ to fulfill radiative electroweak symmetry breaking (EWSB) [1–3]. In the NMSSM μ_{eff} is an input parameter and it can be chosen such that it is of the order of the electroweak scale. This changes both the neutralino and chargino sector. In such natural NMSSM scenarios the lightest neutralino is singlino-like and its mass can be degenerate to the second/third neutralino and the lightest chargino, which all have a mass of the order of μ_{eff}.

4. Analysis

As discussed in sect. 2 the number of free parameters in the NMSSM increases with respect to the MSSM. Six of the nine free