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The Higgs mass and the scale of SUSY breaking in the NMSSM

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ABSTRACT: In this letter we study the Higgs mass in the NMSSM with supersymmetry breaking at high scales M_{SS} . With the Standard Model as the effective low energy theory, the computation of the Higgs mass relies on the matching condition of the quartic coupling λ at M_{SS} . In the MSSM, the latter is fixed to a semi-positive value and, thus, sets an upper bound on the SUSY-breaking scale near $M_{\text{SS}} \simeq 10^{10}$ GeV. In the NMSSM, $\lambda(M_{\text{SS}})$ receives an additional contribution induced by the singlet which allows for negative values of $\lambda(M_{\text{SS}})$. In turn, for the measured value of the Higgs mass we find that M_{SS} can take any value up to the GUT scale. Furthermore, the choice of universal soft terms favors SUSY-breaking scales close to the GUT scale.

KEYWORDS: Supersymmetry Phenomenology

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1 Introduction

The discovery of a Higgs boson of 126 GeV [1–3] is consistent with low energy supersymmetry together with a small degree of fine-tuning. However the absence of supersymmetric particles in the TeV range questions the paradigm of naturalness as a guiding principle. If one abandons the idea of supersymmetry as a solution to the hierarchy problem, reasons remain to study realizations of supersymmetry. In particular, supersymmetry is present in string theory, which is so far the best candidate for a UV-complete theory. Generically, supersymmetric theories in four dimensions obtained from string compactifications favor supersymmetry breaking at high scales, e.g. the GUT scale [4].¹ Furthermore, present data confirmed that the SM Higgs potential becomes metastable at large energy scales [5] and supersymmetric embeddings can stabilize the EW vacuum.²

Let us consider the situation in which supersymmetry is broken at a scale M_{SS} such that $M_{\text{EW}} \ll M_{\text{SS}}$. Under no special assumptions on the corresponding pattern of soft terms, supersymmetric particles receive masses of $\mathcal{O}(M_{\text{SS}})$ and thus decouple from the low energy theory. The requirement of obtaining a light Higgs in the spectrum leads to a fine-tuning condition at the matching scale M_{SS} and leaves the Standard Model as an effective description at lower energies. However, the corresponding quartic coupling $\lambda(\mu)$ is completely fixed by the matching conditions to the supersymmetric theory at the scale M_{SS} .³ In turn, the latter implies that the Higgs mass is determined by the supersymmetric theory,

¹Examples with low energy SUSY were constructed by special choices of the compactification data (e.g. fluxes).

²See [6–8] for earlier results on the stability of the EW potential.

³Here μ denotes the energy scale.

and thus, the measured value of the Higgs mass constrains the values of the parameters of the supersymmetric theory and M_{SS} . This framework is called High-Scale Supersymmetry. A detailed study of the Higgs mass in the High-Scale Supersymmetry within the MSSM was done in [9–15]. In this case the prediction of $\lambda(M_{\text{SS}})$ is strictly positive (or zero), thus, the scale at which the quartic coupling in the SM vanishes, within uncertainties, sets an upper bound on M_{SS} of $M_{\text{SS}} \simeq 10^{10}$ GeV. Hence, a GUT scale SUSY breaking in this setup is ruled out.⁴

In this letter we study High-Scale Supersymmetry within the singlet extension of the MSSM, i.e. Next-to-Minimal Supersymmetric Standard Model (NMSSM), for a comprehensive review see [16]. In the NMSSM the couplings of the extra singlet to the Higgs sector induce tree level corrections to the matching of λ at the M_{SS} scale. Two pieces contribute to $\lambda(M_{\text{SS}})$ that are model independent and model dependent respectively. The former is strictly positive (or zero), and it can significantly modify the parameter values consistent with the Higgs mass w.r.t. the MSSM case. On the other hand, the latter contribution allows to set $\lambda(M_{\text{SS}})$ to a negative value, and thus, can extend M_{SS} up to the GUT or Planck scales.⁵ In this work we calculate the prediction for the Higgs mass in this framework and derive the respective bounds on M_{SS} and the NMSSM parameters.

This letter is organized as follows in section 2 we write down the matching conditions that relate the singlet-extended MSSM framework with the effective SM and discuss the fine-tuning condition required to induce a light Higgs. In section 3 we explain how we calculate the Higgs mass and in section 4 we study the dependence of the Higgs mass as a function of the SUSY-breaking scale and NMSSM parameters. In section 4.3 we study the constraints on the Higgs mass for special choices of soft parameters at the GUT scale. Finally, in section 5 we present the conclusions.

2 Fine-tuning a light Higgs in SUSY and matching to the Standard Model

Let us consider a scenario in which above the (not necessarily low) supersymmetry breaking scale (M_{SS}) the theory is described by a singlet-extended MSSM with the following superpotential

$$W_{\text{NMSSM}} = (\mu_h + y_s S) H_u H_d + \frac{1}{2} \mu_s S^2 + y_u Q H_u U_R + y_d Q H_d D_R + y_e L H_d E_R, \quad (2.1)$$

where S is the NMSSM singlet and H_u, H_d are the MSSM Higgs multiplets. y_s is a dimensionless Yukawa coupling and μ_h, μ_s are the supersymmetric Higgs and singlet mass terms respectively. y_u, y_d, y_e are the Yukawa couplings of the MSSM which should be understood as matrices in the family space, Q are the quark doublets, U_R and D_R are the quark singlets, L are the lepton doublets and E_R are the lepton singlets. After supersymmetry

⁴This statement holds only at tree level. By introducing large one loop threshold corrections to the matching of the quartic coupling, one could fine-tune $\lambda(M_{\text{SS}})$ to a negative value. This is possible by requiring hierarchies in the soft parameters, for a numerical analysis see [14].

⁵This possibility was anticipated in [10] and proposed also in [17].

breaking the scalar potential of the Higgs sector develops soft terms which read

$$V_{\text{soft}}(H_u, H_d, S) = m_{h_u}^2 |H_u|^2 + m_{h_d}^2 |H_d|^2 + m_3^2 (H_u H_d + \text{h.c.}) \\ + m_{h_s}^2 |S|^2 + \left(y_s A_\lambda S H_u H_d + \frac{1}{2} b_s^2 S^2 + \text{h.c.} \right), \quad (2.2)$$

where m_j are the soft scalar masses, A_y the A -term and m_3^2 , b_s^2 are the b -term and bilinear soft term of the singlet respectively.⁶

The explicit computation of the scalar CP-even Higgs potential shows that the condition, at the scale M_{SS} ,⁷

$$\hat{m}_3^4 \simeq (m_{h_u}^2 + \mu^2)(m_{h_d}^2 + \mu^2) \quad (2.3)$$

with $\mu = \mu_h + y_s \langle S \rangle$ and $\hat{m}_3^2 = m_3^2 + y_s (A_\lambda + \mu_s) \langle S \rangle$, generates a massless Higgs field given by the combination

$$H_{\text{SM}} = \sin \beta H_u - \cos \beta \epsilon H_d^* \quad (2.4)$$

where ϵ is the antisymmetric tensor and the angle β is determined by

$$\tan^2 \beta = \frac{|m_{h_d}^2 + \mu^2|}{|m_{h_u}^2 + \mu^2|} \quad (2.5)$$

with m_{h_u} , m_{h_d} and μ evaluated at the scale M_{SS} . It can be easily seen that the choice of superpotential in equation (2.1) yields $\langle S \rangle \ll m_{\text{EW}}$ and thus the singlet contribution to μ is suppressed and can be neglected. Moreover, this implies effective quadratic terms are subleading and hence the fine-tuning conditions in (2.3) and (2.5) are identical to the MSSM case.

Assuming the generic situation that the susy particles get masses of $\mathcal{O}(M_{\text{SS}})$ they can be integrated out, leaving an effective Standard Model description at energies below the cutoff scale M_{SS} . Furthermore, the explicit computation of the effective Lagrangian provides the boundary condition for the quartic coupling in the Standard Model potential given in (3.1). These are the so called matching conditions and at tree level they read

$$\lambda^{\text{tree}}(M_{\text{SS}}) = \frac{1}{4} \left(g_2^2 + \frac{3}{5} g_1^2 \right) \cos^2 2\beta + \frac{1}{2} y_s^2 (1 - \delta) \sin^2 2\beta \quad (2.6)$$

where

$$\delta = \frac{(2\mu_h / \sin 2\beta - A_\lambda - \mu_s)^2}{m_s^2 + b_s^2 + \mu_s^2}. \quad (2.7)$$

The first term in (2.6) is the well known D-term contribution in the MSSM while the second term appears only in the singlet-extension. The latter is generated by two effects, an F-term contribution generated by the Yukawa interaction that couples the singlet to the Higgs, and an extra contribution (proportional to δ) originated from integrating out the

⁶It is worth pointing out that, unless they are forbidden by a symmetry, effective soft cubic and linear terms for the singlet can be generated radiatively. As long as y_s is small, the latter are suppressed and can be neglected. Throughout this letter we will not consider them in the calculations.

⁷Here we used that the off-diagonal terms in the mass matrix (of the three CP-even scalars) that mix the MSSM Higgses with the singlet can be neglected in the diagonalization.

singlet. Interestingly, the denominator in (2.7) corresponds to the mass of the (CP-even) scalar singlet and, thus, it is positive. In turn, δ can only take positive values and the correction to $\lambda(M_{\text{SS}})$ is always negative.

The matching given in (2.6) receives higher order threshold corrections ($\delta\lambda^{\text{th}}$) that for the MSSM were originally computed at one loop level in [10] (and recently reviewed in [14] with leading two loop effect). We follow [14] and parametrize the corrections as follows⁸

$$\delta\lambda^{\text{th}}(M_{\text{SS}}) = \Delta\lambda^{1l,\text{reg}} + \Delta\lambda^{1l,\phi} + \Delta\lambda^{1l,\chi^{1,2}}. \quad (2.8)$$

These originate from the change of renormalization schemes that relate the gauge couplings in the $\overline{\text{DR}}$ scheme to the $\overline{\text{MS}}$ scheme ($\Delta\lambda^{1l,\text{reg}}$) and from integrating out the heavy scalars ($\Delta\lambda^{1l,\phi}$) and fermionic superpartners ($\Delta\lambda^{1l,\chi^{1,2}}$). The effect induced from stop mixing is also included, with the stop mixing parameter defined as

$$\tilde{X}_t = (A_t - \mu_h \cot \beta)^2 / (m_Q m_U). \quad (2.9)$$

Let us comment that one loop threshold corrections generated by the stop mixing can, in principle, take negative values. However, these require very large $\tilde{X}_t$ for which vacuum stability is severely threaten. An analytic bound upon $\tilde{X}_t$ as a function of the stop soft masses was derived in [14] together with a numerical analysis on its effect on the Higgs mass. Furthermore, those values consistent with the bound yield positive corrections to $\lambda(M_{\text{SS}})$ and therefore enhance the Higgs mass with respect to the tree level result. Finally, it is worth pointing out that the one loop threshold corrections introduced in $\delta^{\text{th}}\lambda(M_{\text{SS}})$ can take either sign. These are negligible for nearly degenerated soft masses, but can be sizeable for lower M_{SS} if hierarchies among the soft parameters are allowed.⁹

Before finishing this section it is worth noticing that, as long as one does not assume a special pattern of soft terms, the free parameters that determine $\lambda(M_{\text{SS}})$ in (2.6) are

$$y_s, \delta, \tan \beta \text{ and } M_{\text{SS}}. \quad (2.10)$$

However, if the soft terms are specified, the corresponding soft parameters at M_{SS} completely determine $\tan \beta$ and δ via (2.5) and (2.7) respectively.

3 Calculation of the Higgs mass

The Standard Model Higgs potential reads

$$V_{\text{SM}} = \frac{1}{2} \lambda (|H|^2 - v^2)^2 \quad (3.1)$$

⁸In our setup these are not complete, the threshold corrections coming from integrating out the two scalar singlets and the singlino are not included.

⁹For a numerical study of this effect see [14]. In particular, it was shown that varying soft masses within $0.3M_{\text{SS}} < m_i < 3M_{\text{SS}}$ can yield 2 GeV uncertainty on the Higgs mass at $M_{\text{SS}} \simeq 10^{16}$ GeV and up to 6 GeV for $M_{\text{SS}} \simeq 10^4$ GeV.

where $v = \sqrt{2} \cdot 174.1 \text{ GeV}$ is the the Higgs vacuum expectation value.¹⁰ From (3.1) one immediately learns that value the of λ determines the Higgs mass M_h at loop level via

$$M_h^2 = v^2(\lambda + \delta_\lambda). \quad (3.2)$$

It is worth recalling that the top Yukawa coupling y_t is fixed at loop level by the mass of the top quark through

$$y_t = \frac{m_t}{v} \sqrt{2}(1 + \delta_t) \quad (3.3)$$

δ_λ and δ_t parametrize the threshold corrections at the renormalization scale (m_t) that were originally computed in [18] and [19] respectively. The state-of-the-art computations are given at the two loop level (and dominant three loop correction for y_t) in [5].

3.1 Matching at M_{SS}

We perform the numerical calculations using a modified version of SPheno-3.3.6 [20, 21] created by SARAH-4.5.8 [22–24]. Given $\lambda(M_{\text{SS}})$ the Renormalization Group Equations (RGEs) are calculated at two-loop-level to yield the couplings at the weak scale. All couplings are renormalized at one loop at m_t in the $\overline{\text{MS}}$ scheme and the corresponding Higgs mass is thus calculated at one loop level. For the top Yukawa coupling we include the two loop and dominant three loop QCD correction given in eq. (57) in [5]. For completeness we provide the values of the SM parameters used in the calculations

$$\begin{aligned} m_t &= 173.34 \pm 0.76 \text{ GeV} & \alpha_s &= 0.1184 \\ M_z &= 91.18 \text{ GeV}, & G_F &= 1.16637 \cdot 10^{-5}. \end{aligned} \quad (3.4)$$

A theoretical uncertainty on the Higgs mass of 3 GeV is generically applied to supersymmetric models. This was computed within the MSSM in [25], assuming low energy values of the SUSY-breaking scale. The computation was recently reviewed in [26], for arbitrary (large) values of the SUSY-breaking scale and yielded a 1 GeV uncertainty for the Higgs mass. In the following we use this result.

3.2 Matching at M_{GUT}

In this section we explain how to obtain $\lambda(M_{\text{SS}})$ from a set of universal soft terms at the GUT scale, these are specified in (4.1). The procedure to calculate $\lambda(M_{\text{SS}})$ goes as follows. The values of the gauge and top Yukawa couplings in the NMSSM, $\hat{g}_1, \hat{g}_2, \hat{g}_3, \hat{y}_t$, are fixed by the corresponding g_1, g_2, g_3, y_t in the SM via the matching conditions at M_{SS} .¹¹ The matching conditions are given at tree level by

$$\hat{g}_1 = \sqrt{\frac{5}{3}} g', \quad \hat{g}_2 = g_2, \quad \hat{g}_3 = g_3, \quad \hat{y}_t = \frac{y_t}{\sin \beta} \quad (3.5)$$

¹⁰In the literature another convention for v is often used, without the squared root of 2. In that case, $M_h^2 = 2\lambda v^2$, the result is of course independent of this definition.

¹¹The corresponding values of $\hat{y}_t, \hat{g}_1, \hat{g}_2, \hat{g}_3$ used correspond to $m_h = 125 \text{ GeV}$. Variations of m_h between 50 and 150 GeV yield variations of 10^{-6} in the gauge couplings and 10^{-3} in the top Yukawa.

and receive one loop threshold corrections which can be found in [14]. However, gauge couplings only enter in the calculation of the Higgs mass via the RGEs for the soft terms and thus, higher order corrections can be neglected.¹² With $\hat{y}_t$, $\hat{g}_1$, $\hat{g}_2$, $\hat{g}_3$ at hand we run from M_{SS} up to M_{GUT} , with the RGEs of the NMSSM at two loops, to calculate $\hat{y}_{t_0}$, $\hat{g}_{1_0}$, $\hat{g}_{2_0}$, $\hat{g}_{3_0}$. Using the latter boundary conditions for gauge and top Yukawa couplings together with (4.1) we implement the RGEs of the NMSSM again at the two loop level for Yukawa and gauge couplings and at one loop level for the soft parameters, to obtain the corresponding soft terms at M_{SS} . The RGEs are given in [16] and we neglect the contribution of all Yukawa couplings except $\hat{y}_t$.¹³ The soft parameters at M_{SS} determine the values of $\tan\beta$ and δ via the eqs. (2.5) and (2.7) respectively which yield $\lambda(M_{\text{SS}})$ through (2.6).¹⁴ The one loop corrections given in (2.8), using the stop mixing in (2.9) are also included. With the value of $\lambda(M_{\text{SS}})$ at hand, we proceed as in 3.1.

4 The Higgs mass as a function of M_{SS}

In this section we study the Higgs mass as a function of M_{SS} , varying the NMSSM parameters (2.10) that determine the value of $\lambda(M_{\text{SS}})$ in (2.6). In section 4.3 we proceed as before but using the values of $\tan\beta$ and δ in $\lambda(M_{\text{SS}})$ computed from universal patterns of soft terms at the GUT scale.

4.1 $\lambda > 0$ at SUSY-breaking scale

To begin with, notice that the MSSM-like contribution to (2.6) vanishes for $\tan\beta$ equal to one, while the NMSSM piece is maximized. From this observation we learn that in the NMSSM low values of $\tan\beta$ can severely lessen the upper bound of M_{SS} as y_s increases. In figure 1 and 2 we plot the Higgs mass as a function of M_{SS} for different values of y_s , assuming $\delta = 0$ and $\tan\beta = 1, 2$ respectively. For large $\tan\beta$ the situation resembles the MSSM case [10, 11]. In this regime the first term in (2.6) is maximized and thus pulls M_{SS} to low energies while the NMSSM term is almost vanishing regardless of the value of y_s .

4.2 $\lambda < 0$ at SUSY-breaking scale

As can be seen from (2.6) by setting $\delta = 0$, all universal contributions are strictly positive. This implies that independently of the values of the parameters in the supersymmetric theory, there exists a strict upper bound on M_{SS} (within uncertainties) fixed by the scale μ_0 at which $\lambda(\mu_0)$ vanishes, equivalently, the scale at which the SM becomes unstable. The state-of-the-art computation yields $\mu_0 \simeq 10^{10\pm1}$ GeV [5]. However, if $\lambda(M_{\text{SS}})$ can be matched to the expected negative value determined by the running of λ in the SM, the upper bound on M_{SS} disappears. Let us remark that this statement assumes the metastability of the Standard Model vacuum is not spoiled by the UV-completion. The metastability bound relies on the top and Higgs masses, for a precise determination of this

¹²These could become important in precise estimations of gauge coupling unification.

¹³Neglecting the bottom Yukawa is a good approximation for low (or moderate) values of $\tan\beta$.

¹⁴Notice that the value of $\tan\beta$ already appears in the matching condition of the top Yukawa given in (3.5), the values should of course match.

Figure 1. Higgs mass as a function of M_{SS} for $\tan\beta = 1$. The region shaded in violet(orange) corresponds to $\lambda > 0$ ($\lambda < 0$) and from bottom-up $y_s = 0.2, 0.3, 0.4, 0.5$ ($y_s = 0.3, 0.25, 0.2$ with $\delta = -2$). In red $\lambda = 0$, $y_s = 0$. We assumed $\tilde{X}_t = 0$ and degenerate superparticles at M_{SS} . The bands display the uncertainty from varying $m_t = 173.34 \pm 0.76$ GeV, we did not include them in all the curves to avoid clutter. The line in blue is the measured Higgs mass 125.15 ± 0.25 GeV.

Figure 2. Higgs mass as a function of M_{SS} for $\tan\beta = 2$. The region shaded in blue(orange) corresponds to, from bottom-up, $y_s = 0.2, 0.3, 0.4, 0.5$ ($y_s = 0.4, 0.3, 0.2$ with $\delta = -2$). In red $y_s = 0$. We assumed $\tilde{X}_t = 0$ and degenerate superparticles at M_{SS} . The bands display the uncertainty from varying $m_t = 173.34 \pm 0.76$ GeV. The line in blue is the measured Higgs mass 125.15 ± 0.25 GeV.

region see [5, 8]. Thus, as long as these agree with the experimentally measured values, M_{SS} can lie at any scale between μ_0 and M_{GUT} .¹⁵ In figures 1 and 2 we plot the Higgs mass for various y_s , using $\delta = -2$ and $\tan \beta = 1, 2$ respectively. In these examples it can be clearly seen that M_{SS} could take values up to M_{GUT} .

4.3 Universal soft terms at M_{GUT}

As already anticipated, in this section we study the Higgs mass as a function of M_{SS} assuming an underlying structure of universal soft terms at the GUT scale. In the NMSSM these are specified by the following parameters

$$m_0, M_0, A_0, \mu_{h_0}, \mu_{s_0} \text{ and } b_{s_0} \quad (4.1)$$

where M_0 denote the gaugino masses and the remaining soft terms are as introduced in section 2.¹⁶ The subindex 0 indicates that the values are defined at the GUT scale, with $M_{\text{GUT}} = 10^{16}$ GeV. Examples of universal soft terms in string theory can be obtained e.g. in the *dilaton domination* scenario [31].

Notice from (2.5) that $\tan \beta$ is equal to one at the GUT scale and as $m_{h_u}^2, m_{h_d}^2$ and μ_h run, $\tan \beta$ evolves accordingly. However, $\tan \beta$ remains close to one for large values of M_{SS} . In other words, the unification (or universality) of soft masses predicts small values of $\tan \beta$, as already pointed out in [32]. For low values of the SUSY-breaking scale, $m_{h_u}^2$ becomes smaller and eventually changes sign, at this point there is a sudden increase of $\tan \beta$.

On the other hand, m_s, b_s and μ_s appearing in δ do not run for small values of y_s and stay equal to their boundary conditions at the GUT scale. Thus, the running of δ is induced by μ_h and A_λ . As long as there are no hierarchies among the couplings, δ stays constant at large M_{SS} and increases for low values of the SUSY-breaking scale.

In sum, two effects determine the Higgs mass in this scheme. At large values of M_{SS} , $\tan \beta$ takes very small values and so enhances the NMSSM correction to $\lambda(M_{\text{SS}})$. In this regime, δ does not significantly vary and, thus, the Higgs mass dependence upon M_{SS} is (almost) constant. Furthermore, by tuning the value of y_s near $\mathcal{O}(10^{-2})$, the Higgs mass can be easily accommodated in the experimental bound. For lower values of M_{SS} , $\tan \beta$ starts to increase and thus $\lambda(M_{\text{SS}})$ becomes insensitive to the NMSSM correction. The latter competes with the MSSM contribution which grows with $\tan \beta$. The sum of these two terms leads to a slow decrease of the Higgs mass with M_{SS} .

In figure 3 we show the Higgs mass as a function of M_{SS} for the following choice of soft masses at the GUT scale, i.e. $m_0 = M_0 = \mu_{s_0}, b_{s_0}^2 = -\mu_s^2$ and $A_0 = \mu_{h_0} = -1.5M_0$, and various y_s .¹⁷ As y_s decreases the upper bound on M_{SS} approaches the lower bound of $M_{\text{SS}} \simeq 10^{10}$ GeV, that corresponds to the limit of $\tan \beta = 1$ and $y_s = 0$. Whereas increasing y_s enhances the NMSSM negative contribution to $\lambda(M_{\text{SS}})$ and, thus, pushes M_{SS} to larger

¹⁵One should observe, however, that higher order operators encoding possible effects of new physics could modify the behavior of the quartic coupling near the matching scale and turn it to the unstable regime, spoiling the metastability of the SM vacuum [27] (see also [28–30]).

¹⁶Notice that m_3 is fixed by the fine-tuning condition (2.3).

¹⁷Notice that this choice of A_0 and μ_{h_0} minimizes the effect of stop mixing at large SUSY scales.

Figure 3. Higgs mass as a function of M_{SS} with soft terms at the GUT scale: $m_0 = M_0 = \mu_{s_0}$, $b_{s_0}^2 = -\mu_{s_0}^2$ and $A_0 = \mu_{h_0} = -1.5M_0$ and $y_s = 0.05$ (beige), 0.075 (light orange), 0.1 (dark orange), 0.125 (red). The bands correspond to the uncertainty bound in m_t and the region in lighter brown is $m_h = 125 \pm 1$ GeV. In darker brown the experimental bound on m_h .

Figure 4. Higgs mass as a function of M_{SS} . The bands correspond to the uncertainty bound in m_t and the region in blue is $m_h = 125 \pm 1$ GeV. In darker blue the experimental bound on m_h . (Left) $y_s = 0.075$ and (from dark to light orange) $m_0^2 = M_0^2, 0.6M_0^2, 0.45M_0^2, 0.3M_0^2$. (Right) $y_s = 0.05$ and (from dark to light red) $\mu_{h_0} = -1.5M_0, -1.25M_0, -M_0, -0.9M_0$.

values. Similarly, in figure 4 (left), by fixing y_s we show the effect of lowering $\lambda(M_{\text{SS}})$ by incrementing δ . This can be achieved by taking smaller values for the soft masses.

Notice that in the limit of vanishing y_s , the NMSSM contribution to $\lambda(M_{\text{SS}})$ is negligible. Hence, larger $\tan \beta$ values raise the Higgs mass at low energies. This effect is manifest depending on the choice of soft terms, in particular of μ_{h_0} .¹⁸ In figure 4 (right) we show the Higgs mass as a function of M_{SS} for fixed y_s and the same soft terms as before but varying μ_{h_0} . As seen in figure 4, for lower μ_{h_0} , $\tan \beta$ becomes larger and boosts the Higgs mass.

¹⁸The choice of soft masses and A-terms, i.e. m_0 and A_0 have a milder effect on $\tan \beta$.

5 Conclusions

In this letter we studied the Higgs mass in the NMSSM within High-Scale Supersymmetry. In this setup, the low energy effective theory is described by the Standard Model and the respective couplings, in particular the quartic coupling λ , are fixed by the supersymmetric theory at the SUSY-breaking scale M_{SS} . In the MSSM this matching sets $\lambda(M_{\text{SS}})$ to a positive (or vanishing) value and, thus, sets an upper bound $M_{\text{SS}} \lesssim 10^{10} \text{ GeV}$. In the NMSSM, $\lambda(M_{\text{SS}})$ receives additional tree level corrections given in (2.6). The latter allow $\lambda(M_{\text{SS}})$ to take negative values, and, thus, the SUSY-breaking scale can take any value up to the GUT scale. In this work, we computed the Higgs mass as a function of the SUSY-breaking scale varying the NMSSM parameters. The results are summarized in figures 1 and 2. For large values of M_{SS} , the Higgs mass becomes almost constant and can be easily adjusted to the experimental bound $125.15 \pm 0.25 \text{ GeV}$.

In addition, we studied special scenarios of supersymmetry breaking. In particular, we assumed universal soft terms at the GUT scale to constrain the NMSSM parameters appearing in $\lambda(M_{\text{SS}})$. The unification of masses yields low values of $\tan \beta$ at large M_{SS} and, thus, enhances the NMSSM negative contribution to $\lambda(M_{\text{SS}})$. For

$$10^9 \text{ GeV} \lesssim M_{\text{SS}} \lesssim 10^{16} \text{ GeV}, \quad (5.1)$$

the Higgs mass stays almost constant, and its value can be easily accommodated within the experimental bound.¹⁹ For lower values of M_{SS} consistency with the Higgs mass becomes more model dependent and requires small NMSSM contributions to $\lambda(M_{\text{SS}})$.²⁰ Furthermore, in this regime the soft masses spread out and, thus, one loop contributions to $\lambda(M_{\text{SS}})$ become large. Hence, for low values of M_{SS} the determination of the Higgs mass relies on the details of the soft parameters.

Let us remark that although these scenarios suffer from a severe hierarchy problem, introduced by the fine-tuning of the electroweak scale, supersymmetry might nevertheless be present at high scales as required by UV-completions e.g. string theory. In this case, it is conceivable that intermediate supersymmetric theories appear at scales between M_{SS} and a given cutoff Λ , e.g. the string or Planck scale. As long as $M_{\text{SS}} \ll \Lambda$, non-renormalizable couplings between hidden fields and the NMSSM fields can introduce corrections to the matching conditions together with higher dimensional operators in the effective Standard Model potential which are suppressed and can be safely neglected.²¹

To conclude, even if not directly accessible at the LHC, consistency with the Higgs mass via the matching conditions is a necessary condition for models with large SUSY-breaking scales. As we have studied in this letter, the NMSSM can support SUSY-breaking scales

¹⁹See section 4.3 for details.

²⁰In particular, $\tan \beta$ should take larger values and y_s should be negligible in order to suppress the singlet contribution to $\lambda(M_{\text{SS}})$.

²¹Here we denote as hidden fields unknown fields whose dynamics are relevant at scales within M_{SS} and Λ . Note that if the hidden field is responsible for supersymmetry breaking, soft terms are generated. These were already included in the Lagrangian and they are assumed to sit at a scale M_{SS} . If the hidden field couples via renormalizable operators to the NMSSM fields then the matching should be computed to a different theory and it would not make sense to talk about the NMSSM any longer.

near the GUT scale. These news are of particular interest for string phenomenology, since generic vacua in the landscape allow for supersymmetry breaking only at high scales. It might be interesting to find explicit examples of the NMSSM from string derived setups. In particular, provided the UV completion yields specific patterns of soft terms, the measured value of the Higgs mass can be used to test whether these are plausible embeddings of the Standard Model or to constrain the parameters of the theory, in particular, M_{SS} .

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