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THE LIGHTEST HIGGS BOSON MASS IN THE NEXT-TO-MINIMAL SUPERSYMMETRIC STANDARD MODEL[1]

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We consider the infrared quasi fixed point solutions of the one-loop renormalization group equations for the Yukawa couplings and soft supersymmetry breaking parameters in the Next-to-Minimal Supersymmetric Standard Model. Taking as input the top-quark and Z-boson masses, the values of the gauge coupling constants and the infrared quasi fixed points for Yukawa couplings and the soft parameters, the mass of the lightest Higgs boson is discussed.

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1 Introduction

Over the last ten years supersymmetric extensions of the Standard Model (SM) were the most promising theories at high energies. One of the simplest supersymmetric extension of the SM is Next-to-Minimal Supersymmetric Standard Model (NMSSM) [1, 2] (also called (M+1)SSM) which is defined by the introduction of a gauge singlet superfield Y to the Minimal Supersymmetric Standard Model (MSSM) and besides additional discrete Z_3 symmetry of the superpotential W is assumed to avoid the problematic so-called μ term $\mu H_1 H_2$ in the superpotential of the MSSM, where H_1 and H_2 are Higgs $SU(2)$ doublet superfields. Thus, the superpotential of the NMSSM is given as (apart from the Yukawa terms related to the quarks and leptons)

$$W = \lambda H_1 H_2 Y + \frac{1}{3}\lambda' Y^3 + ... \tag{1}$$

Here λ and λ' are corresponding Yukawa coupling constants. In this case, μ term is generated in the process of the electroweak symmetry breaking, when the scalar component of Y obtains a vacuum expectation value (vev) $y = \langle Y \rangle$, and the effective μ term is defined as $\mu H_1 H_2 \equiv \lambda y H_1 H_2$ with $\mu \equiv \lambda y$.

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When making predictions in the framework of a supersymmetric extension of the Standard Model, and the NMSSM is not an exception, one encounters parameter freedom which is mainly due to the so-called soft supersymmetry breaking terms [3]. A large number of free parameters decrease the predictive power of a theory. A common way to reduce this freedom is to make some assumptions at a high energy scale (for example, at the grand unification (GUT) scale or at the Planck scale). Then, treating the parameters of the model as a running variables and using the corresponding renormalization group equations (RGEs), one can derive their values at an interesting low-energy scale.

The usual assumption, which drastically reduce the parameter freedom, is the universality of soft-breaking terms at high energy. In the framework of the NMSSM and within a supergravity induced supersymmetry breaking mechanism universality leads at low energy to a softly broken supersymmetric theory which depends on the following set of free parameters: a common scalar mass m_0, a common gaugino mass $m_{1/2}$, a common trilinear scalar coupling A, and Yukawa couplings λ and λ'.

It is also possible to reduce the remaining freedom by using the so-called infrared quasi-fixed points (IRQFPs) of the RGEs [4]. These IRQFP solutions of the RGEs were widely studied and used in the analysis of the MSSM (see [5, 6] and references therein), the NMSSM [7] and the so-called modified NMSSM [8].

In what follows we adopt the strategy based on the IRQFP behavior (also known as the strong Yukawa coupling limit) and apply it in making prediction for the lightest Higgs boson in the NMSSM in the regime with small $\tan\beta \equiv v_2/v_1 \sim 1$ (the ratio of the vevs of the Higgs fields). In this special case, the IRQFP behavior is the most natural and probable.

2 Infrared Quasi-Fixed Points and RGEs

It is convenient to explain the IRQFP behavior using the simple example of the one-loop RGE for the top-quark Yukawa coupling in the MSSM with the small $\tan\beta$ (see for example [6]). In this case we have an exact solution [9] and the infrared behavior can be investigated in details [6]. The solution has the following form

$$Y_t(t) = \frac{Y_0 E(t)}{1 + 6Y_0 F(t)}, \tag{2}$$

where $Y_t = h_t^2/(4\pi)^2$ (h_t is top-quark Yukawa coupling), $Y_0 = Y_t(0)$, and $E(t), F(t)$ are some functions of the scale parameter $t = \log M_{GUT}^2/Q^2$, $M_{GUT} = 2 \cdot 10^{16}$ GeV is the scale of grand unification and Q is running mass scale. In the limit of large initial conditions $Y_0 \to \infty$ one can write $Y_t(t) \to Y_{FP} = E(t)/(6F(t))$, where the initial condition disappeared completely. Thus, for the large enough initial values, in practise $Y_0 > 2$, the low-energy value of Y_t is weakly dependent on them.

On the other hand, the well-known relation between the running top-quark mass m_t, corresponding Yukawa coupling h_t and parameter $\sin\beta$:

$$m_t = h_t v \sin\beta, \tag{3}$$

where v is vev: $v^2 = v_1^2 + v_2^2 = (174.1GeV)^2$, dictates us that in the case with small $\tan\beta \sim 1$ to have correct top-quark mass the top-quark Yukawa coupling must be near its IRQFP [6].

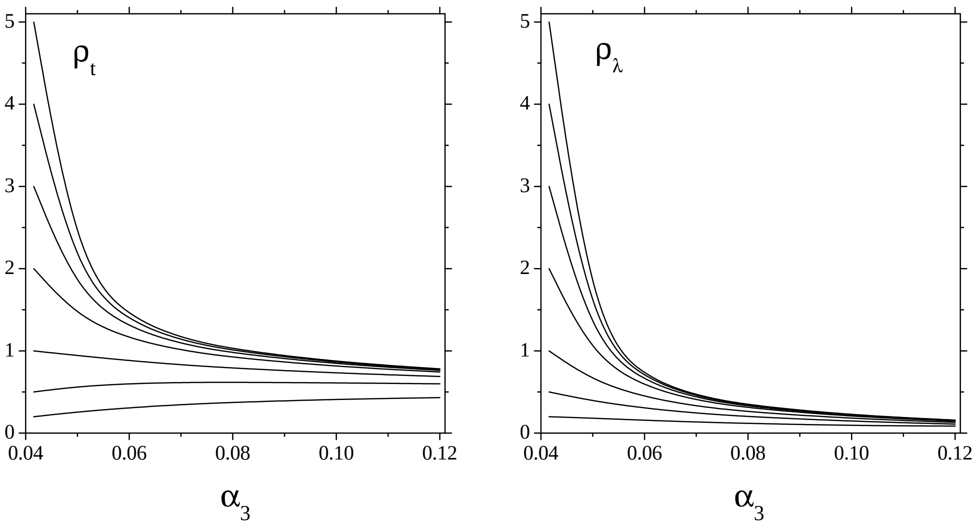


Fig. 1. The IRQFP behavior for $\rho_i = Y_i/\tilde{\alpha}_3, i = t, \lambda$ as functions of α_3. The value $\alpha_3 \approx 0.042$ corresponds to the GUT scale, and the value $\alpha_3 \approx 0.12$ corresponds to the electroweak scale.

The same situation is also held in the NMSSM with small $\tan\beta$. The system of one-loop RGEs for the gauge and the Yukawa couplings has now the following form [2]:

$$\frac{d\tilde{\alpha}_i}{dt} = -b_i\tilde{\alpha}_i^2\,, \tag{4}$$

$$\frac{dY_t}{dt} = -Y_t(6Y_t + Y_\lambda - \frac{16}{3}\tilde{\alpha}_3 - 3\tilde{\alpha}_2 - \frac{13}{15}\tilde{\alpha}_1)\,, \tag{5}$$

$$\frac{dY_\lambda}{dt} = -Y_\lambda(3Y_t + 4Y_\lambda + 2Y_{\lambda'} - 3\tilde{\alpha}_2 - \frac{3}{5}\tilde{\alpha}_1)\,, \tag{6}$$

$$\frac{dY_{\lambda'}}{dt} = -6Y_{\lambda'}(Y_\lambda + Y_{\lambda'})\,, \tag{7}$$

where $\tilde{\alpha}_i = \alpha_i/(4\pi) = g_i^2/(4\pi)^2$ for $i = 1, 2, 3$ are the electroweak and strong gauge coupling constants; $b_1 = 33/5, b_2 = 1, b_3 = -3$, $Y_\lambda = \lambda^2/(4\pi)^2$ and $Y_{\lambda'} = \lambda'^2/(4\pi)^2$. The boton-quark and τ-lepton Yukawa coupling constants Y_b, Y_τ are omitted, because they are negligibly small at $\tan\beta \sim 1$.

In Fig. 1 and 2 the numerical solutions of the RGEs are shown for a wide range of initial values of $Y_t(M_{GUT}) = Y_\lambda(M_{GUT}) = Y_{\lambda'}(M_{GUT})$ from the interval $[0.2, 5]$. As one can see from these figures, there is a strong restriction on all the Yukawa couplings at the electroweak scale. In Fig. 2 is also shown, as an example of behavior of the soft supersymmetry breaking parameter, the infrared behavior of the trilinear soft parameter A_t. In this manner, it is possible to analyse the infrared behavior of all soft supersymmetry breaking parameters (see for example [7]). This analysis strongly reduces the parameter space at the electroweak scale. Thus, using the IRQFP behavior of the parameters of the model rapidly increases the predictive power of the theory. In the next section we will use the infrared behavior of the parameters of the model for calculation of the lightest Higgs boson mass.

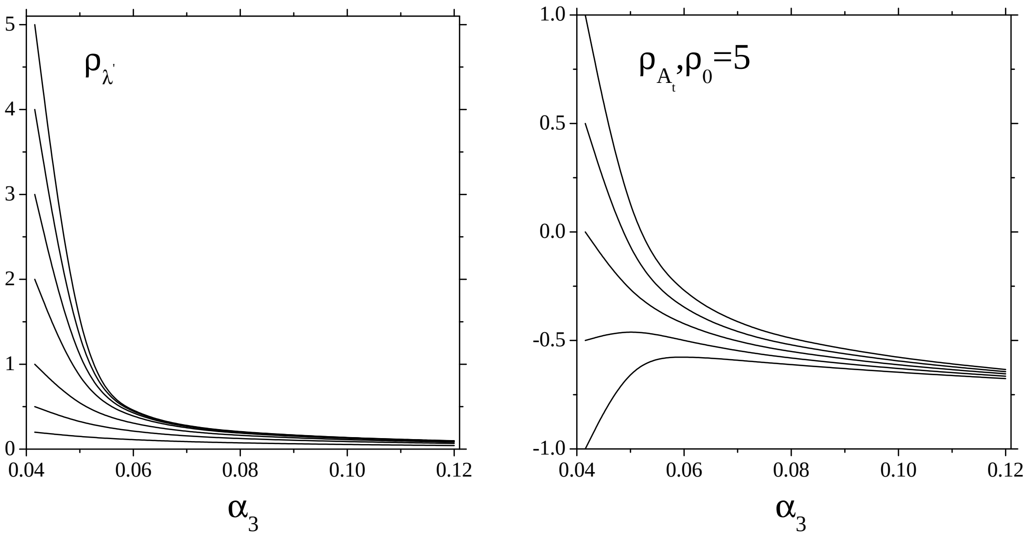


Fig. 2. The IRQFP behavior for $\rho_{\lambda'} = Y_{\lambda'}/\tilde{\alpha}_3$ and for the trilinear soft parameter $\rho_{A_t} = A_t/M_3$ as functions of α_3 (M_3 represents the gluino mass). The value $\alpha_3 \approx 0.042$ corresponds to the GUT scale, and the value $\alpha_3 \approx 0.12$ corresponds to the electroweak scale.

3 Mass of the Lightest Higgs Boson

In this section we use previously obtained IRQFP behavior for computation of the lightest Higgs boson.

In the NMSSM the Higgs sector consists of seven physical states: three neutral CP-even scalars (one of them is the lightest higgs boson h), two neutral CP-odd scalars and one complex charged Higgs scalar. In what follows we will pay attention only to the lightest CP-even Higgs boson mass.

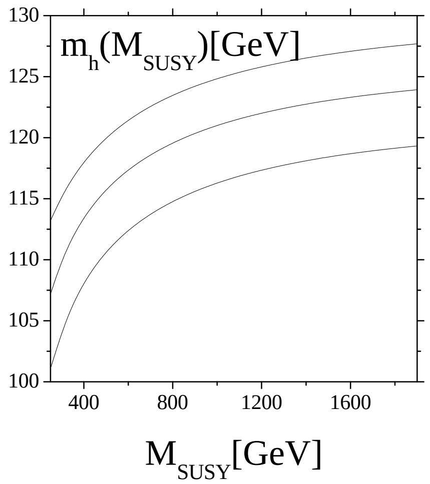
First, we describe our strategy. As input parameters we take the known values of the top-quark pole mass, $m_t^{pole} \approx 174 \pm 5$ GeV, the experimental values of the gauge couplings [10] $\alpha_3 = 0.120 \pm 0.005, \alpha_2 = 0.034, \alpha_1 = 0.017$, the sum of Higgs vevs squared $v^2 = v_1^2 + v_2^2 = (174.1 GeV)^2$ and previously derived fixed-point values for the Yukawa couplings and supersymmetry breaking parameters.

It is important to stress that there is a serious problem in the NMSSM related to the minimization of the corresponding potential. In what follows we will not attack this nontrivial task, rather we will suppose that the minima of the potential exist without proof. Our aim is to determine possible values of the lightest Higgs boson mass.

At the tree level the mass of the lightest Higgs boson h is given by the following expression [11]

$$m_h^2 \leq M_Z^2(\cos^2 2\beta + \frac{2\lambda^2}{g_1^2 + g_2^2} \sin^2 2\beta) \,, \tag{8}$$

where M_Z denotes the mass of Z boson and g_1, g_2 are the gauge couplings of the electroweak interactions. However, loop correction to the effective interaction potential of the Higgs fields



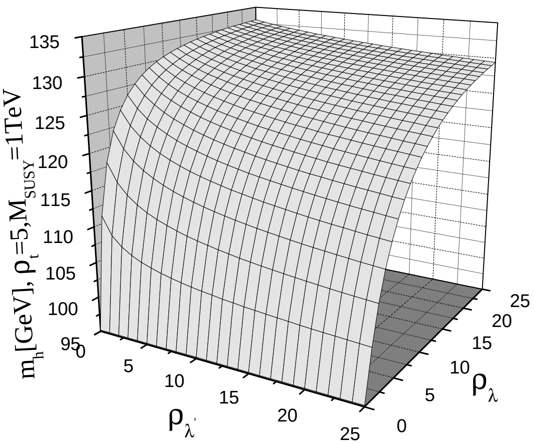


Fig. 3. (Left) The mass of the lightest Higgs boson, h, as a function of M_{SUSY} [GeV]. Central curve corresponds to the "central" values of the parameters of the model. Upper and lower curves describe the influence of the parameter deviation from the central values on the mass of the Higgs boson. (Right) Dependence of the lightest Higgs boson mass on the Yukawa couplings λ and λ' for central values of parameters of the model and for $M_{SUSY} = 1TeV$.

from the t-quark and its superpartners play a very significant role (see for example [12] for one and two loop corrections). In Fig. 3 is shown the dependence of the mass of the lightest Higgs boson as a function of $M_{SUSY} = \sqrt{\tilde{m}_1 \tilde{m}_2}$, where $\tilde{m}_1$ and $\tilde{m}_2$ are masses of the stops (the superpartners of top, see for example [6]). The central values of the parameters are defined as follows (universality is assumed):$\rho_0 = 5$, $\rho_{A0} = 0$, $m_0^2/m_{1/2} = 1$ and we allow the parameters to move in the following intervals: $\rho_0 \in [2, 25]$, $\rho_{A0} \in [-3, 3]$ and $m_0^2/m_{1/2}^2 \in [0.25, 4]$ (details see in Ref. [6]). For a typical value of $M_{SUSY} = 1$TeV we find the following prediction for the lightest Higgs boson mass:

$$m_h = 121^{+1.8+1.3}_{-3.0-1.3} \pm 5GeV. \tag{9}$$

The first uncertainty is connected with the Yukawa couplings, the second with the soft parameters and the last is due to the experimental uncertainty in the top-quark mass.

4 Conclusion

We have analyzed the fixed point behavior of the parameters of the NMSSM in the small $\tan\beta$ scenario. These fixed points were used to make predictions for the mass of the lightest Higgs boson. Our main conclusion is that the present experimental dada ($m_h > 113.4$ GeV [13]) do not exclude the NMSSM as the model relevant in the Universe.

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