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Higgs mass and vacuum stability with high-scale supersymmetry

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In the high-scale (split) MSSM, the measured Higgs mass m_h sets an upper bound on the supersymmetric scalar mass scale $M_{\rm SUSY}$ around 10^{11} (10^8) GeV, for tanβ in the standard range and the central value of the top quark mass m_t. This work discusses how maximal $M_{\rm SUSY}$ is affected by negative threshold corrections to the Higgs quartic coupling arising from the sbottom and stop trilinear couplings. In the high-scale MSSM with very high tanβ, the electroweak vacuum decay due to the large bottom Yukawa coupling rules out the possibility of raising $M_{\rm SUSY}$ beyond the above limit. In cases with large A_b or A_t, $M_{\rm SUSY}$ as a common mass of the extra fermions and scalars can be as high as 10^{17} GeV remaining consistent with m_h and the vacuum longevity if m_t is smaller than the central value by 2σ. For the central value of m_t, the upper limit on $M_{\rm SUSY}$ does not change very much owing to the metastability, which is the case also in the split MSSM even with $\pm 2\sigma$ variations in m_t.

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In this work [1], the possibility of fitting m_h shall be contemplated within the high-scale (split) minimal supersymmetric standard model (MSSM) using the supersymmetric trilinear term,

$$\Delta\mathscr{L}_F = h_b \mu H_u \widetilde{Q}^* \tilde{b}_R, \tag{1}$$

as well as the soft supersymmetry breaking trilinear terms,

$$\Delta\mathscr{L}_{\rm soft} = -T_b H_d \widetilde{Q} \tilde{b}_R^* + T_t H_u \widetilde{Q} \tilde{t}_R^*, \tag{2}$$

wherein it is common to factor the MSSM Yukawa couplings h_b and h_t out of the T-parameters, yielding the familiar definitions of the A-parameters:

$$T_b \equiv h_b A_b, \quad T_t \equiv h_t A_t. \tag{3}$$

To express threshold corrections to the Higgs quartic coupling λ, it is common to define the left-right squark mixing parameters,

$$X_b \equiv A_b - \mu \tan\beta, \quad X_t \equiv A_t - \mu \cot\beta. \tag{4}$$

As large trilinear couplings can cause charge/color breaking (CCB) global minima, the vacuum metastability shall be required as follows:

$$(\Gamma_{\rm vac}/V)\, T^4 < 1, \tag{5}$$

where $\Gamma_{\rm vac}/V$ is the decay rate of the electroweak vacuum per unit volume and T is the age of the Universe. In the semiclassical formulation, the vacuum decay rate reads

$$\Gamma_{\rm vac}/V = A \exp(-S[\overline{\phi}]), \tag{6}$$

where A is a prefactor of mass dimension 4, S is the Euclidean action, and the "bounce" $\overline{\phi}$ is an O(4)-symmetric stationary point of S satisfying appropriate boundary conditions [2].

The high-$\tan\beta$ scenario from [3] is revisited. Making use of the one-loop sbottom threshold correction to λ, one can increase $\tan\beta$ to the extent that a large enough MSSM Yukawa coupling h_b enables the matching of λ for an arbitrarily high $|\mu| = M_{\rm SUSY}$. However, the same product $h_b\mu$ affects not only the threshold correction but also the existence of CCB global minima as suggested by (1). The m_h and vacuum (meta)stability constraints on $M_{\rm SUSY}$ and $\tan\beta$ are plotted in Fig. 1 using `FlexibleSUSY` [4].

An alternative way to enhance negative $\Delta\lambda$ is to increase $|X_b|$ far beyond $\sqrt{12} M_{\rm SUSY}$ via A_b. In this case, one can choose $\tan\beta$ to be 1 to minimize the tree-level contribution to λ and then fit m_h by varying A_b in the high-scale and the split MSSM. The results are shown in Fig. 2, for $\mu > 0$ and $A_b < 0$.

A negative threshold correction can also arise from $|X_t| \gtrsim \sqrt{12} M_{\rm SUSY}$. Values of X_t leading to correct m_h and the vacuum decay limits thereon are shown in Fig. 3, for $\mu > 0$ and $X_t < 0$.

In summary, this work has attempted to address the question of how high the supersymmetry scale can be, given the measured SM-like Higgs mass as a constraint on the parameters of the MSSM. Two types have been considered as to the mass spectrum of the supersymmetric particles including the extra Higgses: (a) nearly degenerate fermions and scalars (high-scale MSSM),

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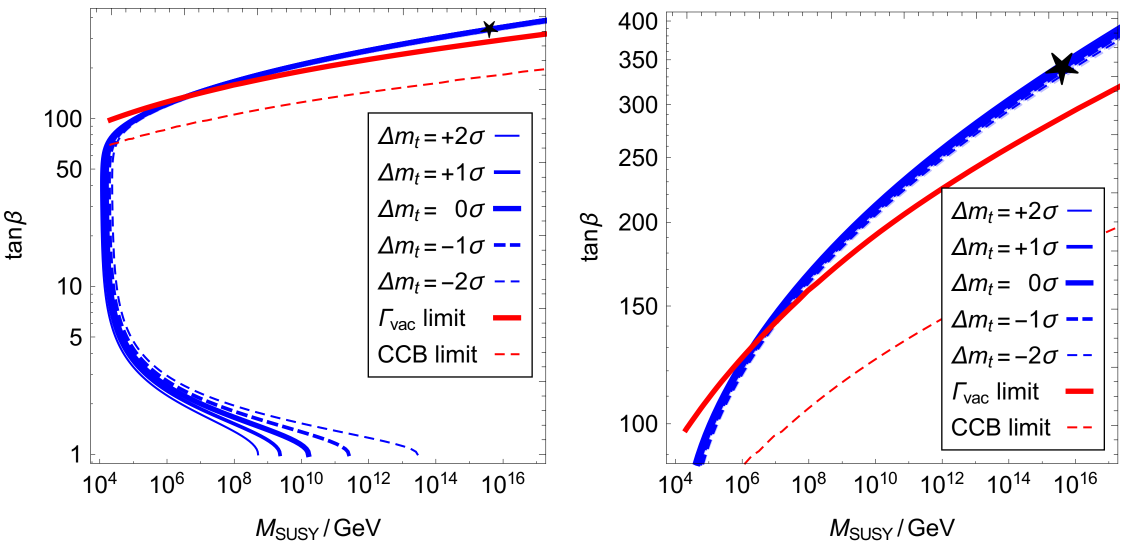
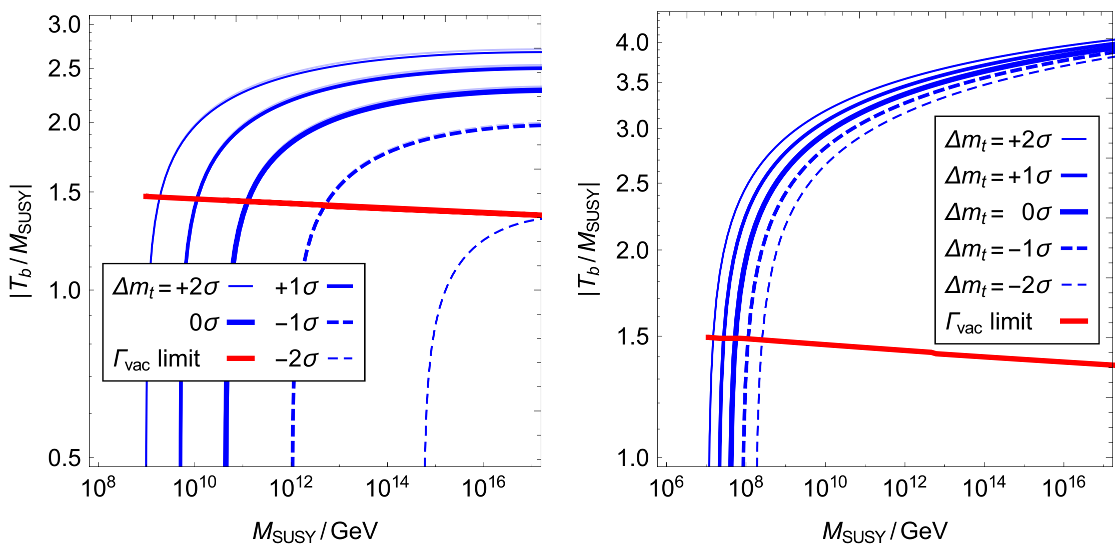


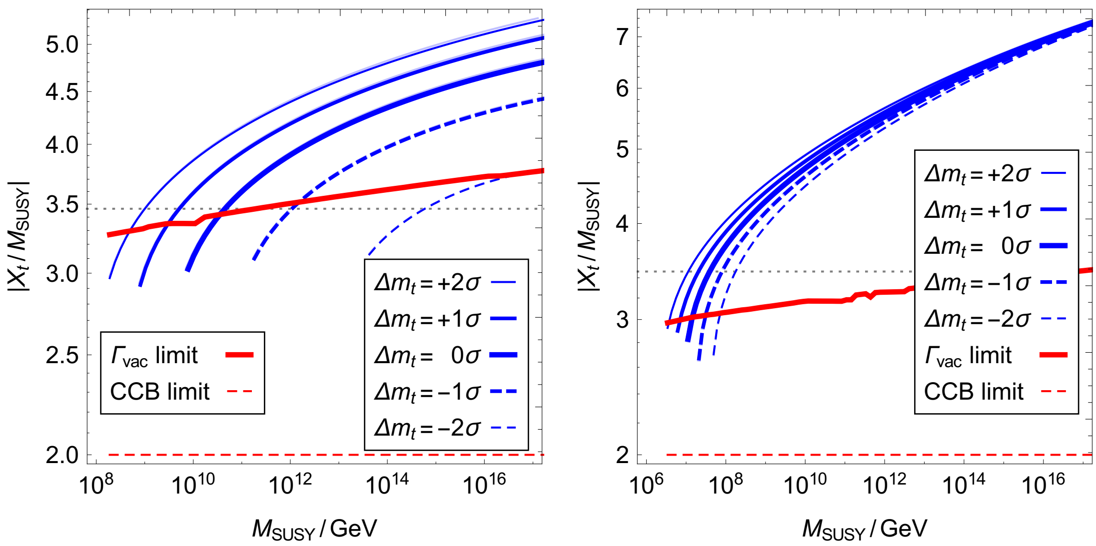
Figure 1: Higgs mass curves (blue) and (meta)stability limit (red) on the $(M_{SUSY}, \tan\beta)$ plane. Both plots are the same except that the right panel is restricted to the high-$\tan\beta$ range. The thickness and pattern of each blue curve reproducing $m_h = 125.09\,\text{GeV}$, indicate the size and sign of the deviation of used m_t from the central value, respectively.



(a) High-scale MSSM

(b) Split MSSM

Figure 2: Sbottom trilinear coupling fitting the Higgs mass (blue) and metastability limit (red) for $\tan\beta = 1$, as a function of M_{SUSY} in (a) the high-scale MSSM and (b) the split MSSM with $\mu = m_{1/2} = 1\,\text{TeV}$. The thickness and pattern of each blue curve reproducing $m_h = 125.09\,\text{GeV}$, indicate the size and sign of the deviation of used m_t from the central value, respectively.



(a) High-scale MSSM (b) Split MSSM

Figure 3: Stop trilinear coupling fitting the Higgs mass (blue) and (meta)stability limit (red) for $\tan\beta = 1$, as a function of M_{SUSY} in (a) the high-scale MSSM and (b) the split MSSM with $\mu = m_{1/2} = 1\,\text{TeV}$. The thickness and pattern of each blue curve reproducing $m_h = 125.09\,\text{GeV}$, indicate the size and sign of the deviation of used m_t from the central value, respectively. The horizontal dotted line marks the height $|X_t/M_{SUSY}| = \sqrt{12}$.

(b) split spectrum where the fermions are at the TeV scale (split MSSM). To satisfy the matching condition on the Higgs quartic coupling, the sbottom and the stop trilinear couplings have been employed as sources of the potentially large negative threshold corrections. In all cases, it is possible to reproduce $m_h = 125.09\,\text{GeV}$, by choosing appropriate values of $\tan\beta$ in combination with A_b or A_t, for M_{SUSY} up to $10^{17}\,\text{GeV}$. However, the lifetime of the electroweak vacuum places severe constraints on the trilinear couplings and mostly brings back the upper limits on M_{SUSY} for $X_b = X_t = 0$: $M_{SUSY} \lesssim 10^{11}\,\text{GeV}$ and $10^8\,\text{GeV}$, in the high-scale and the split MSSM, respectively, for the central value of m_t. Nevertheless, a small extension of the viable parameter volume could be achieved via non-vanishing X_b and/or X_t in the high-scale MSSM: $M_{SUSY} \gtrsim M_{GUT}$ becomes viable if m_t is allowed to be smaller than the central value by 2σ. On the other hand, the vacuum decay rate rules out the scenario where very high $\tan\beta$ reconciles arbitrarily high M_{SUSY} with m_h [3].

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