Residual effects of heavy sparticles in bottom quark Yukawa coupling: A Comparative study for MSSM and NMSSM (Postprint)

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Abstract

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Full Text

Preamble

Residual Effects of Heavy Sparticles in the Bottom Quark Yukawa Coupling: A Comparative Study for the MSSM and NMSSM

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If sparticles are relatively heavy (a few TeV) while the Higgs sector is not particularly heavy (i.e., m_A is not too large), the Higgs boson Yukawa couplings can harbor sizable quantum effects from sparticles. These large residual effects may play a special role in probing supersymmetry at foreseeable colliders. In this work, focusing on the supersymmetric QCD effects in the $hb\bar{b}$ coupling (where h is the lightest CP-even Higgs boson), we present a comparative study of two popular supersymmetric models: the MSSM and NMSSM. While supersymmetric QCD can leave substantial residual quantum effects in the $hb\bar{b}$ coupling for both models, the NMSSM allows for a much broader region of such effects. Since these residual effects can exceed 20% for the $hb\bar{b}$ coupling (and thus over 40%

for the ratio $\mathrm{Br}(h \to b\bar{b})/\mathrm{Br}(h \to \tau^+\tau^-)$), future measurements may reveal the effects of heavy sparticles or even distinguish between the two models.

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Introduction

Supersymmetry is a prime candidate for new physics beyond the Standard Model (SM). Among various supersymmetric models, the most extensively studied is the Minimal Supersymmetric Standard Model (MSSM) [1]. Another popular supersymmetric model, which may be equally or even more attractive than the MSSM, is the Next-to-Minimal Supersymmetric Standard Model (NMSSM) [2], as it can solve the μ-problem and alleviate the little hierarchy problem. These models will soon be tested at the LHC, making their phenomenological study both important and urgent.

Although the most convincing evidence for supersymmetry would be the direct detection of sparticle production (sfermions, gauginos, or Higgsinos), indirect probes through detecting quantum effects of virtual sparticles in measurable interactions will play a complementary role. If sparticles are relatively heavy (say above a few TeV) and thus cannot be directly detected at the LHC, indirect probes through quantum effects could become particularly important. For this purpose, Higgs boson Yukawa interactions may play a special role, as they can harbor sizable quantum effects from heavy sparticles when the Higgs sector is not too heavy (i.e., m_A is not large). The dominant quantum effects from sparticles arise from supersymmetric QCD interactions, and calculations of these effects in the MSSM for Higgs boson Yukawa couplings [3, 4] and associated Higgs production processes at the LHC [5] have been performed in the literature. Studies in the decoupling limit with heavy sparticles showed that for a light Higgs sector (m_A not large), supersymmetric QCD can leave substantial residual quantum effects in both the $h \to b\bar{b}$ decay [4] and production processes at the LHC [5]. Given the popularity of the NMSSM, it is necessary to extend these studies to the NMSSM, which is precisely the aim of this work.

In this work, we focus on supersymmetric QCD effects in the $hb\bar{b}$ coupling (where h is the lightest CP-even neutral Higgs boson) and perform a comparative study for the two popular supersymmetric models: the MSSM and NMSSM. Such a study is interesting for two reasons: (i) The study of the NMSSM encompasses the MSSM, and in some limit the NMSSM results reduce to the MSSM results. One can envisage that supersymmetric residual effects in the MSSM may be magnified in the NMSSM, so future measurements of such effects may help distinguish between the two models. (ii) Compared with the MSSM, the NMSSM may predict a different tree-level $hb\bar{b}$ coupling and different loop contributions. In the NMSSM, the mass matrix and mixings of the Higgs bosons are enriched, and thus the components of the lightest CP-even Higgs boson h differ from the MSSM values. The residual supersymmetric QCD effects in the NMSSM may therefore be larger and more interesting.

Note that supersymmetry is a decoupling theory, and all low-energy observables recover their corresponding SM predictions when the mass scale of all supersymmetric particles (including sparticle masses and m_A) takes heavy limits. The large residual quantum effects of sparticles in Higgs Yukawa couplings occur only when sparticles are heavy but m_A is light. If both sparticles and m_A take their heavy limits, the residual effects of supersymmetry vanish. Since such a split scenario (with light Higgs bosons and relatively heavy sparticles) remains possible, we should examine its phenomenological consequences.

II. Calculations

We begin our analysis by recapitulating the basics of the NMSSM. In the NMSSM, a singlet Higgs superfield $\hat{S}$ is introduced, and the Higgs terms in the superpotential are given by $\lambda \hat{S} \hat{H}_d \cdot \hat{H}_u + \frac{\kappa}{3} \hat{S}^3$, where $\hat{H}_u$ and $\hat{H}_d$ are the Higgs doublet superfields, and λ and κ are dimensionless constants. Note that there is no explicit μ-term, and an effective μ-parameter is generated when the scalar component (S) of $\hat{S}$ develops a VEV s: $\mu_{\text{eff}} = \lambda s$. The corresponding soft SUSY breaking terms are given by $m_d^2 |H_d|^2 + m_u^2 |H_u|^2 + m_s^2 |S|^2 + (A_\lambda \lambda S H_d \cdot H_u + \frac{A_\kappa \kappa}{3} S^3 + \text{h.c.})$.

The scalar Higgs potential is given by:

$$V = V_F + V_D + V_{\text{soft}}$$

where

$$V_F = |\lambda H_d \cdot H_u - \kappa S^2|^2 + |\lambda S|^2 (|H_d|^2 + |H_u|^2)$$

$$V_D = \frac{1}{8} g_1^2 (|H_d|^2 - |H_u|^2)^2 + \frac{1}{8} g_2^2 \left[|H_d|^2 |H_u|^2 - |H_d \cdot H_u|^2 \right]$$

$$V_{\text{soft}} = m_d^2 |H_d|^2 + m_u^2 |H_u|^2 + m_s^2 |S|^2 + (A_\lambda \lambda S H_d \cdot H_u + \frac{A_\kappa \kappa}{3} S^3 + \text{h.c.})$$

Here g_1 and g_2 are the coupling constants of $U_Y(1)$ and $SU_L(2)$, respectively. We can see that in the limit of vanishing λ, κ, A_κ with the input of the effective μ_{eff}, the NMSSM reduces to the MSSM.

With the VEVs v_u, v_d, and s, the scalar fields are expanded as:

$$\begin{pmatrix} H_d^0 \\ H_u^0 \\ S \end{pmatrix} = \begin{pmatrix} v_d + \frac{\phi_d + i\varphi_d}{\sqrt{2}} \\ v_u + \frac{\phi_u + i\varphi_u}{\sqrt{2}} \\ s + \frac{\sigma + i\varphi_s}{\sqrt{2}} \end{pmatrix}$$

The mass eigenstates can be obtained by unitary rotations of the interaction states; for example, for the CP-even neutral mass eigenstates (h, H_1, H_2) we have:

$$(h, H_1, H_2)^T = U_H (\phi_d, \phi_u, \sigma)^T$$

Thus, the lightest CP-even neutral Higgs boson h is composed of $U_{H11}\phi_d + U_{H12}\phi_u + U_{H13}\sigma$. In the MSSM, h can be decomposed in the same way, except that without the singlet component, U_H is a 2×2 matrix parameterized in terms of a mixing angle α.

The sbottom squared-mass matrix in the NMSSM is the same as in the MSSM with μ replaced by μ_{eff}. In the basis of $(\tilde{b}_L, \tilde{b}_R)$, the squared-mass matrix is given by:

$$\begin{pmatrix} M^2_{\tilde{Q}} + m_b^2 + m_Z^2(I_3^b - Q_b s_W^2)\cos 2\beta & m_b X_b \\ m_b X_b & M^2_{\tilde{b}_R} + m_b^2 + m_Z^2 Q_b s_W^2 \cos 2\beta \end{pmatrix}$$

where $X_b = A_b + \mu_{\text{eff}} \tan\beta$, $s_W \equiv \sin\theta_W$, $\tan\beta = v_u/v_d$, I_3^b and Q_b are respectively the isospin and electric charge of the b-quark, $M_{\tilde{Q}}$ and $M_{\tilde{b}_R}$ are the soft breaking masses, and A_b is the soft breaking trilinear coupling. The sbottom mass eigenstates $(\tilde{b}_1, \tilde{b}_2)$ are obtained by the unitary rotation of the interaction eigenstates:

$$\begin{pmatrix} \tilde{b}_L \\ \tilde{b}_R \end{pmatrix} = Z_D \begin{pmatrix} \tilde{b}_1 \\ \tilde{b}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{b}} & -\sin\theta_{\tilde{b}} \\ \sin\theta_{\tilde{b}} & \cos\theta_{\tilde{b}} \end{pmatrix} \begin{pmatrix} \tilde{b}_1 \\ \tilde{b}_2 \end{pmatrix}$$

where the unitary matrix Z_D parameterized by a mixing angle $\theta_{\tilde{b}}$ diagonalizes the mass matrix.

The coupling of sbottoms with the singlet component σ of the Higgs boson h comes from the F-term of the superpotential, given by $2m_W \cos\beta \lambda v_u \sqrt{2}\sigma \tilde{b}_L \tilde{b}_R +$ h.c.. In terms of the sbottom mass eigenstates, the vertex $h\tilde{b}_i\tilde{b}_j$ takes the form:

$$V_{h\tilde{b}_i\tilde{b}_j} = \frac{2m_W \cos\beta}{\sqrt{2}} \left[c_{ij}^{11} U_{H11} + c_{ij}^{12} U_{H12} + c_{ij}^{13} U_{H13}\right]$$

where c_{ij}^{13} is only for the NMSSM (or equivalently set to zero for the MSSM), while c_{ij}^{11} and c_{ij}^{12} are present for both models. They are given by:

$$c_{ij}^{11} = \frac{g_2 m_b}{\sqrt{2} m_W \cos\beta} Z_{D1i} Z_{D1j} - \frac{g_2 m_Z \sin\theta_W \cos^2\beta}{\sqrt{2} m_W \cos\beta} Z_{D1i} Z_{D1j} + \frac{g_2 m_Z \sin\theta_W \sin^2\beta}{\sqrt{2} m_W \cos\beta} Z_{D2i} Z_{D2j}$$

$$c_{ij}^{12} = \frac{g_2 m_b}{\sqrt{2} m_W \cos\beta} Z_{D2i} Z_{D2j} + \frac{g_2 m_Z \sin\theta_W \cos^2\beta}{\sqrt{2} m_W \cos\beta} Z_{D1i} Z_{D1j} - \frac{g_2 m_Z \sin\theta_W \sin^2\beta}{\sqrt{2} m_W \cos\beta} Z_{D2i} Z_{D2j} + \frac{\sqrt{2}\lambda m_W \sin\beta}{g_2} Z_{D1i}$$

Now we calculate the SUSY QCD corrections to the vertex $hb\bar{b}$. At tree level, it takes the same form in both the MSSM and NMSSM, given by:

$$V^0_{hb\bar{b}} = \frac{g_2 m_b U_{H12}}{2 m_W \cos\beta}$$

The one-loop SUSY QCD corrections come from the Feynman diagrams shown in [Figure 1: see original paper], where we do not show the self-energy loop of $\bar{b}$. In our calculations we use the on-shell renormalization scheme [7] and take the external b and $\bar{b}$ quarks on shell to obtain the effective vertex. With the corrections, the effective vertex takes the form:

$$V_{hb\bar{b}} = V^0_{hb\bar{b}} \left[1 + \Delta_v + \Delta_{ct}\right]$$

where Δ_v denotes the vertex correction from diagram (a) in [Figure 1: see original paper] and Δ_{ct} is the counterterm from the renormalization of m_b and the wave functions of b and $\bar{b}$. They are given by:

$$\Delta_v = \frac{2\alpha_s}{3\pi} \sum_{i,j=1}^{2} \int_0^1 dx \int_0^{1-x} dy \frac{m_{\tilde{g}} m_b \sin(2\theta_{\tilde{b}}) \Big[C_{11}(m_b^2, m_h^2, m_b^2, m_{\tilde{g}}^2, m_{\tilde{b}_i}^2, m_{\tilde{b}_j}^2) + m_{\tilde{g}} C_0(m_b^2, m_h^2, m_b^2, m_{\tilde{g}}^2, m_{\tilde{b}_i}^2, m_{\tilde{b}_j}^2}{m_b^2 - m_h^2}$$

$$\Delta_{ct} = -\frac{2\alpha_s}{3\pi} \sin(2\theta_{\tilde{b}}) \Big[B_0(m_b^2, m_{\tilde{g}}^2, m_{\tilde{b}_1}^2) - B_0(m_b^2, m_{\tilde{g}}^2, m_{\tilde{b}_2}^2)\Big]$$

where α_s is the strong coupling constant, $m_{\tilde{g}}$ is the gluino mass, and B_0, B_0', B_1, B_1', C_0, and C_{11} are the scalar loop functions [8] that can be calculated using LoopTools [9].

III. Numerical Results

In our calculation we use the package NMSSMTools [10] for the mass spectrum and the rotation matrix of the Higgs fields (to obtain the corresponding MSSM results, we take the limit of very small values for λ, κ, and A_κ, and the results are checked using the package FeynHiggs [11]). To study the decoupling limit of SUSY particles, we assume all the soft breaking mass parameters $(M_{\tilde{Q}}, M_{\tilde{b}_R}, m_{\tilde{g}}, A_b)$ and the parameter μ_{eff} are degenerate, which we collectively denote by M_{SUSY}. Then in the MSSM the SUSY parameters are $(M_{\text{SUSY}}, M_A, \tan\beta)$, while in the NMSSM there are three additional parameters $(\lambda, \kappa, A_\kappa)$. In our calculations we scan over these three additional parameters in the ranges $-0.5 < \lambda, \kappa < 0.5$ and -500 GeV $< A_\kappa <$ 500 GeV. Note that we did not consider large values of λ or κ. Theoretically, the requirement of perturbativity up to some cutoff scale sets upper bounds on λ and κ at the weak scale (if the cutoff scale is chosen to be the GUT scale, a stringent bound $\lambda^2 + \kappa^2 < 0.5$ is obtained [6]). Phenomenologically, large λ or κ would incur stringent constraints from current experiments (see the last reference in [2]).

Before presenting the numerical results, we make several clarifications regarding our calculations: (1) We use the package NMSSMTools [10], which includes loop corrections (especially stop/sbottom loops) to the effective potential, masses, and mixing angles of the Higgs bosons. These corrections are important and cannot be ignored. (2) Since we use NMSSMTools, in which the Higgs mass matrices are diagonalized numerically, we do not employ any approximate unitary transformation in our calculation. (3) For the b-quark mass m_b, in NMSSM-Tools (and thus in our calculation), it is taken as the running mass $m_b(Q)$ (we take $Q = M_{\rm SUSY}$), which means that sizable QCD loop effects are included. Although both the tree-level coupling $V^0_{hb\bar{b}}$ and the one-loop SUSY QCD contributions $\delta V_{hb\bar{b}}$ are proportional to m_b and thus very sensitive to the value of m_b, the relative correction effects $\delta V_{hb\bar{b}}/V^0_{hb\bar{b}}$ (displayed in our numerical results) are not so sensitive to m_b.

Now we present some numerical results. To see the general features of the corrections, we first switch off the experimental constraints on the parameter space and in [Figure 2: see original paper] and [Figure 3: see original paper] display the results of the relative correction effects $\Delta_{\rm SQCD} \equiv \delta V_{hb\bar{b}}/V^0_{hb\bar{b}} = \Delta_v + \Delta_{ct}$. We see that for light m_A, SUSY QCD with large $M_{\rm SUSY}$ can leave sizable effects in the $hb\bar{b}$ coupling. However, as m_A becomes heavy, such residual effects of SUSY QCD diminish in magnitude, showing the decoupling behavior of supersymmetry. Compared with the MSSM results, the effects in the NMSSM can vary over a much broader region. While the corrections are always negative in the MSSM, in the NMSSM they can be both negative and positive.

To understand in which regions of the NMSSM parameter space the one-loop SUSY QCD effects on the $hb\bar{b}$ coupling become sizable, we present a set of sample points in . We find that for the SUSY QCD loop effects on the $hb\bar{b}$ coupling to be sizable in the NMSSM, the ratio U_{H12}/U_{H11} (where U_{H12} and U_{H11} are respectively the components of ϕ_u and ϕ_d in h, as defined in Eq. (10)) plays a key role for the following reasons. As shown in Eq. (24), $\Delta_{\rm SQCD}$ is composed of two parts: the counterterm part Δ_{ct} and the vertex-loop part Δ_v. We find that in most of the parameter space allowed by LEP constraints, Δ_{ct} is negative and dominant in magnitude, independent of how h is composed. In contrast, Δ_v is positive and cancels Δ_{ct} to some extent. The size of Δ_v can be enhanced by the ratio U_{H12}/U_{H11}, as shown in Eq. (21). Although the ratio U_{H13}/U_{H11} can also enhance the size of Δ_v, its effect is suppressed by the smallness of U_{H13} and λ in c^{13}_{ij} (in our scan we found that both λ and U_{H13} must be small to satisfy the LEP constraints encoded in NMSSMTools). Therefore, as U_{H12}/U_{H11} becomes large, Δ_v becomes more sizable and, due to its cancellation effect, the total correction effects become less sizable. Note that although m_h is below 114 GeV for some points, these points can still satisfy the LEP constraints encoded in NMSSMTools because the LEP bound on the MSSM m_h is 92 GeV (see Fig. 2 in the paper by Barger et al. in Ref. [2]). Incidentally, comprehensive studies on the phenomenology of the NMSSM Higgs sector (which may be quite different from that of the MSSM Higgs sector) have been performed in Ref. [2], where all Higgs couplings, decay modes, and production processes were intensively studied.

From we see that although λ is scanned in the range $[-0.5, 0.5]$, only small values of λ (in magnitude) survive the LEP constraints encoded in NMSSMTools. As λ becomes large, the mixing between singlet and doublet Higgs fields increases (although the mixing is not solely determined by λ, as other parameters also contribute) and consequently becomes more constrained by LEP experiments [2]. Such a small λ, together with other NMSSM parameters appearing in the Higgs mass matrix, leads to small mixing between singlet and doublet Higgs fields. As shown in , the singlet component U_{H13} in h is small, meaning that the lightest Higgs boson h is not singlet-like but rather doublet-dominant (MSSM-like). For the $hb\bar{b}$ coupling with such an MSSM-like h, the NMSSM can still allow for quite different SUSY QCD effects compared with MSSM predictions. The reason is that, as discussed above, the SUSY QCD effects are sensitive to the ratio U_{H12}/U_{H11}, which differs between these two models (even for small λ, the NMSSM can still allow for different-sized components U_{H12} and U_{H11} in h because other NMSSM parameters also contribute to the Higgs mass matrix and mixings).

When we switch on the comprehensive experimental constraints encoded in NMSSMTools [10], we obtain the results for $\Delta_{\rm SQCD}$ displayed in [Figure 4: see original paper]. These experimental constraints are comprehensive, including LEP II searches for Higgs bosons, various B-decays, and the muon anomalous magnetic moment (muon $g-2$). From [Figure 4: see original paper] we see that in the special scenario under consideration (where all soft breaking mass parameters are degenerate), $M_{\rm SUSY}$ is constrained to a certain range. The region $M_{\rm SUSY} < 600$ GeV is not allowed by LEP experiments, while $M_{\rm SUSY} > 1$ TeV cannot explain the muon $g-2$ data (we require supersymmetric effects to account for the deviation $\Delta a_\mu^{\rm exp} = (29.5 \pm 8.8) \times 10^{-10}$ at the 2σ level). In the allowed region of parameter space, the SUSY QCD corrections to the $hb\bar{b}$ coupling can still be significant, exceeding 20% in magnitude. If we switch off the muon $g-2$ constraint (the hadronic contribution to $a_\mu^{\rm SM}$ is not so certain [12]), the allowed parameter space becomes much broader, as shown in [Figure 4: see original paper]. In our study we did not require supersymmetry to explain various plausible dark matter evidence.

Note that the SUSY contributions to muon $g-2$ are sensitive to soft masses in the slepton and chargino sectors, but not dependent on the squark or gluino masses involved in our SUSY QCD loops. The stringent constraint from muon $g-2$ data shown in [Figure 4: see original paper] arises from our simplifying assumption that all soft masses (in the squark, slepton, and gaugino sectors) are degenerate. Of course, the muon $g-2$ constraint is not essential; without such an assumption of degeneracy, the constraint is lifted.

Since the SUSY QCD residual effects can exceed 20% for the $hb\bar{b}$ coupling and thus over 40% for the ratio of branching fractions (SUSY QCD does not contribute to $h \to \tau^+\tau^-$ at one-loop level) $R_{b/\tau} = {\rm Br}(h \to b\bar{b})/{\rm Br}(h \to \tau^+\tau^-)$, future measurements at the LHC or ILC may reveal such supersymmetric effects. This ratio $R_{b/\tau}$ was proposed in [13] as a probe of new physics. To measure this ratio at the LHC, one may count the event numbers of $hb\bar{b}$ production followed respectively by the decays $h \to b\bar{b}$ and $h \to \tau^+\tau^-$, and the ratio of these event numbers can serve as a measure of $R_{b/\tau}$ (the difference in efficiency for b-tagging and τ-tagging should be taken into account).

Finally, we make some remarks regarding our results: (1) We have only investigated the SUSY QCD corrections, which are $\mathcal{O}(\alpha_s)$ and thus should be the most important among SUSY corrections. Among the SUSY electroweak corrections, the Higgs-top Yukawa corrections, which are $\mathcal{O}(\alpha_t)$, may also be sizable, although they appear not as large as the $\mathcal{O}(\alpha_s)$ SUSY QCD corrections. Including SUSY electroweak corrections would leave our conclusions qualitatively unchanged. (2) Since our main interest is the residual effects of heavy sparticles, we assumed all soft SUSY-breaking mass parameters are equal to M_{SUSY}. This is a very strong simplifying assumption. If we lift this assumption and consider multiple free soft parameters, we would obtain results that differ numerically to some extent while qualitatively exhibiting the same feature—that the NMSSM allows broader corrections than the MSSM—because NMSSM parameters can complicate the mass matrix and mixings of Higgs fields. (3) We should stress again that supersymmetry is a decoupling theory, and large residual quantum effects of sparticles in Higgs Yukawa couplings are present only in the case of light m_A. If both M_{SUSY} and m_A take their heavy limits, the SUSY effects vanish. This decoupling behavior is similar in the NMSSM and MSSM, as shown in [Figure 2: see original paper].

IV. Summary

We focused on SUSY QCD effects in the $hb\bar{b}$ coupling and performed a comparative study for the two popular SUSY models: the MSSM and NMSSM. We found that for both models, SUSY QCD can leave large residual quantum effects in the $hb\bar{b}$ coupling if sparticles are relatively heavy (a few TeV) while the Higgs sector is not too heavy (m_A is not too large). Compared with MSSM results, the NMSSM allows for a much broader region of such residual effects. Since these residual effects can exceed 20% in magnitude, future measurements of the $hb\bar{b}$ coupling may reveal such supersymmetric effects or even distinguish between the two models.

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Note: Figure translations are in progress. See original paper for figures.