A SM-like Higgs near 125 GeV in low energy SUSY: a comparative study for MSSM and NMSSM (Postprint)

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Abstract

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Full Text

Preamble

A SM-like Higgs near 125 GeV in low energy SUSY: a comparative study for MSSM and NMSSM

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Abstract

Motivated by recent LHC hints of a Higgs boson around 125 GeV, we assume a SM-like Higgs with mass in the range 123-127 GeV and study its implications in low-energy SUSY by comparing the MSSM and NMSSM. We consider various experimental constraints at the 2 level (including the muon g-2 and dark matter relic density) and perform a comprehensive scan over the parameter space of each model. Then, within the parameter space allowed by current experimental constraints and that also predicts a SM-like Higgs in the 123-127 GeV range, we examine the properties of sensitive parameters (such as the top squark mass and trilinear coupling At) and calculate the rates of the di-photon signal and the VV* (V = W, Z) signals at the LHC. Our typical findings are: (i) In the MSSM the top squark and At must be large, thus incurring some fine-tuning, which can be much ameliorated in the NMSSM; (ii) In the MSSM a light stau is needed to enhance the di-photon rate of the SM-like Higgs beyond its SM prediction, while in the NMSSM the di-photon rate can be readily enhanced in several ways; (iii) In the MSSM the signal rates of pp $\to$ VV* at the LHC are never enhanced compared with their SM predictions, while in the NMSSM they may be significantly enhanced; (iv) A large portion of the parameter space that has so far survived will soon be covered by the expected XENON100(2012) sensitivity (especially for the NMSSM).

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INTRODUCTION

As the only missing particle in the Standard Model (SM), the Higgs boson is being intensively hunted at the LHC. Recently, both the ATLAS and CMS experiments have revealed hints of a Higgs particle around 125 GeV [?, ?]. While such a Higgs mass can be well accommodated in the SM and the reported signal rates in several channels are also in agreement with SM expectations after accounting for large experimental uncertainties [?, ?] (albeit the central value of the observed di-photon rate is somewhat above the SM prediction), low-energy supersymmetry (SUSY) appears to be a better framework to account for such a Higgs. In low-energy SUSY, the SM-like Higgs mass is theoretically restricted to a narrow range and its di-photon rate at the LHC may exceed the SM prediction [?, ?, ?], both features welcomed by the LHC results.

However, as the most popular low-energy SUSY model, the minimal supersymmetric standard model (MSSM) [?, ?] may experience some tension in accommodating such a 125 GeV Higgs. As is well known, in the MSSM the SM-like Higgs mass is bounded above by $M_Z \cos 2\beta$ at tree level, and to obtain a Higgs around 125 GeV we need sizable top/stop loop contributions that depend quartically on the top quark mass and logarithmically on the stop masses [?]. This imposes rather tight constraints on the MSSM and, on the other hand, incurs some fine-tuning [?]. Such problems can be alleviated in the so-called next-to-minimal supersymmetric standard model (NMSSM) [?, ?], which is the simplest singlet extension of the MSSM with a scale-invariant superpotential. In the NMSSM, due to the introduction of new couplings in the superpotential, the SM-like Higgs receives additional contributions at tree level and may be further pushed up by mixing effects when diagonalizing the mass matrix of the CP-even Higgs fields [?, ?]. Consequently, a SM-like Higgs around 125 GeV does not require large loop contributions, thus ameliorating the fine-tuning problem [?].

In this work, motivated by recent LHC results, we assume a SM-like Higgs boson in the mass range 123-127 GeV and study its implications in the MSSM and NMSSM. Different from recent studies in this direction [?, ?, ?, ?, ?], we scan the model parameters by considering various experimental constraints and perform a comparative study of the MSSM and NMSSM. We investigate the features of the allowed parameter space in each model, paying particular attention to regions of NMSSM parameter space that may be distinct from the MSSM. Noting that LHC experiments utilize the channels $pp \to 4l$ and $pp \to WW^* \to 2l2\nu$ in searching for the Higgs boson [?, ?], we also study their normalized production rates defined as $R_{\gamma\gamma} \equiv \sigma_{\rm SUSY}(pp \to h \to \gamma\gamma)/\sigma_{\rm SM}(pp \to h \to \gamma\gamma) = C^2_{hgg} C^2_{h\gamma\gamma} \Gamma_{\rm tot}(h_{\rm SM})/\Gamma_{\rm tot}(h)$ and $R_{VV^*} \equiv \sigma_{\rm SUSY}(pp \to h \to VV^*)/\sigma_{\rm SM}(pp \to h \to VV^*) = C^2_{hVV} C^2_{hgg} \Gamma_{\rm tot}(h_{\rm SM})/\Gamma_{\rm tot}(h)$, where $V = W, Z$, and C_{hgg}, $C_{h\gamma\gamma}$ and C_{hVV} are respectively the Higgs couplings to gluons, photons and weak gauge bosons rescaled by their SM values. We are particularly interested in the case with $R_{\gamma\gamma} > 1$ because it is favored by current ATLAS and CMS results [?, ?, ?]. As shown below, this case typically predicts a slepton or chargino lighter than 250 GeV.

This paper is organized as follows. In Sec. II, we recapitulate the characteristics of the Higgs mass in the models to better understand our numerical results. In Sec. III, we perform a comprehensive scan over the parameter space of each model by imposing current experimental constraints and requiring a SM-like Higgs boson in the 123-127 GeV range. Then we scrutinize the properties of the surviving parameter space. Finally, we draw our conclusions in Sec. IV.

II. THE SM-LIKE HIGGS MASS IN THE MSSM AND NMSSM

In the MSSM, the Higgs sector consists of two doublet fields H_u and H_d, which after electroweak symmetry breaking result in five physical Higgs bosons: two CP-even scalars h and H, one CP-odd pseudoscalar A, and a pair of charged scalars $H^\pm$ [?]. Traditionally, this Higgs sector is described by the ratio of Higgs vacuum expectation values, $\tan\beta$, and the pseudoscalar mass m_A. In most of the MSSM parameter space, the lightest Higgs boson h has the largest coupling to vector bosons (i.e., the so-called SM-like Higgs boson), and for moderate $\tan\beta$ and large m_A its mass is given by [?]:

$$m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right]$$

where $v = 174$ GeV, $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$ with $m_{\tilde{t}_1}$ and $m_{\tilde{t}_2}$ being the stop masses, $X_t \equiv A_t - \mu\cot\beta$ with A_t denoting the trilinear Higgs-stop coupling and μ being the Higgsino mass parameter. Obviously, the larger $\tan\beta$ or M_S is, the heavier h becomes, and for given M_S, m_h reaches its maximum when $X_t/M_S = \sqrt{6}$, which corresponds to the so-called $m_h^{\rm max}$ scenario.

Regarding Eq. (3), three points should be noted [?]. First, this equation is only valid for small splitting between $m_{\tilde{t}_1}$ and $m_{\tilde{t}_2}$. In case of large splitting, generally $X_t/M_S > \sqrt{6}$ is needed to maximize m_h. Second, m_h^2 in Eq. (3) is symmetric with respect to the sign of X_t. This behavior is spoiled once higher-order corrections are considered, and usually a larger m_h is achieved for positive $A_t M_3$ with M_3 being the gluino soft-breaking mass. Finally, in Eq. (3)

we do not include contributions from the sbottom and slepton sectors. Such contributions are negative and become significant only for large $\tan\beta$.

Compared with the MSSM, the Higgs sector in the NMSSM is rather complex, as can be seen from its superpotential and corresponding soft-breaking terms given by [**?**]:

$$W_{\text{NMSSM}} = W_F + \lambda \hat{H}_u \hat{H}_d \hat{S} + \frac{\kappa}{3}\hat{S}^3$$

$$V_{\text{NMSSM}} = \tilde{m}_u^2|H_u|^2 + \tilde{m}_d^2|H_d|^2 + \tilde{m}_S^2|S|^2 + (\lambda A_\lambda S H_u H_d + \frac{\kappa}{3}A_\kappa S^3 + \text{h.c.})$$

Here W_F is the superpotential of the MSSM without the μ term, the dimensionless parameters λ and κ are coefficients of the Higgs self-couplings, and $\tilde{m}_u$, $\tilde{m}_d$, $\tilde{m}_S$, A_λ and A_κ are the soft-breaking parameters.

After electroweak symmetry breaking, the three soft-breaking mass-squared parameters for H_u, H_d and S can be expressed in terms of their VEVs (i.e., v_u, v_d and s) through the minimization conditions of the scalar potential. So in contrast to the MSSM where there are only two parameters in the Higgs sector, the Higgs sector of the NMSSM is described by six parameters [**?**]: λ, κ, M_A, $\tan\beta = v_u/v_d$, $\mu = \lambda s$, and A_κ.

The Higgs fields can be written in the following form:

$$H_1 = \begin{pmatrix} H_u^+ \\ \frac{v_u + S_1 + iP_1}{\sqrt{2}} \end{pmatrix}, \quad H_2 = \begin{pmatrix} \frac{v_d + S_2 + iG^0}{\sqrt{2}} \\ H_d^- \end{pmatrix}, \quad H_3 = \frac{s + (S_3 + iP_2)}{\sqrt{2}}$$

where $H_1 = \cos\beta H_u + \epsilon \sin\beta H_d^*$, $H_2 = \sin\beta H_u + \epsilon\cos\beta H_d^*$ with $\epsilon_{12} = \epsilon_{21} = 1$, $\epsilon_{11} = \epsilon_{22} = 0$, G^+ and G^0 are Goldstone bosons, and $v = \sqrt{v_u^2 + v_d^2}$. In the CP-conserving NMSSM, the fields S_1, S_2 and S_3 mix to form three physical CP-even Higgs bosons, and P_1 and P_2 mix to form two physical CP-odd Higgs bosons. Obviously, the field H_2 corresponds to the SM Higgs field, and the scalar h with the largest S_2 component is called the SM-like Higgs boson.

Under the basis (S_1, S_2, S_3), the elements of the mass matrix for S_i fields at tree level are given by [**?**, **?**]:

$$\mathcal{M}_{11}^2 = M_A^2 + (m_Z^2 - \lambda^2 v^2)\sin^2 2\beta$$

$$\mathcal{M}_{12}^2 = -\frac{1}{2}(m_Z^2 - \lambda^2 v^2)\sin 4\beta$$

$$\mathcal{M}_{22}^2 = m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \frac{2\mu}{\sin 2\beta}(A_\lambda + \kappa s)$$

$$\mathcal{M}_{13}^2 = \lambda v (2\mu - M_A \sin 2\beta)$$

$$\mathcal{M}_{23}^2 = \lambda v (A_\lambda - 2\kappa s) \cos 2\beta$$

$$\mathcal{M}_{33}^2 = \frac{\lambda \kappa v^2 \sin 2\beta}{\mu} + \frac{\mu}{\lambda}(A_\kappa + 4\kappa s)$$

where the second term $\lambda^2 v^2 \sin^2 2\beta$ in $\mathcal{M}_{22}^2$ originates from the coupling $\lambda \hat{H}_u \hat{H}_d \hat{S}$ in the superpotential. For such a complex matrix, it is useful to consider two scenarios to understand the results:

Scenario I: $\lambda, \kappa \to 0$ and μ is fixed. In this limit, since $\mathcal{M}_{13}, \mathcal{M}_{23}, \mathcal{M}_{33} \to 0$, the singlet field S_3 is decoupled from the doublet fields, and the MSSM mass matrix is recovered for the (S_1, S_2) system. This scenario indicates that, even for moderate λ and κ, m_h should change little from its MSSM prediction. So to show the difference between the two models in predicting m_h, we are more interested in the large λ case. Especially, we will mainly discuss the $\lambda > M_Z/v \simeq 0.53$ case, where the tree-level contributions to m_h, i.e., $\mathcal{M}_{22}^2$, are maximized for moderate values of $\tan\beta$ rather than by large values of $\tan\beta$ as in the MSSM.

Scenario II: $\mathcal{M}_{11}^2 \gg \mathcal{M}_{22}^2 \gg \mathcal{M}_{12}^2$ and $|\mathcal{M}_{13}|, |\mathcal{M}_{23}| \ll \mathcal{M}_{11}^2$, which can be easily realized for a large M_A. In this limit, S_1 is decoupled from the (S_2, S_3) system, and the properties of m_h can be qualitatively understood by the 2×2 matrix [**?**]:

$$\tilde{\mathcal{M}}^2 = \begin{pmatrix} \mathcal{M}_{22}^2 + \delta_2 & \mathcal{M}_{23}^2 \\ \mathcal{M}_{23}^2 & \mathcal{M}_{33}^2 \end{pmatrix}$$

where δ_2 denotes the radiative corrections to m_h with its form given by the last two terms of Eq. (3), and Δ^2 represents the potentially important effect of (S_1, S_3) mixing on $\mathcal{M}_{22}^2$. This matrix indicates that the (S_2, S_3) mixing can push m_h up once $\tilde{\mathcal{M}}_{11}^2 > \tilde{\mathcal{M}}_{22}^2$, and such effect is maximized for $\tilde{\mathcal{M}}_{11}^2 \simeq \tilde{\mathcal{M}}_{22}^2$ and $\tilde{\mathcal{M}}_{23}^2$ slightly below $\tilde{\mathcal{M}}_{11}^2$ (larger $\tilde{\mathcal{M}}_{12}$ will destabilize the vacuum) [**?**].

Obviously, in this push-up case, h is the next-to-lightest CP-even Higgs boson and the larger the (S_2, S_3) mixing is, the heavier h becomes. Alternatively, the mixing can pull m_h down under the condition $\tilde{\mathcal{M}}_{11}^2 < \tilde{\mathcal{M}}_{22}^2$, which occurs for large $\kappa\mu$ (for $\mathcal{M}_{33}^2$ and $\mathcal{M}_{23}^2$, see discussion below) as indicated by the expression of $\mathcal{M}_{33}^2$ and the positiveness of Δ^2. Here we remind that, due to the extra contribution $\lambda^2 v^2 \sin^2 2\beta$ to m_h at tree level, m_h in the pull-down case may still be larger than its MSSM prediction for a certain δ_2.

Since our results presented below are approximately described by scenario II, we now estimate the features of its favored region to predict $m_h \simeq 125$ GeV. First, since $\mathcal{M}_{11}^2 \sim \mathcal{O}(100^2)$ GeV^2, $\mathcal{M}_{22}^2 \ll \mathcal{M}_{11}^2$ implies that $M_A \gtrsim (300)$ GeV for the push-up case, and $M_A \gtrsim (500)$ GeV for the pull-down case (see Fig. 7). Numerically, we find $M_A \gtrsim 300$ GeV for the push-up case, and $M_A \gtrsim 500$ GeV for the pull-down case. Second, $\tilde{\mathcal{M}}_{11}^2 \gg \mathcal{M}_{12}^2$ must be relatively small, which implies that $M_A \sin 2\beta/\mu \sim 2$ for $\lambda > 0.53$. This can be understood as follows. In the push-up case, since $\tilde{\mathcal{M}}_{11}^2 \sim \mathcal{O}(100^2)$ GeV^2, the condition $\tilde{\mathcal{M}}_{22}^2$ (for vacuum stability) has limited the size of $\mathcal{M}_{23}$. While in the pull-down case, a very large $\mathcal{M}_{23}$ will greatly suppress m_h, making it difficult to reach 125 GeV, and this in return limits the size of $\mathcal{M}_{23}$. Given that $\mu \gtrsim 100$ GeV as required by the LEP bound on chargino mass and that a larger μ is favored for the pull-down scenario, one can infer that the value of $M_A \sin 2\beta/\mu$ should be around 2 after considering that the third term in $\mathcal{M}_{23}$ is less important. Numerically speaking, we find $\mathcal{M}_{23}/(2\lambda\mu v) \lesssim 0.2$ and $M_A \sin 2\beta/\mu \sim 2$ (see Fig. 7). Lastly, light stops may be possible in the NMSSM with large λ to predict $m_h \simeq 125$ GeV. To see this, we consider the parameters $\lambda = 0.7$ and $\tan\beta = 1.5$, and we get $\delta_2/125^2 \sim 5\%$ without considering the mixing effect to push m_h to 125 GeV. This is in sharp contrast with $\delta_2/125^2 \sim 55\%$ in the MSSM for $\tan\beta = 5$.

In this work we use the package NMSSMTools [?] to calculate the Higgs masses and mixings, which includes the dominant one-loop and leading logarithmic two-loop corrections. We checked our MSSM results for m_h using the code FeynHiggs [?] and found the results given by NMSSMTools and FeynHiggs are in good agreement (for $m_h \simeq 125$ GeV they agree within 0.5 GeV for the same MSSM parameters).

III. NUMERICAL RESULTS AND DISCUSSIONS

In this work, we scan the parameters of the models and investigate the samples that predict 123 GeV $\lesssim m_h \lesssim$ 127 GeV and simultaneously survive the following constraints [?]: (1) The constraint from the LHC search channel $pp \to \tau^+\tau^-$ for non-standard Higgs bosons. (2) The limits from LEP and the Tevatron on sparticle masses as well as on neutralino pair production. (3) The constraints from B-physics, such as $B^+ \to \tau^+\nu$, $B \to X_s\gamma$, the latest experimental results for $B_s \to X_s\mu^+\mu^-$, $B^+ \to \mu^+\mu^-$, B_d mass differences ΔM_d and ΔM_s. (4) The indirect constraints from electroweak precision observables such as $\sin^2\theta_{\rm eff}^\ell$, ρ_ℓ and M_W, and their combinations $\epsilon_i (i = 1, 2, 3)$ [?]. We require ϵ_i to be compatible with LEP/SLD data at 95% confidence level. We also require the SUSY prediction of the observable $R_b \equiv \Gamma(Z \to \bar{b}b)/\Gamma(Z \to \text{hadrons})$ to be within the 2σ range of its experimental value [?]. (5) The constraints from the muon anomalous magnetic moment: $a_\mu^{\rm exp} = (25.5 \pm 8.0) \times 10^{-10}$ [?]. We require the SUSY effects to explain the discrepancy at 2σ level. (6) The dark matter constraints from WMAP relic density ($0.1053 < \Omega h^2 < 0.1193$) [?] and the direct search result from the XENON100 experiment (at 90% C.L.) [?]. (7) For the NMSSM, we also require the absence of a Landau singularity below the GUT scale, which implies $\lambda \lesssim 0.7$ for small κ and $\kappa \lesssim 0.5$ for $\lambda > 0.53$ at weak scale. In our calculation, we fix $m_t = 172.9$ GeV and $f_{T_s} = 0.02$ [?] (f_{T_s} denotes the strange quark fraction in the proton mass), and use the package NMSSMTools to implement most constraints and calculate the observables of interest.

In our scan, we note that the soft parameters in the slepton sector can only significantly affect the muon anomalous magnetic moment a_μ, which in turn limits the important parameter $\tan\beta$, so we assume them to have a common value $m_{\tilde{l}}$ and treat it as a free parameter. For the soft parameters in the first two generation squark sector, due to their minimal effects on Higgs boson properties, we fix them to be 1 TeV. As for the gaugino masses, we assume the grand unification relation $3M_1/5\alpha_1 = M_2/\alpha_2 = M_3/\alpha_3$ with α_i being the fine-structure constants of the different gauge groups, and treat M_1 as a free parameter. To reduce free parameters, we also assume the unimportant parameters M_{D3} and A_b to satisfy $M_{D3} = M_{U3}$ and $A_b = A_t$.

Implication of $m_h \simeq 125$ GeV in generic SUSY

To study the implication of $m_h \simeq 125$ GeV in generic SUSY, we relax the soft mass parameters to 5 TeV and perform an extensive random scan over the following parameter regions:

For the MSSM:

$$
\begin{aligned}
& 1 \leq \tan\beta \leq 60, \\
& 90 \text{ GeV} \leq \mu, m_{\tilde{l}} \leq 1 \text{ TeV}, \\
& M_{Q3}, M_{U3} \leq 5 \text{ TeV}, \\
& |A_t| \leq 5 \text{ TeV}.
\end{aligned}
$$

For the NMSSM:

$$
\begin{aligned}
& 0.2 < \lambda \leq 0.7, \quad 0 < \kappa \leq 0.5, \\
& 1 \leq \tan\beta \leq 60, \\
& 90 \text{ GeV} \leq \mu, m_{\tilde{l}} \leq 1 \text{ TeV}, \\
& M_{Q3}, M_{U3} \leq 5 \text{ TeV}, \\
& |A_t| \leq 5 \text{ TeV}.
\end{aligned}
$$

In our scan, we only keep samples satisfying the requirements listed above (including 123 GeV $\lesssim m_h \lesssim$ 127 GeV). To show the differences between the MSSM and NMSSM, we also perform a scan similar to Eq. (16) except that we require $\lambda > m_Z/v \simeq 0.53$. In Fig. 1, we show the correlation of the lighter top-squark mass ($m_{\tilde{t}_1}$) with the ratio X_t/M_S ($M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$) for the surviving samples in the MSSM and NMSSM.

As expected from Eq. (3), to predict $m_h \simeq 125$ GeV in the MSSM, a large X_t is needed for moderately light $\tilde{t}_1$, and as $\tilde{t}_1$ becomes heavier, the ratio X_t/M_S decreases but is unlikely to vanish for $m_{\tilde{t}_1} < 5$ TeV. These features are maintained for NMSSM with $\lambda < 0.2$ (see the middle panel) but change for NMSSM with large λ, where X_t can vanish even for $m_{\tilde{t}_1} \sim 1$ TeV. Fig. 1 also shows that a $\tilde{t}_1$ as light as 200 GeV is still able to give the required m_h. But in this case X_t is large ($X_t/\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} > \sqrt{6}$), which leads to a large mass splitting between the two stops ($m_{\tilde{t}_2} \gg m_{\tilde{t}_1}$). Note that a $\tilde{t}_1$ as light as 200 GeV does not contradict recent SUSY search results from the LHC [?].

Since in heavy SUSY the radiative correction δ_2 is usually very large, $m_h \simeq 125$ GeV is unlikely to impose tight constraints on other parameters of the models. Considering that heavy SUSY is disfavored by naturalness, in the following we concentrate on the implication of $m_h \simeq 125$ GeV in sub-TeV SUSY.

Implication of $m_h \simeq 125$ GeV in sub-TeV SUSY

In this section, we study the implication of $m_h \simeq 125$ GeV in low-energy MSSM and NMSSM. To illustrate the new features of the NMSSM, we only consider the case with $\lambda > 0.53$. Our scans over the parameter spaces are quite similar to those in Eq. (15) and Eq. (16) except that we narrow the ranges of M_{Q3}, M_{U3} and A_t as follows:

$$100 \text{ GeV} \leq (M_{Q3}, M_{U3}) \leq 3 \text{ TeV},$$
$$|A_t| \leq 3 \text{ TeV}.$$

In Fig. 2 we project the surviving samples of the models in the plane of $m_{\tilde{t}_1}$ versus A_t, showing results with $R_{\gamma\gamma} < 1$ and $R_{\gamma\gamma} > 1$ separately. As analyzed in Sec. II, the SM-like Higgs in the NMSSM may be either the lightest Higgs boson (corresponding to the pull-down case) or the next-to-lightest Higgs boson (the push-up case). In the figure we distinguish these two cases. We note that among the surviving samples, the number of pull-down cases is about twice that of push-up cases.

Fig. 2 shows that to obtain $m_h \simeq 125$ GeV in the MSSM, $m_{\tilde{t}_1}$ and $|A_t|$ must be larger than about 300 GeV and 1.5 TeV respectively, and these bounds are pushed up to 600 GeV and 1.8 TeV respectively for $R_{\gamma\gamma} > 1$. While in the NMSSM, a $\tilde{t}_1$ as light as about 100 GeV (in either the pull-down or push-up case) can still predict $m_h \simeq 125$ GeV, and even if one requires $R_{\gamma\gamma} > 1$, a $\tilde{t}_1$ as light as about 200 GeV is allowed. The fact that the NMSSM allows a lighter $\tilde{t}_1$ than the MSSM indicates that the NMSSM is more natural than the MSSM in light of the LHC results.

Since a light $\tilde{t}_1$ may significantly change the effective couplings C_{hgg} and $C_{h\gamma\gamma}$, we present in Table I their predicted ranges for the surviving samples. This table shows that C_{hgg} is always reduced, and for $m_{\tilde{t}_1} \sim 100$ GeV in the NMSSM, the reduction factor may reach 70%. While $C_{h\gamma\gamma}$ exhibits quite different behaviors: it is enhanced in the MSSM, but may be either enhanced or suppressed in the NMSSM. This is because, unlike C_{hgg} which is affected only by squark loops, $C_{h\gamma\gamma}$ receives new physics contributions from loops mediated by charged Higgs bosons, charginos, sleptons and also squarks, with cancellations occurring among different loops. As shown below, current experiments cannot rule out light sparticles like $\tilde{\tau}_1$ and charginos. Although the contributions of these particles to $C_{h\gamma\gamma}$ are far smaller than the W loop contribution, they may still alter the coupling significantly.

Since the di-photon signal is the most important discovery channel for a Higgs boson around 125 GeV, it is useful to study its rate carefully. From Eq. (1) one can see that the rate is affected by C_{hgg} and $C_{h\gamma\gamma}$ discussed above, and also by the total width of h (or more fundamentally by the $h\bar{b}b$ coupling since $\bar{b}b$ is the dominant decay mode of h). The importance of the $h\bar{b}b$ coupling on the di-photon rate was recently emphasized in [?]. Here we restrict our study to the $m_h \simeq 125$ GeV case. In Fig. 3 we show the dependence of the di-photon signal rate $R_{\gamma\gamma}$ on the effective $h\bar{b}b$ coupling (including potentially large SUSY corrections [?, ?]) normalized by its SM value. This figure indicates that although the rate is suppressed for most surviving samples in both models, some samples with enhanced rate still exist, and the NMSSM is more likely to push up the rate than the MSSM. This feature can be understood as follows. In SUSY, $R_{\gamma\gamma} > 1$ requires approximately the combination $C_{hgg}C_{h\gamma\gamma}/C_{h\bar{b}b}$ to exceed 1. For the MSSM, given $C_{hgg} < 1$ and $C_{h\bar{b}b} \geq 1$ for nearly all cases, this condition is not easy to satisfy. While in the NMSSM, due to mixing between the doublet field S_2 and the singlet field S_3, $C_{h\bar{b}b} < 1$ is possible once the singlet component in h is significant, which helps enhance the combination. In fact, we carefully analyzed the $R_{\gamma\gamma} > 1$ cases and found they are characterized by $C_{hgg}, C_{h\bar{b}b} \simeq 1$ and $C_{h\gamma\gamma} > 1$ in the MSSM, and by $C_{h\bar{b}b} < 1$ in the NMSSM. In other words, it is the enhanced $h\gamma\gamma$ coupling (reduced total width of h) that mainly pushes up the di-photon rate in the MSSM (NMSSM) to exceed its SM prediction. Fig. 3 also indicates that the pull-down case in the NMSSM is less effective in reducing $C_{h\bar{b}b}$ and thus can hardly enhance the di-photon rate. This is because in the push-up case, both $\tilde{\mathcal{M}}^2_{11}$ and $\tilde{\mathcal{M}}^2_{22}$ in Eq. (14) are moderate and often comparable, which helps enhance the (S_2, S_3) mixing. Finally, we note that in some rare cases of the NMSSM the ratio $R_{\gamma\gamma}$ may be very small even for $C_{h\bar{b}b} < 1$. This is because there exists a very light Higgs boson so that h decays dominantly into it.

To further clarify the reason for di-photon rate enhancement in the MSSM, we scrutinize the model parameters carefully and find that samples with $R_{\gamma\gamma} > 1$ correspond to cases with large $\mu \tan\beta$ and $m_{\tilde{\tau}_1} < 200$ GeV, as illustrated in Fig. 4. This means that the stau loop plays an important role in enhancing $C_{\gamma\gamma}$. We note that a similar conclusion was recently reached in [?], but that work did not consider tight experimental constraints. From Fig. 4 we also note that $R_{\gamma\gamma} < 0.95$ is predicted in the MSSM with $m_{\tilde{\tau}_1} > 250$ GeV. Therefore, future precise measurements of $R_{\gamma\gamma}$ and $m_{\tilde{\tau}_1}$ may be utilized to verify the correctness of the MSSM.

Considering that the process $pp \to VV^*$ (V = W, Z) is another important Higgs search channel, in Fig. 5 we show the signal rate versus the hVV coupling. This figure shows that in the MSSM, h is highly SM-like, while in the NMSSM, the singlet component in h may be sizable, especially in the push-up case, so that C_{hVV} is reduced significantly. The signal rate R_{VV} also behaves differently in the two models. In the MSSM, because $C_{hgg} < 1$ and in most cases $C_{h\bar{b}b} > 1$, R_{VV} is always less than 1 (for $R_{\gamma\gamma} > 1$ it varies between 0.7 and 0.95). In the NMSSM, however, R_{VV} may exceed 1, and in this case we find $R_{VV} \simeq R_{\gamma\gamma}$. The reason for such correlation is that the two quantities have the same origin for their enhancement, i.e., the suppression of $h\bar{b}b$ due to the presence of the singlet component in h.

Next we investigate the favored parameter space of the NMSSM to predict $m_h \simeq 125$ GeV. As introduced in Sec. II, besides the soft parameters in the stop sector, the sensitive parameters include $\tan\beta$, μ, κ, and M_A. In Fig. 6, we project the surviving samples in the planes of μ versus $\tan\beta$ and M_A versus κ. This figure shows three distinctive features for the allowed parameters. First, $\tan\beta$ must be moderate, below 4 and 9 for the pull-down and push-up cases, respectively. Two reasons account for this. One is that in the NMSSM with large λ, precision electroweak data, i.e., constraint (4), strongly disfavor large $\tan\beta$ [**?**]. The other reason is that, as far as $\lambda > 0.53$ is concerned, a moderate $\tan\beta$ is welcomed to enhance the tree-level value of m_h^2 (i.e., $\mathcal{M}_{22}^2$) so that even without heavy stops, m_h can still reach 125 GeV. Moreover, since the (S_2, S_3) mixing is to reduce the value of $\tilde{\mathcal{M}}_{11}^2$ in Eq. (14) in the pull-down case, a larger $\tilde{\mathcal{M}}_{22}^2$ (or equivalently a smaller $\tan\beta$) is favored by the Higgs mass. The second feature is that $\kappa\mu$ in the push-up case is usually much smaller than in the pull-down case. This is because, as introduced in Sec. II, a large $\kappa\mu$ is needed by the pull-down case to enhance $\tilde{\mathcal{M}}_{22}^2$ in Eq. (14). The third feature is obtained by comparing the parameter regions in the upper panels with those in the lower panels, which shows that $R_{\gamma\gamma} > 1$ puts a lower bound on κ, i.e., $\kappa \gtrsim 0.1$. The underlying reason is that for $\kappa < 0.1$, the dark matter will be light and singlino-like, and to obtain its currently measured relic density, the dark matter must annihilate in the early universe by exchanging a light Higgs boson [**?**]. In this case, h mainly decays into the light bosons, which in return suppresses the di-photon rate.

In Fig. 7 we show the correlation of M_A with $\mu/\sin 2\beta$. This figure indicates that $M_A \gtrsim 300$ GeV for the push-up case and $M_A \gtrsim 500$ GeV for the pull-down case, which agrees with our expectation. In fact, we checked each surviving sample and found it satisfies the condition: $\mathcal{M}_{12}^2 \ll \mathcal{M}_{22}^2 \ll \mathcal{M}_{11}^2$ and $(\mathcal{M}_{13}, \mathcal{M}_{23}) \ll \mathcal{M}_{11}^2$, so the samples can be well described by scenario II. We also checked that the mixing of the field S_1 with S_2/S_3 is small and M_A is approximately the heaviest CP-even Higgs boson mass. Fig. 7 also shows that the relation $M_A \sin 2\beta/\mu = 2$ is maintained quite well in the push-up case but is moderately spoiled in the pull-down case. The reason is, as introduced in Sec. II, the requirement that $\mathcal{M}_{23}$ should be moderately small actually implies $C_A \simeq 0$ with $C_A = 1 - \frac{M_A \sin 2\beta}{2\mu} + \frac{\lambda\kappa v^2 \sin 2\beta}{2\mu^2}$. In the push-up case the third term in C_A is not important, while in the pull-down case, although it is several times smaller than the second term, it may not be negligible. We checked our results and found $\kappa\mu/(2\lambda\mu v) \lesssim 0.2$ and $1.4 \lesssim M_A \sin 2\beta/\mu \lesssim 2$ for all surviving samples.

Regarding the NMSSM with $\lambda > 0.53$, three points should be noted. First, from the results presented in Fig. 6, one may find the presence of a smuon and/or a chargino lighter than 250 GeV. This is because the surviving samples are characterized by either $\tan\beta < 4$ or $\mu < 250$ GeV or both in the NMSSM (see Fig. 6). Then to explain the discrepancy in the muon anomalous magnetic moment, $m_{\tilde{\mu}} \lesssim 250$ GeV is needed for low $\tan\beta$, and $m_{\tilde{\chi}^\pm} \lesssim 250$ GeV is implied. We numerically checked the validity of this conclusion. Second, although $M_A \sin 2\beta/\mu \sim 2$ may be regarded as a new source of fine-tuning in the NMSSM, it is rather predictive for obtaining the value of M_A once μ and $\tan\beta$ are experimentally determined. Finally, we note that the favored region for μ and $\tan\beta$ shown in Fig. 6 does not overlap with that in Fig. 4. This may be used to discriminate between the models.

Finally, we briefly describe other implications of $m_h \simeq 125$ GeV in the SUSY models. In Fig. 8 we project the surviving samples onto the plane of $\tan\beta$ versus m_{H^+} with H^+ denoting the charged Higgs boson. This figure shows that H^+ must be heavier than about 200 GeV in the MSSM. This bound is much higher than the corresponding LEP bound of about 80 GeV. For the NMSSM with large λ, the bound can be further pushed up to about 300 GeV. This figure also indicates that in the MSSM, $\tan\beta$ may reach 35 for $m_{H^+} = 400$ GeV. Then based on MC simulation by the ATLAS collaboration [**?**], one may expect that the charged Higgs may be observable from the process $pp \to b\bar{b}W^\pm \to \tau\nu_\tau$ at the early stage of the LHC. However, this may be impossible. The reason is that for relatively light H^+ and large $\tan\beta$, μ must be large to satisfy constraints from dark matter direct detection experiments such as XENON100. This greatly suppresses the $\bar{t}bH^+$ coupling [**?**]. For the NMSSM, the hope to observe H^+ is also dim because $\tan\beta$ is small.

In Fig. 9 we show the spin-independent elastic scattering between dark matter and nucleons. We use the formula presented in the Appendix of [**?**] to calculate the scattering rate. As expected, the XENON100 (2012) data to be released in the near future will further exclude some samples, especially the pull-down case of the NMSSM will be strongly disfavored if XENON100 (2012) fails to find any evidence of dark matter (assuming the grand unification relation of gaugino masses). From the left panel of Fig. 9 one can see that for samples with $R_{\gamma\gamma} > 1$ in the MSSM, the scattering rate is small, usually at least one order of magnitude below the sensitivity of XENON100 (2012).

IV. CONCLUSION

Motivated by recent LHC hints of a Higgs boson around 125 GeV, we assume a SM-like Higgs with mass in the range 123-127 GeV and study its implications in low-energy SUSY by comparing the MSSM and NMSSM. Under various experimental constraints at the 2σ level (including the muon $g-2$ and dark matter relic density), we scanned the parameter space of each model. Then, within the parameter space allowed by current experimental constraints and that also predicts a SM-like Higgs in the 123-127 GeV range, we examined the properties of sensitive parameters and calculated the rates of the di-photon signal and the VV^* ($V = W, Z$) signals at the LHC. Among our various findings, the typical ones are: (i) In the MSSM the top squark and A_t must be large, thus incurring some fine-tuning, which can be much ameliorated in the NMSSM; (ii) In the MSSM a light $\tilde{\tau}$ is needed to make the di-photon rate of the SM-like Higgs exceed its SM prediction, while the NMSSM has more ways to achieve this; (iii) In the MSSM the signal rates of $pp \to VV^*$ at the LHC are never enhanced compared with their SM predictions, while in the NMSSM they may be enhanced; (iv) A large portion of the parameter space that has so far survived will soon be covered by the expected XENON100(2012) sensitivity (especially for the NMSSM).

Therefore, although low-energy SUSY can in general accommodate a SM-like Higgs boson near 125 GeV and enhance its di-photon signal rate at the LHC, not all models of low-energy SUSY are equally competent if they are required to satisfy all current experimental constraints. From our present study and other studies in the literature, we conclude:

- The popular CMSSM/mSUGRA is hard-pressed to give a 125 GeV SM-like Higgs boson [**?**].
- The MSSM can give such a 125 GeV Higgs and can also enhance its di-photon signal rate at the LHC, which, however, incurs some fine-tuning.
- The nMSSM (the nearly minimal SUSY model) can give a 125 GeV SM-like Higgs, but severely suppresses its di-photon signal rate at the LHC [**?**].
- The NMSSM is so far the best model to accommodate such a 125 GeV Higgs; it can naturally (without fine-tuning) predict such a SM-like Higgs mass and readily enhance its di-photon signal rate at the LHC. At the same time, in a large part of its parameter space, this model can also enhance the signal rates $pp \to VV^*$ ($V = Z, W$) at the LHC and predict a large scattering rate of dark matter and nucleons at XENON100.

Thus, the interplay of LHC and XENON100 will soon allow for a good test of this model.

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