

## *Review Article*

# **A 125 GeV Higgs and Its Diphoton Signal in Different SUSY Models: A Mini Review**

**Zhaoxia Heng**

*Department of Physics, Henan Normal University, Xixiang 453007, China*

Correspondence should be addressed to Zhaoxia Heng, [zxheng@htu.cn](mailto:zxheng@htu.cn)

Received 22 May 2012; Revised 20 September 2012; Accepted 30 September 2012

Academic Editor: Stefano Moretti

Copyright © 2012 Zhaoxia Heng. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

In this paper we briefly review our recent studies on a 125 GeV Higgs and its diphoton signal rate in different low-energy supersymmetric models, namely, the minimal supersymmetric standard model (MSSM), the next-to-minimal supersymmetric standard model (NMSSM), the nearly minimal supersymmetric standard model (nMSSM), and the constrained MSSM. Our conclusion is as follows (i) in the allowed parameter space the SM-like Higgs boson can easily be 125 GeV in the MSSM, NMSSM, and nMSSM, while it is hard to realize in the constrained MSSM; (ii) the diphoton Higgs signal rate in the nMSSM and constrained MSSM is suppressed relative to the prediction of the SM, while the signal rate can be enhanced in the MSSM and NMSSM; (iii) the NMSSM may allow for a lighter top squark than the MSSM, which can thus ameliorate the fine-tuning problem.

## **1. Introduction**

Considering the important role of the Higgs boson in particle physics, hunting for it has been one of the major tasks of the running Large Hadron Collider (LHC). Recently, both the ATLAS and CMS collaborations have reported some evidence for a light Higgs boson near 125 GeV [1–12] with a diphoton signal rate slightly above the SM prediction [13].

As is well known, in new physics beyond the SM model several Higgs bosons are predicted, among which the SM-like one may be near 125 GeV [14–43]. Recently, in our studies [42, 43] we examined the mass of the SM-like Higgs boson in several supersymmetric (SUSY) models including the minimal supersymmetric standard model (MSSM) [44–47], the next-to-minimal supersymmetric standard model (NMSSM) [48–61], and the constrained MSSM [62–68]. At tree level, these SUSY models are hard to predict a Higgs boson near 125 GeV, and sizable radiative corrections, which mainly come from the top and top-squark loops, are necessary to enhance the Higgs boson mass [69–72]. Due to the different properties

of these SUSY models, the loop contributions to the Higgs boson mass are different for giving a 125 GeV Higgs boson. Therefore, different models have different lower bounds on the top-squark mass which is associated with the fine-tuning problem [73–75]. On the other hand, since the di-photon Higgs signal is the most promising discovery channel for a light Higgs boson at the LHC [76–80], in our recent study [81] we performed a comparative study for the di-photon Higgs signal in different SUSY models, namely, the MSSM, NMSSM, and the nearly minimal supersymmetric standard model (nMSSM) [82–90]. In this note we briefly review these studies on a 125 GeV Higgs boson and its di-photon signal rate in different SUSY models.

This note is organized as follows. In the next section we briefly describe the Higgs sector and the di-photon Higgs signal in these SUSY models. Then we present the numerical results and discussions in Section 3. Finally, the conclusions are given in Section 4.

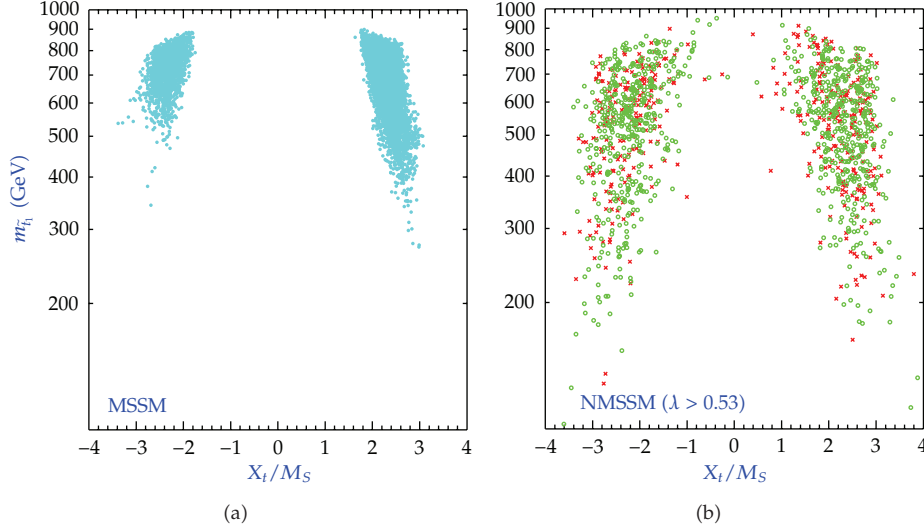
## 2. The Higgs Sector and Di-Photon Signal Rate in SUSY Models

### 2.1. The Higgs Sector in SUSY Models

Different from the SM, the Higgs sector in the supersymmetric models is usually extended by adding Higgs doublets and/or singlets. The most economical realization is the MSSM, which consists of two Higgs doublet  $H_u$  and  $H_d$ . In order to solve the  $\mu$ -problem and the little hierarchy problem in the MSSM, the singlet extension of MSSM, such as the NMSSM [48–51] and nMSSM [82–90], has been intensively studied [91]. The differences between these models come from their superpotentials and the corresponding soft-breaking terms, which are given by

$$\begin{aligned}
W_{\text{MSSM}} &= W_F + \mu \widehat{H}_u \cdot \widehat{H}_d, \\
W_{\text{NMSSM}} &= W_F + \lambda \widehat{H}_u \cdot \widehat{H}_d \widehat{S} + \frac{1}{3} \kappa \widehat{S}^3, \\
W_{\text{nMSSM}} &= W_F + \lambda \widehat{H}_u \cdot \widehat{H}_d \widehat{S} + \xi_F M_n^2 \widehat{S}, \\
V_{\text{soft}}^{\text{MSSM}} &= \tilde{m}_u^2 |H_u|^2 + \tilde{m}_d^2 |H_d|^2 + (B\mu H_u \cdot H_d + h.c.), \\
V_{\text{soft}}^{\text{NMSSM}} &= \tilde{m}_u^2 |H_u|^2 + \tilde{m}_d^2 |H_d|^2 + \tilde{m}_S^2 |S|^2 + \left( A_\lambda \lambda S H_u \cdot H_d + \frac{A_\kappa}{3} \kappa S^3 + h.c. \right), \\
V_{\text{soft}}^{\text{nMSSM}} &= \tilde{m}_u^2 |H_u|^2 + \tilde{m}_d^2 |H_d|^2 + \tilde{m}_S^2 |S|^2 + \left( A_\lambda \lambda S H_u \cdot H_d + \xi_S M_n^3 S + h.c. \right),
\end{aligned} \tag{2.1}$$

where  $W_F$  is the MSSM superpotential without the  $\mu$  term,  $\lambda$ ,  $\kappa$  and  $\xi_F$  are the dimensionless parameters, and  $\tilde{m}_u$ ,  $\tilde{m}_d$ ,  $\tilde{m}_S$ ,  $B$ ,  $A_\lambda$ ,  $A_\kappa$ , and  $\xi_S M_n^3$  are soft-breaking parameters. Note that in the NMSSM and nMSSM the  $\mu$ -term is replaced by the  $\mu_{\text{eff}} = \lambda s$  when the singlet Higgs field  $\widehat{S}$  develops a VEV  $s$ . The differences between the NMSSM and nMSSM reflect the last term in the superpotential, where the cubic singlet term  $\kappa \widehat{S}^3$  in the NMSSM is replaced by a tadpole term  $\xi_F M_n^2 \widehat{S}$  in the nMSSM. This replacement in the superpotential makes the nMSSM have no discrete symmetry and thus free of the domain wall problem that the NMSSM suffers from. Actually, due to that the tadpole term  $\xi_F M_n^2$  does not induce any interaction, the nMSSM is



**Figure 1:** The scatter plots of the samples in the MSSM and NMSSM (with  $\lambda > 0.53$ ) satisfying various constraints listed in the text (including  $123 \text{ GeV} \leq m_h \leq 127 \text{ GeV}$ ), showing the correlation between the mass of the lighter top squark and  $X_t/M_S$  with  $M_S \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$  and  $X_t \equiv A_t - \mu \cot \beta$ . In the right panel the circles (green) denote the pull-down case (the lightest Higgs boson being the SM-like Higgs), and the times (red) denote the push-up case (the next-to-lightest Higgs boson being the SM-like Higgs).

identical to the NMSSM with  $\kappa = 0$ , except for the minimization conditions of the Higgs potential and the tree-level Higgs mass matrices.

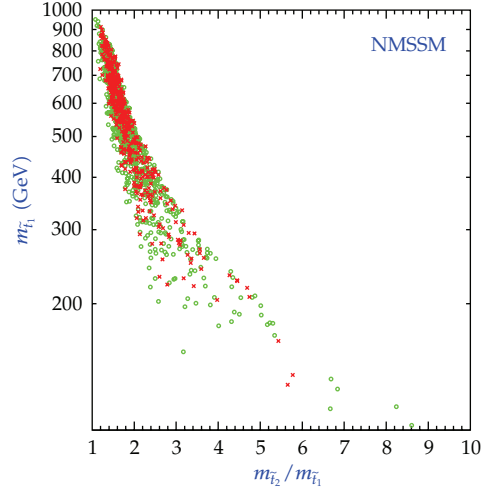
With the superpotentials and the soft-breaking terms giving above, one can get the Higgs potentials of these SUSY models and then can derive the Higgs mass matrices and eigenstates. At the minimum of the potential, the Higgs fields  $H_u$ ,  $H_d$ , and  $S$  are expanded as

$$H_u = \begin{pmatrix} H_u^+ \\ v_u + \frac{\phi_u + i\varphi_u}{\sqrt{2}} \end{pmatrix}, \quad H_d = \begin{pmatrix} v_d + \frac{\phi_d + i\varphi_d}{\sqrt{2}} \\ H_d^- \end{pmatrix}, \quad S = s + \frac{1}{\sqrt{2}}(\sigma + i\xi), \quad (2.2)$$

with  $v = \sqrt{v_u^2 + v_d^2} = 174 \text{ GeV}$ . By unitary rotation the mass eigenstates can be given by

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = S \begin{pmatrix} \phi_u \\ \phi_d \\ \sigma \end{pmatrix}, \quad \begin{pmatrix} a \\ A \\ G^0 \end{pmatrix} = P \begin{pmatrix} \varphi_u \\ \varphi_d \\ \xi \end{pmatrix}, \quad \begin{pmatrix} H^+ \\ G^+ \end{pmatrix} = U \begin{pmatrix} H_u^+ \\ H_d^- \end{pmatrix}, \quad (2.3)$$

where  $h_1$ ,  $h_2$ , and  $h_3$  are physical CP-even Higgs bosons ( $m_{h_1} < m_{h_2} < m_{h_3}$ ),  $a$ ,  $A$  are CP-odd Higgs bosons,  $H^+$  is the charged Higgs boson, and  $G^0 G^+$  are Goldstone bosons eaten by  $Z$  and  $W^+$ . Due to the absence of the singlet field  $S$ , the MSSM only has two CP-even Higgs bosons and one CP-odd Higgs bosons, as well as one pair of charged Higgs bosons.



**Figure 2:** Same as Figure 1, but only for the NMSSM, showing the correlation between  $m_{\tilde{h}_1}$  and the ratio  $m_{\tilde{h}_2}/m_{\tilde{h}_1}$ .

At the tree level, the Higgs masses in the MSSM are conventionally parameterized in terms of the mass of the CP-odd Higgs boson ( $m_A$ ) and  $\tan\beta \equiv v_u/v_d$  and the loop corrections typically come from top and stop loops due to their large Yukawa coupling. For small splitting between the stop masses, an approximate formula of the lightest Higgs boson mass is given by [92]

$$m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2} \ln \frac{M_S^2}{m_t^2} + \frac{3m_t^4}{4\pi^2 v^2} \frac{X_t^2}{M_S^2} \left( 1 - \frac{X_t^2}{12M_S^2} \right), \quad (2.4)$$

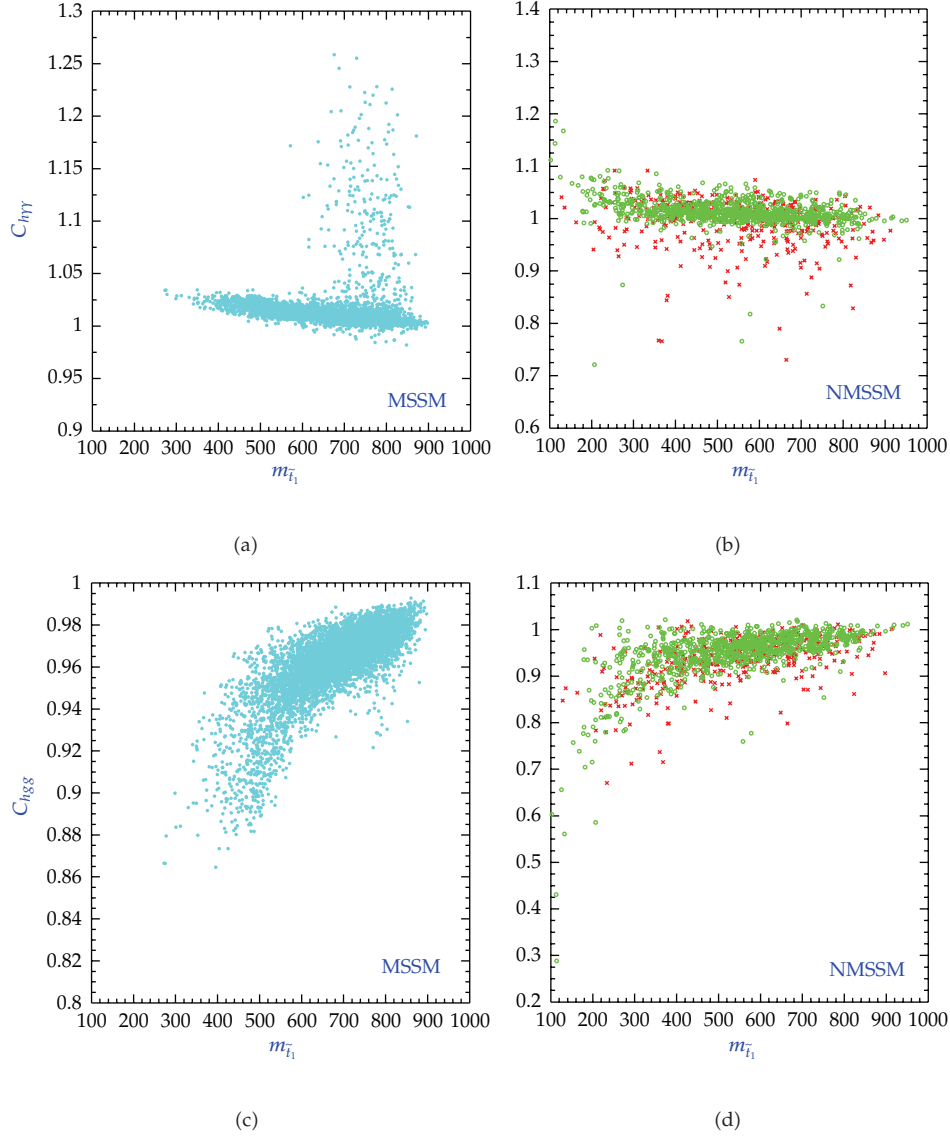
where  $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$  and  $X_t \equiv A_t - \mu \cot\beta$ . The formula manifests that larger  $M_S$  or  $\tan\beta$  is necessary to push up the Higgs boson mass. And the Higgs boson mass can reach a maximum when  $X_t/M_S = \sqrt{6}$  for given  $M_S$  (i.e., the so-called  $m_h^{\max}$  scenario). Note that the lightest Higgs boson is the SM-like Higgs boson  $h$  (with the largest coupling to vector bosons) in most of the MSSM parameter space.

Different from the case in the MSSM, the Higgs sector in the NMSSM depends on the following six parameters:

$$\lambda, \quad \kappa, \quad M_A^2 = \frac{2\mu(A_\lambda + \kappa s)}{\sin 2\beta}, \quad A_\kappa, \quad \tan\beta = \frac{v_u}{v_d}, \quad \mu = \lambda s, \quad (2.5)$$

and in the nMSSM the input parameters in the Higgs sector are

$$\lambda, \quad \tan\beta, \quad \mu, \quad A_\lambda, \quad \tilde{m}_S, \quad M_A^2 = \frac{2(\mu A_\lambda + \lambda \xi_F M_n^2)}{\sin 2\beta}. \quad (2.6)$$

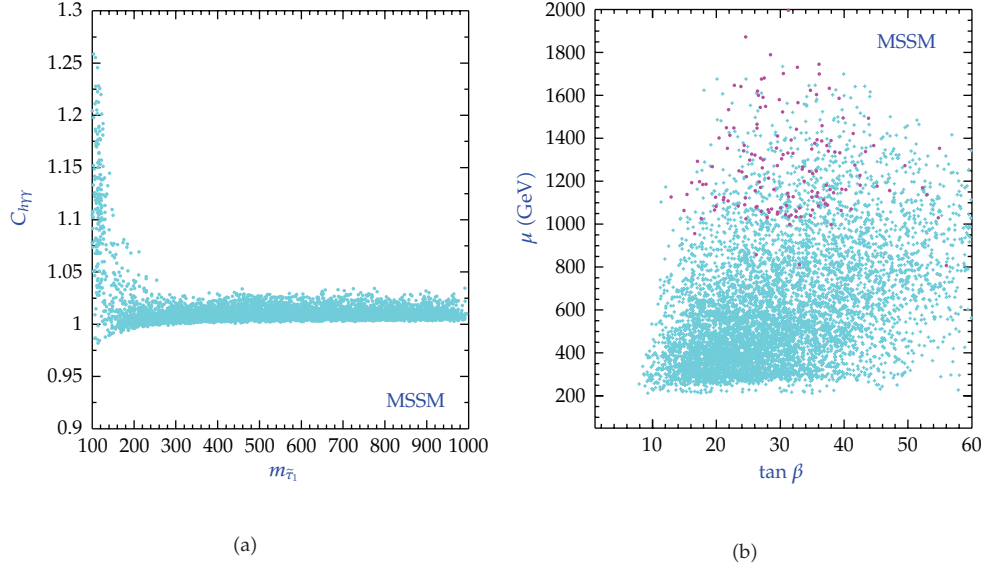


**Figure 3:** Same as Figure 1, projected in the planes of  $m_{\tilde{t}_1}$  versus the reduced couplings  $C_{h\gamma\gamma}$  and  $C_{hgg}$ , respectively.

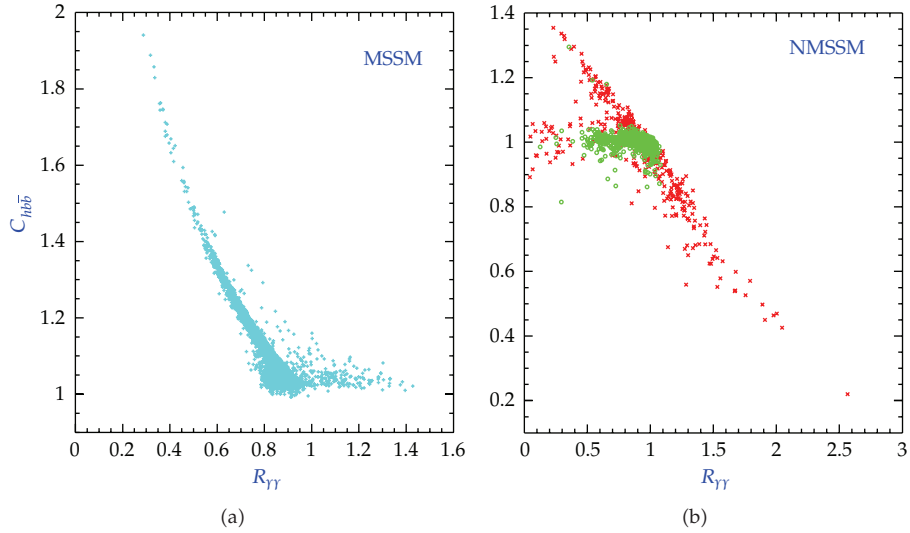
Because of the coupling  $\lambda \widehat{H}_u \cdot \widehat{H}_d \widehat{S}$  in the superpotential, the tree-level Higgs boson mass has an additional contribution in the NMSSM and nMSSM

$$\Delta m_h^2 = \lambda^2 v^2 \sin^2 2\beta. \quad (2.7)$$

In order to push up the tree-level Higgs boson mass,  $\lambda$  has to be as large as possible, and  $\tan \beta$  has to be small. The requirement of the absence of a Landau singularity below the GUT scale implies that  $\lambda \lesssim 0.7$  at the weak scale, and the upper bound on  $\lambda$  at the weak scale depends strongly on  $\tan \beta$  and grows with increasing  $\tan \beta$  [93]. However, this can still lead to a larger



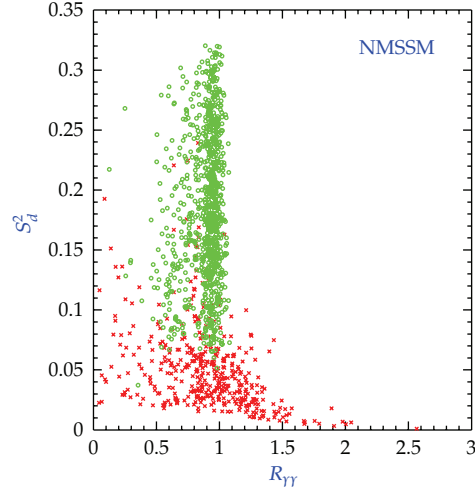
**Figure 4:** Same as Figure 1, but only for the MSSM, showing the correlation between  $m_{\tilde{\tau}_1}$  and the reduced coupling  $C_{h\gamma\gamma}$ ,  $\mu$ , and  $\tan \beta$ , respectively. The purple points correspond to  $R_{\gamma\gamma} > 1$ .



**Figure 5:** Same as Figure 1, but showing the dependence of the di-photon signal rate  $R_{\gamma\gamma}$  on the effective  $h\bar{b}b$  coupling  $C_{h\bar{b}b} \equiv C_{h\bar{b}b}^{\text{SUSY}}/C_{h\bar{b}b}^{\text{SM}}$  (taken for [42]).

tree-level Higgs boson mass than in the MSSM. Therefore, the radiative corrections to  $m_h^2$  may be reduced in the NMSSM and nMSSM, which may induce light top squark and ameliorate the fine-tuning problem [94, 95].

In the NMSSM and nMSSM, due to the mixing between the doublet Higgs fields and the singlet Higgs field, the SM-like Higgs boson  $h$  may either be the lightest CP-even Higgs



**Figure 6:** Same as Figure 2, showing the signal rate  $R_{\gamma\gamma}$  versus  $S_d^2$  with  $S_d = C_{hb\bar{b}} \cos \beta$ .

boson or the next-to-lightest CP-even Higgs boson, which corresponds to the so-called pull-down case or the push-up case [42], respectively. Although the mass of the SM-like Higgs boson in the nMSSM is quite similar to that in the NMSSM, the Higgs signal is quite different. This is because of the peculiarity of the neutralino sector in the nMSSM, where the lightest neutralino  $\tilde{\chi}_1^0$  as the lightest supersymmetric particle (LSP) acts as the dark matter candidate, and its mass takes the form [96]

$$m_{\tilde{\chi}_1^0} \simeq \frac{2\mu\lambda^2 v^2}{\mu^2 + \lambda^2 v^2} \frac{\tan \beta}{\tan^2 \beta + 1}. \quad (2.8)$$

This expression implies that  $\tilde{\chi}_1^0$  must be lighter than about 60 GeV for  $\lambda < 0.7$  (perturbativity bound) and  $\mu > 100$  GeV (from lower bound on chargino mass). And  $\tilde{\chi}_1^0$  must annihilate by exchanging a resonant light CP-odd Higgs boson to get the correct relic density. For such a light neutralino, the SM-like Higgs boson around 125 GeV tends to decay predominantly into light neutralinos or other light Higgs bosons [89, 90].

## 2.2. The Diphoton Higgs Signal

Considering the di-photon signal is of prime importance to searching for Higgs boson near 125 GeV, it is necessary to estimate its signal rate, and we define the normalized production rate as

$$\begin{aligned}
R_{\gamma\gamma} &\equiv \frac{\sigma_{\text{SUSY}}(pp \rightarrow h \rightarrow \gamma\gamma)}{\sigma_{\text{SM}}(pp \rightarrow h \rightarrow \gamma\gamma)} \\
&\simeq \frac{[\Gamma(h \rightarrow gg)\text{Br}(h \rightarrow \gamma\gamma)]}{[\Gamma(h_{\text{SM}} \rightarrow gg)\text{Br}(h_{\text{SM}} \rightarrow \gamma\gamma)]} \\
&= \frac{[\Gamma(h \rightarrow gg)\Gamma(h \rightarrow \gamma\gamma)]}{[\Gamma(h_{\text{SM}} \rightarrow gg)\Gamma(h_{\text{SM}} \rightarrow \gamma\gamma)]} \times \frac{\Gamma_{\text{tot}}(h_{\text{SM}})}{\Gamma_{\text{tot}}(h)} \\
&= C_{hgg}^2 C_{h\gamma\gamma}^2 \times \frac{\Gamma_{\text{tot}}(h_{\text{SM}})}{\Gamma_{\text{tot}}(h)},
\end{aligned} \tag{2.9}$$

where  $C_{hgg}$  and  $C_{h\gamma\gamma}$  are the couplings of Higgs to gluons and photons in SUSY with respect to their SM values, respectively. In SUSY, the  $hgg$  coupling arises mainly from the loops mediated by the third generation quarks and squarks, while the  $h\gamma\gamma$  coupling has additional contributions from loops mediated by W-boson, charged Higgs boson, charginos, and the third generation leptons and sleptons. Their decay widths are given by [47]

$$\begin{aligned}
\Gamma(h \rightarrow gg) &= \frac{G_F \alpha_s^2 m_h^3}{36\sqrt{2}\pi^3} \left| \frac{3}{4} \sum_q g_{hq} A_{1/2}^h(\tau_q) + \frac{3}{4} \mathcal{A}^{gg} \right|^2 \\
\Gamma(h \rightarrow \gamma\gamma) &= \frac{G_F \alpha^2 m_h^3}{128\sqrt{2}\pi} \left| \sum_f N_c Q_f^2 g_{hf} A_{1/2}^h(\tau_f) + g_{hWW} A_1^h(\tau_W) + \mathcal{A}^{\gamma\gamma} \right|^2,
\end{aligned} \tag{2.10}$$

with  $\tau_i = m_h^2/(4m_i^2)$ , and

$$\begin{aligned}
\mathcal{A}^{gg} &= \sum_i \frac{g_{h\tilde{q}_i\tilde{q}_i}}{m_{\tilde{q}_i}^2} A_0^h(\tau_{\tilde{q}_i}), \\
\mathcal{A}^{\gamma\gamma} &= g_{hH^+H^-} \frac{m_W^2}{m_{H^\pm}^2} A_0^h(\tau_{H^\pm}) + \sum_f \frac{g_{h\tilde{f}\tilde{f}}}{m_{\tilde{f}}^2} A_0^h(\tau_{\tilde{f}}) + \sum_i g_{h\chi_i^+\chi_i^-} \frac{m_W}{m_{\chi_i}} A_{1/2}^h(\tau_{\chi_i}),
\end{aligned} \tag{2.11}$$

where  $m_{\tilde{f}}$  and  $m_{\chi_i}$  are the mass of sfermion and chargino, respectively. In the limit  $\tau_i \ll 1$ , the asymptotic behaviors of  $A_i^h$  are given by

$$A_0^h \rightarrow -\frac{1}{3}, \quad A_{1/2}^h \rightarrow -\frac{4}{3}, \quad A_1^h \rightarrow +7. \tag{2.12}$$

One can easily learn that the W-boson contribution to  $h\gamma\gamma$  is by far dominant, however, for light stau or squarks with large mixing, the  $h\gamma\gamma$  coupling can be enhanced, while light squarks



with large mixing can suppress the  $hgg$  coupling. Therefore, light stau with large mixing may enhance the di-photon signal rate [92], while light squarks with large mixing have little effect on the di-photon signal rate.

### 3. Numerical Results and Discussions

In our work the Higgs boson mass is calculated by the package NMSSMTools [97, 98], which include the dominant one-loop and leading logarithmic two-loop corrections. Considering the Higgs hints at the LHC, we focus on the Higgs boson mass between 123 GeV and 127 GeV, furthermore, we consider the following constraints:

- (1) the constraints from LHC experiment for the nonstandard Higgs boson,
- (2) the constraints from LEP and Tevatron on the masses of the Higgs boson and sparticles, as well as on the neutralino pair productions,
- (3) the indirect constraints from B-physics (such as the latest experimental result of  $B_s \rightarrow \mu^+ \mu^-$ ) and from the electroweak precision observables such as  $M_W$ ,  $\sin^2 \theta_{\text{eff}}^\ell$  and  $\rho_\ell$ , or their combinations  $\epsilon_i (i = 1, 2, 3)$  [99, 100],
- (4) the constraints from the muon  $g-2$ :  $a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (25.5 \pm 8.2) \times 10^{-10}$  [101]. We require SUSY to explain the discrepancy at  $2\sigma$  level,
- (5) the dark matter constraints from WMAP relic density ( $0.1053 < \Omega h^2 < 0.1193$ ) [102] and the direct detection exclusion limits on the scattering cross-section from XENON100 experiment (at 90% C.L.) [103].

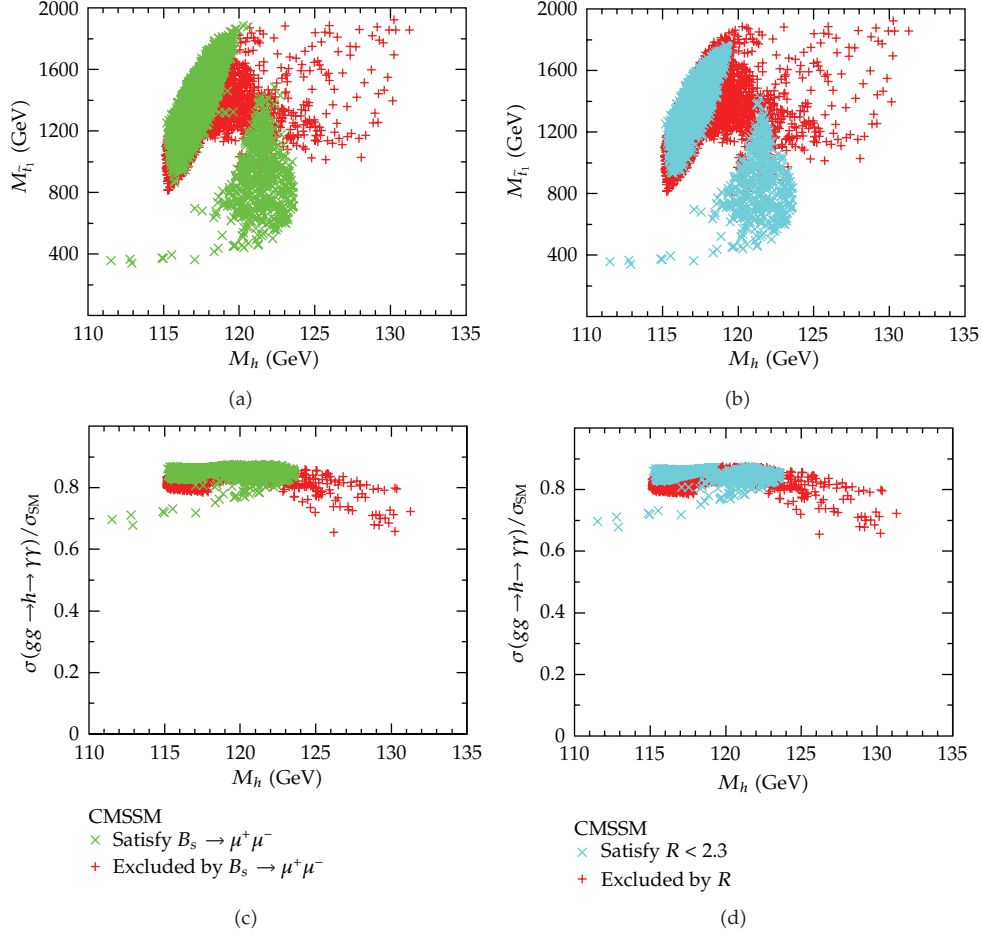
Note that most of the above constraints have been encoded in the package NMSSMTools.

Natural supersymmetry is usually characterized by a small superpotential parameter  $\mu$ , and the third generation squarks with mass  $\lesssim 0.5\text{--}1.5$  TeV [104]. Therefore, we only consider the case with

$$100 \text{ GeV} \leq (M_{Q_3}, M_{U_3}) \leq 1 \text{ TeV}, \quad |A_t| \leq 3 \text{ TeV}. \quad (3.1)$$

For the case with  $\lambda < 0.2$  in the NMSSM, the property of the NMSSM is similar to the case in the MSSM [42]. In order to distinguish the features between MSSM and NMSSM, we only consider the case with  $\lambda > m_Z/v \simeq 0.53$  in the NMSSM. We scan over the parameter space of the MSSM and NMSSM under the above experimental constraints and study the property of the Higgs boson for the samples surviving the constraints.

In Figure 1 we display the surviving samples in the MSSM and NMSSM (with  $\lambda > 0.53$ ), showing the correlation between the lighter top-squark mass and the ratio  $X_t/M_S$  with  $M_S \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$ . From the figure we see that for a moderate light  $\tilde{t}_1$ , large  $X_t$  is necessary to satisfy  $m_h \sim 125$  GeV, and, for large  $m_{\tilde{t}_1}$ , the ratio  $X_t/M_S$  decreases. In the MSSM,  $|X_t/M_S| > 1.6$  for  $m_{\tilde{t}_1} < 1$  TeV; that is, nomixing scenario ( $X_t = 0$ ) cannot survive, and the top-squark mass is usually larger than 300 GeV. This implies that a large top-squark mass or a near-maximal stop mixing is necessary to satisfy the Higgs mass near 125 GeV. However, the case is very different in the NMSSM,  $X_t \approx 0$  may also survive, and the lighter top-squark mass can be as light as about 100 GeV, which may alleviate the fine-tuning problem and make the NMSSM seems more natural. In the case of light  $m_{\tilde{t}_1}$ ,  $|X_t/M_S|$  is usually larger than  $\sqrt{6}$ , which corresponds to a large splitting between  $m_{\tilde{t}_1}$  and  $m_{\tilde{t}_2}$ , as the Figure 2 shown.



**Figure 7:** The scatter plots of the surviving sample in the CMSSM, displayed in the planes of the top-squark mass and the LHC di-photon rate versus the Higgs boson mass. In the left frame, the crosses (red) denote the samples satisfying all the constraints except  $B_s \rightarrow \mu^+\mu^-$ , and the times (green) denote those further satisfying the  $\text{Br}(B_s \rightarrow \mu^+\mu^-)$  constraint. In the right frame, the crosses (red) are the same as those in the left frame, while the times (sky blue) denote the samples further satisfying the  $R$  constraint (taken for [43]).

Due to the clean background, the di-photon signal is crucial for searching for the Higgs boson near 125 GeV. As discussed in the Section 2, the signal rate is relevant with the coupling  $C_{h\gamma\gamma}$  and  $C_{hgg}$  and the total width of the SM-like Higgs boson. Both the coupling  $C_{h\gamma\gamma}$  and  $C_{hgg}$  are affected by the contributions from the squark loops, especially the light top-squark loop, so in the Figure 3 we give the relationship between the lighter top-squark mass and the coupling  $C_{h\gamma\gamma}$  and  $C_{hgg}$ , respectively. The figure shows that the light  $m_{\tilde{t}_1}$  may suppress the coupling  $C_{hgg}$  significantly, especially in the NMSSM, while the light top squark has little effect on the coupling  $C_{h\gamma\gamma}$  because there are additional contributions, as (2.10) and shown. As analyzed in the Section 2, light stau may enhance the coupling  $C_{h\gamma\gamma}$ , so in Figure 4 we give the correlation between  $m_{\tilde{\tau}_1}$  and the coupling  $C_{h\gamma\gamma}$  in the MSSM. The figure clearly shows that the coupling  $C_{h\gamma\gamma}$  can enhance to 1.25 for  $m_{\tilde{\tau}_1} \sim 100$  GeV. Figure 4 also manifests that the

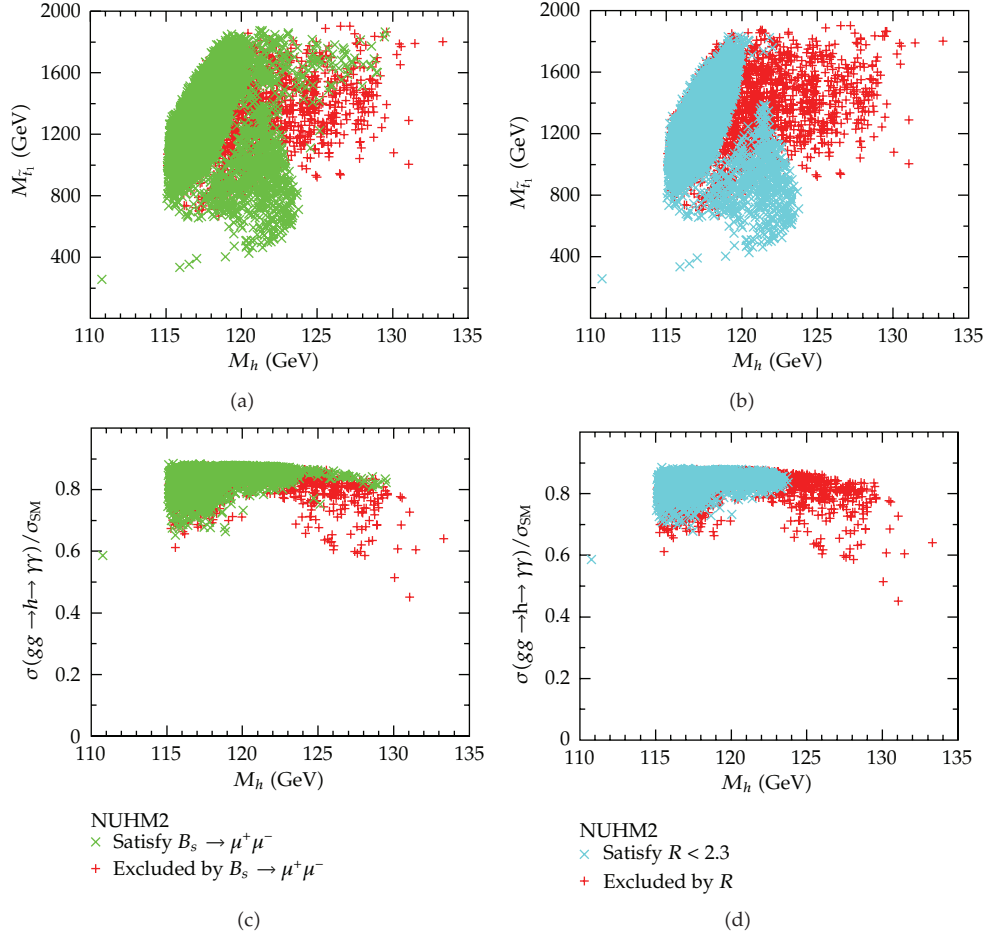


Figure 8: Same as Figure 7, but for the NUHM2 (taken for [43]).

enhancement of the coupling  $C_{h\gamma\gamma}$  corresponds to large  $\mu \tan \beta$ , which leads to large mixing. These results exactly verify the discussions in the Section 2.

Since  $h \rightarrow b\bar{b}$  is the main decay mode of the light Higgs boson, the total width of the SM-like Higgs boson may be affected by the effective  $hb\bar{b}$  coupling  $C_{hb\bar{b}}$ , as discussed in [81]. Under the effect of the combination  $C_{hgg}C_{h\gamma\gamma}/C_{hb\bar{b}}$ , the di-photon Higgs signal rate may be either enhanced or suppressed, as shown in Figure 5, which also manifests that, for the signal rate larger than 1, the effective  $hb\bar{b}$  coupling is enhanced a little in the MSSM, while it is suppressed significantly in the NMSSM. Therefore, we can conclude that the reason for the enhancement in the signal rate is very different between the MSSM and NMSSM. In the MSSM the enhancement of the signal is mainly due to the enhancement of the coupling  $C_{h\gamma\gamma}$ , while in the NMSSM it is mainly due to the suppression of the  $hb\bar{b}$  coupling.

Due to the presence of the singlet field in the NMSSM, the doublet component in the SM-like Higgs boson  $h$  may be different from the case in the MSSM, which will affect the coupling  $hb\bar{b}$  and accordingly affect the total width of  $h$ . At the tree-level,  $C_{hb\bar{b}} = S_d / \cos \beta$ . In Figure 6 we show the dependence of the signal rate  $R_{\gamma\gamma}$  on  $S_d^2$ . Obviously, for the signal

rate larger than 1,  $S_d^2$  is usually very small, which leads to large suppression on the reduced coupling  $hb\bar{b}$ . The figure also shows that the push-up case is more effective to enhance the signal rate than the pull-down case. This is because the push-up case is easier to realize the large mixing between the singlet field and the doublet field [42].

As the case in the NMSSM, nMSSM can also accommodate a 125 GeV SM-like Higgs [81]. However, due to the peculiar property of the lightest neutralino  $\tilde{\chi}_1^0$  in the nMSSM [96], the decay mode of the SM-like Higgs is very different from the case in the MSSM and NMSSM. As discussed in the Section 2,  $h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$  may be dominant over  $h \rightarrow b\bar{b}$  in a major part of parameter space in the nMSSM [81, 105], which induces a severe suppression on the di-photon Higgs signal. Although the Higgs mass can easily reach to 125 GeV, the di-photon signal is not consistent with the LHC experiment. Therefore, the nMSSM may be excluded by LHC experiment.

We also considered the SM-like Higgs boson mass and its di-photon signal in the constrained MSSM (including CMSSM and NUHM2) under various experimental constraints, especially the limits from  $B_s \rightarrow \mu^+ \mu^-$ . Because  $\text{Br}(B_s \rightarrow \mu^+ \mu^-) \propto \tan^6 \beta / M_A^4$ , so it may provide a rather strong constraint on SUSY with large  $\tan \beta$ . Considering the large theoretical uncertainties for the calculation of  $\text{Br}(B_s \rightarrow \mu^+ \mu^-)$ , we use not only the LHCb data, but also the double ratio of the purely leptonic decays defined as  $R \equiv \eta / \eta_{\text{SM}}$  with  $\eta \equiv (\text{Br}(B_s \rightarrow \mu^+ \mu^-) / \text{Br}(B_u \rightarrow \tau \nu_\tau)) / (\text{Br}(D_s \rightarrow \tau \nu_\tau) / \text{Br}(D \rightarrow \mu \nu_\mu))$ . The surviving parameter space is plotted in Figure 7 for the CMSSM and Figure 8 for the NUHM2. It shows that both the CMSSM and NUHM2 are hard to realize a 125 GeV SM-like Higgs boson, and also the di-photon Higgs signal is suppressed relative to the SM prediction due to the enhanced  $hb\bar{b}$  coupling. Therefore, the constrained MSSM may also be excluded by the LHC experiment.

## 4. Conclusion

In this work we briefly review our recent studies on a 125 GeV Higgs and its di-photon signal rate in the MSSM, NMSSM, nMSSM, and the constrained MSSM. Under the current experimental constraints, we find: (i) the SM-like Higgs can easily reach to 125 GeV in the MSSM, NMSSM, and nMSSM, while it is hard to satisfy in the constrained MSSM; (ii) the NMSSM may predict a lighter top squark than the MSSM, even as light as 100 GeV, which can ameliorate the fine-tuning problem; (iii) the di-photon Higgs signal is suppressed in the nMSSM and the constrained MSSM, but, in a tiny corner of the parameter space in the MSSM and NMSSM, it can be enhanced.

## Acknowledgment

The work is supported by the Startup Foundation for Doctors of Henan Normal University under contract no.11108.

## References

- [1] G. Aad, B. Abbott, J. Abdallah et al., "Combined search for the Standard Model Higgs boson using up to  $4.9 \text{ fb}^{-1}$  of  $pp$  collision data at  $\sqrt{s} = 7 \text{ TeV}$  with the ATLAS detector at the LHC," *Physics Letters, Section B*, vol. 710, no. 1, pp. 49–66, 2012.

- [2] G. Aad, B. Abbott, J. Abdallah et al., "Search for the standard model Higgs boson in the diphoton decay channel with  $4.9\text{fb}^{-1}$  of pp collision data at  $\sqrt{s} = 7\text{TeV}$  with atlas," *Physical Review Letters*, vol. 108, no. 11, Article ID 111803, 19 pages, 2012.
- [3] G. Aad, B. Abbott, J. Abdallah et al., "Search for the Standard Model Higgs boson in the decay channel  $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$  with  $4.8\text{fb}^{-1}$  of pp collision data at  $\sqrt{s} = 7\text{TeV}$  with ATLAS," *Physics Letters, Section B*, vol. 710, no. 3, pp. 383–402, 2012.
- [4] S. Chatrchyan, V. Khachatryan, A. M. Sirunyan et al., "Search for a Higgs boson in the decay channel  $H \rightarrow ZZ^{(*)} \rightarrow qq\ell^{-}\ell^{-}$  in pp collisions at  $\sqrt{s} = 7\text{TeV}$ ," *Journal of High Energy Physics*, vol. 2012, no. 4, article 36, 2012.
- [5] S. Chatrchyan, V. Khachatryan, A. M. Sirunyan et al., "Search for the standard model Higgs boson decaying into two photons in pp collisions at  $\sqrt{s} = 7\text{TeV}$ ," *Physics Letters, Section B*, vol. 710, no. 3, pp. 403–425, 2012.
- [6] S. Chatrchyan, V. Khachatryan, A. M. Sirunyan et al., "Combined results of searches for the standard model Higgs boson in pp collisions at  $\sqrt{s} = 7\text{TeV}$ ," *Physics Letters, Section B*, vol. 710, no. 1, pp. 26–48, 2012.
- [7] S. Chatrchyan, V. Khachatryan, A. M. Sirunyan et al., "Search for the standard model Higgs boson decaying to  $W^{+}W^{-}$  in the fully leptonic final state in pp collisions at  $\sqrt{s} = 7\text{TeV}$ ," *Physics Letters, Section B*, vol. 710, no. 1, pp. 91–113, 2012.
- [8] S. Chatrchyan, V. Khachatryan, A. M. Sirunyan et al., "Search for the standard model higgs boson in the decay channel  $H \rightarrow ZZ \rightarrow 4l$  in pp collisions at  $\sqrt{s} = 7\text{TeV}$ ," *Physical Review Letters*, vol. 108, no. 11, Article ID 111804, 17 pages, 2012.
- [9] S. Chatrchyan, V. Khachatryan, A. M. Sirunyan et al., "Search for the standard model Higgs boson in the  $H \rightarrow ZZ \rightarrow 2\ell 2\nu$  channel in pp collisions at  $\sqrt{s} = 7\text{TeV}$ ," *Journal of High Energy Physics*, vol. 2012, no. 3, article 040, 2012.
- [10] S. Chatrchyan, V. Khachatryan, A. M. Sirunyan et al., "Search for the standard model Higgs boson in the  $H \rightarrow ZZ \rightarrow l\ell^{+}\ell^{-}\tau^{+}\tau^{-}$  decay channel in pp collisions at  $\sqrt{s} = 7\text{TeV}$ ," *Journal of High Energy Physics*, vol. 2012, no. 3, article 081, 2012.
- [11] S. Chatrchyan, V. Khachatryan, A. M. Sirunyan et al., "Search for neutral Higgs bosons decaying to tau pairs in pp collisions at  $\sqrt{s} = 7\text{TeV}$ ," *Physics Letters, Section B*, vol. 713, no. 2, pp. 68–90, 2012.
- [12] S. Chatrchyan, V. Khachatryan, A. M. Sirunyan et al., "Search for the standard model Higgs boson decaying to bottom quarks in pp collisions at  $\sqrt{s} = 7\text{TeV}$ ," *Physics Letters, Section B*, vol. 710, no. 2, pp. 284–306, 2012.
- [13] D. Carmi, A. Falkowski, E. Kuflik, and T. Volansky, "Interpreting LHC higgs results from natural new physics perspective," *Energy Physics* <http://arxiv.org/abs/1202.3144>.
- [14] S. Heinemeyer, O. Stål, and G. Weiglein, "Interpreting the LHC Higgs search results in the MSSM," *Physics Letters, Section B*, vol. 710, no. 1, pp. 201–206, 2012.
- [15] A. Arbey, M. Battaglia, A. Djouadi, F. Mahmoudi, and J. Quevillon, "Implications of a 125 GeV Higgs for supersymmetric models," *Physics Letters, Section B*, vol. 708, no. 1-2, pp. 162–169, 2012.
- [16] L. J. Hall, D. Pinner, and J. T. Ruderman, "A natural SUSY Higgs near 125 GeV," *Journal of High Energy Physics*, vol. 2012, no. 4, article 131, 2012.
- [17] P. Draper, P. Meade, M. Reece, and D. Shih, "Implications of a 125 GeV Higgs for the MSSM and Low-Scale SUSY Breaking," *High Energy Physics*, <http://arxiv.org/abs/1112.3068>.
- [18] A. Arbey, M. Battaglia, and F. Mahmoudi, "Constraints on the MSSM from the Higgs sector: a pMSSM study of Higgs searches,  $B_s^0 \rightarrow \mu^{+}\mu^{-}$  and dark matter direct detection," *European Physical Journal C*, vol. 72, no. 3, article 1906, 2012.
- [19] O. Buchmueller, R. Cavanaugh, A. de Roeck et al., "Higgs and supersymmetry," *European Physical Journal C*, vol. 72, no. 6, pp. 1–14, 2012.
- [20] M. Kadastik, K. Kannike, A. Racioppi, and M. Raida, "Implications of the 125 GeV Higgs boson for scalar dark matter and for the CMSSM phenomenology," *Journal of High Energy Physics*, vol. 2012, no. 5, article 061, 2012.
- [21] A. Arvanitaki and G. Villadoro, "A non standard model higgs at the LHC as a sign of naturalness," *Journal of High Energy Physics*, vol. 2012, no. 2, article 144, 2012.
- [22] H. Baer, V. Barger, and A. Mustafayev, "Implications of a 125 GeV Higgs scalar for the LHC supersymmetry and neutralino dark matter searches," *Physical Review D*, vol. 85, no. 7, Article ID 075010, 13 pages, 2012.
- [23] J. F. Gunion, Y. Jiang, and S. Kraml, "The constrained NMSSM and Higgs near 125 GeV," *Physics Letters, Section B*, vol. 710, no. 3, pp. 454–459, 2012.

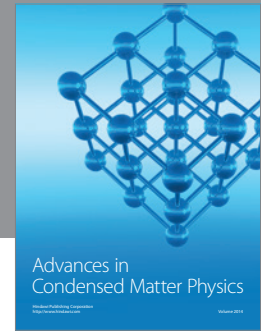
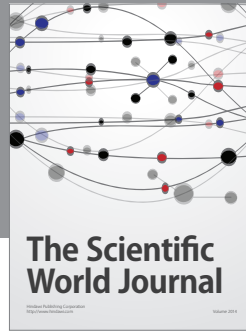
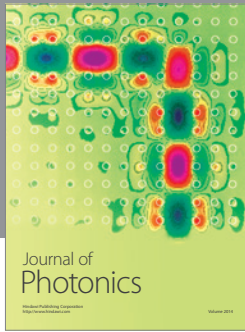
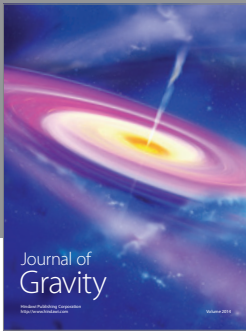
- [24] P. Fileviez Pérez, "SUSY spectrum and the Higgs mass in the BLMSSM," *Physics Letters, Section B*, vol. 711, no. 5, pp. 353–359, 2012.
- [25] Z. Kang, J. Li, and T. Li, "On Naturalness of the (N)MSSM," *High Energy Physics*. In press <http://arxiv.org/abs/1201.5305>.
- [26] L. Aparicio, D. G. Cerdeño, and L. E. Ibáñez, "A 119–125 GeV Higgs from a string derived slice of the CMSSM," *Journal of High Energy Physics*, vol. 2012, no. 4, article 126, 2012.
- [27] C.-F. Chang, K. Cheung, Y.-C. Lin, and T.-C. Yuan, "Mimicking the standard model Higgs boson in UMSSM," *Journal of High Energy Physics*, vol. 2012, no. 6, article 51, 2012.
- [28] J. Ellis and K. A. Olive, "Revisiting the Higgs mass and dark matter in the CMSSM," *European Physical Journal C*, vol. 72, no. 5, pp. 1–13, 2012.
- [29] H. Baer, V. Barger, and A. Mustafayev, "Neutralino dark matter in mSUGRA/CMSSM with a 125 GeV light higgs scalar," *Journal of High Energy Physics*, vol. 2012, no. 5, article 091, 2012.
- [30] N. Desai, B. Mukhopadhyaya, and S. Niyogi, "Constraints on invisible Higgs decay in MSSM in the light of diphoton rates from the LHC," *High Energy Physics*, <http://arxiv.org/abs/1202.5190>.
- [31] F. Boudjema and G. D. La Rochelle, "BMSSM Higgses at 125 GeV," *High Energy Physics*, <http://arxiv.org/abs/1203.3141>.
- [32] D. Albornoz Vásquez, G. Bélanger, C. Bahm, J. Da Silva, P. Richardson, and C. Wymant, "125 GeV Higgs boson in the NMSSM in light of the LHC results and astrophysics constraints," *Physical Review D*, vol. 86, no. 3, Article ID 035023, 10 pages, 2012.
- [33] U. Ellwanger and C. Hugonie, "Higgs bosons near 125 GeV in the NMSSM with constraints at the GUT Scale," *Advances in High Energy Physics*, vol. 2012, Article ID 625389, 18 pages, 2012.
- [34] T. Basak and S. Mohanty, "Triplet-singlet extension of the MSSM with a 125 GeV higgs and dark matter," *High Energy Physics*, <http://arxiv.org/abs/1204.6592>.
- [35] N. Chen and H.-J. He, "LHC signatures of two-Higgs-doublets with fourth family," *Journal of High Energy Physics*, vol. 2012, no. 4, article 62, 2012.
- [36] G. Guo, B. Ren, and X. G. He, "LHC evidence of a 126 GeV higgs boson from  $H$  to  $\gamma\gamma$  with three And four generations," *High Energy Physics*, <http://arxiv.org/abs/1112.3188>.
- [37] X.-G. He, B. Ren, and J. Tandean, "Hints of standard model Higgs boson at the LHC and light dark matter searches," *Physical Review D*, vol. 85, no. 9, Article ID 093019, 10 pages, 2012.
- [38] A. Djouadi, O. Lebedev, Y. Mambrini, and J. Quevillon, "Implications of LHC searches for Higgs-portal dark matter," *Physics Letters, Section B*, vol. 709, no. 1-2, pp. 65–69, 2012.
- [39] K. Cheung and T.-C. Yuan, "Could the excess seen at 124–126 GeV Be due to the Randall-Sundrum radion?" *Physical Review Letters*, vol. 108, no. 14, Article ID 141602, 5 pages, 2012.
- [40] B. Batell, S. Goria, and L.-T. Wang, "Exploring the Higgs portal with  $10 \text{ fb}^{-1}$  at the LHC," *Journal of High Energy Physics*, vol. 2012, no. 6, article 07, 2012.
- [41] T. Li, J. A. Maxin, D. V. Nanopoulos, and J. W. Walker, "A Higgs mass shift to 125 GeV and a multi-jet supersymmetry signal: miracle of the flippons at the  $\sqrt{s} = 7 \text{ TeV}$  LHC," *Physics Letters, Section B*, vol. 710, no. 1, pp. 207–214, 2012.
- [42] J. Cao, Z. Heng, J. M. Yang, Y. Zhang, and J. Zhu, "A SM-like Higgs near 125 GeV in low energy SUSY: a comparative study for MSSM and NMSSM," *Journal of High Energy Physics*, vol. 2012, no. 3, article 086, 2012.
- [43] J. Cao, Z. Heng, D. Li, and J. M. Yang, "Current experimental constraints on the lightest Higgs boson mass in the constrained MSSM," *Physics Letters, Section B*, vol. 710, no. 4-5, pp. 665–670, 2012.
- [44] H. E. Haber and G. L. Kane, *Physics Reports*, vol. 117, p. 75, 1985.
- [45] J. F. Gunion and H. E. Haber, "Higgs bosons in supersymmetric models (I)," *Nuclear Physics, Section B*, vol. 272, no. 1, pp. 1–76, 1986.
- [46] "Higgs bosons in supersymmetric models (I). [Nucl. Phys. B272 (1986) 1] J.F. Gunion and H.E. Haber," *Nuclear Physics, Section B*, vol. 402, no. 1-2, pp. 567–568, 1993.
- [47] A. Djouadi, "The anatomy of electroweak symmetry breaking Tome II: the Higgs bosons in the Minimal Supersymmetric Model," *Physics Reports*, vol. 459, no. 1–6, pp. 1–241, 2008.
- [48] U. Ellwanger, C. Hugonie, and A. M. Teixeira, "The next-to-minimal supersymmetric standard model," *Physics Reports*, vol. 496, no. 1-2, pp. 1–77, 2010.
- [49] M. Maniatis, "The next-to-minimal supersymmetric extension of the standard model reviewed," *International Journal of Modern Physics A*, vol. 25, no. 18-19, pp. 3505–3602, 2010.
- [50] U. Ellwanger, "Higgs bosons in the Next-to-Minimal Supersymmetric Standard Model at the LHC," *The European Physical Journal C*, vol. 71, no. 10, p. 1782, 2011.
- [51] J. Ellis, J. F. Gunion, H. E. Haber, L. Roszkowski, and F. Zwirner, "Higgs bosons in a nonminimal supersymmetric model," *Physical Review D*, vol. 39, no. 3, pp. 844–869, 1989.

- [52] J. Ellis, J. F. Gunion, H. E. Haber, L. Roszkowski, and F. Zwirner, "Higgs bosons in a nonminimal supersymmetric model," *Physical Review D*, vol. 39, no. 3, pp. 844–869, 1989.
- [53] M. Drees, "Supersymmetric models with extended higgs sector," *International Journal of Modern Physics A*, vol. 04, no. 14, article 3635, 1989.
- [54] S. F. King and P. L. White, "Resolving the constrained minimal and next-to-minimal supersymmetric standard models," *Physical Review D*, vol. 52, no. 7, pp. 4183–4216, 1995.
- [55] B. Ananthanarayan and P. N. Pandita, "The non-minimal supersymmetric standard model with  $\tan \beta \approx m_t/m_b$ ," *Physics Letters, Section B*, vol. 353, no. 1, pp. 70–78, 1995.
- [56] B. A. Dobrescu and K. T. Matchev, "Light axion within the next-to-minimal supersymmetric standard model," *Journal of High Energy Physics*, vol. 4, no. 9, article 031, 2000.
- [57] G. Hiller, "b-physics signals of the lightest CP-odd Higgs boson in the next-to-minimal supersymmetric standard model at large  $\tan \beta$ ," *Physical Review D*, vol. 70, no. 3, Article ID 034018, 10 pages, 2004.
- [58] W. Wang, Z. Xiong, and J. M. Yang, "Residual effects of heavy sparticles in the bottom quark Yukawa coupling: a comparative study for the MSSM and NMSSM," *Physics Letters, Section B*, vol. 680, no. 2, pp. 167–171, 2009.
- [59] J. Cao and J. M. Yang, "Anomaly of Zbb coupling revisited in MSSM and NMSSM," *Journal of High Energy Physics*, vol. 2008, no. 12, article 006, 2008.
- [60] J. Cao and J. M. Yang, "Current experimental constraints on the next-to-minimal supersymmetric standard model with large  $\lambda$ ," *Physical Review D*, vol. 78, no. 11, Article ID 115001, 11 pages, 2008.
- [61] J. M. Yang, "SUSY dark matter in light of CDMS/XENON limits," *International Journal of Modern Physics D*, vol. 20, no. 8, pp. 1383–1388, 2011.
- [62] A. H. Chamseddine, R. Arnowitt, and P. Nath, "Locally supersymmetric grand unification," *Physical Review Letters*, vol. 49, no. 14, pp. 970–974, 1982.
- [63] R. Barbieri, S. Ferrara, and C. A. Savoy, "Gauge models with spontaneously broken local supersymmetry," *Physics Letters B*, vol. 119, no. 4–6, pp. 343–347, 1982.
- [64] L. Hall, J. Lykken, and S. Weinberg, "Supergravity as the messenger of supersymmetry breaking," *Physical Review D*, vol. 27, no. 10, pp. 2359–2378, 1983.
- [65] N. Ohta, "Grand unified theories based on local supersymmetry," *Progress of Theoretical Physics*, vol. 70, no. 2, pp. 542–549, 1983.
- [66] J. Ellis, K. A. Olive, and Y. Santoso, "The MSSM parameter space with non-universal Higgs masses," *Physics Letters, Section B*, vol. 539, no. 1–2, pp. 107–118, 2002.
- [67] J. Ellis, T. Falk, K. A. Olive, and Y. Santoso, "Exploration of the MSSM with non-universal Higgs masses," *Nuclear Physics B*, vol. 652, pp. 259–347, 2003.
- [68] H. Baer, A. Mustafayev, S. Profumo, A. Belyaev, and X. Tata, "Neutralino cold dark matter in a one-parameter extension of the minimal supergravity model," *Physical Review D*, vol. 71, no. 9, Article ID 095008, 5 pages, 2005.
- [69] M. Carena, J. R. Espinosa, M. Quirós, and C. E. M. Wagner, "Analytical expressions for radiatively corrected Higgs masses and couplings in the MSSM," *Physics Letters, Section B*, vol. 355, no. 1–2, pp. 209–221, 1995.
- [70] U. Ellwanger and C. Hugonie, "The upper bound on the lightest higgs mass in the NMSSM revisited," *Modern Physics Letters A*, vol. 22, no. 21, pp. 1581–1590, 2007.
- [71] U. Ellwanger and C. Hugonie, "Masses and couplings of the lightest Higgs bosons in (M + 1)SSM," *European Physical Journal C*, vol. 25, no. 2, pp. 297–305, 2002.
- [72] U. Ellwanger, "Higgs bosons in the Next-to-Minimal Supersymmetric Standard Model at the LHC," *The European Physical Journal C*, vol. 71, no. 10, article 1782, 2011.
- [73] P. H. Chankowski, J. Ellis, and S. Pokorski, "The fine-tuning price of LEP," *Physics Letters, Section B*, vol. 423, no. 3–4, pp. 327–336, 1998.
- [74] R. Barbieri and A. Strumia, "About the fine-tuning price of LEP," *Physics Letters, Section B*, vol. 433, no. 1–2, pp. 63–66, 1998.
- [75] G. L. Kane and S. F. King, "Naturalness implications of LEP results," *Physics Letters, Section B*, vol. 451, no. 1–2, pp. 113–122, 1999.
- [76] S. Moretti and S. Munir, "Di-photon Higgs signals at the LHC in the next-to-minimal supersymmetric standard model," *European Physical Journal C*, vol. 47, no. 3, pp. 791–803, 2006.
- [77] K. Hsieh and C. P. Yuan, "Lone Higgs boson at the CERN LHC," *Physical Review D*, vol. 78, no. 5, Article ID 053006, 19 pages, 2008.
- [78] I. Low and S. Shalgar, "Implications of the Higgs discovery in the MSSM golden region," *Journal of High Energy Physics*, vol. 2009, no. 4, article 091, 2009.

- [79] U. Ellwanger, "Enhanced di-photon Higgs signal in the next-to-minimal supersymmetric standard model," *Physics Letters, Section B*, vol. 698, no. 4, pp. 293–296, 2011.
- [80] U. Ellwanger, "A Higgs boson near 125 GeV with enhanced di-photon signal in the NMSSM," *Journal of High Energy Physics*, vol. 2012, no. 3, article 044, 2012.
- [81] J. Cao, Z. Heng, T. Liu, and J. M. Yang, "Di-photon Higgs signal at the LHC: a comparative study in different supersymmetric models," *Physics Letters, Section B*, vol. 703, no. 4, pp. 462–468, 2011.
- [82] C. Panagiotakopoulos and K. Tamvakis, "Stabilized NMSSM without domain walls," *Physics Letters, Section B*, vol. 446, no. 3-4, pp. 224–227, 1999.
- [83] C. Panagiotakopoulos and K. Tamvakis, "New minimal extension of MSSM," *Physics Letters, Section B*, vol. 469, no. 1–4, pp. 145–148, 1999.
- [84] C. Panagiotakopoulos and A. Pilaftsis, "Higgs scalars in the minimal nonminimal supersymmetric standard model," *Physical Review D*, vol. 63, no. 5, Article ID 055003, 33 pages, 2001.
- [85] A. Dedes, C. Hugonie, S. Moretti, and K. Tamvakis, "Phenomenology of a new minimal supersymmetric extension of the standard model," *Physical Review D*, vol. 63, no. 5, Article ID 055009, 9 pages, 2001.
- [86] A. Menon, D. E. Morrissey, and C. E. M. Wagner, "Electroweak baryogenesis and dark matter in a minimal extension of the MSSM," *Physical Review D*, vol. 70, no. 3, Article ID 035005, 20 pages, 2004.
- [87] V. Barger, P. Langacker, and H.-S. Lee, "Lightest neutralino in extensions of the MSSM," *Physics Letters, Section B*, vol. 630, no. 3-4, pp. 85–99, 2005.
- [88] C. Balázs, M. Carena, A. Freitas, and C. E. M. Wagner, "Phenomenology of the nMSSM from colliders to cosmology," *Journal of High Energy Physics*, vol. 2007, no. 6, article 066, 2007.
- [89] J. Cao, H. E. Logan, and J. M. Yang, "Experimental constraints on the nearly minimal supersymmetric standard model and implications for its phenomenology," *Physical Review D*, vol. 79, no. 9, Article ID 091701, 5 pages, 2009.
- [90] J. Cao, Z. Heng, and J. M. Yang, "Rare Z-decay into light CP-odd Higgs bosons: a comparative study in different new physics models," *Journal of High Energy Physics*, vol. 2010, no. 11, article 110, 2010.
- [91] V. Barger, P. Langacker, H.-S. Lee, and G. Shaughnessy, "Higgs sector in extensions of the minimal supersymmetric standard model," *Physical Review D*, vol. 73, no. 11, Article ID 115010, 31 pages, 2006.
- [92] M. Carena, S. Gori, N. R. Shah, and C. E. M. Wagner, "A 125 GeV SM-like Higgs in the MSSM and the  $\gamma\gamma$  rate," *Journal of High Energy Physics*, vol. 2012, no. 3, article 014, 2012.
- [93] S. F. King, M. Mühlleitner, and R. Nevzorov, "NMSSM Higgs benchmarks near 125 GeV," *Nuclear Physics B*, vol. 860, no. 2, pp. 207–244, 2012.
- [94] R. Dermšek and J. F. Gunion, "Escaping the large fine-tuning and little hierarchy problems in the next to minimal supersymmetric model and  $h \rightarrow aa$  decays," *Physical Review Letters*, vol. 95, no. 4, Article ID 041801, 4 pages, 2005.
- [95] U. Ellwanger, G. Espitalier-Noel, and C. Hugonie, "Naturalness and fine tuning in the NMSSM: implications of early LHC results," *Journal of High Energy Physics*, vol. 2011, no. 9, article 105, 2011.
- [96] J. Cao, Z. Heng, and J. M. Yang, "Rare Z-decay into light CP-odd Higgs bosons: a comparative study in different new physics models," *Journal of High Energy Physics*, vol. 2010, no. 11, article 110, 2010.
- [97] U. Ellwanger, J. F. Gunion, and C. Hugonie, "NMHDECAY: a fortran code for the Higgs masses, couplings and decay widths in the NMSSM," *Journal of High Energy Physics*, vol. 0502, article 066, 2005.
- [98] U. Ellwanger and C. Hugonie, "NMHDECAY 2.1: an updated program for sparticle masses, Higgs masses, couplings and decay widths in the NMSSM," *Computer Physics Communications*, vol. 175, no. 4, pp. 290–303, 2006.
- [99] G. Altarelli and R. Barbieri, "Vacuum polarization effects of new physics on electroweak processes," *Physics Letters, Section B*, vol. 253, no. 1-2, pp. 161–167, 1991.
- [100] M. E. Peskin and T. Takeuchi, "Estimation of oblique electroweak corrections," *Physical Review D*, vol. 46, no. 1, pp. 381–409, 1992.
- [101] M. Davier, A. Hoecker, B. Malaescu, C. Z. Yuan, and Z. Zhang, "Reevaluation of the hadronic contribution to the muon magnetic anomaly using new  $e^+e^- \rightarrow \pi^+\pi^-$  cross section data from BABAR," *European Physical Journal C*, vol. 66, no. 1, pp. 1–9, 2010.
- [102] J. Dunkley, E. Komatsu, M. R. Nolte et al., "Five-year wilkinson microwave anisotropy probe observations: likelihoods and parameters from the WMAP data," *Astrophysical Journal, Supplement Series*, vol. 180, no. 2, pp. 306–329, 2009.
- [103] E. Aprile, K. Arisaka, F. Arneodo et al., "Dark matter results from 100 live days of XENON100 data," *Physical Review Letters*, vol. 107, no. 13, Article ID 131302, 6 pages, 2011.



- [104] H. Baer, V. Barger, P. Huang, and X. Tata, "Natural supersymmetry: LHC, dark matter and ILC searches," *Journal of High Energy Physics*, vol. 2012, no. 5, article109, 2012.
- [105] J. Cao, Z. Heng, J. M. Yang, and J. Zhu, "Higgs decay to dark matter in low energy SUSY: is it detectable at the LHC?" *Journal of High Energy Physics*, vol. 2012, no. 6, article 34, 2012.



**Hindawi**

Submit your manuscripts at  
<http://www.hindawi.com>

