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Abstract

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A Light Higgs Scalar in the NMSSM Confronted with the Latest LHC Higgs Data

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Abstract

In the Next-to-Minimal Supersymmetric Standard Model (NMSSM), one of the neutral Higgs scalars (CP-even or CP-odd) may be lighter than half of the SM-like Higgs boson. In this case, the SM-like Higgs boson h can decay into such a light scalar pair, and consequently the $\gamma\gamma$ and ZZ^* signal rates at the LHC will be suppressed. In this work, we examine the constraints of the latest LHC Higgs data on such a possibility. We perform a comprehensive scan over the parameter space of the NMSSM by considering various experimental constraints and find that the LHC Higgs data can readily constrain the parameter space and the properties of the light scalar; for example, at the 3σ level this light scalar should be highly singlet-dominant and the branching ratio of the SM-like Higgs boson decay into the scalar pair should be less than about 30%. We also investigate

the detection of this scalar at various colliders. Through a detailed Monte Carlo simulation we find that, under the constraints of the current Higgs data, this light scalar can be accessible at the LHC-14 with an integrated luminosity over 300 fb^{-1} .

Introduction

The ATLAS and CMS collaborations have discovered a new scalar with a significance of 9σ and 7σ , respectively [?, ?, ?, ?]. So far the mass of this scalar has been rather precisely determined to be around 125 GeV, and its other properties, albeit with large experimental uncertainties, agree with the Standard Model (SM) prediction [?, ?]. Despite this, this newly discovered scalar has been interpreted in various new physics models since the SM suffers from the gauge hierarchy problem and cannot provide a dark matter candidate. Studies in this direction have been carried out intensively in low-energy supersymmetric models, and the NMSSM was found to be most favored [?, ?, ?, ?, ?, ?, ?, ?].

In this work we focus on the NMSSM, which is the simplest extension of the MSSM with one extra gauge singlet Higgs field [?]. One virtue of such an extension is that it provides a dynamical mechanism for the generation of the μ parameter and thus solves the so-called μ -problem suffered by the MSSM [?]. Another virtue is that the interactions of the singlet field in the Higgs sector give a new contribution to the tree-level mass of the SM-like Higgs boson and thus alleviate the little hierarchy problem [?, ?]. For LHC phenomenology, one notable feature of the NMSSM is that a Higgs scalar (CP-even or CP-odd) may be rather light [?, ?], which can affect the signals of sparticles at the LHC [?, ?]. For example, if the lightest supersymmetric particle is singlino-like, squarks may decay dominantly as [?] $\tilde{q} \rightarrow q\tilde{\chi}_{2,3}^0 \rightarrow q\tilde{\chi}_1^0 S \rightarrow q\tilde{\chi}_1^0 b\bar{b}$, where $\tilde{\chi}_2^0$ and $\tilde{\chi}_3^0$ represent the second and third lightest neutralinos respectively, and S denotes a light scalar.

We note that if this scalar is lighter than half of the SM-like Higgs boson, the SM-like Higgs boson can decay exotically into the light scalar pair [?, ?, ?]. Since the width of the Higgs boson in the SM is quite narrow (about 4 MeV), such an exotic decay may have a sizable branching ratio. This in turn can greatly suppress the visible signals of the SM-like Higgs boson at the LHC. Motivated by this observation, we investigate the constraints of the latest LHC Higgs data on the properties of such a light scalar. We also study the detection of this scalar at the LHC-14 via a detailed Monte Carlo simulation.

The outline of this paper is as follows. In Section II we briefly review the NMSSM model. Then in Section III we scan the parameter space of the NMSSM under current experimental constraints. In Section IV the properties of the light scalar are analyzed and its detection at the LHC-14 is studied via a detailed Monte Carlo simulation. Finally, we present our conclusion in Section V.

II. The Higgs Sector of the NMSSM

As one of the most economical extensions of the MSSM, the NMSSM contains two $SU(2)$ doublet Higgs fields and one gauge singlet Higgs field [?]. Traditionally, these fields are labeled by

$$\hat{H}_u = \begin{pmatrix} H_u^+ \\ v_u + \frac{\phi_u + i\phi_u}{\sqrt{2}} \end{pmatrix}, \quad \hat{H}_d = \begin{pmatrix} v_d + \frac{\phi_d + i\phi_d}{\sqrt{2}} \\ H_d^- \end{pmatrix}, \quad \hat{S} = v_s + \frac{\phi_s + i\phi_s}{\sqrt{2}}$$

where H_i^+ , ϕ_i and ϕ_i ($i = u, d$) represent the charged, neutral CP-even and neutral CP-odd component fields respectively, and v_u , v_d and v_s are the vacuum expectation values with $v_u/v_d = \tan \beta$ and $\sqrt{v_u^2 + v_d^2} = v \equiv 174$ GeV. Since one purpose of the extension is to solve the μ -problem of the MSSM, a Z_3 symmetry is implemented in the construction of the superpotential to avoid the appearance of parameters with mass dimension. Consequently, the superpotential and the soft breaking terms in the NMSSM are given by [?]

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

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

where \hat{H}_u , \hat{H}_d and \hat{S} are Higgs superfields, W_F is the superpotential of the MSSM without the μ -term, and \tilde{m}_u , \tilde{m}_d , \tilde{m}_S , A_λ and A_κ are soft-breaking parameters.

In order to present the mass matrices of the Higgs fields in a physical way, we redefine the Higgs fields as [?]

$$H_1 = \cos \beta H_u - \varepsilon \sin \beta H_d^*, \quad H_2 = \sin \beta H_u + \varepsilon \cos \beta H_d^*, \quad H_3 = S,$$

where $\varepsilon_{12} = \varepsilon_{21} = -1$ and $\varepsilon_{11} = \varepsilon_{22} = 0$. With such a definition, H_i ($i = 1, 2, 3$) are given by

$$H_1 = \frac{S_1 + iP_1}{\sqrt{2}}, \quad H_2 = v + \frac{S_2 + iG^0}{\sqrt{2}}, \quad H_3 = v_s + (S_3 + iP_2),$$

where ϕ_s and ϕ_s in Eq.(1) are rewritten as S_3 and P_2 respectively. Obviously, the field H_2 corresponds to the SM Higgs field with G^+ and G^0 denoting Goldstone bosons, and S_2 representing the SM Higgs boson.

In the CP-conserving NMSSM, the fields S_1 , S_2 and S_3 mix to form three (instead of two in the MSSM) physical CP-even Higgs bosons h_i ($i = 1, 2, 3$). In

the basis (S_1, S_2, S_3) , the elements of the corresponding mass matrix are given by [?]

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

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

$$\mathcal{M}_{13}^2 = -\left(\frac{2\mu}{\sin 2\beta} - \kappa v_s\right) \lambda v \cos 2\beta,$$

$$\mathcal{M}_{22}^2 = m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta,$$

$$\mathcal{M}_{23}^2 = 2\lambda\mu v \left[1 - \left(\frac{2\mu}{\sin 2\beta} + \kappa v_s\right) \frac{\lambda}{2\kappa}\right],$$

$$\mathcal{M}_{33}^2 = \frac{\lambda^2 v^2}{\kappa^2} \left(\frac{2\mu}{\sin 2\beta}\right)^2 + \kappa v_s A_\kappa + 4(\kappa v_s)^2 - \lambda \kappa v^2 \sin 2\beta.$$

Similarly, the fields P_1 and P_2 mix to form two physical CP-odd Higgs bosons A_i ($i = 1, 2$), and in the basis (P_1, P_2) the mass matrix elements for the CP-odd Higgs sector are given by

$$\mathcal{M}_{P,11}^2 = \frac{M_A^2}{\sin 2\beta} (A_\lambda + \kappa v_s),$$

$$\mathcal{M}_{P,22}^2 = \frac{M_A^2}{\sin 2\beta} (A_\lambda + 4\kappa v_s) - 3\kappa v_s A_\kappa,$$

$$\mathcal{M}_{P,12}^2 = \lambda v \left(\frac{2\mu}{\sin 2\beta} - 3\lambda \kappa v_s v\right).$$

About the Higgs sector of the NMSSM, the following points should be noted:

- Compared with the MSSM where only two parameters are involved in the Higgs sector, six parameters are needed to describe the Higgs sector of the NMSSM [?]. These parameters are usually chosen as $\tan \beta$, $\mu = \lambda v_s$, $M_A^2 = \frac{\lambda v_s}{\sin 2\beta} (A_\lambda + \kappa v_s)$, $M_P^2 = \frac{3\lambda}{2\kappa} (A_\lambda + \frac{4}{3}\kappa v_s) \mu \sin 2\beta - 3\kappa v_s A_\kappa$. Since the NMSSM predicts one more CP-odd Higgs field than the MSSM, M_A here no longer represents the mass of one CP-odd state. Obviously, the Higgs sector of the NMSSM is quite complicated.

- After diagonalizing the mass matrix in Eq.(6), one can get the mass eigenstates of CP-even states h_i as $h_i = \sum_j V_{ij} S_j$, where V_{ij} is the element of the transition matrix satisfying $\sum_j V_{ij}^2 = 1$, and it represents the component of S_j in the physical state h_i . In the following, we assume $m_{h_3} > m_{h_2} > m_{h_1}$, and call the state whose squared component coefficient of S_2 larger than 0.5 the SM-like Higgs boson. Similarly, the mass eigenstates of the CP-odd states A_i are given by $A_i = \sum_j U_{ij} P_j$. If the lighter state A_1 satisfies $U_{11}^2 > 0.5$, we call it doublet-dominated; otherwise we call it singlet-dominated.
- Like the MSSM, the mass of the SM-like Higgs boson may be greatly changed by radiative corrections. Denoting the loop-corrected mass matrix of the CP-even states by \tilde{M}^2 , one can conclude that for $\tilde{M}_{22}^2 > \tilde{M}_{11}^2 > \tilde{M}_{33}^2$, the state h_1 corresponds to the SM-like Higgs boson, while for $\tilde{M}_{22}^2 > \tilde{M}_{33}^2 > \tilde{M}_{11}^2$, the state h_2 is the SM-like Higgs boson [?].
- Obviously, in order to get a light CP-odd Higgs boson, either M_A or M_P should be moderately small, and a large $\mathcal{M}_{P,12}^2$ can further suppress the mass of the lighter CP-odd state.

III. Numerical Results and Discussion

In this work, we first perform a comprehensive scan over the parameter space of the NMSSM by considering various experimental constraints. Then for the surviving samples we investigate the features of the light scalar. Since the NMSSM has too many free parameters, we make the following assumptions to simplify our analysis:

- First, we note that the first two generation squarks have little effect on the Higgs sector of the NMSSM, and the LHC search for SUSY particles implies that they should be heavier than 1 TeV. So we fix all soft breaking parameters (i.e., soft masses and trilinear coefficients) in this sector to be 2 TeV. We checked that our conclusions are not sensitive to this sector.
- Second, considering that the third generation squarks can significantly change the properties of the Higgs bosons, we set free all soft parameters in this sector except that we assume $m_{U_3} = m_{D_3}$ and $A_t = A_b$ to reduce the number of free parameters.
- Third, since we require the NMSSM to explain the discrepancy of the measured value of the muon anomalous magnetic moment from its SM prediction, i.e., $a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (28.7 \pm 8.0) \times 10^{-10}$ [?], we assume all soft breaking parameters in the slepton sector to take a common value $m_{\tilde{l}}$ and treat $m_{\tilde{l}}$ as a free parameter.
- Finally, we note that our results are not sensitive to the gluino mass, so we fix it at 2 TeV. We also assume the grand unification relation $3M_1/5\alpha_1 = M_2/\alpha_2$ for electroweak gaugino masses.

With the above assumptions, we use the package NMSSMTools-4.0.0 [?] to scan randomly the free parameters of the model in the following ranges:

$$0.1 \leq \lambda, \kappa \leq 0.8, \quad 1 \text{ GeV} \leq M_A, M_P \leq 2 \text{ TeV}, \quad 1 \leq \tan \beta \leq 30,$$

$$100 \text{ GeV} \leq \mu, M_2, m_{\tilde{t}} \leq 1 \text{ TeV}, \quad |A_t| \leq 5 \text{ TeV}, \quad 100 \text{ GeV} \leq M_{Q_3}, M_{U_3} \leq 2 \text{ TeV}.$$

In our scan, we only keep the samples that predict a SM-like Higgs boson h with mass around 125 GeV (e.g., $123 \text{ GeV} \leq m_h \leq 127 \text{ GeV}$) along with a light neutral Higgs scalar (CP-even or CP-odd) with mass less than $m_h/2$, and meanwhile satisfy the following constraints:

- (1) All the constraints implemented in the package NMSSMTools-4.0.0. These constraints are from vacuum stability, the LEP search for sparticles (including lower bounds on various sparticle masses and upper bounds on neutralino pair production rates), the Z -boson invisible decay, the Υ decay into a light scalar plus one photon [?], B -physics observables (such as the branching ratios for $B \rightarrow X_s \gamma$, $B_s \rightarrow \mu^+ \mu^-$ and $B^+ \rightarrow \tau^+ \nu_\tau$, and the mass differences ΔM_d and ΔM_s) [?, ?, ?], the discrepancy of the muon anomalous magnetic moment, the dark matter relic density [?], and the XENON100 (2012) limits on the scattering rate of dark matter with nucleons [?, ?]. In imposing the constraint from a certain observable which has an experimental central value, we use its latest measured result and require the NMSSM to explain the result at 2σ level.
- (2) The constraints from the search for Higgs bosons at LEP, the Tevatron and the LHC. We implement these constraints using the package HiggsBounds-4.0.0 [?].
- (3) Indirect constraints from electroweak precision observables such as ρ_ℓ , $\sin^2 \theta_{\text{eff}}^\ell$ and M_W , or their combinations ϵ_i ($i = 1, 2, 3$) [?]. We require ϵ_i to be compatible with the LEP/SLD data at 95% confidence level [?]. We also require R_b in the NMSSM to be within the 2σ range of its experimental value. We compute these observables with the formulae presented in [?].

For each surviving sample, we further perform a fit using the latest Higgs data presented at the Rencontres de Moriond 2013. These data include the measured signal strengths for $\gamma\gamma$, ZZ^* , WW^* , $b\bar{b}$ and $\tau\bar{\tau}$ channels, and their explicit values are summarized in Fig. 2 of [?] for the ATLAS results, in Fig. 4 of [?] for the CMS results, and in Fig. 15 of [?] for the CDF+D0 results. We use a total of 24 sets of experimental data, with 22 of them corresponding to measured signal strengths and the other 2 being the combined mass of the Higgs boson reported by the ATLAS and CMS collaborations respectively. As in our previous works [?], we use the method first introduced in [?] to perform the fit, properly

considering the correlations of the data as in [?, ?]. As will be shown below, the χ^2 values in the fit vary from several tens to 170 for the surviving samples of the scan, and in optimal cases it may be as low as about 17. In our discussion, we pay particular attention to the surviving samples with $\chi^2 \leq 26$. These samples can be used to obtain the 3σ range of any observable \mathcal{O}_i once they are projected on the \mathcal{O}_i versus $\delta\chi^2$ plane, so hereafter we call them 3σ samples. Obviously, the 3σ samples are a subset of the surviving samples.

For each surviving sample, we also calculate the tuning extent defined by $\Delta = \text{Max}\{|\partial \ln m_Z / \partial \ln p_{\text{SUSY}}|\}$ [?], where p_{SUSY} denotes a soft breaking parameter at the SUSY scale (fixed at 2 TeV in this work). For the convenience of our analysis, we categorize the surviving samples into three cases according to the nature of the light Higgs scalar (note that a doublet-dominated h_1 is ruled out by the LEP search for Higgs bosons and $B \rightarrow X_s \gamma$):

- **Case A:** The light scalar is the CP-odd A_1 ($A_1 < h/2$) and it is singlet-dominated.
- **Case B:** The light scalar is the CP-odd A_1 ($A_1 < h/2$) and it is doublet-dominated.
- **Case C:** The light scalar is the CP-even h_1 ($h_1 < h/2$) and it is singlet-dominated.

[TABLE:N]

A. Case A ($A_1 < h/2$, singlet-dominated)

In Case A, the SM-like 125 GeV Higgs boson h may be either the lightest CP-even state h_1 or the next-to-lightest CP-even state h_2 . In Table I, we list the favored parameter ranges for all the surviving samples and the 3σ samples in Case A. We note that in this case the parameter $\tan\beta$ can be very large [?]. This table indicates that in each scenario the ranges of some parameters for the surviving samples are significantly wider than the corresponding 3σ samples. Furthermore, we compare the number of all surviving samples with the 3σ samples and find that the latter is at most one fifth of the former. These facts reflect that the current LHC Higgs data can severely constrain the parameter space of the NMSSM.

This table also indicates that, in order to predict a light singlet-dominated A_1 , the value of M_P should be less than 160 GeV. From analyzing the surviving samples, we find two features for Case A. First, the χ^2 value in the fit of the Higgs data may be rather low with $\chi^2_{\text{min}} \approx 17$ for 24 sets of experimental data, and it increases as the branching ratio of the exotic decay $h \rightarrow A_1 A_1$ becomes larger. This feature is exhibited in [Figure 1: see original paper]. This figure reflects the fact that the NMSSM can explain the Higgs data quite well given that $\text{Br}(h \rightarrow A_1 A_1)$ is moderately small. It also reveals that, without the Higgs data, $\text{Br}(h \rightarrow A_1 A_1)$ can exceed 90%, while after considering the constraints from the Higgs data at 3σ , it is less than 28% for h_1 being the SM-like Higgs (the “SM-like h_1 ” scenario) and 34% for h_2 being the SM-like Higgs (the “SM-

like h_2 ” scenario). This conclusion is independent of the value of m_{A_1} . As a comparison, we checked that for any exotic decays of the Higgs boson (with SM Higgs couplings to fermions and gauge bosons), the Higgs data restrict the exotic decay branching ratio to be less than 28% at the 3σ level. This result can be seen as an update of that in [?] after the Rencontres de Moriond 2013, but differs from those in [?] due to different data treatments.

The second feature is that the tuning extent Δ can be less than 10, reflecting that the NMSSM is quite natural. This feature is shown in [Figure 2: see original paper]. Compared with the “SM-like h_1 ” scenario, a lower Δ is predicted for the “SM-like h_2 ” scenario. This is because m_Z is sensitive to the value of μ (note the tree-level relation $m_Z^2 = 2(m_{H_u}^2 \tan^2 \beta - m_{H_d}^2)/(\tan^2 \beta - 1) - 2\mu^2$ with m_{H_u} and m_{H_d} representing the weak-scale soft SUSY breaking masses of the Higgs fields [?]), and for the “SM-like h_2 ” scenario a lower μ is preferred.

Additional points should be noted about Case A. First, the “SM-like h_1 ” scenario and the “SM-like h_2 ” scenario actually correspond to two distinct parameter regions of the NMSSM. To illustrate this point, we consider the parameters λ and κ and project the 3σ samples on the λ versus κ plane in [Figure 3: see original paper]. This figure indicates that, in contrast with the fact that most samples for the “SM-like h_1 ” scenario satisfy $\lambda \lesssim \kappa$, the “SM-like h_2 ” scenario is characterized by $\lambda \gtrsim \kappa$. The reason is that as far as the 3σ samples are concerned, \mathcal{M}_{33}^2 in Eq.(6) is approximated by $\mathcal{M}_{33}^2 \approx 4(\kappa v_s)^2 = 4(\kappa\mu/\lambda)^2$. Given $\mu > 100$ GeV as required by the LEP bound on chargino mass, λ should be much larger than κ to guarantee $\mathcal{M}_{22}^2 > \mathcal{M}_{33}^2 > 0$, which is a necessary condition to predict $h_2 \approx 125$ GeV.

Second, A_1 should be highly singlet-dominated and the properties of the SM-like Higgs boson for the “SM-like h_1 ” scenario and the “SM-like h_2 ” scenario may be quite different. To exhibit this conclusion, we show in [Figure 4: see original paper] the singlet component coefficients of A_1 and h for the 3σ samples. This figure indicates that the singlet component coefficient of A_1 (i.e., U_{12}) is larger than 0.99 for both scenarios. It also indicates that the SM-like h_1 has a very small singlet component (i.e., $V_{13} \sim 1\%$) while the SM-like h_2 may have a sizable singlet component with the corresponding coefficient V_{23} reaching 0.7. In fact, we checked that the $h\bar{b}b$ coupling is approximately equal to the SM value for the “SM-like h_1 ” scenario and may be much smaller for the “SM-like h_2 ” scenario. Due to the singlet nature of A_1 , the hA_1A_1 interaction should be very weak, but on the other hand, since the total width of the SM-like Higgs boson is also small (about 4 MeV in the SM), $\text{Br}(h \rightarrow A_1A_1)$ may still be sizable.

Third, since we require the theory to predict a light scalar while simultaneously satisfying various experimental constraints, some parameters are limited to certain narrow ranges or correlate with other parameters, as shown in [Figure 5: see original paper]. The left panel indicates that in the “SM-like h_1 ” scenario we have $A_\kappa \approx 0$, and the right panel shows that in the “SM-like h_2 ” scenario we have $M_A \sin 2\beta/\mu \approx 2$. We checked that a very small A_κ is needed to predict a light singlet-dominated A_1 , while the correlation $M_A \sin 2\beta/\mu \approx 2$ is characteristic in

predicting $h_2 \approx 125$ GeV, as observed in [?].

B. Case B ($A_1 < h/2$, doublet-dominated)

As in Case A, the SM-like 125 GeV Higgs boson in Case B may be either h_1 or h_2 , and the corresponding favored parameter regions of the surviving samples are shown in Table I. We emphasize that the parameter M_A in this table is defined at the scale of 2 TeV, and in calculating the CP-odd Higgs boson masses by NMSSMTools we use the value at the mass scale of the third generation squarks which can be obtained by the renormalization group equation. Moreover, we checked that the surviving samples are characterized by a relatively large matrix element $\mathcal{M}_{P,12}^2$ in Eq.(7). This is helpful to suppress the mass of A_1 .

In [Figure 6: see original paper] we project the surviving samples on the plane of m_{A_1} versus $\text{Br}(h \rightarrow A_1 A_1)$ and the plane of χ^2 versus $\text{Br}(h \rightarrow A_1 A_1)$ respectively. This figure indicates that in the “SM-like h_1 ” scenario, the branching ratio of the decay $h \rightarrow A_1 A_1$ is always larger than 60% so that $\chi^2 > 100$, while in the “SM-like h_2 ” scenario, although the rate of the decay $h \rightarrow A_1 A_1$ may be small, e.g., about 10% for $m_{A_1} \approx 55$ GeV, the χ^2 value is still larger than 100. The reason is that the $hb\bar{b}$ coupling in the “SM-like h_2 ” scenario is at least one times larger than its SM prediction. In fact, the “SM-like h_2 ” scenario in Case B actually corresponds to a non-decoupling region of the NMSSM since the mass of the charged Higgs boson varies from 130 GeV to 150 GeV. Consequently, the properties of the SM-like Higgs boson are expected to deviate greatly from the SM prediction. To summarize, [Figure 6: see original paper] indicates that Case B is actually disfavored by the fit of the Higgs data (no 3σ samples exist).

Also as in Case A, a strong correlation between some parameters is needed to predict a doublet-dominated A_1 . In [Figure 7: see original paper] we show the correlation between the parameter A_λ and the parameter $\kappa\mu/\lambda$ for the surviving samples in this case. From Eq.(7), one can infer that such a correlation is needed to reduce the value of M_A .

C. Case C ($h_1 < h/2$, singlet-dominated)

In Case C the SM-like Higgs boson is the next-to-lightest CP-even state h_2 , and due to the strong constraints from the LEP search for Higgs bosons and $B \rightarrow X_s \gamma$, a doublet-dominated h_1 is actually ruled out. In Table I, we show the favored parameter regions for the surviving samples and also the 3σ samples. As pointed out in [?], in order to predict a light h_1 , one only needs to tune the value of A_κ when other parameters are fixed. So, except for the correlation shown in the left panel of [Figure 5: see original paper] and the condition $\kappa < \lambda$ which is necessary to predict $m_{h_2} \approx 125$ GeV, there are no other special features for the parameters of Case C.

Like the “SM-like h_2 ” scenario in Case A, the χ^2 value and the parameter Δ may be as low as about 17 and 10 respectively. These features are presented in [Figure 8: see original paper] and [Figure 9: see original paper]. Regarding Case

C, one should note that the branching ratio of $h \rightarrow h_1 h_1$ should be less than 28% at the 3σ level (see [Figure 8: see original paper]). One should also note that, as shown in [Figure 10: see original paper] where the singlet component coefficients of h_1 and h_2 are presented for the 3σ samples, h_1 in Case C is highly singlet-dominated while h_2 is highly doublet-dominated.

In summary, one may conclude that current experiments still allow for the existence of a light scalar (CP-even or CP-odd), but the LHC Higgs data require it to be highly singlet-dominated. Moreover, in the NMSSM either h_1 or h_2 may play the role of the SM-like Higgs boson h , and for each case the properties of h may be quite different.

IV. Detection of a Light Scalar at Future Colliders

As discussed in the preceding section, if there exists a light scalar with mass lighter than half the SM-like Higgs boson mass in the NMSSM, it should be highly singlet-dominated. Consequently, its interactions with the fermions and gauge bosons in the SM are very weak, which implies that this scalar is difficult to search for at colliders. But on the other hand, although the interaction of this scalar with the SM-like Higgs boson is also weak, the rate of h decay into the scalar pair may still be sizable due to the narrow width of h . This fact motivates us to scrutinize the decay products of h to search for the light scalar. In the following, we take Case A as an example to discuss the prospects of such a search via different processes at colliders.

First, we consider the light A_1 coming from Z decay. For this purpose, we calculate the branching ratios of the rare decays $Z \rightarrow A_1 b\bar{b}$ and $Z \rightarrow A_1 \gamma$ with the code from our previous work [?] and show these ratios in [Figure 11: see original paper]. This figure indicates that, as far as the 3σ samples in Case A are concerned, the ratios are at most 10^{-8} and 10^{-12} , respectively. Since the dominant decay product of A_1 is $b\bar{b}$ with a branching ratio of about 90%, the main signals of the decays are $b\bar{b}b\bar{b}$ and $b\bar{b}\gamma$, respectively. Compared with the LEP uncertainties on these signals, we learn that the ratios are at least 10^{-4} lower than the LEP sensitivity [?].

Second, we consider the hA_1 associated production at an electron-positron collider with $\sqrt{s} = 250$ GeV. In [Figure 12: see original paper] we show the production rate as a function of m_{A_1} . Obviously, since the rate is maximally of order 10^{-3} fb, this associated production process can hardly be utilized to search for the scalar.

Next we investigate the possibility of searching for A_1 at the LHC via the decay $h \rightarrow A_1 A_1 \rightarrow 4b$. Such an issue has been discussed in [?, ?] and it was found that the process $pp \rightarrow Vh \rightarrow \ell + 4b + X$ ($V = W, Z$, ℓ denotes one lepton and X denotes anything) is well suited for such a search. In this work, we fix $m_h = 125$ GeV and perform an analysis as in [?]. The signal contains at least one isolated lepton, e or μ , and exactly 4 b -tagged jets. The corresponding backgrounds mainly come from $t\bar{t}$ production with one top quark

decaying hadronically and the other decaying semi-leptonically, $t\bar{t}b\bar{b}$ production with some of the top quark decay products missed, $t\bar{t}c\bar{c}$ production with charm quark jets mistagged as bottom quark jets, and also $W/Z + 4b$ production processes.

In our simulation, the signal and background processes are modeled with MadGraph 5 [?], which includes Pythia 6.4 [?] for initial and final state radiation, parton shower and hadronization, and passes through the fast detector simulation with DELPHES [?]. Jets are reconstructed with FastJet [?, ?] using the anti- k_T algorithm with a distance parameter of 0.5. The cuts we consider are:

- The basic cuts: $p_T(j) \geq 15$ GeV, $|\eta(j)| \leq 2.5$, $p_T(\ell) \geq 15$ GeV, $|\eta(\ell)| \leq 2.5$, $\Delta R(b, b) \geq 0.4$, $\Delta R(b, \ell) \geq 0.4$, where p_T denotes the transverse momentum, η represents pseudorapidity, and $\Delta R(b, j) = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ is the angular separation of the b -jet and the particle j ($j = b, \ell$).
- $|M_{4b} - 115| \leq 15$ GeV with M_{4b} denoting the invariant mass of the four bottom quarks. This cut is motivated by the fact that the four bottom quarks originate from the SM-like Higgs boson decay, and due to possible momentum missing in jet reconstruction, M_{4b} is peaked at about 115 GeV instead of at the Higgs boson mass [?].

Moreover, in order to obtain a realistic estimation of the signal and backgrounds, we assume a b -tagging efficiency of 70% for a bottom quark jet and a mis-tagging probability of 5% (1%) for a charm quark jet (light quark or gluon jet).

Noting that the signal rate after the cuts depends only on an overall scaling factor $C_{4b}^2 = (g_{\text{NMSSM}}^{Vh}/g_{\text{SM}}^{Vh})^2 \times \text{Br}(h \rightarrow A_1 A_1) \times (\text{Br}(A_1 \rightarrow b\bar{b}))^2$, which determines the cross section of the process $pp \rightarrow Vh \rightarrow V4b$ at the LHC, and the mass of A_1 which determines the cut efficiency, we fix $m_{A_1} = 45$ GeV and $C_{4b}^2 = 0.33$, and illustrate the distributions of M_{4b} for both the signal and various backgrounds in [Figure 13: see original paper]. We also list the rates of the signal and the backgrounds after different cuts in Table II. These results indicate that the M_{4b} cut is very efficient in suppressing the backgrounds, and also that the $t\bar{t}$ background is still dominant over other backgrounds after the cut. Moreover, for the benchmark point we considered, we estimate that its significance S/\sqrt{B} is about 6.37 for an integrated luminosity of 300 fb^{-1} .

In order to exhibit the capability of the LHC in the A_1 search, in [Figure 14: see original paper] we plot the 3σ samples together with the significance curves of $S/\sqrt{B} = 2, 3, 5$ for a luminosity of 300 fb^{-1} on the m_{A_1} versus C_{4b}^2 plane. This figure shows that in order to discover the light scalar, C_{4b}^2 should be larger than 1 for $m_{A_1} \lesssim 25$ GeV, and with increasing m_{A_1} the requirement decreases to 0.2 for $m_{A_1} = 60$ GeV. We can also see that nearly all of the 3σ samples in the two scenarios are under the $S/\sqrt{B} = 5$ curve, which means that in order to discover the light scalar a luminosity over 300 fb^{-1} is needed.

Compared with the simulation result in [?], we note our significance is much

lower. The reason is that the authors of [?] performed the simulation at parton level, while in our analysis we considered initial and final state radiation, parton shower and hadronization effects with Pythia, detector effects with DELPHES, and jet reconstruction with FastJet. Consequently, the M_{4b} distribution of the $t\bar{t}$ production moves towards the lower end so that the $t\bar{t}$ production is still the dominant background after the cuts. This is quite different from the results of [?] where the main background comes from $t\bar{t}b\bar{b}$ production. Another consequence of our treatment is that jet reconstruction can hurt both the signal and the backgrounds greatly, especially for our case where the signal contains exactly four b -jets. We checked that if we perform the simulation at parton level as in [?], we can reproduce its results.

Finally, since the properties of h can be precisely measured through the Zh associated production at an electron-positron collider, we also calculate the cross section of the process $e^+e^- \rightarrow Zh \rightarrow Z4b$ for collision energies $\sqrt{s} = 250$ GeV and 300 GeV respectively. The results are shown in [Figure 15: see original paper]. This figure indicates that, as far as the 3σ samples in Case A are concerned, the rate can be as large as 56 fb for $\sqrt{s} = 250$ GeV. Compared with the same final state at the LHC with $\sqrt{s} = 14$ TeV, although such a production rate is only about one fourth, the signal is free of the backgrounds listed in Table II. So a rather low production rate at an electron-positron collider may still lead to A_1 discovery. We checked that a production rate over 10 fb corresponds to $C_{4b}^2 > 0.04$ (such a small C_{4b}^2 is not accessible at the LHC for 300 fb^{-1} integrated luminosity). [Figure 15: see original paper] also indicates that, since the Zh associated production is an s -channel process, the signal rate decreases as the collision energy increases.

V. Conclusion

In the NMSSM, due to the introduction of one new gauge singlet Higgs field, one of the neutral Higgs scalars (CP-even or CP-odd) may be lighter than half the SM-like Higgs boson. In this case, the SM-like Higgs boson h can decay into the scalar pair and consequently the visible $\gamma\gamma$ and ZZ^* signal rates at the LHC will be suppressed. In this work, we examined the constraints of the latest LHC Higgs data on such a possibility. First, we comprehensively scanned the parameter space of the NMSSM by considering various experimental constraints. Then we focused on the surviving samples which predict a light scalar. According to the properties of the scalar, we categorized the samples into three case classes: Case A ($A_1 < h/2$, singlet-dominated), Case B ($A_1 < h/2$, doublet-dominated) and Case C ($h_1 < h/2$, singlet-dominated). For the surviving samples we performed a fit using the latest LHC Higgs data. We found that the Higgs data can severely constrain the parameter space; for example, for Case A and Case C, less than one fifth of the surviving samples are allowed by the Higgs data at the 3σ level, and for Case B all samples are actually ruled out. We further focused on the 3σ samples allowed by the Higgs data and analyzed the properties of the light scalar, including its favored parameter region, its

composition, and the ratio of h decay into the scalar pair. Finally, we examined the detection of such a scalar at future colliders. From our analysis we obtained the following observations: (i) Without the LHC Higgs data, the light Higgs boson A_1 can be either singlet-dominated or doublet-dominated; while after considering the constraints from the Higgs data, it should be highly singlet-dominated. (ii) In the “SM-like h_1 ” and “SM-like h_2 ” scenarios of Case A, the Higgs data require the branching ratio of $h \rightarrow A_1 A_1$ to be less than 28% and 34% respectively; while in the “SM-like h_2 ” scenario of Case C, the Higgs data require the ratio of $h \rightarrow h_1 h_1$ to be less than 28%. (iii) An efficient way at the LHC to detect the light scalar is through the Vh ($V = W, Z$) associated production with h decaying exotically into four bottom quarks. A detailed Monte Carlo simulation indicates that, if the branching ratio of the exotic decay is less than 30%, more than 300 fb^{-1} luminosity is needed to discover the scalar. At a future electron-positron collider with $\sqrt{s} \gtrsim 250 \text{ GeV}$, the capability to detect the light scalar may be greatly improved by looking for the process $e^+ e^- \rightarrow Zh \rightarrow ZA_1 A_1 \rightarrow Z4b$.

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