NMSSM extended with vectorlike particles and the diphoton excess at the LHC

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We investigate the parameter space of a model that extends to the next to minimal supersymmetric standard model with the vectorlike particles [Y.-L. Tang, Phys. Rev. D **90**, 075020 (2014)]. We find that the $10 + \overline{10}$ model can explain the possible diphoton excess recently revealed by the ATLAS and CMS collaborations, although the predicted signal strength is a little smaller than the observed one.

I. INTRODUCTION

Recently, both the ATLAS and CMS collaborations probed the possible diphoton resonance near $m_{\gamma\gamma} = 750$ GeV [1,2]. Regardless of the insufficient significance of the data at present, theoretical efforts have been made [3–107] and perhaps the most straightforward approach is to introduce a scalar field together with some additional vectorlike (VL) particles. Just similar to the production of the standard model (SM)-like Higgs boson, the exotic scalar particle is produced through the gluon-gluon fusion process induced by the vectorlike quark loops, and subsequently decays into gamma-gamma final states induced by the vectorlike particle loops. However, as for many specific models, it is fairly difficult to enhance the signal strength of the diphoton channel up to ∼10 fb, which competes at least with the digluon, $Z\gamma$, and other tree-level ZZ, W^+W^-, $h_{SM}h_{SM}$ decay channels. Sometimes other fermionic final state channels, e.g., $t\bar{t}$, $b\bar{b}$, may also dominate the total width. Symmetries are sometimes utilized in order to forbid some final states. For example, ignoring the CP-violation effects, if the exotic scalar particle A is CP odd, its decay to $h_{SM}h_{SM}$ is forbidden. Furthermore, if A does not carry the $U(1)_Y \times SU(2)_L \times SU(3)_C$ quantum charges, its decays to ZZ, W^+W^- are eliminated at tree level as well. Additionally, decays into standard model fermions need to be further taken care of. However, in some specific models, there are quite a number of exotic fields, which need to be examined carefully.

Rather than building new models specifically for explaining the possible 750 GeV resonance, it is interesting to investigate through the existing models motivated by other problems. Supersymmetric models (for a review, see [108]) can solve the hierarchy problem by adding each particle with a superpartner, which cancels the quadratic divergences in the Higgs self-energy diagrams. Unfortunately, within the framework of the minimal supersymmetric standard model, explaining the possible 750 GeV resonance is far from possible. However, in Ref. [109], one of the authors proposed a supersymmetric model that combined the next to minimal supersymmetric standard model (NMSSM) (for reviews, see [108,110]) together with the VL particles (for examples, see [111–129]). In this model, VL masses originate from the vacuum expectation value (VEV) of the singlet Higgs field, which offers a possible dynamical explanation to the origin of VL mass terms. Vectorlike particles contribute to the Higgs masses via the loop diagrams. On the other hand, extra Yukawa couplings adjust the trajectories of the renormalization group (RG) flow of the gauge coupling constants, helping the interactions to unify. In order not to bother the unification of the gauge coupling constants, which is an important feature of the supersymmetric models, complete $SU(5)$ multiplets are introduced. In Ref. [109], we discussed only the $5 + \overline{5}$, $10 + \overline{10}$, and $5 + \overline{5} + 10 + \overline{10}$ cases. This model contains exactly an exotic scalar field together with some VL particles that couple strongly with the scalar field. However, in order not to counter the Landau pole below the unification scale, values of the Yukawa coupling constants are limited, resulting in a constraint of the $\gamma\gamma$ signal strength. In the following, we go through the parameter space of this model and show that the $10 + \overline{10}$ case provides a possible explanation to the diphoton excess, although the final signal strength seems to be a little bit smaller than the observed central value ∼10 fb. In fact one needs more data

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to determine the true value of the signal strength. Historically, there are precedents that the best-fitted experimental diphoton signal strength exceeds the predicted values [130,131].

II. THE MODEL AND SOME CONVENTIONS

Since this model is based on the NMSSM, we write down the pure NMSSM part of the superpotential and the supersymmetry soft breaking terms,

$$W_{\text{NMSSM}} = \lambda H_u H_d S + \frac{\kappa}{3} S^3 + y_t Q_3 H_u U_3, \quad (1)$$

$$\begin{aligned}
V_{\text{NMSSM}}^{\text{soft}} &= m_{Hu}^2 |\tilde{H}_u|^2 + m_{Hd}^2 |\tilde{H}_d|^2 + M_S^2 |\tilde{S}|^2 \\
&+ \left(\lambda A_\lambda \tilde{H}_u \tilde{H}_d \tilde{S} + \frac{1}{3} \kappa A_\kappa \tilde{S}^3 + y_t A_{y_t} \tilde{Q}_3 \tilde{H}_u \tilde{U}_3 \right. \\
&\left. + \text{H.c.} \right),
\end{aligned} \quad (2)$$

where $H_{u,d}$ are the up- and down-type Higgs doublet. S is the $U(1)_Y \times SU(2)_L \times SU(3)_C$ singlet Higgs superfield. Here we only show the couplings involving the top quark due to the relatively large coupling constant.

If we extend the NMSSM with the vectorlike particles, we need to introduce pairs of the vectorlike leptonic doublets L, $\overline{L}$, the vectorlike down-type quark singlets D, $\overline{D}$, the vectorlike quark doublets Q, $\overline{Q}$, the vectorlike up-type quark singlets U, $\overline{U}$, and the vectorlike charged lepton singlet E, $\overline{E}$. Their quantum numbers are listed in Table I of Ref. [109]. In this paper, we only discuss the $5 + \overline{5}$ model and the $10 + \overline{10}$ model. Their superpotentials and supersymmetry soft breaking terms are listed below,

$$W_{5+\overline{5}} = \lambda_D \overline{D} D S + \lambda_L \overline{L} L S, \quad (3)$$

$$\begin{aligned}
V_{5+\overline{5}}^{\text{soft}} &= m_D^2 (\tilde{D} \tilde{D}^\dagger + \tilde{\overline{D}} \tilde{\overline{D}}^\dagger) + m_L^2 (\tilde{L} \tilde{L}^\dagger + \tilde{\overline{L}} \tilde{\overline{L}}^\dagger) \\
&+ (\lambda_D A_{\lambda_D} \tilde{\overline{D}} \tilde{D} \tilde{S} + \lambda_L A_{\lambda_L} \tilde{\overline{L}} \tilde{L} S + \text{H.c.}), \quad (4)
\end{aligned}$$

and

$$\begin{aligned}
W_{10+\overline{10}} &= \lambda_Q \overline{Q} Q S + \lambda_U \overline{U} U S + \lambda_E \overline{E} E S + y_U Q H_u U \\
&+ y_{\overline{U}} \overline{Q} H_d \overline{U}, \quad (5)
\end{aligned}$$

$$\begin{aligned}
V_{10+\overline{10}}^{\text{soft}} &= m_Q^2 (Q Q^\dagger + U U^\dagger) + m_E^2 E E^\dagger + (A_{\lambda_Q} \lambda_Q \tilde{\overline{Q}} \tilde{Q} \tilde{S} \\
&+ A_{\lambda_U} \lambda_U \tilde{\overline{U}} \tilde{U} \tilde{S} + A_{\lambda_E} \lambda_E \tilde{\overline{E}} \tilde{E} \tilde{S} + A_{y_U} y_U \tilde{Q} \tilde{H}_u \tilde{U} \\
&+ A_{y_{\overline{U}}} y_{\overline{U}} \tilde{\overline{Q}} \tilde{H}_d \tilde{\overline{U}} + \text{H.c.}). \quad (6)
\end{aligned}$$

After the Higgs fields acquire VEVs,

$$\begin{aligned}
H_u^0 &= v_u + \frac{H_{uR} + i H_{uI}}{\sqrt{2}}, \\
H_d^0 &= v_d + \frac{H_{dR} + i H_{dI}}{\sqrt{2}}, \\
S &= v_s + \frac{S_R + i S_I}{\sqrt{2}}, \quad (7)
\end{aligned}$$

we acquire three CP-even Higgs fields,

$$h_i = S_{i1} H_{uR} + S_{i2} H_{dR} + S_{i3} S_R, \quad (8)$$

together with the CP-odd Higgs fields,

$$\begin{aligned}
A &= \cos\beta H_{uI} + \sin\beta H_{dI}, \\
G &= -\sin\beta H_{uI} + \cos\beta H_{dI}, \quad (9)
\end{aligned}$$

and

$$\begin{aligned}
a_1 &= P_{11} A + P_{12} S_I, \\
a_2 &= P_{21} A + P_{22} S_I, \quad (10)
\end{aligned}$$

where S_{ij}, P_{ij} are the mixing matrix elements, $\tan\beta = \frac{v_u}{v_d}$, and G is the Goldstone state to be rotated away.

III. THE LHC DIPHOTON EXCESS IN THE MODEL

In this model, it is mainly the extra quarks that contribute to the production and the decay of the 750 GeV scalar particle. The unwanted decay modes of this scalar particle should be avoided. If one of the CP-even Higgs fields, say h_2, is the 750 GeV resonance, it is difficult to avoid the large branching ratio of $h_2 \to h_{\text{SM}} + h_{\text{SM}}$; thus the diphoton rate is severely suppressed. As a result, we need to choose between a_1 and a_2. Without loss of generality, we adopt the convention that $P_{12} > P_{11}$. From (1) and (9) we know that the A couples with the top quark, and in fact, it also couples with other SM fermions then we need to choose the singletlike CP-odd Higgs boson in order to eliminate large branching ratios to the SM fermions. That is to say, without loss of generality, we can choose a_1 when $|P_{12}|$ approaches 1.

Unfortunately, the CP-odd scalar particles do not couple with the squarks, which lowers the signal strength. After integrating out all the particles in the loop, we acquire the effective operators

$$\mathcal{L}_{\text{eff}} \supset \frac{e^2}{2\Lambda_\gamma} a_1 F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{g_3^2}{2\Lambda_g} a_1 G_{\mu\nu} \tilde{G}^{\mu\nu}, \quad (11)$$

where e and g_3 are the electromagnetic and the QCD coupling constants. $\tilde{F}, \tilde{G}_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\lambda\rho} F, G^{\lambda\rho}$. To calculate the Λ_g and the Λ_γ, we use the following formulas [132,133],

$$\frac{1}{\Lambda_g} = \frac{1}{4\pi^2 M_{a_1}} \sum_i \frac{1}{2} \frac{1}{\sqrt{\tau_i}} y_{fi} \arcsin^2(\sqrt{\tau_i}),$$

$$\frac{1}{\Lambda_\gamma} = \frac{1}{4\pi^2 M_{a_1}} \sum_i N_{ci} Q_{fi}^2 \frac{1}{\sqrt{\tau_i}} y_{fi} \arcsin^2(\sqrt{\tau_i}), \qquad (12)$$

where N_{ci} equals 1 or 3 for the $SU(3)_c$ singlet or triplet of the Dirac particle i, Q_{fi} is the charge number, and $\tau_i = \frac{M_{a_1}^2}{4M_i^2}$, where M_i is the mass of the Dirac particle i. The branching widths of the $a_1 \to gg$ and the $a_1 \to \gamma\gamma$ are given by

$$\Gamma(a_1 \to gg) = 8\pi\alpha_3^2 \frac{M_{a_1}^3}{\Lambda_g^2},$$

$$\Gamma(a_1 \to \gamma\gamma) = \pi\alpha^2 \frac{M_{a_1}^3}{\Lambda_g^2}, \qquad (13)$$

where $\alpha_3 = \frac{g_3^2}{4\pi}$, and $\alpha = \frac{e^2}{4\pi}$ is the fine-structure constant.

A. The $5 + \bar{5}$ model

For the $5 + \bar{5}$ model, the loop diagrams involve $H_{u,d}$, L, $\bar{L}$, D, and $\bar{D}$. In order to avoid the Landau pole before the grand unification scale, the value of the Yukawa coupling constants is limited. We adopt the benchmark point

$$\lambda_D(Q_{\text{GUT}}) = 3,$$

$$\lambda_L(Q_{\text{GUT}}) = 1.7,$$

$$\lambda(Q_{\text{GUT}}) = 3.0,$$

$$Q_{\text{GUT}} = 1.8 \times 10^{16}, \qquad (14)$$

as the boundary condition, and do the RG running down to the scale $Q = 1$ TeV with the formula listed in the appendix of Ref. [109], then

$$\lambda_D(1 \text{ TeV}) = 0.91,$$

$$\lambda_L(1 \text{ TeV}) = 0.44,$$

$$\lambda(1 \text{ TeV}) = 0.59. \qquad (15)$$

We calculate the cross sections and the decay widths by the MadGraph5_aMC@NLO v2.3.3. We adopt $v_s = 0.9$ TeV during the numerical calculation, and then we obtain $\sigma_{pp \to a_1} = 17.7$ fb, $\Gamma(a_1 \to gg) = 2.47 \times 10^{-3}$ GeV, and $\Gamma(a_1 \to \gamma\gamma) = 8.84 \times 10^{-5}$ GeV. Even if there are no other decay modes, the signal strength $\sigma_{pp \to a_1} \times \text{Br}(a_1 \to \gamma\gamma) = 0.63$ fb, which is far from explaining the observed excess.

One might think about adding several more copies of the $5 + \bar{5}$ multiplets. In order not to encounter the Landau pole until the gauge coupling constants unify, only a limited number of copies can be added. From Ref. [134], we learn that

$$N_{5+\bar{5}} \lesssim 4. \qquad (16)$$

For example, naively speaking, three copies of $D + \bar{D}$ might enhance the signal strength by a factor of about 9. However, due to the interaction terms between different couplings in the β-function, generally the Yukawa coupling constants near the TeV scale are further lowered, and what is worse, the λ_L usually becomes so small that it is difficult to keep the masses of the vectorlike leptons above $\sim(750/2)$ GeV, which opens the $a_1 \to \bar{L}L$ channel and severely suppresses the branching ratio of the $a_1 \to \gamma\gamma$ channel.

B. The $10 + \overline{10}$ model

For the $10 + \overline{10}$ model, the loop diagrams involve Q, $\bar{Q}$, U, $\bar{U}$, E, $\bar{E}$, and $H_{u,d}$. We adopt the boundary condition

$$\lambda_Q(Q_{\text{GUT}}) = 0.5,$$

$$\lambda_U(Q_{\text{GUT}}) = 0.52,$$

$$\lambda_E(Q_{\text{GUT}}) = 1.1,$$

$$\lambda(Q_{\text{GUT}}) = 1.6,$$

$$\kappa(Q_{\text{GUT}}) = 3.5,$$

$$Q_{\text{GUT}} = 3.6 \times 10^{16} \qquad (17)$$

as our benchmark point, then at $Q = 1$ TeV,

$$\lambda_Q(1 \text{ TeV}) = 0.73,$$

$$\lambda_U(1 \text{ TeV}) = 0.58,$$

$$\lambda_E(1 \text{ TeV}) = 0.46,$$

$$\lambda(1 \text{ TeV}) = 0.56,$$

$$\kappa(Q_{1 \text{ TeV}}) = 0.30. \qquad (18)$$

Again, we adopt $v_s = 0.9$ TeV, then $\sigma_{pp \to a_1} = 186$ fb, $\Gamma(a_1 \to gg) = 0.0261$ GeV, and $\Gamma(a_1 \to \gamma\gamma) = 0.000327$ GeV. If there is no other decay mode, the signal strength $\sigma_{pp \to a_1} \times \text{Br}(a_1 \to \gamma\gamma) = 2.31$ fb.

Compared with the $5 + \bar{5}$ situation, there are more charged heavy quarks running in the loops, resulting in an enhancement of the production rate. The vectorlike D particles take the charge of $\frac{1}{3}$, but in the $10 + \overline{10}$, there are another two $\frac{2}{3}$-charged heavy quarks, which also result in the enhancement of the branching ratio of the $\gamma\gamma$ decay rate. However, due to too much influence on the trajectories of the running gauge coupling constants, there is not much room to add copies of other $SU(5)$ multiplets to further enhance the signal strength.

We should also note that if v_s is within our typical range of 700–900 GeV, the masses of the exotic quarks we introduce should lie roughly $\gtrsim 400$ GeV. According to Ref. [135], the current lower bounds on the exotic t', b'

quarks can reach about 700 GeV. However, these constraints are all based on the assumption that the exotic quarks only mix with and then decay into the third generation SM quarks. If we only let the exotic quarks mix with the first two generation SM quarks, the lower bounds can be relaxed into ∼400 GeV, which is compatible with our needed range. As for the charged exotic leptons, we can easily see that the bounds listed in Ref. [135] are far below our needed range.

IV. THE NMSSM TOLERANCE

More realistically, in the NMSSM, a_1 decays to other particles. As has been mentioned, $a_1 \to h_{SM}h_{SM}$ is forbidden due to the conservation of the CP charge. $a_1 \to a_j h_{1,2}$ is also forbidden kinematically if $m_{a_1} < m_{a_2}$. a_1 cannot decay into vectorlike particles and the Higgsinos because $2m_{Q,U,D,\cdots} > m_{a_1}$. However, in order to eliminate $a_1 \to W^+ W^-$, $a_1 \to ZZ$, $a_1 \to t\bar{t}$, $a_1 \to b\bar{b}$, …, we can only hope $|P_{11} - 1| \ll 1$ so that these channels are suppressed by the small mixings between the CP-even singletlike Higgs and the doubletlike Higgs. We define the pure NMSSM width as $\Gamma_{a_1,\text{NMSSM}}$, which only sums over all the possible decay channels of a_1 calculated without the effects of the vectorlike sectors. If $\Gamma_{a_1,\text{NMSSM}} \gg \Gamma(a_1 \to gg)$, the signal strength is highly suppressed, which of course should not be the case. In order to have a look at the $\Gamma_{a_1,\text{NMSSM}}$, we scan the NMSSM parameter

space by the NMSSMTools 4.8.2 [136–138] within this area,

$$400\,\text{GeV} < M_{1,2} < 800\,\text{GeV}, \quad M_3 = 3M_{1,2}, \quad 2 < \tan\beta < 15,$$
$$0.5 < \lambda < 0.65, \quad 0.05 < \kappa < 0.32,$$
$$400\,\text{GeV} < \mu_{\text{eff}} = \lambda v_s < 800\,\text{GeV},$$
$$400\,\text{GeV} < M_A < 1000\,\text{GeV},$$
$$700\,\text{GeV} < M_P < 800\,\text{GeV}, \quad \Omega_{\text{DM}} < 0.131, \tag{19}$$

where $M_{1,2,3}$ are the soft masses of the gauginos, M_A is the diagonal doublet CP-odd mass matrix element, and M_P is the diagonal singlet CP-odd mass matrix element. In order to forbid $a_1 \to 2h_X$, or $a_1 \to$ doubletlike neutralinos, we set the lower limit of these mass parameters as 400 GeV, which is near $\frac{750\,\text{GeV}}{2}$. The $a_1 \to$ doubletlike neutralino + singletlike neutralino can be suppressed if the singlet-doublet neutralino mixings are small. We also set the relic density of the lightest neutralino $\Omega_{\text{DM}} < 0.131$ because the dark matter might not be composed of only one component.

Vectorlike particles may modify the masses of the Higgs bosons. In this paper, we do not consider the y_U and $y_{\overline{U}}$ and set them as 0 for simplicity. Thus, only the mass of the singletlike Higgs boson receives some loop corrections. As for the $5 + \overline{5}$ model, these corrections to the mass of the CP-even singletlike Higgs are given by [109]

$$\Delta m_S^2 = \lambda_L^2 \frac{3A_{\lambda_L} v_s^2 \kappa + 4v_s^3 \kappa^2 + A_{\lambda_L} v^2 \sin\beta\cos\beta\lambda}{8\pi^2 v_s} \ln\frac{m_L^2}{Q^2}$$

$$+ 3\lambda_D^2 \frac{3A_{\lambda_D} v_s^2 \kappa + 4v_s^3 \kappa^2 + A_{\lambda_D} v^2 \sin\beta\cos\beta\lambda}{16\pi^2 v_s} \ln\frac{m_D^2}{Q^2}$$

$$+ \frac{\lambda_L^4}{48\pi^2 m_L^4} \left(-2A_{\lambda_L}^4 v_s^2 + 24A_{\lambda_L}^2 m_L^2 v_s^2 - 15A_{\lambda_L}^3 v s^3 \kappa + 90A_{\lambda_L} m_L^2 v_s^3 \kappa - 36A_{\lambda_L}^2 v_s^4 \kappa^2 \right.$$

$$+ 72m_L^2 v_s^5 \kappa^2 - 35A_{\lambda_L} v_s^5 \kappa^3 - 12v_s^6 \kappa^4 + 3A_{\lambda_L}^3 v_d v_s v_u \lambda - 18A_{\lambda_L} m_L^2 v_d v_s v_u \lambda$$

$$+ 24A_{\lambda_L}^2 v_d v_s^2 v_u \kappa\lambda - 48m_L^2 v_d v_s^2 v_u \kappa\lambda + 45A_{\lambda_L} v_d v_s^3 v_u \kappa^2\lambda + 24v_d v_s^4 v_u \kappa^3\lambda$$

$$\left. - 9A_{\lambda_L} v_d^2 v_s v_u^2 \kappa\lambda^2 - 12v_d^2 v_s^2 v_u^2 \kappa^2\lambda^2 - A_{\lambda_L} v_d^3 v_u^3 \lambda^3 + 24m_L^4 v_s^2 \ln\frac{m_L^2}{\lambda^2 v_s^2} \right)$$

$$+ \frac{\lambda_D^4}{32\pi^2 m_D^4} \left(-2A_{\lambda_D}^4 v_s^2 + 24A_{\lambda_D}^2 m_D^2 v_s^2 - 15A_{\lambda_D}^3 v s^3 \kappa + 90A_{\lambda_D} m_D^2 v_s^3 \kappa - 36A_{\lambda_D}^2 v_s^4 \kappa^2 \right.$$

$$+ 72m_D^2 v_s^5 \kappa^2 - 35A_{\lambda_D} v_s^5 \kappa^3 - 12v_s^6 \kappa^4 + 3A_{\lambda_D}^3 v_d v_s v_u \lambda - 18A_{\lambda_D} m_D^2 v_d v_s v_u \lambda$$

$$+ 24A_{\lambda_D}^2 v_d v_s^2 v_u \kappa\lambda - 48m_D^2 v_d v_s^2 v_u \kappa\lambda + 45A_{\lambda_D} v_d v_s^3 v_u \kappa^2\lambda + 24v_d v_s^4 v_u \kappa^3\lambda$$

$$\left. - 9A_{\lambda_D} v_d^2 v_s v_u^2 \kappa\lambda^2 - 12v_d^2 v_s^2 v_u^2 \kappa^2\lambda^2 - A_{\lambda_D} v_d^3 v_u^3 \lambda^3 + 24m_D^4 v_s^2 \ln\frac{m_D^2}{\lambda^2 v_s^2} \right). \tag{20}$$

The corrections to the CP-odd singletlike Higgs boson are calculated as

$$\Delta m_A^2 = \frac{1}{4\pi^2}\left[\frac{3}{8}\frac{I_{AD}}{I_D}(I_D^- - I_D^+) + \frac{1}{4}\frac{I_{AL}}{I_L}(I_L^- - I_L^+) - \frac{3}{4}\lambda_D^2(I_D^- + I_D^+) + \frac{3}{2}v_s^2\lambda_D^4\right.$$
$$-\frac{1}{2}\lambda_L^2(I_L^- + I_L^+) + v_s^2\lambda_L^4 + \frac{3}{8}\frac{I_{AD}}{I_D}\left(I_D^+\ln\left(\frac{I_D^+}{Q^2}\right) - I_D^-\ln\left(\frac{I_D^-}{Q^2}\right)\right)$$
$$+\frac{3}{4}\lambda_D^2\left(I_D^-\ln\left(\frac{I_D^-}{Q^2}\right) + I_D^+\ln\left(\frac{I_D^+}{Q^2}\right)\right) + \frac{1}{4}\frac{I_{AL}}{I_L}\left(I_L^+\ln\left(\frac{I_L^+}{Q^2}\right) - I_L^-\ln\left(\frac{I_L^-}{Q^2}\right)\right)$$
$$\frac{1}{2}\lambda_L^2\left(I_L^-\ln\left(\frac{I_L^-}{Q^2}\right) + I_L^+\ln\left(\frac{I_L^+}{Q^2}\right)\right) - \frac{3}{2}v_s^2\lambda_D^4\ln\left(\frac{v_s^2\lambda_D^2}{Q^2}\right) - v_s^2\lambda_L^4\ln\left(\frac{v_s^2\lambda_L^2}{Q^2}\right)\right],$$

(21)

where

$$I_D = |\lambda_D(A_{\lambda_D}v_s + v_s^2\kappa - v_uv_d\lambda)|,$$
$$I_L = |\lambda_L(A_{\lambda_L}v_s + v_s^2\kappa - v_uv_d\lambda)|,$$
$$I_D^+ = I_D + m_D^2 + v_s^2\lambda_D^2,$$
$$I_D^- = -I_D + m_D^2 + v_s^2\lambda_D^2,$$
$$I_L^+ = I_L + m_L^2 + v_s^2\lambda_L^2,$$
$$I_L^- = -I_L + m_L^2 + v_s^2\lambda_L^2,$$
$$I_{AD} = A_{\lambda_D}^2\lambda_D^2 + 2A_{\lambda_D}v_s\kappa\lambda_D^2 + 2v_s^2\kappa^2\lambda_D^2 + 2v_dv_u\kappa\lambda\lambda_D^2,$$
$$I_{AL} = A_{\lambda_L}^2\lambda_L^2 + 2A_{\lambda_L}v_s\kappa\lambda_L^2 + 2v_s^2\kappa^2\lambda_L^2 + 2v_dv_u\kappa\lambda\lambda_L^2.$$

(22)

The related formula in the $10 + \overline{10}$ case is too complicated to be listed in this paper. However, if we ignore all the vectorlike A-terms A_{λ_D}, A_{λ_L}, A_{λ_Q}, A_{λ_U}, A_{λ_E}, the typical corrections to the *CP*-odd singletlike Higgs boson are about a few percent, which can be ignored under the current experimental data. Therefore, during the scanning process, we ignore these corrections.

We plot the scanned points in Fig. 1. We can see that there are at least some points that can reach $\Gamma_{a_1\text{NMSSM}} \lesssim \Gamma_{10+\overline{10}}(a_1 \to gg)$, $\Gamma_{3\times(5+\bar5)}(a_1 \to gg)$, lowering the signal strength a little, so the results in Sec. III B are still not severely altered. Here we show a benchmark point,
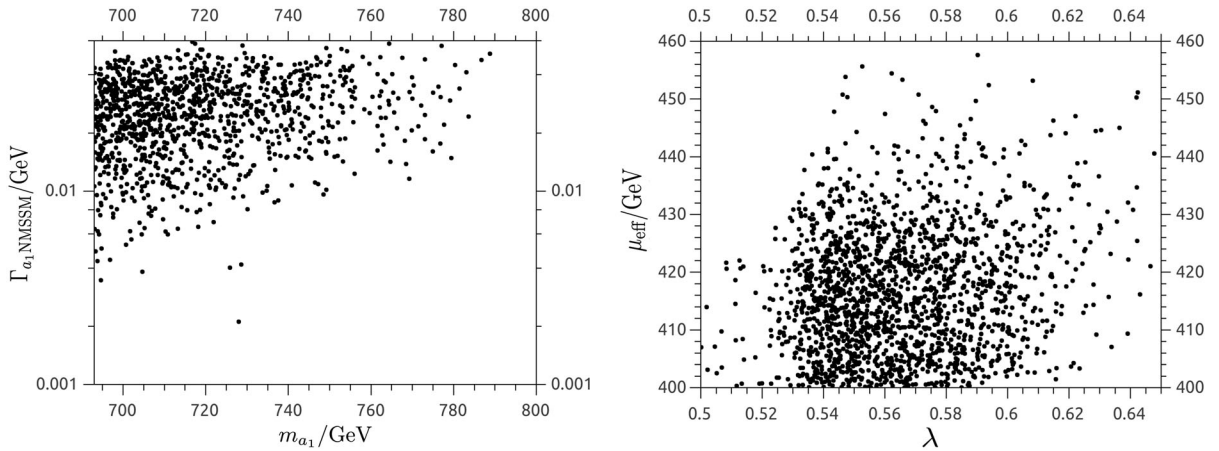

FIG. 1. The scanned points in the NMSSM parameter space, plotted on the m_{a_1}-$\Gamma_{a_1\text{NMSSM}}$ plane, and λ-μ_{eff} plane.

$$\lambda = 0.5471,$$

$$\kappa = 0.3190,$$

$$\mu_{\text{eff}} = 453.9 \text{ GeV},$$

$$\tan\beta = 2.060,$$

$$A_\lambda = 589.6 \text{ GeV},$$

$$A_\kappa = -664.5 \text{ GeV},$$

$$m_{a_1} = 728.0 \text{ GeV},$$

$$\Gamma_{a_1,\text{NMSSM}} = 0.00211 \text{ GeV}. \tag{23}$$

In this point, the values of the λ and the κ approach the values in (18), and the mass CP-odd singletlike Higgs is near 750 GeV, while its pure NMSSM width is small compared with the vectorlike particle induced one.

V. CONCLUSIONS AND DISCUSSIONS

In this paper, we find that the NMSSM with the additional $10 + \overline{10}$ vectorlike particles can explain the possible diphoton excess recently revealed by the ATLAS and CMS collaborations. From the aspect of the NMSSM, there is also enough parameter space to acquire a singletlike CP-odd Higgs with the narrow-enough $\Gamma_{a_1\text{NMSSM}}$, which is the necessary condition to account for the diphoton excess.

In Ref. [75], the authors discussed the loop induced associated W^+W^-, ZZ, $Z\gamma$ decay modes in Table III, together with the relevant experimental bound on page 2. In the NMSSM extended with the $10 + \overline{10}$ model, Q, $\overline{Q}$, U, $\overline{U}$ mainly contribute to the loop, roughly succeeded in escaping the experimental bounds. This will be tested as more and more data are collected.

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