Vacuum Stability Constraints on the Enhancement of the $h \rightarrow \gamma\gamma$ Rate in the MSSM

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Abstract

The ATLAS and CMS collaborations discovered a new boson particle. If the new boson is the Higgs boson, the diphoton signal strength is 1.5 - 1.8 times larger than the Standard Model (SM) prediction, while the $WW$ and $ZZ$ signal strength are in agreement with the SM one. In the Minimal Supersymmetric Standard Model (MSSM), this situation can be achieved by a light stau and the large left-right mixing of staus. However, a light stau and the large left-right mixing of staus may suffer from vacuum instability. We first apply the vacuum meta-stability condition to the Higgs to diphoton decay rate in the MSSM. We show that the vacuum meta-stability severely constrains the enhancement of the Higgs to diphoton rate. For example, when the lighter stau mass is 100 GeV, the upper bound of the enhancement of the Higgs to diphoton rate is 25%.

Keywords: Supersymmetry, Higgs boson, Higgs to diphoton rate

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1 Introduction

The ATLAS [1] and CMS [2] collaborations at the Large Hadron Collider (LHC) have announced about 6 $\sigma$ (ATLAS) and 5 $\sigma$ (CMS) discovery of the new boson particle around the mass region of 126 GeV in the search for the Standard Model (SM) Higgs boson. This boson has signal strength almost consistent with the prediction of SM Higgs boson except the diphoton channel. The signal strength $\mu(X)$ is defined by

$$\mu(X) \equiv \frac{\sigma(pp \rightarrow h)BR(h \rightarrow X)}{\sigma(pp \rightarrow h)_{SM}BR(h \rightarrow X)_{SM}} = \frac{\sigma(pp \rightarrow h)}{\sigma(pp \rightarrow h)_{SM}} \times \frac{\Gamma(h \rightarrow All)_{SM}}{\Gamma(h \rightarrow All)} \times \frac{\Gamma(h \rightarrow X)}{\Gamma(h \rightarrow X)_{SM}},$$

where $X$ indicates a final state of the Higgs decay, for example $b\bar{b}$, $WW$ and $\gamma\gamma$. Both the ATLAS and CMS have reported that the observed diphoton signal strength is $1.5 - 1.8$ times larger than the SM prediction value [1, 2].

$$\mu(\gamma\gamma)_{ATLAS} = 1.8 \pm 0.5,$$

$$\mu(\gamma\gamma)_{CMS} = 1.56 \pm 0.43.$$ (2)

On the other hand, $\mu(ZZ)$ and $\mu(WW)$ are consistent with SM,

$$\mu(ZZ^{(*)} \rightarrow 4l)_{ATLAS} = 1.4 \pm 0.6,$$

$$\mu(ZZ^{(*)} \rightarrow 4l)_{CMS} = 0.7^{+0.4}_{-0.3},$$

$$\mu(WW^{(*)} \rightarrow l\bar{\nu}l\nu)_{ATLAS} = 1.3 \pm 0.5,$$

$$\mu(WW^{(*)} \rightarrow l\bar{\nu}l\nu)_{CMS} = 0.6 \pm 0.4.$$ (3)

Although statistics of experiments are not enough accumulated yet, this enhanced diphoton signal strength implies various new physics beyond the SM [3, 4, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. The Minimal Supersymmetric (SUSY) Standard Model (MSSM) scenarios are known to be able to enhance $\mu(\gamma\gamma)$ in the decoupling limit, the lighter CP-even Higgs $h$ has the mass 126 GeV [17, 18, 19, 20], and in the non-decoupling limit, the heavier CP-even Higgs $H$ has the mass 126 GeV [21, 22, 23]. In the former scenario, a light stau and the large left-right mixing of staus can appropriately enhance $\mu(\gamma\gamma)$ [17, 19, 20]. However, it was pointed out that the light stau and the large left-right mixing of staus may suffer from vacuum instability [24, 25]. For this reason, in this paper we will analyze the Higgs to diphoton rate with the stau vacuum stability conditions at the broad parameter regions in the MSSM without assuming any particular high energy supersymmetry breaking structure. In addition, we show that the vacuum stability severely constrains the enhancement of the Higgs to diphoton rate, and the upper bound of the enhancement of the Higgs to diphoton rate is about 25% when the lighter stau mass is larger than 100 GeV.

This paper is organized as follows. In section 2 the enhancement of the diphoton signal strength $\mu(\gamma\gamma)$ in the MSSM will be reviewed, and necessity for light stau and large left-right mixing of staus will be discussed. In section 3 we will discuss the vacuum meta-stability of staus. In section 4 we will analyze numerically the Higgs to diphoton rate under the stau vacuum meta-stability condition in the large parameter region. Section 5 is devoted to our conclusions and discussion.


2 Corrections to the signal strength from the MSSM sector

In this section, we briefly review the enhancement of the diphoton signal strength $\mu(\gamma\gamma)$ in the MSSM.

There are three patterns of the enhancement of the diphoton signal strength $\mu(\gamma\gamma)$. The first pattern is making the Higgs production cross-section $\sigma(pp \to h)$ enhance. Since the Higgs production cross-section is mainly the gluon fusion $\sigma(gg \to h)$, in order to enhance the diphoton signal strength we should just add new colored particles [27, 20].

The second pattern is making the Higgs total decay width $\Gamma(h \to \text{All})$ suppress. Since the Higgs total decay width is mainly the Higgs $b\bar{b}$ partial width $\Gamma(h \to b\bar{b})$, we should make the Higgs to $b\bar{b}$ partial width suppress. In the MSSM, large value of the squark left-right mixing parameters, small value of CP-odd Higgs mass, $M_A$ and moderate value of $\tan\beta$ (a fraction of vacuum expectation values of the two Higgs doublets: $\langle H_d^0 \rangle = v_1 = v\cos\beta$, $\langle H_u^0 \rangle = v_2 = v\sin\beta$ and $v \simeq 174$ GeV) can lead to suppress the Higgs to $b\bar{b}$ partial width, named the “small $\alpha_{\text{eff}}$ scenario” [28]. Singlet multiplets extended the MSSM (e.g. NMSSM) can also lead to suppress the Higgs to $b\bar{b}$ partial width because of singlet-doublet Higgs mixing effect [29]. Finally, the third pattern is making the Higgs to $\gamma\gamma$ partial width $\Gamma(h \to \gamma\gamma)$ enhance. Generally, since these three pattern is intricately related, the analysis of the enhancement of the signal strength is difficult.

Eq. (1) turns out that above the first and second pattern are independent of the Higgs decay channel, on the other hand, only the third pattern is dependent of the Higgs decay channel. In addition, in the MSSM the Higgs to $WW$ and $ZZ$ partial width are almost equal to the SM value, since the leading orders are tree level gauge couplings and SUSY particle contributions receive loop suppression. Therefore, when with the first and second pattern, the $WW$ and $ZZ$ signal strength will naively enhance like the diphoton signal strength. However, in fact, the signal strength of the remaining channels except diphoton channel, specially $WW$ and $ZZ$ channels, are in good agreement with the SM prediction in the range of $1 \sigma$ [1, 2]. Hence, we assume that the decay channel independent part of the signal strength $\sigma(pp \to h)/\sigma(pp \to h)_{\text{SM}} \times (\Gamma(h \to \text{All})_{\text{SM}}/\Gamma(h \to \text{All}))$ is almost unity, and we consider only the third pattern. For that reason, in this paper we have investigated behavior of the Higgs to diphoton partial width as compared with the SM prediction $\Gamma(h \to \gamma\gamma)/\Gamma(h \to \gamma\gamma)_{\text{SM}}$ instead of the diphoton signal strength $\mu(\gamma\gamma)$.

In the MSSM, the Higgs to diphoton partial width arises dominantly from $W$ boson loop, and subdominantly from top quark loop. The analytic expression for the Higgs to diphoton partial width is given in Ref. [30, 31] and its rewritten expression is as follows,

\[
\Gamma(h \to \gamma\gamma) = \frac{\alpha^2 m_h^3}{1024 \pi^3} \left| \frac{g_{hWW}}{m_W^2} A_h^W (\tau_W) + \sum_f \frac{2 g_{hff}}{m_f} N_{c,f} Q_f^2 A_{\text{SU}}^A (\tau_f) + A_{\text{SUSY}}^h \right|^2, \tag{4}
\]

where $\tau_i = m_i^2/4m_i^2$, $m_i$ is the lightest CP-even Higgs mass, $N_{c,i}$ is the number of color
of particle $i$, $Q_i$ is electric charge of particle $i$, and

$$ A_{SUSY}^{h\gamma\gamma} = \sum_{f} \frac{g_{h} f f}{m_f^2} N_{c,f} Q_f^2 A_0^h (\tau_f) + \sum_{i=1,2} \frac{g_{h} x_{h_i}^2}{m_{\chi_i^\pm}} A_{h}^h (\tau_{\chi_i^\pm}) + \frac{g_{h} H^+ H^-}{m_{H^\pm}^2} A_0^h (\tau_{H^\pm}), \quad (5) $$

where the loop functions $A_i(\tau)^h$ and the Higgs coupling constants $g$ are given in Appendix [A].

At the heavy particle loop limit $\tau_i \ll 1$, the loop functions $A_i(\tau)^h$ take the following asymptotic value,

$$ A_1^h \rightarrow 7, A_2^h \rightarrow -\frac{4}{3}, A_0^h \rightarrow -\frac{1}{3}. \quad (6) $$

Since the Higgs mass is 126 GeV and top quark mass is 173.2 GeV [32], the loop functions of $W$ and top quark loop are

$$ A_1^h (\tau_W) = 8.36, 3 \times \left(\frac{2}{3}\right)^2 \times A_2^h = -1.84. \quad (7) $$

In the MSSM, charged Higgs loop cannot sufficiently enhance the Higgs to diphoton partial width, since the coupling constant to the Higgs is gauge coupling. Chargino loop cannot also sufficiently enhance one by the same reason and by $\tan \beta$ suppression [33]. On the other hand, since sfermion with large left-right mixing can have the large coupling constant to the Higgs, light sfermion loop can sufficiently enhance the Higgs to diphoton partial width. Light stop and sbottom loop, however, would not be appropriate to enhance the diphoton signal strength. These loops usually raise larger suppression of the gluon fusion than the enhancement of the Higgs to diphoton partial width [27, 17]. This reason is that the Higgs to diphoton amplitude is dominantly constructed by $W$ boson loop, but the $hgg$ amplitude is dominantly constructed by top quark loop. On the other hand, stau loop does not influence the gluon fusion, since stau has no color. Hence, in the MSSM, only stau loop would be appropriate to enhance the diphoton signal strength.

The stau loop correction to the Higgs to diphoton amplitude is roughly proportional to $|m_\tau \mu \tan \beta|/m_\tilde{\tau}_i^2$, for the large $\mu \tan \beta$ region, where $m_\tilde{\tau}_i$ is the lighter stau mass. It is contribution from a diagram like Figure 1. Light stau and large left-right mixing, which means large $\mu \tan \beta$ can sufficiently enhance the Higgs to diphoton partial width, named “light stau scenario” [17, 19, 22, 20]. We obtain simple formula of the leading stau corrections as follows,

$$ \frac{\Gamma(h \rightarrow \gamma \gamma)}{\Gamma(h \rightarrow \gamma \gamma)_{SM}} \approx \left(1 + \sum_{i=1,2} \frac{0.05 m_\tau \mu \tan \beta}{m_{\tilde{\tau}_i}^2} x_{\tilde{\tau}_i}^L x_{\tilde{\tau}_i}^R \right)^2, \quad (8) $$

where stau mass eigenstates are $\tilde{\tau}_i = x_{\tilde{\tau}_i}^L \tilde{\tau}_L + x_{\tilde{\tau}_i}^R \tilde{\tau}_R$, $(x_{\tilde{\tau}_i}^L)^2 + (x_{\tilde{\tau}_i}^R)^2 = 1$.

Furthermore, light stau scenario is also motivated by the anomalous magnetic moment of the muon [19, 34], which is $3.2 \sigma$ discrepancy between the experimentally measured value $a_\mu^{\text{exp}}$ and the theoretical prediction value in the SM $a_\mu^{\text{SM}}$, $\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} =$
Figure 1: The diagram of leading staus correction of the Higgs to diphoton amplitude. The cross represents the left-right mixing of staus.

$$(26.1 \pm 8.0) \times 10^{-10}$$\cite{35}. The reason for this is that light stau are compatible light $\mu$-slepton when one considers high energy physics, and light $\mu$-slepton and large $\tan \beta$ are favored to explain the discrepancy of the anomalous magnetic moment of the muon \cite{36}.

3 The Vacuum meta-stability constraints

In the MSSM, the large left-right mixing of stau mass matrix can enhance Higgs to diphoton rate as compared to the SM prediction. However, it is known that large left-right mixing which means large $\mu \tan \beta$ may suffer from vacuum instability \cite{24,25}. The scalar potential develops the new charge-breaking minimum which have the $\tilde{\tau}_L \neq 0$ or $\tilde{\tau}_R \neq 0$ vacuum for sufficiently large $\mu \tan \beta$. And then, it becomes deeper than the ordinary electroweak-breaking minimum which have the $\tilde{L} = 0$ and $\tilde{\tau}_R = 0$ and $v \neq 0$ vacuum. In order to prohibit vacuum decay to charged-breaking vacuum, the lifetime of the electroweak-breaking vacuum is required to be longer than the age of the universe.

The vacuum transition rate of false vacuum can be evaluated by semiclassical technique \cite{37}. We evaluate imaginary part of the energy of the false vacuum state. It gives us the vacuum transition rate to the true vacuum. In semiclassical technique we evaluate the energy of the false vacuum state using path integral method in Euclidean space-time.

The vacuum transition rate per unit volume is evaluated as follows,

$$\frac{\Gamma}{V} = Ae^{-B},$$

(9)

where the coefficient $A$ is difficult to evaluate precise value and do not have a dramatic dependence on the parameters of the theory. Therefore, we can roughly estimate it the fourth power of the typical scale in the potential,

$$A \simeq (100 \text{ GeV})^4.$$  

(10)
While the power index $B$ is sensitive parameter of the vacuum transition rate per unit volume. It can be evaluated by an $O(4)$ symmetric solution as follows,

$$B = S_E[\bar{\phi}(\rho)] - S_E[\phi^f],$$  \hspace{1cm} (11)$$

where $\rho$ is a radial coordinate in four-dimensional spacetime, $S_E[\phi]$ is the Euclidean action as follows,

$$S_E[\phi(\rho)] = \int_0^{\infty} 2\pi^2 \rho^3 d\rho \left[ \frac{1}{2} \left( \frac{d\phi}{d\rho} \right)^2 + V(\phi) \right],$$  \hspace{1cm} (12)$$

$\phi^f$ is value of the fields at false vacuum and $\bar{\phi}$ is the bounce configuration. The bounce configuration is a stationary point of the action and also satisfy the following boundary condition,

$$\lim_{\rho \to \infty} \bar{\phi}(\rho) = \phi^f, \quad \frac{d\bar{\phi}(\rho)}{d\rho} \bigg|_{\rho=0} = 0.$$  \hspace{1cm} (13)$$

On the other hand, the current value of the Hubble parameter is $H_0 \simeq 1.5 \times 10^{-42}$ GeV. When the vacuum transition rate per unit volume $\Gamma/V$ is smaller than the fourth power of $H_0$, this means that the lifetime of false vacuum is longer than the age of the universe, the power index $B$ is larger than 403.6. Therefore, the vacuum meta-stability condition is approximately given as follows,

$$B \gtrsim 400.$$  \hspace{1cm} (14)$$

A first study of the meta-stability condition of the left-right mixing of stau sector has done in Ref.[26] which evaluate numerically bounce configuration in three-field space (up-type neutral Higgs field and left- and right-handed stau field) at tree level which only included dominant top/stop loop correction. The scalar potential expanding around the electroweak-breaking vacuum in three-field space is follows,

$$V = \frac{1}{2} m_2^2 \sin^2 \beta (1 + \Delta_t) \phi^2 + (m_L^2 + \frac{g^2 - g'^2}{4} v_2^2) \tilde{L}^2 + (m_R^2 + \frac{g'^2}{2} \tilde{v}_2^2) \tilde{\tau}_R^2 - 2 g_t \mu \tilde{L} \tilde{H}_R (v_2 + \frac{\phi}{\sqrt{2}}) + \frac{g^2 - g'^2}{2\sqrt{2}} v_2 \phi \tilde{L}^2 + \frac{g'^2}{\sqrt{2}} v_2 \phi \tilde{\tau}_R^2 + \frac{m_2^2 \sin^2 \beta (1 + \Delta_t)}{2\sqrt{2} v_2} \phi^3 + \frac{m_2^2 (1 + \Delta_t)}{16v_2^2} \phi^4 + \frac{g^2 + g'^2}{8} \tilde{L}^4 + \frac{g'^2}{2} \tilde{\tau}_R^2 + (y_t^2 - \frac{1}{2} g'^2) \tilde{L}^2 \tilde{\tau}_R^2 + \frac{g^2 - g'^2}{8} \phi^2 \tilde{L}^2 + \frac{g'^2}{4} \phi^2 \tilde{\tau}_R^2,$$  \hspace{1cm} (15)$$

where $H_u^0 = v_2 + \phi/\sqrt{2}$ and $\Delta_t$ is leading log term of one loop corrections for top/stop loop,

$$\Delta_t = \frac{3}{2\pi^2} \frac{y_t^4}{g^2 + g'^2} \log \frac{\sqrt{m_{t_1}^2 m_{t_2}^2}}{m_t^2}.$$  \hspace{1cm} (16)$$
When Higgs boson mass accomplishes 126 GeV, $\Delta_t$ have to be about 1. In Eq. (16), the scalar potential (15) includes only real parts of scalar bosons. Note that because of the Yukawa coupling of tau lepton is $y_\tau = m_\tau/v_1$, the first term of the second line of (15) is proportional to $\mu \tan \beta$ at large $\tan \beta$. Therefore, this term can make a new minimum point of the scalar potential and has negative influence on vacuum stability.

The obtained approximate meta-stability conditional function [26] is as follows,

$$|\mu \tan \beta| < 76.9 \sqrt{m_Lm_{\tilde{\tau}_R}} + 38.7(m_L + m_{\tilde{\tau}_R}) - 1.04 \times 10^4 \text{ GeV}. \quad (17)$$

Note that vacuum meta-stability condition is sensitive to only $m_{\tilde{\tau}}^2$, $m_{\tilde{\tau}}^3$ and $\mu \tan \beta$, but not $\tan \beta$ or $\mu$ itself, and not $\Delta_t$ and $A_\tau$. And also note that in Ref. [26] we assume that the $H_u^0$ mass term, $\mu^2 + m_{H_u^0}^2$, is negative so that $H_u$ gets a vacuum expectation values $v_2$. However, it is known that even when this term is positive, correct electroweak symmetry breaking can be worked. For this reason, in order to know validity of the meta-stability condition, we analyze global minimum of scalar potential and probe upper bound of $\mu$ requiring that electroweak-breaking minimum is global minimum in Appendix [13]. As a result, we find that regardless of sign of $m_{H_u^0}^2$, the parameter $m_{H_u^0}^2$ cannot affect the upper bound of $\mu$.

We apply this vacuum meta-stability condition to the Higgs to diphoton rate. Naively, this condition means that when large $\mu \tan \beta$ and small stau mass are severely restricted. Namely, the enhancement of the Higgs to diphoton rate by light stau loop would be also severely restricted.

### 4 Numerical analysis

In this section we analyze numerically the Higgs to diphoton partial width as compared with the SM prediction $\Gamma(h \to \gamma\gamma)/\Gamma(h \to \gamma\gamma)_{SM}$ and apply the stau vacuum meta-stability condition to the $\Gamma(h \to \gamma\gamma)/\Gamma(h \to \gamma\gamma)_{SM}$ in large parameter region.

The lower bound of stau mass is obtained by the collider experiments [35],

$$m_{\tilde{\tau}_1} > 81.9 \text{ GeV}, \quad (18)$$

and we naively adopt the lower mass bound $m_{\tilde{\tau}_1} \geq 100 \text{ GeV}$ in the following calculation.

In Figure 2 we showed the dependence of the $\Gamma(h \to \gamma\gamma)/\Gamma(h \to \gamma\gamma)_{SM}$ in the $m_{\tilde{\tau}_1} - m_L$ plane for $m_{\tilde{\tau}_1} = m_L$ (left side panel), as well as in the $m_L - m_{\tilde{\tau}_1}$ plane for $\mu = 600$ GeV (right side panel). Solid lines represent contours of the $\Gamma(h \to \gamma\gamma)/\Gamma(h \to \gamma\gamma)_{SM}$. Dashed lines represent contours of the lighter stau mass $m_{\tilde{\tau}_1}$. The gray (dark gray) areas are the region that the lighter stau is tachyonic and the yellow (mostly white) areas are $m_{\tilde{\tau}_1} \geq 100 \text{ GeV}. In addition, the red (gray) areas are the region that the vacuum meta-stability condition (17) is broken. We fixed at $\tan \beta = 20$ (top panel) and $\tan \beta = 60$ (bottom panel). In all panel, $M_A = 1 \text{ TeV}$, $M_3 = 1 \text{ TeV}$, $M_2 = 300 \text{ GeV}$, $A_\tau = 0 \text{ GeV}$, $m_{Q_3} = m_{t_R} = m_{b_R} = 850 \text{ GeV}$, other squark mass are $1 \text{ TeV}$ and $A_t = 1.7 \text{ TeV}$, which gives $m_h \sim 126 \text{ GeV}$ at the two loop level. In calculation, the value of $\Gamma(h \to \gamma\gamma)$ contains not only stau loop, but also full one loop order. We have checked that the results are sensitive to only $m_L$, $m_{\tilde{\tau}_1}$, $\mu$ and $\tan \beta$, on the other hand, however, are insensitive to the Higgs mass.
Figure 2: Solid lines are contour plots of the $\Gamma(h \rightarrow \gamma\gamma)/\Gamma(h \rightarrow \gamma\gamma)_{SM}$, in the $\mu - m_{\tilde{L}}$ plane for $m_{\tilde{\tau}R} = m_{\tilde{L}}$ (left side), as well as in the $m_{\tilde{L}} - m_{\tilde{\tau}R}$ plane for $\mu = 600$ GeV (right side). $\tan\beta = 20$ (top) and $\tan\beta = 60$ (bottom). In all panel, $M_A = 1$ TeV, $A_\tau = 0$ GeV, $m_{\tilde{Q}3} = m_{\tilde{t}R} = 850$ GeV and $A_t = 1.7$ TeV giving $m_h \sim 126$ GeV at the two loop level. Dashed lines are contour plot of the lighter stau mass $m_{\tilde{\tau}1}$. The red (gray) areas are breaking the vacuum meta-stability condition. The gray (dark gray) areas are the region that the lighter stau is tachyonic.
Figure 3: The upper bound line of the $\Gamma(h \to \gamma\gamma)/\Gamma(h \to \gamma\gamma)_{\text{SM}}$ as a function of $\mu \tan \beta$, for $\tan \beta = 50$, varying $m_L$ and $m_{\tilde{\tau}^R}$ with remaining the lighter stau mass $m_{\tilde{\tau}^1} = 100$ GeV. Other parameters are the same value as Figure 2. If we would not consider the vacuum stability, the upper bound line of the $\Gamma(h \to \gamma\gamma)/\Gamma(h \to \gamma\gamma)_{\text{SM}}$ is dashed line.

For $\tan \beta = 20$, in low $\mu$ region, the enhancement of the $\Gamma(h \to \gamma\gamma)/\Gamma(h \to \gamma\gamma)_{\text{SM}}$ is small. While in high $\mu$ region, the enhancement becomes gradually large along with light stau region. The vacuum stability (17) has given weak constraint to the parameter. In fact, when $\mu = 600$ GeV no constraint from the vacuum stability at $m_{\tilde{\tau}^1} \geq 100$ GeV region. At this time, it is a case of $m_L = m_{\tilde{\tau}^R} \sim 170$ GeV that gives the maximum enhancement of diphoton rate about 10%. On the other hand, for $\tan \beta = 60$, the enhancement of the $\Gamma(h \to \gamma\gamma)/\Gamma(h \to \gamma\gamma)_{\text{SM}}$ is larger than for $\tan \beta = 20$. However, it would be given more severe constraint from vacuum stability. As can be seen from the lower left and right panels of Figure 2, large enhancement areas are violating the vacuum stability. After all, for $\tan \beta = 60$, the enhancement of diphoton rate goes only about 20%.

Next, we showed the upper bound line of the $\Gamma(h \to \gamma\gamma)/\Gamma(h \to \gamma\gamma)_{\text{SM}}$ as a function of $\mu \tan \beta$, varying $m_L$ and $m_{\tilde{\tau}^R}$ with remaining the lighter stau mass $m_{\tilde{\tau}^1} = 100$ GeV in Figure 3. We fixed $\tan \beta = 50$, and other parameters are the same value as Figure 2. In low $\mu \tan \beta$ region, $\mu \tan \beta \lesssim 24$ TeV, there are no constraints from the vacuum stability at $m_{\tilde{\tau}^1} \geq 100$ GeV region like the upper right panels of Figure 2. Note that the lowest $\mu \tan \beta$ peak is caused by light chargino loop. On the other hand, high $\mu \tan \beta$ region, 24 TeV $\lesssim \mu \tan \beta$, the vacuum stability condition line and $m_{\tilde{\tau}^1} = 100$ GeV line begin to cross like the lower right panels of Figure 2. Hence, the vacuum stability severely constraint to the $\Gamma(h \to \gamma\gamma)/\Gamma(h \to \gamma\gamma)_{\text{SM}}$. If we would not consider the vacuum stability, the upper bound line of the $\Gamma(h \to \gamma\gamma)/\Gamma(h \to \gamma\gamma)_{\text{SM}}$ is dashed line. Note that although in Figure 3 we fixed $\tan \beta = 50$, we have checked that this results are insensitive to $\tan \beta$, but sensitive to $\mu \tan \beta$. This reason is that the stau
mass matrix and the vacuum stability condition \(^{17}\) and the \(\Gamma(h \rightarrow \gamma \gamma)/\Gamma(h \rightarrow \gamma \gamma)_{\text{SM}}\) are dependent on the form of \(\mu \tan \beta\) at large \(\mu \tan \beta\) region. Thus we find that the Higgs to diphoton decay rate can enhance only 25\% from SM value, at \(\mu \tan \beta \sim 24\) TeV in the MSSM.

For completeness, we probed the distribution of the \(\Gamma(h \rightarrow \gamma \gamma)/\Gamma(h \rightarrow \gamma \gamma)_{\text{SM}}\) with scanning the parameter space of the MSSM. Although there are many parameters in the MSSM, most of parameter (for example, \(M_2\) and \(M_4\)) hardly contribute to the upper bound of the \(\Gamma(h \rightarrow \gamma \gamma)/\Gamma(h \rightarrow \gamma \gamma)_{\text{SM}}\) and we have checked it numerically. Therefore, we scanned only sensitive parameters to the \(\Gamma(h \rightarrow \gamma \gamma)/\Gamma(h \rightarrow \gamma \gamma)_{\text{SM}}\) as

Figure 4: The scatter plots of the \(\Gamma(h \rightarrow \gamma \gamma)/\Gamma(h \rightarrow \gamma \gamma)_{\text{SM}}\) as a function of \(\mu \tan \beta\) (left), \(\tan \beta\) (right) and the lighter stau mass \(m_{\tilde{\tau}_1}\) (bottom) in the MSSM. Parameter scan ranges are shown in Eq. \(^{19}\), and other parameters are the same value as Figure 2. The red (dark gray) circles denote the case of violating vacuum meta-stability and \(m_{\tilde{\tau}_1} > 0\) GeV. The gray circles denote the case of satisfying vacuum meta-stability and \(100\) GeV > \(m_{\tilde{\tau}_1}\) > 0 GeV. The blue (black) circles denote the case of satisfying vacuum meta-stability and \(m_{\tilde{\tau}_1}\) > 100 GeV.
follows,

\[
\begin{align*}
100 \text{ GeV} & \leq m_L \leq 1 \text{ TeV}, \\
100 \text{ GeV} & \leq m_{\tilde{\tau}_R} \leq 1 \text{ TeV}, \\
200 \text{ GeV} & \leq \mu \leq 1.5 \text{ TeV}, \\
20 & \leq \tan \beta \leq 60,
\end{align*}
\]

(19)

at one million points, where all input parameters are value of low energy scale. The scatter plots of the result are Figure 4. We showed the \( \Gamma(h \to \gamma\gamma)/\Gamma(h \to \gamma\gamma)_{\text{SM}} \) as a function of \( \mu \tan \beta \) (left panel), tan \( \beta \) (right panel) and the lighter stau mass \( m_{\tilde{\tau}_1} \) (bottom panel) in the MSSM. Other parameters of Eq. (19) are the same value as Figure 2. The red (dark gray) circles denote the case of violating vacuum meta-stability and \( m_{\tilde{\tau}_1} > 0 \) GeV. The gray circles denote the case of satisfying vacuum meta-stability and \( 100 \text{ GeV} > m_{\tilde{\tau}_1} > 0 \) GeV. The blue (black) circles denote the case of satisfying vacuum meta-stability and \( m_{\tilde{\tau}_1} > 100 \) GeV.

In the panel as a function of \( \mu \tan \beta \), the upper bound line of the \( \Gamma(h \to \gamma\gamma)/\Gamma(h \to \gamma\gamma)_{\text{SM}} \) (the blue (black) circles) have reconstructed the results of Figure 3. Note that since we scanned \( m_L, m_{\tilde{\tau}_R} < 1 \) TeV, in large \( \mu \tan \beta \) region the upper bound line of the \( \Gamma(h \to \gamma\gamma)/\Gamma(h \to \gamma\gamma)_{\text{SM}} \) could not reconstruct. In the panel as a function of \( \tan \beta \), we find that the upper bound of the \( \Gamma(h \to \gamma\gamma)/\Gamma(h \to \gamma\gamma)_{\text{SM}} \) is independent to \( \tan \beta \). It means the upper bounds are decided only by value of \( \mu \tan \beta \). Finally, in the panel as a function of \( m_{\tilde{\tau}_1} \), we find \( m_{\tilde{\tau}_1} \) dependence property on the upper bound of the \( \Gamma(h \to \gamma\gamma)/\Gamma(h \to \gamma\gamma)_{\text{SM}} \). The lighter stau mass, the larger value the upper bound becomes, however, the more severe the vacuum stability constraint becomes. As a result, in the case of \( m_{\tilde{\tau}_1} = 200 \) GeV, 120 GeV, 100 GeV and 80 GeV, the upper bounds of the enhancement are 9%, 20%, 25% and 40%, respectively. If we would not consider the vacuum stability, in the case of \( m_{\tilde{\tau}_1} = 100 \) GeV, the upper bound of the enhancement is 100% at scanned parameters region (19).

5 Conclusions and Discussion

In this paper, motivated recent enhanced diphoton Higgs decay and consistent \( WW / ZZ \) Higgs decay, we first analyzed the \( \Gamma(h \to \gamma\gamma)/\Gamma(h \to \gamma\gamma)_{\text{SM}} \) with the stau vacuum meta-stability conditions at the broad parameter regions in the MSSM. We found that large enhancement of the \( \Gamma(h \to \gamma\gamma)/\Gamma(h \to \gamma\gamma)_{\text{SM}} \) parameter regions are severely constrained from vacuum stability. We showed that in the case of the lighter stau mass \( m_{\tilde{\tau}_1} = 200 \) GeV, 120 GeV, 100 GeV and 80 GeV, the upper bounds of the enhancement of the Higgs to diphoton rate are 9%, 20%, 25% and 40%, respectively. Especially, in the case of \( m_{\tilde{\tau}_1} = 100 \) GeV, \( \mu \tan \beta \sim 24 \) TeV gives the largest enhancement of the Higgs to diphoton rate.

This result implies that if the stability of the scalar potential is taken into consideration, the Higgs to diphoton and \( WW/ZZ \) decay ratios cannot deviate from the SM so much in the MSSM. And also, it implies that when one would like to explain over 30% enhancement of the diphoton signal strength in the MSSM, the decay channel independent part of the signal strength \( \sigma(pp \to h)/\sigma(pp \to h)_{\text{SM}} \times \Gamma(h \to \text{All})_{\text{SM}}/\Gamma(h \to \text{All}) \)
is required to enhance, and hence the enhancement of the $WW/ZZ$ signal strength is inevitable.

Note that the vacuum stability condition used this paper is the condition of tree-level (only included top/stop loop correction) scalar potential. Since the parameter regions which can enhance the diphoton rate would have large loop corrections, in a strict sense one should take into account the vacuum stability condition of loop-level.

Furthermore, note that not only in the MSSM but also in general models, “light charged scalar particles scenarios” or “light charged vector-like lepton scenarios” would need large cubic or large quartic interaction with the Higgs boson to enhance the diphoton signal strength [3, 7]. Large cubic scalars interaction, however, may suffer from vacuum instability like the MSSM. Also, large quartic interaction may suffer from vacuum instability when dimensionless coupling constants are negative value, and from Landau pole when it rapidly blows up at high scales. Hence in the light charged scalar particles or vector-like lepton scenarios, we should take into consideration of the vacuum stability and Landau pole.

At the end of this project, the Ref. [39] was reported. The Ref. [39] also first applied the vacuum meta-stability to the diphoton signal strength in some gauge mediation models. As a result, they showed that parameter regions which are consistent with the Higgs mass and muon $g - 2$ can enhance the $BR(h \rightarrow \gamma\gamma)/BR(h \rightarrow \gamma\gamma)_{SM}$ to $20\% - 30\%$.

Acknowledgements

The author would like to thank Takeo Moroi for useful discussions, and also thank Koichi Hamaguchi and Motoi Endo for motive argument of this paper.

Appendix

A Loop functions and Higgs couplings

Loop functions $A^h_i(\tau)$ are given as follows

$$
A^h_1(\tau) = 2 + 3\tau + 3\tau(2 - \tau)f(\tau),
$$

$$
A^h_2(\tau) = -2\tau (1 + (1 - \tau)f(\tau)),
$$

$$
A^h_0(\tau) = \tau(1 - \tau f(\tau)),
$$

and

$$
f(\tau) = \begin{cases} \arcsin^2(\sqrt{\frac{1}{\tau}}), & \text{if } \tau \geq 1, \\ \frac{-1}{4} \left( \ln \left( \frac{\eta_+}{\eta_-} \right) - i\pi \right)^2, & \text{if } \tau \leq 1, \end{cases}
$$

where

$$
\eta_\pm \equiv (1 \pm \sqrt{1 - \tau}).
$$
In the MSSM, the Higgs coupling constants are given as follows

\[
g_{hW} = \frac{g^2 v}{\sqrt{2}} \sin(\beta - \alpha), \quad \tag{23}
\]

\[
g_{hff(\text{up type})} = \frac{m_f \cos \alpha}{\sqrt{2} v \sin \beta}, \quad \tag{24}
\]

\[
g_{hff(\text{down type})} = \frac{m_f - \sin \alpha}{\sqrt{2} v \cos \beta}, \quad \tag{25}
\]

\[
g_{h\tilde{f}_i\tilde{f}_i(\text{up type})} = \left(\frac{-Y_L \sin^2 \theta_W}{\cos \theta_W} \frac{gm_Z}{\cos \theta_W} \sin(\alpha + \beta) + \frac{\sqrt{2} m_f^2 \cos \alpha}{v \sin \beta}\right) (x_{f_i}^L)^2
\]

\[
+ \left(\frac{Y_R \sin^2 \theta_W}{\cos \theta_W} \frac{gm_Z}{\cos \theta_W} \sin(\alpha + \beta) - \frac{\sqrt{2} m_f^2 \sin \alpha}{v \cos \beta}\right) (x_{f_i}^R)^2
\]

\[
+ \frac{\sqrt{2} m_f \mu \sin \alpha + A_f \cos \alpha}{v} x_{f_i}^L x_{f_i}^R, \quad \tag{26}
\]

\[
g_{h\tilde{f}_i\tilde{f}_i(\text{down type})} = \left(\frac{-Y_L \sin^2 \theta_W}{\cos \theta_W} \frac{gm_Z}{\cos \theta_W} \sin(\alpha + \beta) - \frac{\sqrt{2} m_f^2 \sin \alpha}{v \cos \beta}\right) (x_{f_i}^L)^2
\]

\[
+ \left(\frac{Y_R \sin^2 \theta_W}{\cos \theta_W} \frac{gm_Z}{\cos \theta_W} \sin(\alpha + \beta) + \frac{\sqrt{2} m_f^2 \sin \alpha}{v \cos \beta}\right) (x_{f_i}^R)^2
\]

\[
- \frac{\sqrt{2} m_f \mu \cos \alpha + A_f \sin \alpha}{v} x_{f_i}^L x_{f_i}^R,
\]

\[
g_{h\chi_i^+\chi_i^-} = \frac{g}{\sqrt{2}} (-V_{i1} U_{i2} \sin \alpha + V_{i2} U_{i1} \cos \alpha), \quad \tag{28}
\]

\[
g_{hH+H-} = \frac{g}{m_W \sin(\beta - \alpha) + \frac{m_Z \cos 2\beta}{2 \cos \theta_W} \sin(\alpha + \beta)}, \quad \tag{29}
\]

where \(Y_{L/R}\) and \(I_{3,L/R}\) are hypercharge and isospin of left/right-handed sfermion, sfermion mass eigenstates are \(\tilde{f}_i = x_{f_i}^L \tilde{f}_L + x_{f_i}^R \tilde{f}_R\), angle \(\theta_W\) is the Weinberg angle, and angle \(\alpha\) is a rotation angle which translates gauge-eigenstate basis CP-even Higgs mass matrix into mass-eigenstate basis one. The chargino mass matrix is diagonalized to real positive diagonal mass matrix by two \(2 \times 2\) unitary matrices \(U\) and \(V\) as follows,

\[
U^* \left(\begin{array}{cc}
M_2 \\
\sqrt{2} m_W \cos \beta \mu
\end{array}\right) V^\dagger = \left(\begin{array}{cc}
m_{\chi^\pm} \\
0
\end{array}\right).
\]

\[
B \quad \text{Analysis of global minimum of scalar potential}
\]

In this appendix we analyze numerically global minimum of scalar potential in four-field space \((h_d, h_u, \tilde{L}, \tilde{R})\), and probe upper bound of \(\mu\) requiring that the electroweak-breaking minimum is global minimum. Note that \(h_u\) is the same as \(\phi\) in the main text and \(h_d\) is down-type neutral Higgs field. The tree level scalar potential which only
Figure 5: The upper bound of $\mu$ requiring that the electroweak-breaking minimum is global minimum as a function of $m_{H_u}^2$. We take $\tan \beta = 50$ (left) and $\tan \beta = 10$ (right). In both of the panels, $m_L = m_{\tilde{\tau}_R} = 400$ GeV, $A_{\tau} = 0$ GeV and $\Delta_t = 1$.

Green dashed lines are meta-stability bound $[17]$. Dotted lines are contour plot of $\sqrt{B_{\mu}}$ [GeV]. Gray areas are the region that cannot success electroweak symmetry breaking.

included dominant top/stop loop correction in four-field space is as follows,

$$
V = (\mu^2 + m_{H_d}^2)(H_d^0)^2 + (\mu^2 + m_{H_u}^2)(H_u^0)^2 - 2B_{\mu}H_d^0H_u^0
+ y^2 \gamma^2 \left( \frac{1}{2}(H_d^0)^2 + \frac{1}{2}(H_u^0)^2 - \frac{1}{2}L^2 + \frac{1}{2}\tilde{\tau}_R^2 \right)^2 + \frac{g^2}{8} \left( (H_d^0)^2 - (H_u^0)^2 - \tilde{L}^2 \right)^2
+ \frac{g^2 + g^2}{8} \Delta_t (H_u^0)^4,
$$

(31)

where $H_d^0 = v_1 + h_d/\sqrt{2}$, $H_u^0 = v_2 + h_u/\sqrt{2}$ and $\Delta_t$ is given as Eq. (16). The scalar potential (31) includes only real parts of scalar bosons. When the scalar potential (31) is expanded around the electroweak-breaking vacuum and down-type neutral Higgs field is omitted, it reconstructs the scalar potential (15).

In Figure 5, we showed the upper bound of $\mu$ requiring that the electroweak-breaking minimum is global minimum as a function of $m_{H_u}^2$ for $\tan \beta = 50$ (left side panel) and $\tan \beta = 10$ (right side panel). In both of the panels, $m_L = m_{\tilde{\tau}_R} = 400$ GeV, $A_{\tau} = 0$ GeV and $\Delta_t = 1$. Green dashed lines are meta-stability bound [17]. Dotted lines are contour plot of $\sqrt{B_{\mu}}$. Gray areas are the region that cannot success electroweak symmetry breaking.

Moreover in Figure 6, we showed the upper bound of $\mu$ requiring that the electroweak-breaking minimum is global minimum as a function of $\sqrt{B_{\mu}}$. We take $\tan \beta = 10$, $m_L = m_{\tilde{\tau}_R} = 400$ GeV, $\Delta_t = 1$ and $A_{\tau} = 0$ GeV (blue solid line), $-500$ GeV (red dashed line). Green dashed line is meta-stability bound [17]. Gray lines are contour plot of $m_{H_u}^2$. We find that regardless of sign of $m_{H_u}^2$, the parameter $m_{H_u}^2$ cannot affect the upper
Figure 6: The upper bound of $\mu$ requiring that the electroweak-breaking minimum is global minimum as a function of $\sqrt{B_\mu}$. We take $\tan \beta = 10$ and $A_\tau = 0$ GeV (blue solid line), $-500$ GeV (red dashed line). Green dashed line is meta-stability bound (17). Gray lines are contour plot of $m_{H_u}^2$ [GeV$^2$].

bound of $\mu$. And also we find that low $\sqrt{B_\mu}$ and low $\tan \beta$ regions can affect upper bound of $\mu$ and are sensitive to $A_\tau$. This reason is that these regions lead low $M_A$ and $h_d$ component gives considerable contribution, then it bring down another charged-breaking vacuum which becomes global minimum earlier than usual charged-breaking vacuum. Furthermore we find that shape of scalar potential (31) remain unaltered by change of $m_{H_u}^2$ and $\sqrt{B_\mu}$, except low $\sqrt{B_\mu}$ and low $\tan \beta$ regions. These results imply that approximate meta-stability conditional function (17) is considered reasonable except low $\sqrt{B_\mu}$ and low $\tan \beta$ regions.

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