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Enhancement of Higgs to diphoton decay width in non-perturbative Higgs model

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Abstract

We investigate a possibility if a loop diagram via Higgsino can enhance the Higgs to diphoton decay width in supersymmetric models with an extension of Higgs sector. A model with an additional non-renormalizable term of Higgs fields is firstly analyzed where the higher order term can introduce the Higgs coupling to Higgsinos as well as charged Higgs bosons. We point out that a choice of the Higgs coupling to obtain a significant size of enhancement of diphoton decay width reduces the Higgs mass and/or a size of non-renormalizable term needs to be large and a cut-off scale is around the weak scale. Another model in which the Higgsino mass term is generated by a non-perturbative instanton effect via a strong dynamics in a context of SUSY QCD is also suggested. It is shown that the sign of the Higgs coupling to fermions is opposite from perturbative models due to an operator including bosonic fields in the denominator and a constructive contribution to the diphoton decay amplitude can be easily obtained in this kind of model.

1 Introduction

The CMS/ATLAS collaborations at the Large Hadron Collider (LHC) released a historical announcement about the observation of a new particle consistent with a Higgs boson [1, 2] at about 5 sigma [3]. Needless to say, it is important to test that the observed boson is really identified to the Higgs boson in the standard model (SM) or not. The current data analyses agree with the SM prediction. Possible hint of the deviation from the SM prediction is an excess of the $h \to \gamma\gamma$ channel, especially at the ATLAS experiment [3]*:

$$\sigma/\sigma_{\rm SM} = 1.56 \pm 0.43 \quad \text{(CMS)}, \tag{1.1}$$

$$\sigma/\sigma_{\rm SM} = 1.9 \pm 0.5 \quad \text{(ATLAS)}. \tag{1.2}$$

More statistics will be needed to determine if the excess is real or just due to a statistical fluctuation, in the experimental side. In the theoretical side, simultaneously, it is worth to investigate the possibility of the enhancement of the diphoton partial decay width, without significantly modifying the total decay width or production cross section of the Higgs boson in SM [5].

The Higgs coupling to photons is induced at the loop-level [6, 7], and therefore, it is sensitive to the presence of new charged particles which couple to the Higgs boson [8]. The colored particle can also modify the production cross section via gluon fusion, as well as the partial digluon decay width. Such modification via the colored particle may become significant rather than the diphoton rate due to a color factor. Therefore, if only the diphoton decay width differs from the SM expectation, a colorless charged particle is a preferable target. In SM, the dominant contribution comes from a W boson loop, and a correction comes from the top quark loop, which gives a destructive contribution to the W boson loop. In order to enhance the diphoton rate, one needs a constructive contribution to the W contribution. The loop contributions via sequential chiral fermions whose masses are generated by Higgs vacuum expectation values (VEVs) always generate destructive ones, and thus, a devised structure of the couplings to the Higgs boson is needed. The LEP experiments provide a strong bound of the mass of light new charged particles, and as a consequence, a large coupling to the Higgs boson is implied if the diphoton decay width is significantly modified.

The mass of the boson observed at the LHC is 125–126 GeV. Such mass of the Higgs boson may require a new physics, such as supersymmetry (SUSY), if a stabilization condition is applied to the Higgs self-coupling [9, 10] (see also [11] and references therein). Minimal

*The ATLAS experiment has reported $\sigma/\sigma_{\rm SM} = 1.80 \pm 0.30(\text{stat})^{+0.21}_{-0.15}(\text{syst})^{+0.20}_{-0.14}(\text{theory})$ [4].

SUSY standard model (MSSM) is, of course, nicely compatible with the 125 GeV Higgs boson [12, 13, 14]. The enhancement of diphoton rate can be also realized within MSSM [15, 16, 17] because there are plenty of new charged particles. However, a large loop correction is needed to the Higgs boson mass because the Higgs boson mass is predicted to be around the Z boson mass at the tree level. The required large loop correction needs a heavy stop mass or large A_t trilinear scalar term and they may spoil naturalness which is one of the motivation of SUSY [18]. Extension of the Higgs sector in MSSM is also the issue to explain the 125 GeV mass naturally (e.g. see [19, 20] also for its various implications).

In this paper, we consider an extension of the Higgs sector in a SUSY model, and investigate whether the enhancement of diphoton decay width and increasing the Higgs mass can cooperate in the model. The simplest extension of MSSM may be so-called Next-to-MSSM [21] in which a singlet field which couples to the Higgs fields is added. We will concentrate a possibility of non-renormalizable term in the Higgs sector without adding a new field. Those extensions of MSSM are related to the origin of the Higgsino mass (so-called μ), which is indeed one of the issues in MSSM. We consider a model in which the Higgsino mass depends on the Higgs VEV, and see if a large Higgs coupling to Higgsino (SUSY partner of the Higgs boson) can be obtained to enhance the diphoton decay width.

This paper is organized as follows: In section 2, we give a brief review of the Higgs to diphoton decay width. In section 3, a possibility of enhancement of the diphoton decay width and a realization of the Higgs mass with 125 GeV are investigated in a SUSY model with non-renormalizable Higgs term, namely Beyond MSSM (BMSSM). The discussions of diphoton decay width enhancement with the appropriate Higgs mass is presented also in a non-perturbative Higgs model in section 4. Section 5 is devoted to our conclusion and discussion.

2 The Higgs to diphoton decay width

The Higgs to diphoton decay is obtained loop diagram, and the analytical expression can be found in literature [6, 7, 11]. In SM, the leading contribution comes from the W boson loop and the next-to-leading contribution is from the top quark loop. The expression of the diphoton partial decay width can be found in [6, 7]. A convenient formula to study the diphoton decay width in terms of the Higgs coupling to the charged particles in the loop is given in [8]:

$$\Gamma(h \to \gamma\gamma) = \frac{\alpha^2 m_h^3}{1024\pi^3} \left| \frac{g_{hVV}}{m_V^2} Q_V^2 A_1(\tau_V) + \frac{2 g_{hf\bar{f}}}{m_f} N_{c,f} Q_f^2 A_{1/2}(\tau_f) + N_{c,S} Q_S^2 \frac{g_{hSS}}{m_S^2} A_0(\tau_S) \right|^2 . \quad (2.1)$$

In the expression, V, f, and S refer to generic vector, fermion and scalar particles, respectively, Q_i is the electric charge of the particle, and $N_{c,i}$ is the number of particles with color. The loop functions $A_{1,1/2,0}$ are found in the references. If $\tau_i \equiv 4m_i^2/m_h^2 > 1$ (no on-shell decays to the charged particles), the loop function $A_1(\tau_V)$ is negative, and $A_{1/2}(\tau_f)$ and $A_0(\tau_S)$ are positive. The SM contributions come from W boson ($V = W$) and top quark ($f = t$), and the quantities of the loop functions in the case of $m_h = 125$ GeV are

$$A_1 = -8.32, \qquad N_c Q_t^2 A_{1/2} = 1.84. \tag{2.2}$$

The couplings of hWW and $ht\bar{t}$ in SM are obtained as $g_{hWW}/m_W^2 = 2g_{ht\bar{t}}/m_t = 2/v$, where $v \approx 246$ GeV.

The enhancement of diphoton decay width via fermion or scalar loop can be obtained if $g_{hf\bar{f}}/m_f < 0$ or $g_{hSS} < 0$. If the new charged fermion is a chiral fermion such as sequential fourth generation, its loop contribution is always destructive to the SM contribution because $g_{hf\bar{f}}/m_f$ has same sign of g_{hWW} coupling (which is positive in the current convention).

Surely, it is possible to have a constructive contribution via fermion loop if there are VEV-independent Dirac mass terms as well as the Yukawa interaction [8]. In the next section, we will study if the Higgsino loop can enhance the diphoton rate by a constructive contribution to the W boson loop.

3 Non-renormalizable Higgs term (BMSSM)

In MSSM there exists Higgs-Higgsino-gaugino coupling, and therefore, chargino loop diagram can contribute to the diphoton decay amplitude. However, the interaction is the $SU(2)_L$ weak gauge coupling, and the charginos have to be heavier than about 100 GeV due to the LEP bound. As a consequence, the loop diagram via a gaugino-like chargino that mainly consists of gaugino cannot provide a significant contribution to the decay amplitude. Hereafter, we neglect the gaugino-Higgsino mixing for simplicity to describe, and we consider the contribution from the Higgs-Higgsino-Higgsino coupling and the loop diagram via a chargino which mainly consists of Higgsino.

The Higgs-Higgsino-Higgsino coupling can be generated if we add a non-renormalizable term to the superpotential:

$$W = \mu H_u \cdot H_d + \frac{c}{\Lambda}(H_u \cdot H_d)^2. \tag{3.1}$$

This type of superpotential is studied named as Beyond MSSM (BMSSM) [22]. In the above expression, Λ is a cutoff scale of the model, and c is a coupling constant. Let us redefine the

parameter Λ to make $c = 1$ just to make the expression below simple. Expanding the SU(2) contract explicitly, we obtain:

$$W = \mu(H_u^+ H_d^- - H_u^0 H_d^0) + \frac{1}{\Lambda}(H_u^+ H_d^- - H_u^0 H_d^0)^2. \tag{3.2}$$

Then, in the Lagrangian, the charged Higgsino mass and the Higgs to Higgsino coupling can be extracted as

$$-\mathcal{L} \supset \left(\mu - \frac{2}{\Lambda} H_u^0 H_d^0\right) \tilde{H}_u^+ \tilde{H}_d^- . \tag{3.3}$$

The charged Higgs scalar and Higgsino coupling terms are suppressed. Using

$$\mathrm{Re}\, H_d^0 = v_d + \frac{1}{\sqrt{2}}(H\cos\alpha - h\sin\alpha), \tag{3.4}$$

$$\mathrm{Re}\, H_u^0 = v_u + \frac{1}{\sqrt{2}}(H\sin\alpha + h\cos\alpha), \tag{3.5}$$

we obtain the Higgs to Higgsino coupling as

$$g_{hf\bar{f}} = -\frac{v}{\Lambda}\cos(\alpha+\beta), \tag{3.6}$$

where $v/\sqrt{2} = \sqrt{v_u^2 + v_d^2}$. If μ and Λ have the same signs, the Higgsino loop can provide a constructive contribution to the diphoton decay amplitude. However, in order to obtain a significant contribution, Λ has to be about $v\cos(\alpha+\beta)$, which means that a large size of non-renormalizable interaction is required.

The non-renormalizable term can induce the Higgs coupling to charged Higgs bosons. Using

$$H_d^+ = \chi^+\cos\beta - H^+\sin\beta, \tag{3.7}$$

$$H_u^+ = \chi^+\sin\beta + H^+\cos\beta, \tag{3.8}$$

where χ^+ is a Goldstone boson eaten by the W boson, we obtain

$$g_{hH^+H^-} = \frac{v\mu}{\Lambda}(\cos(3\beta-\alpha) - 3\cos(\alpha+\beta)) - \frac{v^3}{2\Lambda^2}(\cos(3\beta-\alpha) - 5\cos(\alpha+\beta))\sin 2\beta. \tag{3.9}$$

The Higgs coupling to vector bosons in two Higgs doublets is given as $g_{hVV} = g_{hVV}^{\mathrm{SM}}\sin(\beta-\alpha)$. If $h \to ZZ \to 4\ell$ is not reduced and W loop contribution to diphoton decay width in SM is kept, $\beta - \alpha$ should be about 90°. The first term of $g_{hH^+H^-}$ is expected to be larger than the second term because of $\mu \gg v$, and then, the absolute value of the coupling is maximized when

$\beta \sim -\alpha \sim 45^{\rm o}$. The Higgs coupling with the maximized magnitude is $g_{hH^+H^-} \simeq -4v\mu/\Lambda$, which is negative if $\mu/\Lambda > 0$.

The Higgs mass correction due to the non-renormalizable term is obtained as (see Appendix)[†]:

$$\Delta m_h^2 \simeq \frac{3v^4 \sin^2 2\beta}{\Lambda^2} - \frac{4\mu v^2 \sin 2\beta}{\Lambda}, \tag{3.10}$$

if the heavier neutral Higgs boson is decoupled. As explained, in order to obtain a significant enhancement of the diphoton decay rate, we require a sizable values of the Higgs couplings, and as a result, we need a large value of v/Λ (for Higgsino loop) or μ/Λ (for charge Higgs loop). In the case that Higgsino loop provides a significant contribution, v/Λ has to be very large if $\beta - \alpha \sim 90^{\rm o}$, and such a large value can induce too large correction to the Higgs mass to obtain 125 GeV mass. The charged Higgs loop can contribute to the diphoton decay, and enhance the decay width if $\mu/\Lambda > 0$. However, in that case, it reduces the SM-like Higgs mass. Although there is freedom to cancel those two corrections by adjusting $4\mu/\Lambda = 3v^2/\Lambda^2 \sin 2\beta$, such cancellation is not very natural.

Totally, the non-renormalizable term is not a good candidate of source to enhance the diphoton decay width. It is true that the term can generate the Higgs coupling to charged particles, but the direction to generate a constructive contribution to the decay amplitude reduces the Higgs boson mass. To obtain a significant contribution to the decay width, the size of non-renormalizable term needs to be large, and it can modify the Higgs boson mass too much. It may be possible to tune the Higgs mass to be 125 GeV with enhancing the decay width, but it is not a natural situation.

4 Non-perturbative Higgs model

Let us consider the following VEV-dependent fermion mass term:

$$-\mathcal{L} = \lambda\Lambda \frac{(|H|^2)^a}{\Lambda^{2a}} \bar{f} f. \tag{4.1}$$

[†]As one can find from the derivation in Appendix, the tree-level Higgs mass does not depend on the soft SUSY breaking mass parameters explicitly as long as Z boson mass is fixed. Therefore, we do not mention about the size of SUSY breaking to investigate the tree-level corrections to Higgs boson mass. As well-known, in MSSM, the minimization condition requires an unnatural cancellation between $-m_{H_u}^2$ and μ^2. However, in the model beyond MSSM we concern in this paper, the minimization condition is modified, and such unnatural cancellation is not required because the Higgs potential is lifted by a new term with a scale parameter Λ. As a consequence, a little hierarchy between the SUSY breaking masses and Z boson mass is not very unnatural contrary to MSSM.

Using $H = v/\sqrt{2} + (h + i\phi)/\sqrt{2}$, we obtain the mass and the Higgs coupling as

$$m_f = \lambda\Lambda \left(\frac{v^2}{2\Lambda^2}\right)^a, \qquad g_{hf\bar{f}} = 2\lambda a \frac{\Lambda}{v}\left(\frac{v^2}{2\Lambda^2}\right)^a, \tag{4.2}$$

and

$$\frac{g_{hf\bar{f}}}{m_f} = \frac{2a}{v}. \tag{4.3}$$

Therefore, as far as we consider the perturbative term (i.e. a is a natural number), the fermion loop provides a destructive contribution to the diphoton decay amplitude in SM. However, in non-perturbative case, the exponent a can be negative, and the fermion loop enhances the diphoton decay width. In fact, we know an example of negative a in SUSY QCD (SQCD) as a runaway potential generated by instanton effects [23].

In $SU(N)$ SQCD with N_f flavor, the runaway non-perturbative potential is generated if $N > N_f$. The representations of matter chiral superfields under the symmetry $SU(N) \times SU(N_f)_L \times SU(N_f)_R$ are

$$Q : (\mathbf{N}, \mathbf{N_f}, 1), \quad \bar{Q}(\bar{\mathbf{N}}, 1, \mathbf{N_f}). \tag{4.4}$$

The non-perturbative superpotential is

$$W \propto \frac{\Lambda^{3+\frac{2N_f}{N-N_f}}}{(\det \bar{Q}Q)^{\frac{1}{N-N_f}}}. \tag{4.5}$$

In order to construct a Higgs model, let us consider the case of $N_f = 2$. Suppose that $SU(N_f)_L$ is the weak gauge symmetry, and a $U(1)$ subgroup of $SU(N_f)_R$ is the hyper charge symmetry. (In this case, the color number N of SQCD should be even to eliminate $SU(2)_L$ anomaly). Moduli fields of SQCD, $\bar{Q}Q$, can be identified as a Higgs bidoublet:

$$\Lambda H_1^a = \bar{Q}_1 Q^a, \quad \Lambda H_2^a = \bar{Q}_2 Q^a. \tag{4.6}$$

One can easily find $\det \bar{Q}Q = \Lambda^2 H_1 \cdot H_2$ (where $\cdot$ stands for a SU(2) contract), and therefore, we obtain

$$W = c\frac{\Lambda^{3+2\kappa}}{(H_1 \cdot H_2)^\kappa}, \tag{4.7}$$

where $\kappa = 1/(N-2)$. This kind of superpotential for the composite Higgs model has been considered in [24]. Redefining Λ, we will choose $c = 1$ hereafter.

As it is called as runaway potential, if there is non-perturbative potential alone, the vacua goes to infinity along the flat direction. However, if the scalar potential is lifted due to SUSY breaking terms, the potential can be stabilized and the chiral symmetry is spontaneously

broken [25]. As a result, Higgsino mass is generated non-perturbatively, and its scale is determined by the non-perturbative scale Λ and the SUSY breaking scale. Therefore, this model can be one of the solution of so-called μ-problem (i.e. origin of the Higgsino mass).

The interesting point in this model is that the Higgsino loop generates a constructive contribution to the diphoton decay amplitude due to the fact that the fields are placed in the denominator.

Let us describe the Higgsino mass and the Higgs coupling from the superpotential:

$$W = \frac{\Lambda^{3+2\kappa}}{(H_u^0 H_d^0 - H_u^+ H_d^-)^\kappa}. \tag{4.8}$$

The Kähler metric of the Higgs fields may not be canonical. However, we assume the canonical form of the Kähler metric (just for simplicity), and we neglect terms from Kähler connection. Suppressing the charged Higgs scalar and Higgsino coupling terms, we obtain

$$\begin{aligned} -\mathcal{L} &\supset -\kappa\Lambda^{3+2\kappa}(H_u^0 H_d^0)^{-\kappa-1}\tilde{H}_u^+\tilde{H}_d^- && (4.9)\\ &= -\kappa\Lambda\left(\frac{\Lambda^2}{v_u v_d}\right)^{1+\kappa}\left(1-(\kappa+1)\frac{2}{v}\frac{\cos(\alpha+\beta)}{\sin 2\beta}h+\cdots\right)\tilde{H}_u^+\tilde{H}_d^-. && (4.10)\end{aligned}$$

and

$$\frac{g_{h\tilde{H}^+\tilde{H}^-}}{m_{\tilde{H}^+}} = -(\kappa+1)\frac{2}{v}\frac{\cos(\alpha+\beta)}{\sin 2\beta}. \tag{4.11}$$

Note that $\frac{\cos(\alpha+\beta)}{\sin 2\beta} \simeq 1$ if h is the SM-like Higgs (i.e. $\sin(\beta-\alpha)\simeq 1$) and the heavier Higgs mass is much larger than the Z boson mass (i.e. $\tan 2\alpha \simeq \tan 2\beta$). Therefore, it can easily generate the constructive contribution to the diphoton decay.

The ratio of the decay amplitude from top quark loop and Higgsino loop can be obtained as

$$\frac{A^{\gamma\gamma}_{\tilde{H}^+}}{A^{\gamma\gamma}_t} \simeq -\frac{2(1+\kappa)}{3(2/3)^2}\frac{A_{1/2}(\tau_{\tilde{H}^+})}{A_{1/2}(\tau_t)} \simeq -1.5\times(1+\kappa). \tag{4.12}$$

If the charged Higgsino is heavier than 100 GeV, $A_{1/2}$ loop function does not have much difference between top and Higgsino loops. The decay amplitude depends on $\kappa = 1/(N-2)$, and N is a number of color in SQCD. We find that the Higgs to Higgsino coupling can modify the SM amplitude about at least 40% ($1.5\times 1.84/(8.32-1.84) = 0.42$), and it can enhance the decay width twice as the SM one. Interestingly, the recent results at the ATLAS experiments, the center value of the diphoton rate is about twice as large as the SM prediction.

The scalar potential from the superpotential is obtained as

$$V = \Lambda^{6+4\kappa}\frac{|H_u^0|^2+|H_u^+|^2+|H_d^0|^2+|H_d^-|^2}{|H_u^0 H_d^0 - H_u^+ H_d^-|^{2(\kappa+1)}}. \tag{4.13}$$

The Higgs coupling to the charged Higgs from the non-perturbative scalar potential is

$$g_{hH^+H^-} = 4(1+\kappa)\left(\frac{\Lambda^2}{v_u v_d}\right)^{2(\kappa+1)} \frac{\Lambda^2}{v}\left(2(1+\kappa)\frac{\cos(\alpha+\beta)}{\sin 2\beta} - \sin(\beta-\alpha)\right). \tag{4.14}$$

The Higgs coupling to the charged Higgs bosons is positive for $\cos(\alpha+\beta)/\sin 2\beta \simeq 1$ and $\sin(\beta-\alpha) \simeq 1$, and it induces a destructive contribution to the diphoton decay amplitude. The charged Higgs mass can (mainly) come from SUSY breaking mass terms, and therefore, $g_{hH^+H^-}/m_{H^+}^2$ depends on the charged Higgs mass and is less predictive than the Higgsino case. If the charged Higgs is much heavier than the lightest Higgs boson, the contribution is not significant.

The neutral Higgs mass correction from the F-term scalar potential is obtained as

$$\Delta m_h^2 = 4(1+\kappa)(1+2\kappa)\Lambda^2\left(\frac{\Lambda^2}{v_u v_d}\right)^{2(1+\kappa)}. \tag{4.15}$$

We note that the correction of the Higgs boson mass is comparable to the Higgsino mass. Therefore, if there are no additional non-quadratic terms (quadratic terms are consumed to satisfy the stationary condition and those freedom is fixed by the VEVs of Higgs fields, and so, Higgs mass does not depend on the quadratic terms explicitly), the naive size of the Higgsino mass is about 100 GeV. However, such light Higgsino with a sizable coupling to Higgs is harmful phenomenologically, because the Higgsinos can be resonantly produced by the Higgs coupling to Higgsinos. At least, the neutral Higgsino (which can also have a large Higgs coupling) should not be the lightest SUSY particle (if R-parity conservation is assumed) since no missing energy is observed. Because of the non-perturbative effects, other types of SUSY breaking term can be generated, and it may break the naive relation between Higgs boson and Higgsino masses. One can add a VEV-independent Higgsino mass to avoid a possible difficulty, though the predictivity and the motivation to solve μ problem are lost. We do not go to the detail of the particle spectroscopy in this paper. The particle spectroscopy and the phenomenological study of the non-perturbative Higgs model will be studied somewhere else [26].

Before concluding this section, we comment on the Yukawa interaction to SM fermions. Possible Yukawa interaction to top quark is generated by a non-renormalizable term

$$W_Y = \frac{1}{M_*} q_L t_R^c Q \bar{Q}_2, \tag{4.16}$$

where q_L is a left-handed quark doublet and t_R^c is a right-handed quark field. As described in this section, the (up-type) Higgs superfield is a composite of the SQCD fields Q, $\bar{Q}$:

$H_u = Q\bar{Q}/\Lambda$. A proper top mass requires $M_* \sim \Lambda$. In order to obtain a proper size of top quark mass, one can also consider an extension of the SQCD model in which top quark fields are also moduli fields in SQCD. For example, the number of SQCD flavor is chosen as $N_f = 6$, and the SM gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$ is a subgroup of $SU(6)_L \times SU(6)_R$. In order to describe it simply, let us use Pati-Salam symmetry base: $SU(4)_c \times SU(2)_L \times SU(2)_R$ (The gauged symmetry can be the SM subgroup of the Pati-Salam symmetry). $SU(4) \times SU(2) \times U(1)$ is a subgroup of $SU(6)$, and diagonal subgroup of $SU(4)_L \times SU(4)_R$ is $SU(4)_c$. The composite field $\bar{Q}Q$ can be decomposed as

$$\begin{pmatrix} H : (\mathbf{1}, \mathbf{2}, \mathbf{2}) & L : (\mathbf{4}, \mathbf{2}, \mathbf{1}) \\ \bar{R} : (\bar{\mathbf{4}}, \mathbf{1}, \mathbf{2}) & \Sigma : (\mathbf{15}, \mathbf{1}, \mathbf{1}) + S : (\mathbf{1}, \mathbf{1}, \mathbf{1}) \end{pmatrix}. \tag{4.17}$$

The third generation fields (top, bottom and tau) are unified in the SQCD moduli fields $L, \bar{R}$. The non-perturbative superpotential is $W_{np} \propto 1/(\det \bar{Q}Q)^\alpha$, and $\det \bar{Q}Q = (S+\Sigma)^4 H_1 H_2 + L\bar{R}H(S+\Sigma)^3 + LL\bar{R}\bar{R}(S+\Sigma)^2 + \cdots$. The fermion masses of the third generation are obtained by $\frac{\partial^2 W_{np}}{\partial L \partial \bar{R}}$, and the order 1 size of (effective) Yukawa coupling can be generated naturally. In this setup, the Higgs couplings to fermions can be different from the SM ones. Actually, the signature of the Higgs coupling to top quarks can be opposite to SM in the same way as Higgsino case, and top quark contribution can become constructive to the W boson loop. In this kind of model, the Higgs coupling to SM fermions may be different from SM and further investigation is needed. The LHC experiments have not yet observed $h \to \tau\tau$ and $h \to bb$ via Yukawa couplings (though $h \to bb$ is indicated by Tevatron [27])[‡].

5 Conclusion and Discussion

The observation of a new boson which is consistent with SM opens a new era of Higgs physics. It is important to investigate all the decay modes to see that the new boson is really identified to the SM Higgs boson. Among the decay modes, a possible hint beyond SM is the enhancement of diphoton decay rate indicated by ATLAS/CMS measurements. The diphoton decay rate is larger than the SM expectation since the 2011 data, though there is no enough statistics yet. The Higgs to diphoton decay is induced at the loop level, and therefore, it is sensitive to new physics beyond SM. Motivated from the excess of diphoton decay rate, we investigate the possibility if the loop diagram via Higgsino (which is a superpartner of the Higgs boson) can enhance the diphoton decay width.

[‡]The CMS and ATLAS experiments are starting to observe these channels but there is still room for considerations of new physics [28].

We first analyze an additional non-renormalizable term of Higgs fields. The higher order term can introduce the Higgs coupling to Higgsino as well as charged Higgs bosons. In this type of model, however, we learn that the choice of the Higgs coupling to obtain a significant size of constructive contribution to the diphoton decay amplitude in SM via W boson loop can reduce the Higgs boson mass (which is not preferable to obtain 125 GeV Higgs boson mass since the MSSM Higgs boson mass is less than Z boson mass at the tree-level) and/or the size of non-renormalizable term needs to be large and a cutoff scale may be just around the weak scale. There may be a solution in a complicate situation, but it is not quite attractive.

We suggest another model in which the Higgsino mass term is generated by a non-perturbative instanton effect via a strong dynamics in SUSY QCD. In this kind of model, the bosonic fields are in the denominator of the operator, and thus, the Higgs coupling to fermions flips its sign compared to the perturbative (polynomial) interaction. As a result, the constructive contribution to the diphoton decay amplitude is easily obtained. If the Higgsino mass purely comes from the non-perturbative superpotential, the loop correction of the diphoton decay amplitude is predictive, and the Higgsino loop can enhance the decay width (more than) twice as large as SM prediction. Interestingly, the current center value of the diphoton decay rate is about two times larger than the SM expectation.

Various types of non-perturbative Higgs coupling can be constructed using the strong dynamics in SQCD. In those models, the Higgs couplings to the quarks and leptons can be also modified from the SM ones. The LHC experiments will soon provide tons of data to see various decay modes, and the non-perturbative Higgs model can be tested.

A Appendix: Higgs mass

In this appendix, we show how to obtain the (tree-level) physical Higgs mass in a general form scalar potential.

In the beginning, let us describe a case of single Higgs doublet H. The scalar potential is in general a function of $|H|^2$:

$$V = V(|H|^2). \tag{A.1}$$

Denoting

$$H = \begin{pmatrix} \chi^+ \\ \frac{v}{\sqrt{2}} + \frac{h+i\chi}{\sqrt{2}} \end{pmatrix}, \tag{A.2}$$

we obtain

$$|H|^2 = \frac{v^2}{2} + vh + \frac{h^2+\chi^2}{2} + \chi^+\chi^-. \tag{A.3}$$

Expanding the potential around the VEV v, we obtain

$$V = V(v^2/2) + V'(v^2/2)(vh + \frac{h^2+\chi^2}{2} + \chi^+\chi^-) + \frac{1}{2}V''(v^2/2)(vh + \frac{h^2+\chi^2}{2} + \chi^+\chi^-)^2. \quad \text{(A.4)}$$

The stationary condition (vanishing the linear term of h) is $V' = 0$. Then, one can find that χ and χ^+ are massless Goldstone bosons, and would be eaten by the gauge bosons. The mass of the physical Higgs boson h is easily obtained as $m_h^2 = v^2 V''$. For example, in ϕ^4 theory, $V(x) = m^2 x + \lambda x^2$, and we obtain $m_h^2 = 2\lambda v^2$.

In the case of two Higgs doublet H_1, H_2, the scalar potential is a function of $|H_1|^2$, $|H_2|^2$ and $H_1 \cdot H_2$. In order to make the following calculation simple, it is convenient to define linear combinations of the Higgs doublet:

$$\Phi_1 = H_1 \cos\beta + \hat{H}_2 \sin\beta, \quad \Phi_2 = -H_1 \sin\beta + \hat{H}_2 \cos\beta, \quad \text{(A.5)}$$

where $\hat{H} = i\sigma_2 H^*$, so that the VEV of Φ_2^0 is zero by definition. We define

$$x = |\Phi_1|^2, \quad y = |\Phi_2|^2, \quad z = \Phi_1 \cdot \hat{\Phi}_2, \quad \bar{z} = \Phi_2 \cdot \hat{\Phi}_1, \quad \text{(A.6)}$$

and the general potential is a function $V(x, y, z, \bar{z})$. The stationary conditions are $V_x = V_z = V_{\bar{z}} = 0$, where V_x denotes a partial derivative by x for example.

Expanding the potential around the VEV, $\langle x \rangle = v^2/2$, we obtain the mass term of the neutral Higgs bosons:

$$\frac{1}{2}\begin{pmatrix} \Phi_1^0 & \Phi_2^0 \end{pmatrix} \begin{pmatrix} v^2 V_{xx} & \frac{v^2}{2}(V_{xz} + V_{x\bar{z}}) \\ \frac{v^2}{2}(V_{xz} + V_{x\bar{z}}) & V_y + \frac{1}{4}v^2(V_{zz} + V_{\bar{z}\bar{z}} + 2V_{z\bar{z}}) \end{pmatrix} \begin{pmatrix} \Phi_1^0 \\ \Phi_2^0 \end{pmatrix}. \quad \text{(A.7)}$$

If V_y is large and Φ_1^0-Φ_2^0 mixing is small, Φ_1^0 is roughly the lightest Higgs boson, and $m_h^2 \simeq v^2 V_{xx}$. The mass of CP odd Higgs boson A is obtained as $m_A^2 = V_y + \frac{1}{4}v^2(-V_{zz} - V_{\bar{z}\bar{z}} + 2V_{z\bar{z}})$. The charged Higgs mass is $m_{H^+}^2 = V_y$.

The Higgs mass corrections from the additional potential in the text are obtained by $v^2 V_{xx}$ by using the following expressions :

$$|H_1|^2 = x\cos^2\beta + y\sin^2\beta - \frac{1}{2}(z + \bar{z})\sin 2\beta, \quad \text{(A.8)}$$

$$|H_2|^2 = x\sin^2\beta + y\cos^2\beta + \frac{1}{2}(z + \bar{z})\sin 2\beta, \quad \text{(A.9)}$$

$$H_1 \cdot H_2 = \frac{1}{2}(x - y)\sin 2\beta + z\cos^2\beta - \bar{z}\sin^2\beta. \quad \text{(A.10)}$$

We exhibit examples of the Higgs mass calculations using the general expressions above. First, we consider the case of MSSM. The D-term scalar potential in terms of $|H_1|^2$, $|H_2|^2$ and

$H_1 \cdot H_2$ is $V_D = (g^2+g'^2)/8(|H_1|^2-|H_2|^2)^2+g^2/2(|H_1|^2|H_2|^2-|H_1\cdot H_2|^2)$. Extracting the neutral component of the potential (in order to exhibit the essential part), we obtain the quartic Higgs coupling as $g_Z^2/8(|H_1^0|^2-|H_2^0|^2)^2 = g_Z^2/8(x-y)^2\cos^2 2\beta$, where $g_Z^2 = g^2+g'^2$. Because $V_{xx}|_{y=0} = g_Z^2/4\cos^2 2\beta$, the lightest Higgs mass is roughly obtained as $m_h^2 \simeq g_Z^2/4v^2\cos^2 2\beta = M_Z^2\cos^2 2\beta$ at the tree-level.

Secondly, let us derive the Higgs mass corrections from simple extensions of MSSM. In the case of Next-to-MSSM, $\lambda S H_1\cdot H_2$ term in the superpotential generates a quartic Higgs coupling $\lambda^2|H_1\cdot H_2|^2 = \lambda^2|1/2(x-y)\sin 2\beta + z\cos^2\beta - \bar{z}\sin^2\beta|^2$. One obtains $\partial^2|H_1\cdot H_2|^2/\partial x^2|_{y=z=\bar{z}=0} = 1/2\sin^2 2\beta$, and $\Delta m_h^2 \simeq v^2\lambda^2\partial^2|H_1\cdot H_2|^2/\partial x^2 = \lambda^2 v^2/2\sin^2 2\beta$. For small $\tan\beta$, this contribution is helpful to enlarge the lightest Higgs mass as it is well known. One can add an SU(2) adjoint Σ (with hypercharge $Y=-1$) and a superpotential term $\lambda_2 H_2^\alpha H_2^\beta \Sigma_{\alpha\beta}$ (α and β are SU(2) indices). Then, additional potential $\lambda_2^2|H_2|^4$ is generated, and we obtain $\Delta m_h^2 \simeq 2\lambda_2^2 v^2\sin^4\beta$. This term is helpful to enlarge the Higgs mass in the case of large $\tan\beta$.

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