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Gauge-Higgs unification at CERN LHC

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The Higgs boson production by the gluon fusion and its decay into two photons at the LHC are investigated in the context of the gauge-Higgs unification scenario. The qualitative behaviors for these processes in the gauge-Higgs unification are quite distinguishable from those of the standard model and the universal extra dimension scenario because of the overall sign difference for the effective couplings induced by one-loop corrections through the Kaluza-Klein modes. For the Kaluza-Klein mode mass smaller than 1 TeV, the Higgs production cross section and its branching ratio into two photons are sizably deviated from those in the standard model. Associated with the discovery of the Higgs boson, this deviation may be measured at the LHC.

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I. INTRODUCTION

The gauge-Higgs unification [1] is a very fascinating scenario beyond the standard model (SM) since the SM Higgs doublet is identified with the extra component of the higher dimensional gauge field, and its mass squared correction is predicted to be finite [2] regardless of the nonrenormalizable theory. This fact has opened a new possibility to solve the gauge hierarchy problem without, for example, supersymmetry. The finiteness of the Higgs mass has been discussed and checked by the various explicit calculations [3]. Furthermore, there has attracted a large amount of attention from the various viewpoints [4–24].

The Large Hadron Collider (LHC) will start its operation soon and the collider signatures of various new physics models beyond the SM have been extensively studied. However, as far as we know, the gauge-Higgs unification has not been so much explored from this respect. The gauge-Higgs unification shares the similar structure with the universal extra dimension (UED) scenario [25] [26]; namely, in effective the four dimensional theory, Kaluza-Klein (KK) states of the standard model particles appear. The collider phenomenology on the KK particles will be quite similar to the one in the UED scenario. A crucial difference should lie in the Higgs sector, because the Higgs doublet originates from the higher dimensional gauge field. The discovery of the Higgs boson is expected at the LHC, by which the origin of the electroweak symmetry breaking and the mechanism responsible for generating fermion masses will be revealed. Precise measurements of the Higgs boson properties will provide us the information of a new physics relevant to the Higgs sector.

In this paper, we investigate the effect of the gauge-Higgs unification on the Higgs boson phenomenology at the LHC, namely, the production and decay processes of the Higgs boson. At the LHC, the gluon fusion is the dominant Higgs boson production process and for the light Higgs boson with mass $m_h < 150$ GeV, the two photon decay mode of the Higgs boson becomes the primary discovery mode [27], nevertheless its branching ratio is $\mathcal{O}(10^{-3})$. The coupling between the Higgs boson and these gauge bosons are induced through quantum corrections at one-loop level, even in the standard model. Therefore, we can expect a sizable effect from new particles if they contribute to the coupling at the one-loop level. In a five dimensional gauge-Higgs unification model, we calculate one-loop diagrams with KK fermions for the effective couplings between the Higgs boson and the gauge bosons (gluons and photons). If the KK mass scale is small enough, we can see a sizable deviation from the SM couplings, and as a result, the number of signal events from the Higgs production at the LHC can be altered from the SM one. Interestingly, reflecting the special structure of the Higgs sector in the gauge-Higgs unification, there is a clear qualitative difference from the UED scenario; the signs of the effective couplings are opposite to those in the UED scenario.

II. TOY MODEL

In this paper, we consider a toy model of five dimensional (5D) $SU(3)$ gauge-Higgs unification with an orbifold S^1/Z_2 compactification in order to avoid unnecessary complications for our discussion. Although the predicted Weinberg angle in this toy model is unrealistic, $\sin^2\theta_W = \frac{3}{4}$, this does not affect our analysis. We introduce an $SU(3)$ triplet fermion as a matter field, which is identified with top and bottom quarks and their KK excited states, although the top quark mass vanishes and the bottom quark mass

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$m_b = M_W$ in this toy model. In this work, we neglect other generations since the effects of light generations are very small comparing to the effect by the top quark.

The $SU(3)$ gauge symmetry is broken to $SU(2) \times U(1)$ by the orbifolding on S^1/Z_2 and adopting a nontrivial Z_2 parity assignment for the members of an irreducible representation of $SU(3)$, as stated below. The remaining gauge symmetry $SU(2) \times U(1)$ is supposed to be broken by the vacuum expectation value (VEV) of the zero mode of A_5, the extra space component of the gauge field identified with the SM Higgs doublet, through the Hosotani mechanism [4]. We do not address the origin of the $SU(2) \times U(1)$ gauge symmetry breaking and the resultant Higgs boson mass in the one-loop effective Higgs potential, which is highly model dependent and out of our scope in this paper.

The Lagrangian is simply given by

$$\mathcal{L} = -\frac{1}{2}\mathrm{Tr}(F_{MN}F^{MN}) + i\bar{\Psi}\not{D}\Psi \tag{1}$$

where $\Gamma^M = (\gamma^\mu, i\gamma^5)$,

$$F_{MN} = \partial_M A_N - \partial_N A_M - ig_5[A_M, A_N] \quad (M, N = 0, 1, 2, 3, 5), \tag{2}$$

$$\not{D} = \Gamma^M(\partial_M - ig_5 A_M) \quad \left(A_M = A_M^a \frac{\lambda^a}{2} (\lambda^a\text{: Gell-Mann matrices})\right), \tag{3}$$

$$\Psi = (\psi_1, \psi_2, \psi_3)^T. \tag{4}$$

The periodic boundary conditions are imposed along S^1 for all fields. The nontrivial Z_2 parities are assigned for each field as follows,

$$A_\mu = \begin{pmatrix} (+,+) & (+,+) & (-,-) \\ (+,+) & (+,+) & (-,-) \\ (-,-) & (-,-) & (+,+) \end{pmatrix}, \quad A_5 = \begin{pmatrix} (-,-) & (-,-) & (+,+) \\ (-,-) & (-,-) & (+,+) \\ (+,+) & (+,+) & (-,-) \end{pmatrix}, \tag{5}$$

$$\Psi = \begin{pmatrix} \psi_{1L}(+,+) + \psi_{1R}(-,-) \\ \psi_{2L}(+,+) + \psi_{2R}(-,-) \\ \psi_{3L}(-,-) + \psi_{3R}(+,+) \end{pmatrix}, \tag{6}$$

where $(+,+)$ means that Z_2 parities are even at the fixed points $y = 0$ and $y = \pi R$, for instance. y is the fifth coordinate and R is the compactification radius. $\psi_{1L} \equiv \frac{1}{2} \times (1 - \gamma_5)\psi_1$, etc.

Following these boundary conditions, KK mode expansions for the gauge fields and the fermions are carried out.

$$A_{\mu,5}^{(+,+)}(x, y) = \frac{1}{\sqrt{2\pi R}}\left[A_{\mu,5}^{(0)}(x) + \sqrt{2}\sum_{n=1}^{\infty} A_{\mu,5}^{(n)}(x) \times \cos(ny/R)\right], \tag{7}$$

$$A_{\mu,5}^{(-,-)}(x, y) = \frac{1}{\sqrt{\pi R}}\sum_{n=1}^{\infty} A_{\mu,5}^{(n)}(x)\sin(ny/R), \tag{8}$$

$$\psi_{1L,2L,3R}^{(+,+)}(x, y) = \frac{1}{\sqrt{2\pi R}}\left[\psi_{1L,2L,3R}^{(0)}(x) + \sqrt{2}\sum_{n=1}^{\infty}\psi_{1L,2L,3R}^{(n)}(x)\cos(ny/R)\right], \tag{9}$$

$$\psi_{3L,1R,2R}^{(-,-)}(x, y) = i\frac{1}{\sqrt{\pi R}}\sum_{n=1}^{\infty}\psi_{3L,1R,2R}^{(n)}(x)\sin(ny/R). \tag{10}$$

For the zero mode of the bosonic sector, we obtain exactly what we need for the standard model,

$$A_\mu^{(0)} = \frac{1}{2}\begin{pmatrix} W_\mu^3 + \frac{B_\mu}{\sqrt{3}} & \sqrt{2}W_\mu^+ & 0 \\ \sqrt{2}W_\mu^- & -W_\mu^3 + \frac{B_\mu}{\sqrt{3}} & 0 \\ 0 & 0 & -\frac{2}{\sqrt{3}}B_\mu \end{pmatrix}, \quad A_5^{(0)} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 & h^+ \\ 0 & 0 & h^0 \\ h^- & h^{0*} & 0 \end{pmatrix}, \tag{11}$$

where W_μ^3, $W_\mu^\pm$, B_μ are $SU(2)_L$, $U(1)_Y$ gauge fields, respectively, and $h = (h^+, h^0)^t$ is the Higgs doublet. For the zero mode in the fermion sector, a fermion corresponding to the right-handed top quark t_R is missing as we mentioned above,

$$\Psi^{(0)} = \begin{pmatrix} t_L \\ b_L \\ b_R \end{pmatrix}. \tag{12}$$

In order to obtain a realistic model, a more elaborate gauge-Higgs unification model should be considered. The $SU(2)_L \times U(1)_Y$ gauge symmetry is broken by the Higgs VEV, $\langle h^0 \rangle = v/\sqrt{2}$, in other words, $\langle A_5 \rangle = v/2\lambda_6$.

After the gauge symmetry breaking, 4D effective Lagrangian among KK fermions, the SM gauge boson and Higgs boson (h) defined as $h^0 = (v + h)/\sqrt{2}$ can be derived from the term $\mathcal{L}_{\rm fermion} = i\bar{\Psi}D/\Psi$ in Eq. (1). Integrating over the fifth dimensional coordinate, we obtain a 4D effective Lagrangian,

$$\mathcal{L}^{(4D)}_{\text{fermion}} = \sum_{n=1}^{\infty}\left\{ i(\bar\psi_1^{(n)}, \bar\psi_2^{(n)}, \bar\psi_3^{(n)})\gamma^\mu\partial_\mu\begin{pmatrix}\psi_1^{(n)}\\ \psi_2^{(n)}\\ \psi_3^{(n)}\end{pmatrix} + \frac{g}{2}(\bar\psi_1^{(n)}, \bar\psi_2^{(n)}, \bar\psi_3^{(n)})\begin{pmatrix} W^3_\mu + \frac{B_\mu}{\sqrt3} & \sqrt2 W^+_\mu & 0\\ \sqrt2 W^-_\mu & -W^3_\mu + \frac{B_\mu}{\sqrt3} & 0\\ 0 & 0 & -\frac{2}{\sqrt3}B_\mu\end{pmatrix}\gamma^\mu\begin{pmatrix}\psi_1^{(n)}\\ \psi_2^{(n)}\\ \psi_3^{(n)}\end{pmatrix} \right.$$
$$\left. - (\bar\psi_1^{(n)}, \bar\psi_2^{(n)}, \bar\psi_3^{(n)})\begin{pmatrix} m_n & 0 & 0\\ 0 & m_n & -(m+gh)\\ 0 & -(m+gh) & m_n\end{pmatrix}\begin{pmatrix}\psi_1^{(n)}\\ \psi_2^{(n)}\\ \psi_3^{(n)}\end{pmatrix}\right\}$$
$$+ i\bar t_L\gamma^\mu\partial_\mu t_L + \bar b(i\gamma^\mu\partial_\mu - m - gh)b + \frac{g}{\sqrt2}(\bar t\gamma_\mu P_L b W^{+\mu} + \bar b\gamma_\mu P_L t W^{-\mu}) + \frac{g}{2}(\bar t\gamma_\mu P_L t - \bar b\gamma_\mu P_L b)W_3^\mu$$
$$+ \frac{\sqrt3 g}{6}(\bar t\gamma_\mu P_L t + \bar b\gamma_\mu P_L b - 2\bar b\gamma_\mu P_R b)B^\mu, \tag{13}$$

where $P_L \equiv \frac12(1-\gamma_5)$, $m_n = \frac{n}{R}$, $g = \frac{g_5}{\sqrt{2\pi R}}$ is the 4D gauge coupling, and $m = \frac{gv}{2}(= M_W)$ is the bottom quark mass in this toy model. In deriving the 4D effective Lagrangian (13), a chiral rotation

$$\psi_{1,2,3} \to e^{-i(\pi/4)\gamma_5}\psi_{1,2,3} \tag{14}$$

has been made in order to get rid of $i\gamma_5$.

We easily see that the mass matrix for the KK modes can be diagonalized by use of the mass eigenstates $\tilde\psi_2^{(n)}$, $\tilde\psi_3^{(n)}$,

$$\begin{pmatrix}\psi_1^{(n)}\\ \tilde\psi_2^{(n)}\\ \tilde\psi_3^{(n)}\end{pmatrix} = U\begin{pmatrix}\psi_1^{(n)}\\ \psi_2^{(n)}\\ \psi_3^{(n)}\end{pmatrix}, \qquad U = \frac{1}{\sqrt2}\begin{pmatrix}\sqrt2 & 0 & 0\\ 0 & 1 & -1\\ 0 & 1 & 1\end{pmatrix}, \tag{15}$$

as

$$U\begin{pmatrix} m_n & 0 & 0\\ 0 & m_n & -m\\ 0 & -m & m_n\end{pmatrix}U^\dagger = \begin{pmatrix} m_n & 0 & 0\\ 0 & m_n+m & 0\\ 0 & 0 & m_n - m\end{pmatrix}. \tag{16}$$

Note that the mass splitting $m_\pm^{(n)} \equiv m_n \pm m$ occurs associated with a mixing between the $SU(2)$ doublet component and singlet component. Each of the mass eigenvalues has a periodicity with respect to m: $m_n \pm (m + \frac1R) = m_{n\pm1} \pm m$, which is a remarkable feature of the gauge-Higgs unification, not shared in the UED scenario, where the mass of KK modes is given by $\sqrt{m_n^2 + m^2}$.

In terms of the mass eigenstates for nonzero KK modes, the Lagrangian is described as

$$\mathcal{L}^{(4D)}_{\text{fermion}} = \sum_{n=1}^{\infty}\left\{ (\bar\psi_1^{(n)}, \bar{\tilde\psi}_2^{(n)}, \bar{\tilde\psi}_3^{(n)})\begin{pmatrix} i\gamma^\mu\partial_\mu - m_n & 0 & 0\\ 0 & i\gamma^\mu\partial_\mu - (m_+^{(n)} + \frac{m}{v}h) & 0\\ 0 & 0 & i\gamma^\mu\partial_\mu - (m_-^{(n)} - \frac{m}{v}h)\end{pmatrix}\begin{pmatrix}\psi_1^{(n)}\\ \tilde\psi_2^{(n)}\\ \tilde\psi_3^{(n)}\end{pmatrix}\right.$$
$$\left. + \frac{g}{2}(\bar\psi_1^{(n)}, \bar{\tilde\psi}_2^{(n)}, \bar{\tilde\psi}_3^{(n)})\begin{pmatrix} W^3_\mu + \frac{\sqrt3 B_\mu}{3} & W^+_\mu & W^+_\mu\\ W^-_\mu & -\frac{W^3_\mu}{2} - \frac{\sqrt3 B_\mu}{6} & -\frac{W^3_\mu}{2} + \frac{\sqrt3 B_\mu}{2}\\ W^-_\mu & -\frac{W^3_\mu}{2} + \frac{\sqrt3 B_\mu}{2} & -\frac{W^3_\mu}{2} - \frac{\sqrt3 B_\mu}{6}\end{pmatrix}\gamma^\mu\begin{pmatrix}\psi_1^{(n)}\\ \tilde\psi_2^{(n)}\\ \tilde\psi_3^{(n)}\end{pmatrix}\right\} + \text{zero-mode part.} \tag{17}$$

The relevant Feynman rules for our calculation can be read off from this Lagrangian. Note that the mass eigenstate for $m_+^{(n)}$ has the Yukawa coupling $-m/v$, which is exactly the same as the one for the zero mode, while the Yukawa coupling of the mass eigenstate for $m_-^{(n)}$ has an opposite sign, $+m/v$. Together with the mass splitting of KK modes, this property is a general one realized in any gauge-Higgs unification model and leads to a clear qualitative difference of the gauge-Higgs unification from the UED scenario, as we will see.

III. EFFECTIVE COUPLINGS BETWEEN HIGGS BOSON AND GAUGE BOSONS

Before calculating contributions of KK fermions to one-loop effective couplings between Higgs boson and gauge bosons (gluons and photons), it is instructive to recall the SM result. We parametrize the effective coupling between the Higgs boson and gluons as

$$\mathcal{L}_{\text{eff}} = C_g^{\text{SM}} h G^{a\mu\nu}G^a_{\mu\nu}, \tag{18}$$

where $G^a_{\mu\nu}$ is a gluon field strength tensor. This coupling is generated by one-loop corrections (triangle diagram) on which quarks are running. The top quark loop diagram gives the dominant contribution and the coupling $C_g^{\rm SM}$ is described in the following instructive form:

$$C_g^{\rm SM} = -\frac{m_t}{v} \times \frac{\alpha_s F_{1/2}(4m_t^2/m_h^2)}{8\pi m_t} \times \frac{1}{2}, \qquad (19)$$

where, in the right-hand side, the first term, $-\frac{m_t}{v}$, is top Yukawa coupling, the second term is from the loop integral with the QCD coupling α_s at QCD vertexes, the loop function $F_{1/2}(\tau)$ given by (for $\tau \geq 1$)

$$F_{1/2}(\tau) = -2\tau(1 + (1-\tau)[\sin^{-1}(1/\sqrt{\tau})]^2) \rightarrow -\tfrac{4}{3} \quad \text{for } \tau \gg 1, \qquad (20)$$

and $1/2$ is a QCD group factor (Dynkin index). Mass of the fermion (top quark) running the loop appears in the denominator in the second term, which is canceled with top quark mass from the Yukawa coupling. It is well-known that in the top quark decoupling limit, namely, top quark mass m_t is much heavier than the Higgs boson mass m_h, $F_{1/2}$ becomes a constant and the resultant effective coupling becomes independent of m_t and m_h.

Calculations of KK mode contributions are completely analogous to the top loop correction. The structure described in our toy model is common in any gauge-Higgs unification model and in some realistic model, we will have KK modes of top quark with mass eigenvalue $m_\pm^{(n)} = m_n \pm m_t$ and Yukawa couplings $\mp m_t/v$, respectively. The KK mode contributions in the gauge-Higgs (GH) unification $C_g^{\rm KK(GH)}$ are found to be

$$\mathcal{L}_{\rm eff} = C_g^{\rm KK(GH)} h G^{a\mu\nu} G^a_{\mu\nu},$$

$$C_g^{\rm KK(GH)} = -\sum_{n=1}^{\infty}\left[\frac{m_t}{v} \times \frac{\alpha_s F_{1/2}(4m_+^{(n)2}/m_h^2)}{8\pi m_+^{(n)}} \times \frac{1}{2}\right] + \sum_{n=1}^{\infty}\left[\frac{m_t}{v} \times \frac{\alpha_s F_{1/2}(4m_-^{(n)2}/m_h^2)}{8\pi m_-^{(n)}} \times \frac{1}{2}\right] \simeq \frac{m_t \alpha_s}{12\pi v}\sum_{n=1}^{\infty}\left[\frac{1}{m_+^{(n)}} - \frac{1}{m_-^{(n)}}\right] \simeq -\frac{\alpha_s}{6\pi v}\sum_{n=1}^{\infty}\frac{m_t^2}{m_n^2}, \qquad (21)$$

where we have taken the limit m_h^2, $m_t^2 \ll m_n^2$, to simplify the results. Note that this result is finite and this finiteness is a consequence of cancellation between two divergent corrections with opposite signs. Also, note that the KK mode contribution is subtractive against the top quark contribution in the SM.

It is interesting to compare our result to that in the UED scenario [28,29], where the KK mode mass spectrum and Yukawa couplings are given by $M_n = \sqrt{m_n^2 + m_t^2}$ without mass splitting and $-(m_t/v) \times (m_t/M_n)$, respectively. In this case, we find

$$\mathcal{L}_{\rm eff} = C_g^{\rm KK(UED)} h G^{a\mu\nu} G^a_{\mu\nu},$$

$$C_g^{\rm KK(UED)} = -\sum_{n=1}^{\infty}\left[\frac{m_t}{v}\frac{m_t}{M_n} \times \frac{\alpha_s F_{1/2}(4M_n^2/m_h^2)}{8\pi M_n} \times \frac{1}{2}\right] \times 2 \simeq \frac{\alpha_s}{6\pi v}\sum_{n=1}^{\infty}\frac{m_t^2}{m_n^2}, \qquad (22)$$

where we have, again, taken the limit m_h^2, $m_t^2 \ll m_n^2$, to simplify the result. In the limit, we arrive at the same result as the one in the gauge-Higgs unification model, except for the sign. This KK mode contribution is constructive to the top quark one in the SM.

The contribution of top quark KK modes to the effective coupling between Higgs boson and photons is calculated in the same way. In fact, the final result can be obtained by the replacements, $\alpha_s \rightarrow \alpha_{\rm em}$ and the group factor $1/2 \rightarrow Q_t^2 \times 3$, top quark electric charge^2 $\times$ number of colors,

$$\mathcal{L}_{\rm eff} = C_\gamma^{{\rm KK}(GH)} h F^{\mu\nu} F_{\mu\nu},$$

$$C_\gamma^{{\rm KK}(GH)} = -\sum_{n=1}^{\infty}\left[\frac{m_t}{v} \times \frac{\alpha_{\rm em} F_{1/2}(4m_+^{(n)2}/m_h^2)}{8\pi m_+^{(n)}} \times \frac{4}{3}\right] + \sum_{n=1}^{\infty}\left[\frac{m_t}{v} \times \frac{\alpha_{\rm em} F_{1/2}(4m_-^{(n)2}/m_h^2)}{8\pi m_-^{(n)}} \times \frac{4}{3}\right] \simeq \frac{2m_t \alpha_{\rm em}}{9\pi v}\sum_{n=1}^{\infty}\left[\frac{1}{m_+^{(n)}} - \frac{1}{m_-^{(n)}}\right] \simeq -\frac{4\alpha_{\rm em}}{9\pi v}\sum_{n=1}^{\infty}\frac{m_t^2}{m_n^2}, \qquad (23)$$

where we have taken the limit m_h^2, $m_t^2 \ll m_n^2$, to simplify the results. For the effective coupling with photons, in addition to the KK fermion contributions, there is another contribution, namely, the KK W-boson loop corrections, as in the SM. This calculation is quite complicated, because we have to include contributions by KK Nambu-Goldstone bosons and KK ghosts, according to the five dimensional gauge invariance. In this paper, we neglect such contributions compared to those from the KK top quark contributions for the following reasons: First, the KK mode contributions are decoupling effects, and the KK top quark and KK W-boson loop contributions are proportional to top quark mass squared and W-boson mass squared, respectively. Top quark is much heavier than the W boson, so that KK top quark contributions are likely to be dominant. Second, in the gauge-Higgs unification, Yukawa coupling is nothing but the gauge coupling and a fermion mass is naturally the same as a W-boson mass and this is too small for the realistic top quark mass. One way to ameliorate this problem is to introduce a large dimensional representation as discussed in [12], in which the SM top quark is implemented, so that the top Yukawa coupling can be correctly reproduced with a Clebsch-Gordan coefficient (a factor 2 is suitable). In this setup, the effective 4D theory includes extra vectorlike toplike quarks and its KK modes. Thus, the fermion KK mode contributions are enhanced by a number of extra toplike quarks. Third, in some gauge-Higgs unification models, bulk toplike quarks with the half-periodic boundary condition are often introduced to realize the correct electroweak symmetry breaking and a Higgs boson mass consistent with the current experimental lower bound. The lowest KK mass of the half-periodic fermions is half of the lowest KK mass of periodic fields, so that their loop contributions can dominate over those by periodic KK mode fields.

In the SM, both the top and W-boson loop corrections should be taken into account because of nondecoupling effects that for a light Higgs boson, the effective coupling is not so sensitive to top and W-boson masses. The effective coupling between the Higgs boson and two photons is given by

$$\mathcal{L}_{\rm eff} = C_\gamma^{\rm SM} h F^{\mu\nu} F_{\mu\nu}, \tag{24}$$

where the coupling is the sum of the top loop contribution ($C_{\gamma,t}^{\rm SM}$) and the W-boson loop contribution ($C_{\gamma,W}^{\rm SM}$) such as

$$\begin{aligned} C_{\gamma,t}^{\rm SM} &= -\frac{m_t}{v} \times \frac{\alpha_{\rm em} F_{1/2}(4m_t^2/m_h^2)}{8\pi m_t} \times \frac{4}{3}, \\ C_{\gamma,W}^{\rm SM} &= -\frac{m_W^2}{v} \times \frac{\alpha_{\rm em} F_1(4m_W^2/m_h^2)}{8\pi m_W^2} \end{aligned} \tag{25}$$

with the loop function,

$$\begin{aligned} F_1(\tau) &= 2 + 3\tau + 3\tau(2-\tau)[\sin^{-1}(1/\sqrt{\tau})]^2 \\ &\to 7 \quad \text{for } \tau \gg 1. \end{aligned} \tag{26}$$

In the SM, signs of the top quark and W-boson loop contributions are opposite to each other and the W-loop contribution dominates for the effective coupling. Therefore, the fermion KK mode contributions in the gauge-Higgs unification model is constructive to the SM one.

IV. EFFECTS ON HIGGS BOSON SEARCH AT LHC

As we have shown, the KK mode loop contribution to the effective coupling between the Higgs boson and gluons or photons is subtractive to the top quark loop contribution in the SM. This fact leads to remarkable effects on the Higgs boson search at the LHC. The main production process of the Higgs boson at the LHC is through gluon fusion so that the deviation of the effective coupling between the Higgs boson and gluons directly affects the Higgs boson production cross section. When the Higgs boson is light $m_h < 150$ GeV, the primary discovery mode of the Higgs boson is its two photon decay channel. Therefore, the deviation of the effective coupling between the Higgs boson and photons from the SM one gives important effect on the number of two photon events from the Higgs boson decay.

Let us first consider the ratio of the Higgs boson production cross section in the gauge-Higgs unification model to the SM one, which is described as

$$\frac{\sigma(gg \to h; \text{SM}+\text{KK})}{\sigma(gg \to h; \text{SM})} = \left(1 + \frac{C_g^{\text{KK}(GH)}}{C_g^{\rm SM}}\right)^2. \tag{27}$$

The results are depicted in Fig. 1 as a function of the mass of the lightest KK mode (diagonal) mass eigenvalue (m_1). For the bulk fermion with the periodic boundary condition, $m_1 = 1/R$ with the fifth dimensional radius R, while we define $m_1 = 1/(2R)$ for the bulk fermion with the half-periodic boundary condition. In this analysis, we take $m_h = 120$ GeV. The result is not sensitive to the Higgs boson mass if $m_h < 2m_t$. For reference, the result in the UED scenario is also shown, for which only the periodic fermion has been considered. The KK fermion contribution is subtractive and the Higgs production cross section is reduced in the gauge-Higgs unification scenario, while it is increased in the UED scenario. This is a crucial point to distinguish the gauge-Higgs unification from the UED scenario. Interestingly, even for $m_1 = 1$ TeV, the KK fermion contribution is sizable and the production cross section is reduced by about 18%.

As mentioned before, in a realistic model, top quark would be implemented in a large representation fermion. If this is the case, the effective 4D theory includes extra toplike quarks and their KK modes. If such extra toplike quarks appear, the effective Higgs boson coupling receives more contributions. In Fig. 2, we show the ratio in the case that n_t KK towers of toplike quark multiplets are introduced. In this case, the KK mode contributions are enhanced by the replacement $C_g^{\text{KK}(GH)} \to C_g^{\text{KK}(GH)} \times n_t$

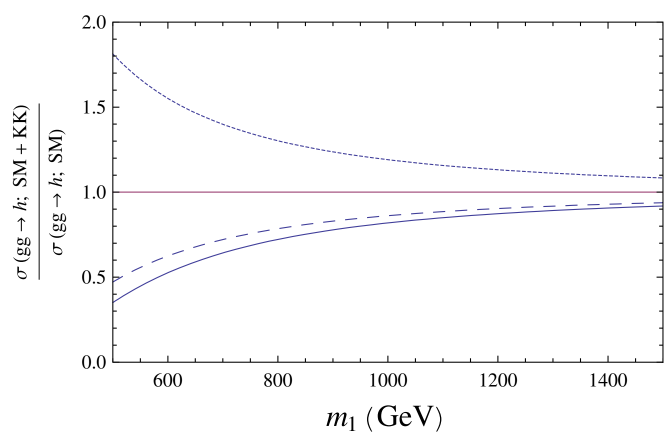

FIG. 1 (color online). The ratio of the Higgs boson production cross sections in the gauge-Higgs unification scenario and in the SM, as a function of the KK mode mass m_1. The solid and dashes lines correspond to the results including the periodic and the half-periodic fermion contributions, respectively. As a reference, the result in the UED scenario with top quark KK modes is also shown (dotted line). Here (in all figures), we have taken $m_h = 120$ GeV.

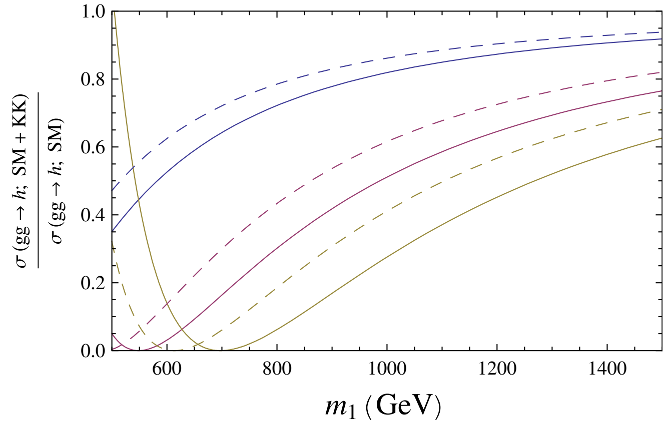

FIG. 2 (color online). The ratio of the Higgs boson production cross sections in the gauge-Higgs unification scenario with n_t periodic and half-periodic KK modes and in the SM, as a function of the KK mode mass m_1. The solid lines represent the results including the periodic KK fermion contributions. Each solid line corresponds to $n_t = 1$, 3, and 5 from top to bottom at $m_1 = 1500$ GeV. The results for the n_t half-periodic fermions are depicted as the dashed lines, corresponding to $n_t = 1$, 3, and 5 from top to bottom at $m_1 = 1500$ GeV. The results for $n_t = 1$ are those shown in Fig. 1.

($n_t = 1$ corresponds to Fig. 1). The value of n_t is highly model dependent. As n_t becomes large, the KK mode contributions can even dominate over the effective coupling of the SM. In other words, the Higgs boson production cross section can be quite altered in the gauge-Higgs unification scenario. This happens also in the UED scenario if extra toplike fermions are introduced. However, in the UED scenario, there is no constraint (or prediction) in the Yukawa and Higgs sectors and there is no positive motivation for introduction of extra fermions.

Next, we analyze the ratio of the partial Higgs boson decay width in the gauge-Higgs unification model to the SM one. The KK mode contribution to the effective coupling between the Higgs boson and two photons can alter the coupling from the SM one. The ratio of the partial Higgs boson decay width into two photons is given as

$$\frac{\Gamma(h \to \gamma\gamma; \mathrm{SM} + \mathrm{KK})}{\Gamma(h \to \gamma\gamma; \mathrm{KK})} = \left(1 + \frac{C_\gamma^{\mathrm{KK}(GH)}}{C_\gamma^{\mathrm{SM}}}\right)^2. \qquad (28)$$

The ratio as a function of m_1 is depicted in Fig. 3 for both the periodic and half-periodic fermions and for $n_t = 1$, 3, and 5. The KK mode contribution is constructive to the SM result. For $m_1 = 1$ TeV and $n_t = 1$, the deviation from the SM result is small, about 5%. As m_1 is lowered and n_t is raised, the KK mode contributions are dominating as expected. The Higgs boson branching ratio into two photons is very small and thus, this ratio can be approximated as the ratio of the partial decay width into two photons in the gauge-Higgs unification model to the SM one. This ratio

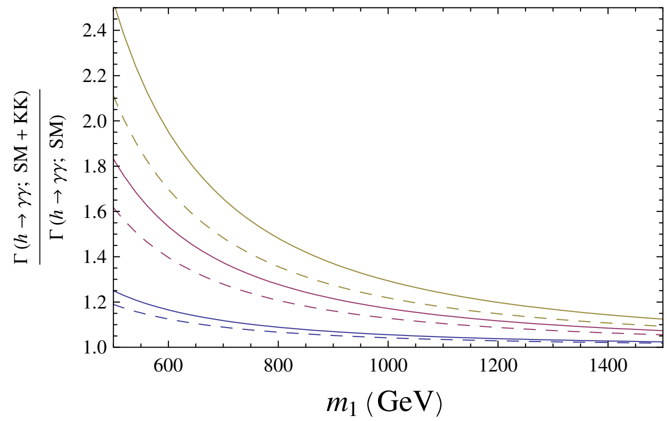

FIG. 3 (color online). The ratio of the Higgs boson partial decay widths into two photons in the gauge-Higgs unification scenario and in the SM, as a function of the KK mode mass m_1. The solid lines represent the results including the n_t periodic KK fermion contributions. Each solid line corresponds to $n_t = 1$, 3, and 5 from bottom to top at $m_1 = 500$ GeV. The results for the n_t half-periodic fermions are depicted as the dashed lines, corresponding to $n_t = 1$, 3, and 5 from bottom to top at $m_1 = 500$ GeV.

directly reflects the number of two photon events, at the LHC, from the Higgs production through the weak-boson fusion and the Higgs decay into two photons, when the Higgs boson is light.

Finally, we show the ratio of the number of two photon events from Higgs decay produced through gluon fusion at the LHC. As a good approximation, this ratio is described as

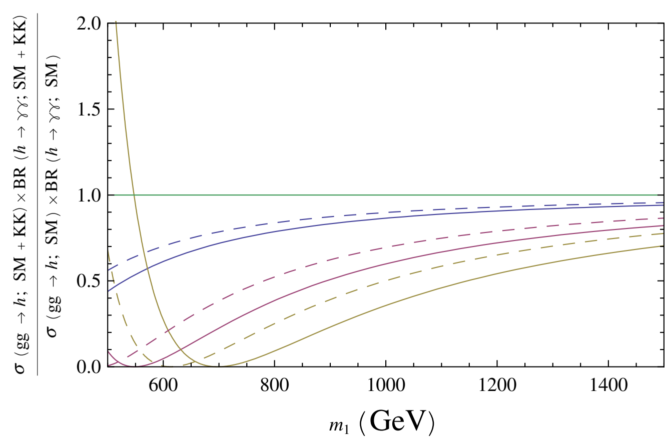

FIG. 4 (color online). The ratio of the number of two photon events in the gauge-Higgs unification scenario with n_t periodic and half-periodic KK modes to those in the SM, as a function of the KK mode mass m_1. The solid lines represent the results including the periodic KK fermion contributions. Each solid line corresponds to $n_t = 1$, 3, and 5 from top to bottom at $m_1 = 1500$ GeV. The results for the n_t half-periodic fermions are depicted as the dashed lines, corresponding to $n_t = 1$, 3, and 5 from top to bottom at $m_1 = 1500$ GeV.

$$\frac{\sigma(gg \to h; \mathrm{SM} + \mathrm{KK}) \times \mathrm{BR}(h \to \gamma\gamma; \mathrm{SM} + \mathrm{KK})}{\sigma(gg \to h; \mathrm{SM}) \times \mathrm{BR}(h \to \gamma\gamma; \mathrm{SM})}$$
$$\simeq \frac{\sigma(gg \to h; \mathrm{SM} + \mathrm{KK}) \times \Gamma(h \to \gamma\gamma; \mathrm{SM} + \mathrm{KK})}{\sigma(gg \to h; \mathrm{SM}) \times \Gamma(h \to \gamma\gamma; \mathrm{SM})}$$
$$= \left(1 + \frac{C_g^{\mathrm{KK}(GH)}}{C_g^{\mathrm{SM}}}\right)^2 \left(1 + \frac{C_\gamma^{\mathrm{KK}(GH)}}{C_\gamma^{\mathrm{SM}}}\right)^2. \quad (29)$$

Figure 4 shows the results for the periodic and half-periodic KK modes as a function of m_1 for $n_t = 1$, 3 and 5. Even for $m_1 = 1$ TeV and $n_t = 1$, the deviation is sizable $\simeq 14\%$. When m_1 is small and n_t is large, the new physics contribution can dominate.

V. CONCLUSIONS AND DISCUSSIONS

In the gauge-Higgs unification scenario, we have discussed the KK mode contributions to the effective couplings between the Higgs boson and the gauge bosons (gluons and photons). Even in the standard model, the effective couplings are induced through loop corrections, so that the KK mode contributions can be sizable. At the LHC, the main production process of the Higgs boson is through gluon fusion and if the Higgs boson is light, the primary discovery mode is its two photon decay. Therefore, the effects on the effective couplings in the gauge-Higgs unification have a great impact on the Higgs boson search at the LHC.

We have calculated the fermion KK mode contributions to the Higgs effective couplings through one-loop diagrams and found that the contributions are finite, nevertheless the summation is taken for the infinite tower of KK states. This finiteness is achieved by nontrivial cancellations between two KK mass eigenstates, each of whose contributions is divergent. The overall sign of the contributions is opposite compared to the SM result by top quark loop corrections and the similar result in the UED scenario. Therefore, this feature is the key to distinguish the gauge-Higgs unification from the UED scenario. Our analysis has shown that even with the KK mode mass around 1 TeV, the KK mode loop corrections provide $\mathcal{O}(10\%)$ deviations from the SM results in Higgs boson phenomenology at the LHC: Higgs boson production cross section through gluon fusion is reduced by $\mathcal{O}(10\%)$, the branching ratio into two photons is increased by about 10%, and the number of two photons evens from the Higgs boson is reduced by $\mathcal{O}(10\%)$. In a realistic gauge-Higgs unification model, some extra toplike quarks would be introduced to reproduce the top Yukawa coupling in the SM. If this is the case, the KK mode contributions are enhanced and can dominate over the SM one. In a realistic model, the signal events of the Higgs boson production at the LHC are quite different from those in the SM.

A remarkable feature of the KK mode contributions to the effective couplings is that the overall sign is opposite to the results in the SM and the UED scenario. Interestingly, the same results (opposite sign) have been found in other models such as the little Higgs model [30] and supersymmetric models [31], all of which are free from the problem of the quadratic divergence in the Higgs mass squared corrections (at least, at one-loop level). Although we do not have a definite opinion on this opposite sign issue for the time being, this may have something to do with the Higgs mass squared corrections. This is because the one-loop diagrams providing the effective couplings between the Higgs boson and the gluons/photons can be obtained from the one-loop Higgs boson self-energy diagram by attaching two gauge boson external lines and replacing one of the Higgs boson field into its VEV. A model which is free from the quadratic divergence of the Higgs self-energy (at one-loop level) may always provide the opposite sign to the effective Higgs coupling.

Finally, a few comments are in order.

We have considered the gauge-Higgs unification model in flat space. In a simple gauge-Higgs unification model, it is known that the lightest KK mode appears around the electroweak scale, to realize the electroweak symmetry breaking with the correct Higgs VEV in effective Higgs potential. For a realistic model, we need to generate a hierarchy between the electroweak scale and the KK mode mass. In an elaborate gauge-Higgs model in flat space (see for example, [12]), this situation is realized by introducing several additional bulk fermions (and fermions in higher representations). As mentioned in the previous section, such new KK fermions give additional contributions to effective Higgs couplings. In a realistic gauge-Higgs unification model in flat space, it would be natural that the KK mode contribution dominates over the SM one.

Recently, the gauge-Higgs unification in the warped background has been recently paid much attention, where the hierarchy between the electroweak scale and the KK mode mass is realized by a nontrivial Higgs zero-mode function. We expect that our results hold true even in the gauge-Higgs models on the warped background. Namely, the overall sign of the effective couplings from the KK mode loop is opposite to that of the SM and the UED. However, note that in the warped case, the nontrivial Higgs zero-mode function induces a mixing between the SM top quark and its KK modes, so that the coupling between the Higgs boson and the SM top quark is reduced. This effect should also be taken into account in the calculations for the processes $gg \to h$ and $h \to \gamma\gamma$.

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Note added.—After completing this work, we were aware of the recent paper by Falkowski [32], where basically the same subjects are discussed and similar results are presented. Our result presented in this paper is based on the talk given by N. Okada on January 10, 2007, at a mini-workshop held at the National Center for Theoretical Sciences (NCTS), National Tsing Hua University, Taiwan. We are also aware that the related subjects have been discussed by a few seminar talks by I. Low (in collaboration with R. Rattazzi) this year [33].

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