Novel universality and Higgs decay $H \to \gamma\gamma, gg$

in the $SO(5) \times U(1)$ gauge-Higgs unification

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Abstract

The $SO(5) \times U(1)$ gauge-Higgs unification in the Randall-Sundrum warped space with the Higgs boson mass $m_H = 126$ GeV is constructed. An universal relation is found between the Kaluza-Klein (KK) mass scale $m_{KK}$ and the Aharonov-Bohm (AB) phase $\theta_H$ in the fifth dimension; $m_{KK} \sim 1350\text{ GeV}/(\sin \theta_H)^{0.787}$. The cubic and quartic self-couplings of the Higgs boson become smaller than those in the standard model (SM), having universal dependence on $\theta_H$. The decay rates $H \to \gamma\gamma, gg$ are evaluated by summing contributions from KK towers. Corrections coming from KK excited states are finite and about 0.2% (2%) for $\theta_H = 0.12 (0.36)$, branching fractions of various decay modes of the Higgs boson remaining nearly the same as in the SM. The signal strengths of the Higgs decay modes relative to the SM are $\sim \cos^2 \theta_H$. The mass of the first KK $Z$ is predicted to be $5.9 (2.4)$ TeV for $\theta_H = 0.12 (0.36)$. We also point out the possible enhancement of $\Gamma(H \to \gamma\gamma)$ due to the large $U(1)_X$ charge of new fermion multiplets.
With the discovery of a Higgs-like boson at LHC [1, 2] it is emergent to pin down its properties to see if it is the Higgs boson in the standard model (SM). The mechanism of electroweak (EW) symmetry breaking is at issue. It is not clear if the EW symmetry is spontaneously broken in a way described in the SM. The mass of the discovered boson is about 126 GeV. Its couplings to other fields, however, may or may not be the same as in the SM. The excess in the decay mode $H \to \gamma\gamma$ has been reported, though more data are necessary for the issue to be settled. [3, 4]

Many alternative mechanisms for the EW symmetry breaking have been proposed with new physics beyond the SM. Supersymmetry with a light Higgs boson has been a popular scenario in the past, though no evidence has been found so far. It has been discussed that the value $m_H = 126$ GeV can lead to the direct connection to physics at the Planck scale through the vacuum stability of the SM or conformality. [5]-[7] Many scenarios have been proposed to account for the apparent excess rate for the Higgs decay to two photons at LHC. [8]-[16]

The gauge-Higgs unification scenario is one of the models with new physics at the TeV scale, in which the 4D Higgs boson is identified with the zero mode of the extra-dimensional component of the gauge fields. [17]-[19] In this paper we show that the value of the Higgs boson mass $m_H = 126$ GeV has profound implications in the gauge-Higgs unification. We evaluate the decay rates $H \to \gamma\gamma, gg$ by summing contributions from all Kaluza-Klein (KK) excited states of the $W$ boson and fermions in the internal loops. Surprisingly there arises no divergence associated with the infinite sum, thanks to destructive interference in the amplitude. The corrections to the decay rates $H \to \gamma\gamma, gg$ are finite and small, being independent of a cutoff scale. With $m_H = 126$ GeV as an input, the deviation of the branching fractions of the $H$ decay from the values in the SM is found to be 2% or less.

In the $SO(5) \times U(1)$ gauge-Higgs unification model [20] the 4D neutral Higgs field appears as 4D fluctuations of the AB, or Wilson line, phase $\theta_H$ along the fifth dimension in the Randall-Sundrum (RS) warped space-time. In the minimal model with quark and lepton multiplets in the vector representation of $SO(5)$ [21, 22] the effective potential $V_{\text{eff}}(\theta_H)$ is minimized at $\theta_H = \pm \frac{1}{2}\pi$, where the Higgs boson becomes absolutely stable. [23] This is due to the emergence of the $H$ parity invariance. [24] To have an unstable Higgs boson with a mass $m_H = 126$ GeV the model need to be modified by breaking the $H$ parity. Further in the minimal model the consistency with the electroweak precision measurements requires a large warp factor $z_L$, which typically leads to a larger value $m_H \sim 135$ GeV. [25] The Higgs mass can be made smaller in the supersymmetric version of the model. [26]
To solve these problems we introduce $n_F$ fermion multiplets, $\Psi_F$, in the spinor representation of $SO(5)$ in the model specified in Ref. [22]. The metric of the RS is given by $ds^2 = e^{-2\sigma(y)}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$ where $\sigma(y) = k|y|$ for $|y| \leq L$ and $\sigma(y + 2L) = \sigma(y)$. The warp factor is $z_L = e^{kL} \gg 1$. $\Psi_F$ satisfies the boundary conditions $\Psi_F(x, -y) = \gamma_5 P \Psi_F(x, y)$ and $\Psi_F(x, L - y) = -\gamma_5 P \Psi_F(x, L + y)$ where $P = \text{diag} (1, 1, -1, -1)$ acts on $SO(5)$ spinor indices. Then the mass spectrum $m_n = k\lambda_n$ of the KK tower of $\Psi_F$ is determined by $S_{L,R}(z; \lambda, c) = \pm \frac{1}{2}\pi \lambda \sqrt{zz_L} F_{c\pm(1/2), c\pm(1/2)}(\lambda z, \lambda z_L)$, where the upper (bottom) sign refers to $L$ ($R$). $F_{\alpha, \beta}(u, v) = J_\alpha(u)Y_\beta(v) - Y_\alpha(u)J_\beta(v)$ where $J_\alpha, Y_\alpha$ are Bessel functions. It has been shown that all 4D anomalies in the model of Ref. [22] cancel. This property is not spoiled by the addition of $\Psi_F$ multiplets, as 4D fermions of $\Psi_F$ are vectorlike.

The effective potential $V_{\text{eff}}(\theta_H)$ is cast in a simple form of an integral. The relevant part of $V_{\text{eff}}(\theta_H)$ is given by

$$V_{\text{eff}}(\theta_H; \xi, c_t, c_F, n_F, k, z_L) = 2(3 - \xi^2)I[Q_W] + (3 - \xi^2)I[Q_Z] + 3\xi^2 I[Q_S] - 12\{I[Q_{\text{top}}] + I[Q_{\text{bottom}}]\} - 8n_F I[Q_F] ,$$

$$I[Q(q; \theta_H)] = \frac{(kz_L^{-1})^4}{(4\pi)^2} \int_0^\infty dq q^2 \ln\{1 + Q(q; \theta_H)\} ,$$

$$Q_W = \cos^2 \theta_W Q_Z = \frac{1}{2}Q_S = \frac{1}{2}Q_0[q; \frac{1}{2}] \sin^2 \theta_H ,$$

$$Q_{\text{top}} = \frac{Q_{\text{bottom}}}{r_t} = \frac{Q_0[q; c_t]}{2(1 + r_t)} \frac{z_L}{\sin^2 \theta_H} ,$$

$$Q_{\text{bottom}} = \frac{Q_0[q; c_F]}{2(1 + r_t)} \frac{z_L}{\sin^2 \theta_H} ,$$

$$Q_0[q; c] = \frac{q^2 F_{c\pm(1/2), c\mp(1/2)}(q z_L^{-1}, q) F_{c\pm(1/2), c\mp(1/2)}(q z_L^{-1}, q)}{e^{-\frac{1}{2}q c} - e^{-\frac{1}{2}q c}} .$$

Here $\hat{F}_{\alpha, \beta}(u, v) = I_\alpha(u)K_\beta(v) - e^{-i(\alpha-\beta)\pi}K_\alpha(u)I_\beta(v)$, where $I_\alpha, K_\alpha$ are modified Bessel functions. $\xi$ is a gauge parameter in the generalized R\_\xi gauge introduced in Ref. [22]. The formula for $V_{\text{eff}}$ in the $\xi = 1$ gauge without the $I[Q_F]$ term has been given in Refs. [21] and [23]. $c_t$ and $c_F$ are the bulk mass parameters for the top-bottom multiplets and $\Psi_F$, respectively. $r_t \sim (m_b/m_t)^2$ where $m_b$ and $m_t$ are the masses of the bottom and top quark. $V_{\text{eff}}(-\theta_H) = V_{\text{eff}}(\theta_H)$. Further in the absence of $I[Q_F]$, $V_{\text{eff}}$ has symmetry $V_{\text{eff}}(\frac{1}{2}\pi + \theta_H) = V_{\text{eff}}(\frac{1}{2}\pi - \theta_H)$, representing the $H$ parity invariance. The $I[Q_F]$ term breaks this symmetry. The contributions from light quarks and leptons are negligible.

In the pure gauge theory without fermions $V_{\text{eff}}$ is minimized at $\theta_H = 0, \pi$ where the EW symmetry remains unbroken. The top quark contribution has minima at $\theta_H = \pm \frac{1}{2}\pi$,
dominating over the gauge field contribution. The fermion $\Psi_F$ shifts the minima toward $\theta_H = 0$. The minimum at $0 < |\theta_H| < \frac{1}{2}\pi$ gives desired phenomenology. The number of the fermion multiplets $\Psi_F, n_F$, affects the shape of $V_{\text{eff}}$ significantly. It will be shown below that the resulting physics, however, is almost independent of $n_F$. The mass of the Higgs boson, $m_H$, is given by

$$m_H^2 = \frac{1}{f_H^2} \left. \frac{d^2 V_{\text{eff}}}{d\theta_H^2} \right|_{\text{min}}, \quad f_H = \frac{2}{g_w} \sqrt{\frac{k}{L(z_L^2 - 1)}}$$

where the second derivative of $V_{\text{eff}}$ is evaluated at the minimum of $V_{\text{eff}}$, and $g_w$ is the 4D weak $SU(2)_L$ coupling. The experimental data dictate $m_H \sim 126$ GeV.

The parameters of the model are specified in the following manner. Pick values for $n_F$ and $z_L$. The parameters, $k$, two gauge coupling constants associated with $SO(5) \times U(1)$, $c_t$, $r_t$, and $c_F$ are self-consistently determined such that at the minimum $\theta_H$ of $V_{\text{eff}}$, $m_Z$, $\sin^2 \theta_W$, $\alpha(m_Z)$, $m_t$, $m_b$ and $m_H = 126$ GeV are reproduced. We note that all of $k$, $c_t$, $r_t$ and $c_F$ implicitly depend on $\theta_H$ as well. The KK mass scale is given by $m_{\text{KK}} = \pi k z_L^{-1}$. Hence $m_{\text{KK}}$ and $\theta_H$, for instance, are determined as functions of $n_F$ and $z_L$. $V_{\text{eff}}(\theta_H)$ for $n_F = 3$ and $z_L = 10^7$ is displayed in Fig. 1.

![Figure 1](image)

Figure 1: $V_{\text{eff}}(\theta_H)$ for $n_F = 3$, $c_F = 0.353$, $z_L = 10^7$ and $\xi = 1$. $U = (4\pi)^2 (k z_L^{-1})^{-4} V_{\text{eff}}$ is plotted. The minimum is located at $\theta_H = \pm 0.082 \pi = \pm 0.258$. (a): $-\pi \leq \theta_H \leq \pi$, (b): $0 \leq \theta_H \leq 0.13 \pi$.

The AB phase $\theta_H$ is the key parameter in gauge-Higgs unification, which controls the couplings of the Higgs boson to other fields. In Table 1 the values for $z_L, \theta_H, m_{\text{KK}}, k, c_t, c_F, m_{\Psi_F(1)}$ and $m_{Z(1)}$ are summarized for $n_F = 3$, where $m_{\Psi_F(1)}$ is the mass of the lowest mode in the KK tower of $\Psi_F$ and $m_{Z(1)}$ is the mass of the first KK $Z$ boson. As $z_L$ is decreased, $\theta_H$ becomes smaller whereas $m_{\text{KK}}$ becomes larger. There appears a critical value for $z_L$ below which $m_H = 126$ GeV cannot be realized.
Table 1: Values of the various quantities determined from $m_H = 126$ GeV with given $z_L$ for $n_F = 3$. Universal relations among $\theta_H$, $m_{KK}$ and $m_{Z(1)}$, independent of $n_F$, are observed. See the text.

| $z_L$ | $\theta_H$ (TeV) | $m_{KK}$ (GeV) | $k$ | $c_t$ (GeV) | $c_F$ (GeV) | $m_{F(1)}$ (TeV) | $m_{Z(1)}$ (TeV) |
|-------|------------------|----------------|-----|-------------|-------------|-----------------|-----------------|
| $10^{12}$ | 1.02 | $1.54 \times 10^{14}$ | 0.413 | 0.476 | 0.155 | 1.19 |
| $10^{11}$ | 0.805 | 1.75 | $5.56 \times 10^{13}$ | 0.403 | 0.454 | 0.232 | 1.36 |
| $10^{10}$ | 0.632 | 2.03 | $6.47 \times 10^{12}$ | 0.391 | 0.433 | 0.329 | 1.59 |
| $10^9$ | 0.485 | 2.45 | $7.79 \times 10^{11}$ | 0.376 | 0.411 | 0.465 | 1.93 |
| $10^8$ | 0.360 | 3.05 | $9.72 \times 10^{10}$ | 0.357 | 0.385 | 0.668 | 2.41 |
| $10^7$ | 0.258 | 3.95 | $1.26 \times 10^{10}$ | 0.330 | 0.353 | 0.993 | 3.15 |
| $10^6$ | 0.177 | 5.30 | $1.69 \times 10^9$ | 0.296 | 0.309 | 1.54 | 4.25 |
| $10^5$ | 0.117 | 7.29 | $2.32 \times 10^8$ | 0.227 | 0.235 | 2.53 | 5.91 |
| $2 \times 10^4$ | 0.086 | 9.21 | $5.87 \times 10^7$ | 0.137 | 0.127 | 3.88 | 7.54 |

Both $\theta_H$ and $m_{KK}$ are physical quantities. They are functions of $n_F$ and $z_L$. The relation between them are plotted in Fig. 2 for various values of $n_F$ and $z_L$. As the number of the extra fermions $n_F$ is increased, the location of the minimum of $V_{\text{eff}}$ is shifted toward the origin. Nevertheless the relation between $\theta_H$ and $m_{KK}$ remains universal. It is approximately given by

$$m_{KK} \sim \frac{1350 \text{ GeV}}{(\sin \theta_H)^{0.787}},$$

irrespective of $n_F$ and $z_L$. We note that $m_Z \sim m_{KK}|\sin \theta_H|/(\pi \cos \theta_W \sqrt{kL})$, in which $\theta_H$ and $kL = \ln z_L$ are not independent, once $m_H$ is fixed. There must be an underlying reason for the universality relation (3), which remains as a mystery and is left for future investigation. The relation between $\theta_H$ and $m_{KK}$, with $m_{KK} > 3$ TeV for the consistency with low energy data, implies that $\theta_H < 0.3$, which also satisfies the $S$ parameter constraint [20] and the tree-level unitarity constraint [27]. For $\theta_H = 0.1 \sim 0.3$, $m_{KK}$ is predicted to be around $3 \sim 7$ TeV, in a region which can be explored at LHC in the coming years. We have also checked that the $m_{KK}-\theta_H$ relation in the $\xi = 0$ gauge is almost the same as in the $\xi = 1$ gauge.

The gauge-Higgs unification model has one parameter, $\theta_H$, to be determined from experiments. With $\theta_H$ fixed, all physical quantities are evaluated. By expanding $V_{\text{eff}}(\theta_H + (H/f_H))$ in a power series in $H$ around the minimum, one finds $\lambda_n H^n$ couplings. These couplings $\lambda_3$ and $\lambda_4$ are plotted in Fig. 3 for $n_F = 1, 3$ and 9. The couplings are smaller than those in the SM. For large $\theta_H > 0.55$, $\lambda_4$ becomes negative though $V_{\text{eff}}$ is bounded from
Figure 2: The relation between $\theta_H$ and $m_{KK}$ for $\xi = 1$. Triangles, squares, and circles are for $n_F = 1, 3$ and $9$, respectively. The solid curve represents the universal relation (3).

below. It is seen that the relations $\lambda_3(\theta_H)$ and $\lambda_4(\theta_H)$ are also universal and independent of $n_F$, once $m_H = 126$ GeV is fixed.

The Higgs couplings to $W$, $Z$, quarks/leptons and their KK excited states are determined. All of the 3 point couplings of SM particles to $H$ at the tree level are suppressed by a common factor $\cos \theta_H$.\cite{28, 31} It is necessary to find these 3 point couplings of KK states for evaluating the 1-loop processes such as $gg \rightarrow H$ and $H \rightarrow \gamma\gamma, gg$.

Let us first consider the process $H \rightarrow \gamma\gamma$. It proceeds through one-loop diagrams. All charged particles with non-vanishing Higgs couplings contribute. The dominant contributions come from the $W$ boson, top quark, and their KK towers. The extra fermion $\Psi_F$ also
The decay rate is given by \[32, 33, 34\]
\[
\Gamma(H \to \gamma\gamma) = \frac{\alpha^2 g_w^2 m_H^3}{1024\pi^2 m_W^2} \left| F_W + \frac{4}{3} F_{\text{top}} + \left(2(Q_X^{(F)})^2 + \frac{1}{2}\right) n_F F_F \right|^2,
\]
where \(W^{(0)} = W, t^{(0)} = t, \tau_a = 4m_a^2/m_H^2\) and the functions \(F_1(\tau)\) and \(F_{1/2}(\tau)\) are defined in Ref. [34]. \(Q_X^{(F)}\) is the \(U(1)_X\) charge of \(\Psi_F\). \(y^\text{SM}_t\) denotes the top Yukawa coupling in the SM. Note that \(F_1(\tau) \to 7\) and \(F_{1/2}(\tau) \to -\frac{4}{3}\) for \(\tau \to \infty\). The extra fermion multiplet \(\Psi_F\) contains particles with electric charges \((Q_X^{(F)} \pm \frac{1}{2})e\). It will be seen below that the contribution \(F_F\) is small for \(\theta_H < 0.5\). The \(HW^{(n)}W^{(n)\dagger}\) coupling \(g_{HW^{(n)}W^{(n)}}\) and the Yukawa couplings \(y_{t(n)}\) and \(y_{F(n)}\) are unambiguously determined in the gauge-Higgs unification. The infinite sums in \([34]\) turn out finite. The expression for \(F_W\) corresponds to the amplitude in the unitary gauge. It has been shown in Ref. [35] that the correct amplitude is reproduced in the unitary gauge in the SM.

In the gauge-Higgs unification the \(HW^{(n)}W^{(n)\dagger}\) and Yukawa couplings result from the \(\text{tr} F_{\mu 5} F^{\mu 5}\) term and the \(\overline{\Psi}\Psi A_5\Psi\) terms in the action, where the vector potential \(A_5\) contains the 4D Higgs field. To good approximation \(g_{HWW} \sim g^\text{SM}_{HWW} \cos \theta_H = g_w m_W \cos \theta_H\) and \(y_t \sim y^\text{SM}_t \cos \theta_H\).

One finds that
\[
I_{W^{(n)}} = \frac{g_{HW^{(n)}W^{(n)}}}{g_w m_{W^{(n)}} \cos \theta_H} = -\sqrt{kL(z_L^2 - 1)} \frac{\sin \theta_H}{N_{W^{(n)}}} \frac{C(1; \lambda_{W^{(n)}})}{S(1; \lambda_{W^{(n)}})},
\]
\[
N_{W^{(n)}} = \int_{1}^{z_L} \frac{dz}{z} \left\{(1 + \cos^2 \theta_H)C(z; \lambda_{W^{(n)}})^2 + \sin^2 \theta_H S(z; \lambda_{W^{(n)}})^2\right\},
\]
\[
C(z; \lambda) = \frac{\pi}{2} \lambda z z_L F_{1,0}(\lambda z, \lambda z_L),
\]
\[
S(z; \lambda) = \frac{\pi}{2} \lambda z F_{1,1}(\lambda z, \lambda z_L), \quad \hat{S}(z; \lambda) = \frac{C(1; \lambda)}{S(1; \lambda)} S(z; \lambda).
\] (5)

We note that \(S(1; \lambda_{W^{(n)}}) = 0\) at \(\theta_H = 0\). The values \(I_{W^{(n)}}\) are plotted in Fig. [3] for \(n_F = 3\) and \(\theta_H = 0.360\) \((z_L = 10^8)\). One sees that the sign of \(I_{W^{(n)}}\) alternates as \(n\) increases, and
its magnitude is almost constant; \( I_{W(n)} \sim (-1)^n \{0.14 + 0.0025 \ln n + 0.0011(\ln n)^2\} \) in the range \( 50 < n < 200 \). Note that \( |g_{HW(n)W(n)}| \) itself increases with \( m_{W(n)} \), in sharp contrast to the behavior in the UED models.\(^8\)

Similar behavior is observed for the Yukawa couplings of the top tower. One finds that

\[
I_{t(n)} = \frac{y_{t(n)}}{y_t^{SM} \cos \theta_H} = -\frac{g_w}{2y_t^{SM}} \sqrt{2} kL(z_2^{2} - 1) \frac{\sin \theta_H}{N_t(n)} \frac{C_L(1; \lambda_{t(n)}, c_t)}{S_L(1; \lambda_{t(n)}, c_t)},
\]

\[
N_t(n) = \int_1^{z_L} dz \{(1 + \cos^2 \theta_H + 2r_t)C_L(z; \lambda_{t(n)}, c_t)^2 + \sin^2 \theta_H S_L(z; \lambda_{t(n)}, c_t)^2 \},
\]

\[
C_L(z; \lambda, c) = \frac{\pi}{2} \lambda \sqrt{z z_L} F_{c+1/2, c-(1/2)}(\lambda z, \lambda z_L),
\]

\[
S_L(z; \lambda, c) = \frac{C_L(1; \lambda, c)}{S_L(1; \lambda, c)} S_L(z; \lambda, c).
\]

The values \( I_{t(n)} \) are plotted in Fig. 4. The value of \( I_{t(n)} \) alternates in sign as \( n \) increases, and the magnitude of \( y_{t(n)} \) are almost constant for large \( n \).

![Figure 4: The ratios \( I_{W(n)} = g_{HW(n)W(n)} / g_{\omega} m_{W(n)} \cos \theta_H \) in (5), \( I_{t(n)} = y_{t(n)} / y_t^{SM} \cos \theta_H \) in (6) and \( I_{F(n)} = y_{F(n)} / y_t^{SM} \sin \frac{1}{2} \theta_H \) in (7) are plotted for \( n_F = 3 \) and \( \theta_H = 0.360 \) (\( z_L = 10^3 \)) in the range \( 1 \leq n \leq 100 \). (\( \Box \): the top quark tower, (\( \o \): the \( W \) tower, (\( \circ \): the \( \Psi_F \) tower) \( I_{W(n)} = 1.004 \) and \( I_{t(n)} = 1.012 \). The sign of \( g_{HW(n)W(n)} \), \( y_{t(n)} \) and \( y_{F(n)} \) alternates as \( n \) increases. \( I_{W(1)}, I_{t(1)}, I_{F(1)} < 0 \).

The behavior of the \( y_{F(n)} \) of the extra fermion is slightly different. In contrast to quarks and leptons, the lowest mode \( F^{(1)} \) in the KK tower of \( \Psi_F \) is massive at \( \theta_H = 0 \); its mass is approximately given by \( m_{F^{(1)}}(\theta_H) \propto \cos \frac{1}{2} \theta_H \). Its Yukawa coupling is, therefore, expected to be \( y_{F^{(1)}} \propto \sin \frac{1}{2} \theta_H \), becoming small for small \( \theta_H \). Indeed one finds

\[
I_{F(n)} = \frac{y_{F(n)}}{y_t^{SM} \sin \frac{1}{2} \theta_H} = -\frac{g_w}{4y_t^{SM}} \sqrt{kL(z_2^{2} - 1)} \frac{\cos \frac{1}{2} \theta_H}{N_{F(n)}(1; \lambda_{F(n)}, \lambda_{F(n)}, c_F)} \frac{C_R(1; \lambda_{F(n)}, c_F)}{S_R(1; \lambda_{F(n)}, c_F)},
\]
Let \( \Psi \) be the contribution of KK excited states, which is small. Consequently the correction to the branching fraction of \( H \to \gamma \gamma \) turns out very small, about 2\% (0.2\%) in the gauge-Higgs unification for \( \theta_H = 0.360 (0.117) \). The observed event rate for \( H \to \gamma \gamma \), for instance, is determined by the product of the Higgs production rate and the branching fraction, \( \sigma_H^{\text{prod}} \cdot B(H \to \gamma \gamma) \). The production rate is suppressed, compared to the SM, by \( \cos^2 \theta_H \), but the branching fractions remain nearly the same as in the SM. The gauge-Higgs unification predicts that the signal strength relative to the SM is \( \sim \cos^2 \theta_H \). For \( \theta_H = 0.1 (0.3) \), it is about 0.99.
This is in sharp contrast to other models. In the UED models the contributions of KK states to $F_{\text{top}}$ add up in the same sign and may become sizable.\textsuperscript{8} In the gauge-Higgs unification the contributions alternate in sign in the amplitudes, resulting in the destructive interference and giving very small correction.

The rate $\Gamma(H \to \gamma\gamma)$ in Eq. (4) can be enhanced through the factor $2(Q_X^{(F)})^2 + \frac{1}{2}$ for sufficiently large $Q_X^{(F)}$. For example, for $Q_X^{(F)} = 4$ and $n_F = 3$, we obtain the enhancement by a factor 2.22 (1.13) compared with the SM.

The fact $m_H \sim 126$ GeV leads to important consequences in the gauge-Higgs unification. We have found the universal relations among $m_{KK}$, $\lambda_3$, $\lambda_4$ and $\theta_H$, which are independent of how many extra fermions are introduced. The low energy data, the $S$ parameter constraint, and the tree-level unitarity constraint indicate small $\theta_H < 0.3$. The KK mass scale $m_{KK}$ is predicted to be $3 \sim 7$ TeV for $\theta_H = 0.1 \sim 0.3$. The existence of new charged heavy particles can affect the production and decay rates of the Higgs boson through loop diagrams. There are many proposals of models which employ such a mechanism to predict the enhancement of the $H \to \gamma\gamma$ mode over other decay channels.\textsuperscript{8-16} In the gauge-Higgs unification there are new charged heavy particles, namely KK excited states of $W$ and top quark. However, we have shown that their couplings to the Higgs boson alternate in sign in each KK tower so that the correction to the decay and production rates becomes very small. The gauge-Higgs unification gives phenomenology at low energies very close to that of the SM so long as $Q_X^{(F)}$ is moderately small.

Nevertheless new rich structure is predicted to emerge. We have seen above that the cubic and quartic self-couplings of the Higgs boson significantly deviate from the SM. The most clear signal for the gauge-Higgs unification would be the production of the first KK states of the $Z$ boson and photon at LHC. Their masses are predicted, for $\theta_H = 0.117$ (0.360), to be $m_{Z(1)} = 5.910$ (2.414) TeV and $m_{\gamma(1)} = 5.913$ (2.421) TeV. The current data\textsuperscript{11-14} indicate $m_{Z(1)} > 2.5$ TeV. We have checked that there is a universal relation between $\theta_H$ and $m_{Z(1)}$, independent of $n_F$. The data therefore imply that $\theta_H < 0.35$. Another robust signal would be the production of a pair of the first KK state of the extra fermion, $F^{(1)}F^{(1)}$, which become stable. So far no new exotic stable charged fermion has been observed at LHC.\textsuperscript{15} Its current limit puts a constraint $m_{F^{(1)}} > 0.5$ TeV. The value of $m_{F^{(1)}}$ depends on both $\theta_H$ and $n_F$ so that no universal relation between $m_{F^{(1)}}$ and $\theta_H$ is found. $m_{F^{(1)}}$ becomes smaller as $n_F$ increases with $\theta_H$ fixed. $m_{F^{(1)}} > 0.5$ TeV implies $\theta_H < 0.45$ for $n_F = 3$. We will come back to these issues with more details separately.
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