126 GeV Higgs boson and universality relations
in the $SO(5) \times U(1)$ gauge-Higgs unification

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The Higgs boson mass $m_H = 126$ GeV in the $SO(5) \times U(1)$ gauge-Higgs unification in the Randall-Sundrum space leads to important consequences. An universal relation is found between the Kaluza-Klein (KK) mass scale $m_{KK}$ and the Aharonov-Bohm phase $\theta_H$ in the fifth dimension; $m_{KK} \sim 1350$ GeV$/\sin \theta_H^{0.787}$. The cubic and quartic self-couplings of the Higgs boson become smaller than those in the SM, having universal dependence on $\theta_H$. The decay rates $H \rightarrow \gamma\gamma, gg$ are evaluated by summing contributions from KK towers. Corrections coming from KK excited states turn out very small. With $\theta_H = 0.1 \sim 0.35$, the mass of the first KK $Z$ is predicted to be $2.5 \sim 6$ TeV.

I. INTRODUCTION

The discovery of a Higgs-like boson with $m_H = 126$ GeV at LHC may give a hint for extra dimensions. We show [1] that the observed Higgs boson mass in the gauge-Higgs unification scenario leads to universal relations among the AB phase $\theta_H$, the KK mass $m_{KK}$, the Higgs self couplings, and the KK $Z$ boson mass $m_{Z(1)}$, independent of the details of the model.

The gauge-Higgs unification scenario is predictive. As a result of the Hosotani mechanism [2-6] the Higgs boson mass emerges at the quantum level without being afflicted with divergence. The Higgs couplings to the KK towers of quarks and $W/Z$ bosons have a distinctive feature that their signs alternate in the KK level, significant departure from other extra dimensional models such as UED models. As a consequence contributions of KK modes to the decay rate $\Gamma(H \rightarrow \gamma\gamma)$ turn out very small. Surprisingly the gauge-Higgs unification gives nearly the same phenomenology at low energies as the standard model (SM).

The gauge-Higgs unification can be confirmed by finding the KK $Z$ boson in the range $2.5 \sim 6$ TeV and by determining the Higgs self couplings and Yukawa couplings at LHC and ILC.

II. $SO(5) \times U(1)$ GAUGE-HIGGS UNIFICATION IN RS

The model is given by $SO(5) \times U(1)$ gauge theory in the Randall-Sundrum (RS) warped space

$$ds^2 = e^{-2\sigma(y)}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$

where $\eta_{\mu\nu} = \text{diag}(-1,1,1,1)$, $\sigma(y) = \sigma(y+2L) = \sigma(-y)$, and $\sigma(y) = k|y|$ for $|y| \leq L$. The RS space is viewed as bulk AdS space ($0 < y < L$) with AdS curvature $-6k^2$ sandwiched by the Planck brane at $y = 0$ and the TeV brane at $y = L$. The $SO(5) \times U(1)$ model was proposed by Agashe et al [7,8]. It has been elaborated in refs. [9,10], and a concrete realistic model has been formulated in ref. [1]. The schematic view of the gauge-Higgs unification is given below.

$$\begin{align*}
5D \ A_M & \begin{cases}
\text{four-dim. components } A_\mu & \in \text{4D gauge fields } \gamma, W, Z \\
\text{extra-dim. component } A_y & \in \text{4D Higgs field } H
\end{cases} \\
\sim & \text{AB phase } \theta_H \text{ in extra dim.}
\end{align*}$$

Hosotani mechanism $\Downarrow$

Dynamical EW symmetry breaking
The 5D Lagrangian density consists of
\[ \mathcal{L} = \mathcal{L}_{\text{bulk}}^{\text{gauge}}(A, B) + \mathcal{L}_{\text{bulk}}^{\text{fermion}}(\Psi_a, \Psi_F, A, B) 
+ \mathcal{L}_{\text{brane}}^{\text{fermion}}(\tilde{\chi}_a, A, B) + \mathcal{L}_{\text{brane}}^{\text{scalar}}(\tilde{\Phi}, A, B) + \mathcal{L}_{\text{brane}}^{\text{int}}(\Psi_a, \tilde{\chi}_a, \tilde{\Phi}). \] (2)

SO(5) and U(1)_X gauge fields are denoted by A_M and B_M, respectively. The two associated gauge coupling constants are g_A and g_B. Two quark multiplets and two lepton multiplets \Psi_a are introduced in the vector representation of SO(5) in each generation, whereas \Psi_F extra fermion multiplets are introduced in the spinor representation. These bulk fields obey the orbifold boundary conditions at y_0 = 0 and y_1 = L given by

\[ \begin{align*}
A_y(x, y_j) &= \frac{A_y}{A_y} (x, y_j + y) P_j^{-1}, \\
B_x(x, y_j) &= \frac{B_x}{B_x} (x, y_j + y), \\
\Psi_a(x, y_j) &= P_j \Gamma^5 \Psi_a (x, y_j + y), \\
\Psi_F(x, y_j) &= (-1)^j P_j^{\text{sp}} \Gamma^5 \Psi_F (x, y_j + y), \\
P_j &= \text{diag} (-1, -1, -1, -1, 1), \\
P_j^{\text{sp}} &= \text{diag} (1, 1, 1, 1, 1).
\end{align*} \] (3)

The orbifold boundary conditions break SO(5) × U(1)_X to SO(4) × U(1)_X ≃ SU(2)_L × SU(2)_R × U(1)_Y.

The brane interactions are invariant under SO(4) × U(1)_X. The brane scalar \tilde{\Phi} is in the (1, 2)_{-1/2} representation of [SU(2)_L, SU(2)_R|U(1)_X]. It spontaneously breaks SU(2)_R × U(1)_Y to U(1)_Y by non-vanishing \langle \tilde{\Phi} \rangle whose magnitude is supposed to be much larger than the KK scale m_{KK}. At this stage the residual gauge symmetry is SU(2)_L × U(1)_Y. Brane fermions \tilde{\chi}_a are introduced in the (2, 1) representation. The quark-lepton vector multiplets \Psi_a are decomposed into (2, 2) + (1, 1). The (2, 2) part of \Psi_a, \chi_a in (2, 1) and \tilde{\Phi} in (1, 2) form SO(4) × U(1)_X invariant brane interactions. All exotic fermions become heavy, acquiring masses of O(m_{KK}).

Further with brane fermions all anomalies associated with gauge fields of SO(4) × U(1)_X are cancelled.[10]

With the orbifold boundary conditions \[ \int \mathcal{L}_{\text{brane}}^{\text{fermion}}(\tilde{\chi}_a, A, B) \]
there appear four zero modes of A_y in the components (A_y)_a^5 = -(A_y)_a (a = 1, \cdots, 4). They form an SO(4) vector, or an SU(2)_L doublet, corresponding to the Higgs doublet in the SM. The AB phase is defined with these zero modes by

\[ e^{i \Theta_H/2} \sim P \exp \left\{ ig_A \int_0^L dy A_y \right\}. \] (4)

At the tree level the value of the AB phase \Theta_H is not determined, as it gives vanishing field strengths. At the quantum level its effective potential V_{eff} becomes non-trivial. The value of \Theta_H is determined by the location of the minimum of V_{eff}. This is the Hosotani mechanism and induces dynamical gauge symmetry breaking. It leads to gauge-Higgs unification, resolving the gauge-hierarchy problem. Without loss of generality one can assume that (A_y)_4^5 component develops a non-vanishing expectation value. Let us denote the corresponding component of \Theta_H by \theta_H. If \theta_H takes a non-vanishing value, the electroweak symmetry breaking takes place.

III. \ V_{eff}(\theta_H) AND m_H

Given the matter content one can evaluate V_{eff}(\theta_H) at the one loop level unambiguously. The \theta_H dependent part of V_{eff}(\theta_H) is finite, being free from divergence. V_{eff}(\theta_H) depends on several parameters of the theory: \theta_H = V_{eff}(\theta_H; \xi, c_t, c_F, n_F, k, z_L) where \xi is the gauge parameter in the generalized RG gauge, c_t and c_F are the bulk mass parameters of the top and extra fermion multiplets, n_F is the number of the extra fermion multiplets, and k, z_L are parameters specifying the RS metric [11]. Given these parameters, V_{eff} is fixed, and the location of the global minimum of V_{eff}(\theta_H), \theta_H^{\text{min}} is determined.

With \theta_H^{\text{min}} determined, m_Z, g_w, \sin^2 \theta_W are determined from g_A, g_B, k, z_L and \theta_H^{\text{min}}. The top mass m_t is determined from c_t, k, z_L, \theta_H^{\text{min}}, whereas the Higgs boson mass m_H is given by

\[ m_H^2 = \frac{1}{f^2_H} \left. \frac{d^2 V_{eff}}{d \theta_H^2} \right|_{\theta_H^{\text{min}}}, \quad f_H = \frac{2}{g_w} \sqrt{\frac{k}{L (z_L^2 - 1)}}. \] (5)
Let us take $\xi = 1$. Then the theory has seven parameters $\{g_A, g_B, k, z_L, c_I, c_F, n_F\}$. Adjusting these parameters, we reproduce the values of five observed quantities $\{m_2, g_w, \sin^2 \theta_W, m_t, m_H\}$. This leaves two parameters, say $z_L$ and $n_F$, free. Put differently, the value of $\theta_H^{\text{min}}$ is determined as a function of $z_L$ and $n_F$: $\theta_H^{\text{min}} = \theta_H(z_L, n_F)$. We comment that contributions from other light quark/lepton multiplets to $V_{\text{eff}}$ are negligible.

$V_{\text{eff}}(\theta_H)$ in the absence of the extra fermions ($n_F = 0$) was evaluated in refs. $[2, 11]$. It was found there that the global minima naturally appear at $\theta_H = \pm \frac{\pi}{2}$ at which the Higgs boson becomes absolutely stable. It is due to the emergence of the $H$ parity invariance. $\theta_H = \pm \frac{\pi}{2}$ is related to $m_{H^\pm}$ and $m_{A^\pm}$.

In particular the Higgs trilinear coupling to $W$, $Z$, quarks and leptons are all proportional to $\cos \theta_H$ and vanish at $\theta_H = \pm \frac{\pi}{2}$. This, however, conflicts with the observation of an unstable Higgs boson at LHC. To have an unstable Higgs boson the $H$ parity invariance must be broken, which is most easily achieved by introducing extra fermion multiplets $\Psi_F$ in the spinor representation of $SO(5)$.\footnote{For simplicity, only right-handed fermions are considered.}

Let us take $n_F = 3, z_L = e^{kL} = 10^7$ as an example. $\{g_w, \sin^2 \theta_W\}$ are related to $\{g_A, g_B\}$ by

$$g_w = \frac{g_A}{\sqrt{L}}, \quad \tan \theta_W = \frac{g_B}{\sqrt{g_A^2 + g_B^2}}, \tag{6}$$

where $z_L = e^{kL}$. The observed values of $\{m_2, g_w, \sin^2 \theta_W, m_t, m_H\}$ are reproduced with $k = 1.26 \times 10^{10} \text{GeV}$, $c_I = 0.330$, $c_F = 0.353$ for which the minima of $V_{\text{eff}}$ are found at $\theta_H = \pm 0.258$. The KK mass scale is $m_{KK} = \pi k z_L^{-1} = 3.95 \text{TeV}$. $V_{\text{eff}}(\theta_H)$ is depicted in Fig. 1 with red curves. For comparison $V_{\text{eff}}$ in the case of $n_F = 0$ is also plotted with a blue curve. When $n_F = 0$ and $z_L = 10^7$, the minima are located at $\theta_H = \pm \frac{\pi}{2}$. The observed values of $\{m_2, g_w, \sin^2 \theta_W, m_t\}$ are reproduced with $k = 3.16 \times 10^9 \text{GeV}$ and $c_I = 0.345$. In this case the Higgs boson mass determined by $\{6\}$ becomes $m_H = 87.9 \text{GeV}$, and $m_{KK} = 993 \text{GeV}$. One can see how the position of the minima is shifted from $\theta_H = \pm \frac{\pi}{2}$ to $\theta_H = \pm 0.082\pi = \pm 0.258$ by the introduction of the extra fermions.

![Fig. 1](image-link)  
**FIG. 1**: The effective potential $V_{\text{eff}}(\theta_H)$ for $z_L = 10^7$. $U = 16\pi^6 m_{KK}^{-4} V_{\text{eff}}$ is plotted. The red curves are for $n_F = 3$ with $m_H = 126 \text{GeV}$. $V_{\text{eff}}$ has minima at $\theta_H = \pm 0.258$ and $m_{KK} = 3.95 \text{TeV}$. The blue curve is for $n_F = 0$ in which case $m_H = 87.9 \text{GeV}$ and $m_{KK} = 993 \text{GeV}$.

### IV. UNIVERSALITY

As explained above, the AB phase $\theta_H = \theta_H^{\text{min}}$ is determined as a function of $z_L$ and $n_F$: $\theta_H(z_L, n_F)$. The KK mass scale $m_{KK} = \pi k z_L^{-1}$ is also determined as a function of $z_L$ and $n_F$: $m_{KK}(z_L, n_F)$. The relation between them is plotted for $n_F = 1, 3, 9$ in the top figure in Fig. 2. One sees that all points fall on one universal curve to good accuracy, independent of $n_F$.

Similarly one can evaluate the cubic ($\lambda_3$) and quartic ($\lambda_4$) self-couplings of the Higgs boson $H$ by expanding $V_{\text{eff}}[\theta_H + (H/f_H)]$ around the minimum in a power series in $H$. They are depicted in the bottom figure in Fig. 2. Although the shape of $V_{\text{eff}}(\theta_H)$ heavily depends on $n_F$, the relations $\lambda_3(\theta_H)$ and $\lambda_4(\theta_H)$ turn out universal, independent of $n_F$.

It is rather surprising that there hold universal relations among $\theta_H$, $m_{KK}$, $\lambda_3$ and $\lambda_4$. Once $\theta_H$ is determined from one source of observation, then many other physical quantities are fixed and predicted. The gauge-Higgs unification gives many definitive predictions to be tested by experiments. We tabulate values of various quantities determined from $m_H = 126 \text{GeV}$ with given $z_L$ for $n_F = 3$ in Table I.
\[ m_{\text{KK}} \sim \frac{1350 \text{ GeV}}{(\sin \theta_H)^{0.787}}. \]  

TABLE I: Values of the various quantities with given \( n_F \) for \( n_F = 3 \). \( m_{Z(1)} \) and \( m_{F(1)} \) are masses of the first KK Z boson and the lowest mode of the extra fermion multiplets. Relations among \( \theta_H, m_{\text{KK}} \) and \( m_{Z(1)} \) are universal, independent of \( n_F \).

| \( z_L \) | \( \theta_H \) | \( m_{\text{KK}} \) | \( m_{Z(1)} \) | \( m_{F(1)} \) |
|------|--------|--------|--------|--------|
| \( 10^8 \) | 0.360  | 3.05 TeV | 2.41 TeV | 0.668 TeV |
| \( 10^7 \) | 0.258  | 3.95    | 3.15    | 0.993    |
| \( 10^6 \) | 0.177  | 5.30    | 4.25    | 1.54     |
| \( 10^5 \) | 0.117  | 7.29    | 5.91    | 2.53     |

V. \( H \to \gamma \gamma \gamma \gamma \)

In the gauge-Higgs unification all of the 3-point couplings of \( W, Z \), quarks and leptons to the Higgs boson \( H \) at the tree level are suppressed by a common factor \( \cos \theta_H \) compared with those in the SM.\[13\] The decay of the Higgs boson to two photons goes through loop diagrams in which \( W \) boson, quarks, leptons, extra fermions and their KK excited states run. The decay rate \( \Gamma[H \to \gamma \gamma] \) is given by

\[ \Gamma(H \to \gamma \gamma) = \frac{\alpha^2 g_w^2 m_H^3}{1024 \pi^3 m_W^2} |F_{\text{total}}|^2, \]
\[ F_{\text{total}} = F_W + \frac{4}{3} F_{\text{top}} + \left( 2(Q_X^{(F)})^2 + \frac{1}{2} \right) n_F F_F , \]

\[ F_W = \cos \theta_H \sum_{n=0}^{\infty} I_{W(n)} \frac{m_W}{m_{W(n)}} F_1(\tau_{W(n)}) , \quad I_{W(n)} = \frac{g_{\text{SM}(n)} W_{(n)}}{g_\alpha m_{W(n)} \cos \theta_H} , \]

\[ F_{\text{top}} = \cos \theta_H \sum_{n=0}^{\infty} I_{t(n)} \frac{m_t}{m_{t(n)}} F_{1/2}(\tau_{t(n)}) , \quad I_{t(n)} = \frac{y_t(n)}{y_t^{\text{SM}} \cos \theta_H} , \]

\[ F_F = \sin \frac{1}{2} \theta_H \sum_{n=0}^{\infty} F_{n}(F(n)) \frac{m_t}{m_{F(n)}} F_{1/2}(\tau_{F(n)}) , \quad I_{F(n)} = \frac{y_{F(n)}}{y_t^{\text{SM}} \sin \frac{1}{2} \theta_H} , \]

where \( W^{(0)} = W, \ t^{(0)} = t, \ \tau_a = 4m_a^2/m_H^2 \). The functions \( F_1(\tau) \) and \( F_{1/2}(\tau) \) are defined in Ref. [19], and \( F_1(\tau) \sim 7 \) and \( F_{1/2}(\tau) \sim -\frac{1}{3} \) for \( \tau \gg 1 \). \( Q_X^{(F)} \) is the \( U(1)_X \) charge of the extra fermions. \( I_{W(0)} \) and \( I_{t(0)} \) are \( \sim 1 \).

In Fig. 3 \( I_{W(n)}, \ I_{t(n)}, \) and \( I_{F(n)} \) are plotted. One sees that the values of these \( I \)'s alternate in sign as \( n \) increases, which gives sharp contrast to the UED models.

\[ I_{W(n)} \sim (-1)^n I_{W}^\infty , \quad I_{t(n)} \sim (-1)^n I_{t}^\infty , \quad I_{F(n)} \sim (-1)^n I_{F}^\infty \quad \text{for} \ n \gg 1 \]

up to \((\ln n)^p\) corrections. This is special to the gauge-Higgs unification models. It has been known in the models in flat space as well [21]. As a consequence of the destructive interference due to the alternating sign, the infinite sums in the rate [18] converges rapidly. There appears no divergence.

Let \( F_{W \text{only}} \) and \( F_{t \text{only}} \) be the contributions of \( W = W^{(0)} \) and \( t = t^{(0)} \) to \( F_{\text{total}} \). The numerical values of the amplitudes \( F \)'s are tabulated in Table II for \( n_F = 3 \). It is seen that contributions of KK states to the amplitude are small. The dominant effect for the decay amplitude is the suppression factor \( \cos \theta_H \).

All Higgs couplings \( HWW, HZZ, H\bar{c}c, Hbb, H\tau\bar{\tau} \) are suppressed by a factor \( \cos \theta_H \) at the tree level. The corrections to \( \Gamma[H \rightarrow \gamma\gamma] \) and \( \Gamma[H \rightarrow gg] \) due to KK states amount only to 0.2% (2%) for \( \theta_H = 0.117(0.360) \). Hence we conclude

branching fraction: \( B(H \rightarrow j) \sim B^{\text{SM}}(H \rightarrow j) \)

\[ j = WW, ZZ, \gamma\gamma, gg, bb, \bar{c}c, \tau\bar{\tau}, \cdots \]

\( \gamma\gamma \) production rate: \( \sigma^{\text{prod}}(H) \cdot B(H \rightarrow \gamma\gamma) \sim (\text{SM}) \times \cos^2 \theta_H \).

The signal strength in the \( \gamma\gamma \) production relative to the SM is about \( \cos^2 \theta_H \). It is about 0.99 (0.91) for \( \theta_H = 0.1 \) (0.3). This contrasts to the prediction in the UED models in which the contributions of KK states can add up in the same sign to sizable amount. [22]
VI. SIGNALS OF GAUGE-HIGGS UNIFICATION

There are several constraints to be imposed on the gauge-Higgs unification.

(i) For the consistency with the $S$ parameter, we need $\sin \theta_H < 0.3$.\[7\]
(ii) The tree-level unitarity requires $\theta_H < 0.5$.\[23\]
(iii) $Z'$ search at Tevatron and LHC. The first KK $Z$ corresponds to $Z'$. No signal has been found so far, which implies that $m_{Z(1)} > 2\text{ TeV}$. With the universality relations in Sec. IV it requires $\theta_H < 0.4$.
(iv) In ref. \[24\] the consistency with other precision measurements such as the $Z$ boson decay and the forward-backward asymmetry on the $Z$ resonance has been investigated when $n_F = 0$. Reasonable agreement was found for $m_{KK} > 1.5\text{ TeV}$. We need to reanalyze in the case $n_F \geq 1$.

All of those constraints above point $\theta_H < 0.4$. When $\theta_H$ is very small, the KK mass scale $m_{KK}$ becomes very large and it becomes very difficult to distinguish the gauge-Higgs unification from the SM. The range of interest is $0.1 < \theta_H < 0.35$, which can be explored at LHC with an increased energy 13 or 14 TeV. The gauge-Higgs unification predicts the following signals.

1) The first KK $Z$ should be found at $m_{KK} = 2.5 \sim 6\text{ TeV}$ for $\theta_H = 0.35 \sim 0.1$.
2) The Higgs self-couplings should be smaller than those in the SM. $\lambda_3$ ($\lambda_4$) should be $10 \sim 20\%$ ($30 \sim 60\%$) smaller for $\theta_H = 0.1 \sim 0.35$, according to the universality relations. This should be explored at ILC.
3) The lowest mode ($F(1)$) of the KK tower of the extra fermion $\Psi_F$ should be discovered at LHC. Its mass depends on both $\theta_H$ and $n_F$. For $n_F = 3$, the mass is predicted to be $m_{F(1)} = 0.7 \sim 2.5\text{ TeV}$ for $\theta_H = 0.35 \sim 0.1$.

VII. FOR THE FUTURE

The $SO(5) \times U(1)$ gauge-Higgs unification model of ref. \[1\] has been successful so far. Yet further elaboration may be necessary.

1) Flavor mixing has to be incorporated to explore flavor physics.\[25\]
2) It is curious to generalize the model to incorporate SUSY. The Higgs boson mass becomes smaller than in non-SUSY model. $m_H = 126\text{ GeV}$ should give information about SUSY breaking scales.\[26\]
3) The orbifold boundary conditions ($P_0$, $P_1$) in \[3\] have been given by hand so far. It is desirable to have dynamics which determine the boundary conditions.\[27, 28\]
4) Not only electroweak interactions but also strong interactions should be integrated in the form of grand gauge-Higgs unification.\[29\]

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