Gauge-Higgs Unification at the LHC

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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 scenario 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 Kaluza-Klein (KK) modes.

Keywords: Gauge-Higgs unification, Higgs production and decay at LHC

1. Introduction

Gauge-Higgs unification (GHU) is a fascinating scenario solving the hierarchy problem without invoking supersymmetry. In this scenario, Higgs scalar field in the Standard Model (SM) is identified with extra components of higher dimensional gauge field. The remarkable thing in this scenario is that the quantum correction to Higgs mass is finite due to the higher dimensional gauge symmetry regardless of the nonrenormalizability of the theory. Such a UV insensitivity in other physical observables has been also investigated for $S$ and $T$ parameters, $g-2$, the violation of gauge-Yukawa universality and the gluon fusion (two photon decay) of Higgs boson. The last one is the issue discussed in this talk.

The Large Hadron Collider (LHC) started its operation again and the collider signatures of various new physics models beyond the SM have been extensively studied. The GHU shares the similar structure with the universal extra dimension (UED) scenario, namely, Kaluza-Klein (KK) states of the SM 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

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Higgs doublet originates from the higher dimensional gauge field and its interactions are controlled by the higher dimensional gauge invariance. The discovery of 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 Higgs boson properties will provide us the information of a new physics relevant to the Higgs sector.

In this talk, we investigate the effect of GHU on Higgs boson phenomenology at the LHC, namely, the production and decay processes of Higgs boson (See also.\textsuperscript{9})\textsuperscript{10}. At the LHC, the gluon fusion is the dominant Higgs boson production process and for light Higgs boson with mass $m_h < 150$ GeV, and two photon decay mode of Higgs boson becomes the primary discovery mode\textsuperscript{11} nevertheless its branching ratio is $\mathcal{O}(10^{-3})$. The coupling between Higgs boson and these gauge bosons are induced through quantum corrections at one-loop level even in the SM. Therefore, we can expect a sizable effect from new particles if they contribute to the coupling at one-loop level. In a five dimensional GHU model, we calculate one-loop diagrams with KK fermions for the effective couplings between 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 Higgs production at the LHC can be altered from the SM one. Interestingly, reflecting the special structure of Higgs sector in the GHU, there is a clear qualitative difference from the UED scenario, the signs of the effective couplings are opposite to those in the UED scenario.

2. Model

Let us consider a toy model of five dimensional (5D) $SU(3)$ GHU 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 $m_b = M_W$ in this simple toy model. In our analysis, we will take into account a situation where a realistic top quark mass is realized and the bottom quark contributions are negligible comparing to the top quark ones.

The $SU(3)$ gauge symmetry is broken to $SU(2) \times U(1)$ by the orbifolding on $S^1/Z_2$. 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. We do not address the origin of $SU(2) \times U(1)$ 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 of this work.

The Lagrangian is simply given by

\begin{equation}
\mathcal{L} = -\frac{1}{2} \text{Tr}(F_{MN}F^{MN}) + i\bar{\Psi}\slashed{D}\Psi.
\end{equation}
The periodic boundary conditions are imposed along $S^1$ for all fields. The non-trivial $Z_2$ parities are assigned for each field as follows,

\[
A_\mu (y_i - y) = P A_\mu (y_i + y) P^\dagger,
\]

\[
A_y (y_i - y) = -P A_y (y_i + y) P^\dagger,
\]

\[
\Psi (y_i - y) = P \gamma^5 \Psi (y_i + y)
\]

where $\gamma^5 \Psi_L = \Psi_L$, $P = \text{diag}(+, +, -)$ at fixed points $y_i = 0, \pi R$. By this $Z_2$ parity assignment, $SU(3)$ is explicitly broken to $SU(2) \times U(1)$. Higgs scalar field is identified with the off-diagonal block of zero mode $A_{y(0)}$.

After the electroweak 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 $L_{\text{fermion}} = i \bar{\Psi} D / \Psi$ in Eq. (1). Integrating over the fifth dimensional coordinate, we obtain a relevant 4D effective Lagrangian in the mass eigenstate of nonzero KK modes:

\[
L_{\text{fermion}}^{(4D)} = \sum_{n=1}^{\infty} \begin{pmatrix} \bar{\psi}^{(n)}_1, \bar{\psi}^{(n)}_2, \bar{\psi}^{(n)}_3 \end{pmatrix} \begin{pmatrix}
 i\gamma^\mu \partial^\mu - m_{n} & 0 & 0 \\
 0 & i\gamma^\mu \partial^\mu - \left(m_{+}^{(n)} + \frac{m_{t}}{v}\right) & 0 \\
 0 & 0 & i\gamma^\mu \partial^\mu - \left(m_{-}^{(n)} - \frac{m_{t}}{v}\right)
\end{pmatrix} \begin{pmatrix} \psi^{(n)}_1 \\
 \psi^{(n)}_2 \\
 \psi^{(n)}_3
\end{pmatrix} + \text{gauge interaction part} + \text{zero-mode part}
\]

where $m = \frac{m_t}{2} (= M_W)$ is the bottom quark mass in this toy model, $g = \frac{g_5}{\sqrt{2\pi R}}$ is the 4D gauge coupling. Note that the mass splitting $m_{\pm}^{(n)} \equiv m_n \pm m = \frac{m_t}{R} \pm m$ occurs associated with a mixing between the $SU(2)$ doublet component and singlet component. Note that the mass eigenstate for $m_{\pm}^{(n)}$ has the Yukawa coupling $\mp m/v$, which is exactly the same as the one for the zero mode. In UED, however, 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. Together with the mass splitting of KK modes, this property is a general one realized in any GHU model and leads to a clear qualitative difference of the GHU from the UED scenario, as we will see.

3. Effective couplings between Higgs boson and gauge bosons

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

\[
L_{\text{eff}} = C_g^SM h G^\alpha_{\mu
u} G^{\alpha}_{\mu\nu},
\]

\[
L_{\text{eff}} = C_S^M h F^\mu\nu F_{\mu\nu},
\]
where $G^{a}_{\mu\nu}(F_{\mu\nu})$ is a gluon (photon) 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 $C^{SM}_{\gamma}$ is described in the following form:

\begin{align}
C^{SM}_{\gamma} &= \frac{\alpha_s F_{1/2}(4m_t^2/m_h^2)}{8\pi v} \times \frac{1}{2} \approx \frac{\alpha_s}{12\pi v}, \\
C^{SM}_{\gamma} &= \frac{m_t}{v} \times \frac{\alpha_{em} F_{1/2}(4m_t^2/m_h^2)}{8\pi m_t} \times \frac{4}{3} - \frac{m_W^2}{v} \times \frac{\alpha_{em} F_{1}(4m_W^2/m_h^2)}{8\pi m_W^2}
\end{align}

(8)

where the first (second) term in $C^{SM}_{\gamma}$ is KK top quark (KK W-boson) contributions, respectively, $\alpha_{s,em}$ is the fine structure constant of QCD, electromagnetic coupling, the loop function $F_{1/2,1}(\tau)$ given by

\begin{align}
F_{1/2}(\tau) &= -2\tau(1 + (1 - \tau)[\sin^{-1}(1/\sqrt{\tau})]^2) \rightarrow -\frac{4}{3} \text{ for } \tau \gg 1, \\
F_{1}(\tau) &= 2 + 3\tau + 3\tau(2 - \tau)[\sin^{-1}(1/\sqrt{\tau})]^2 \rightarrow 7 \text{ for } \tau \gg 1.
\end{align}

(10)

It is well-known that in the top quark decoupling limit $m_t \gg m_h$, $F_{1/2,1}$ becomes a constant and the resultant effective coupling becomes independent of $m_t$, $m_W$ 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 GHU 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 are found to be

\begin{align}
\mathcal{L}_{eff} &= C_{g}^{KK(GH)} h G^{a\mu\nu} G^{a}_{\mu\nu}, \\
C_{g}^{KK(GH)} &= -\sum_{n=1}^{\infty} \left[ \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} \right] + (m_{\pm}^{(n)} \leftrightarrow m_{-}^{(n)}) \\
&\approx \frac{m_t\alpha_s}{12\pi v} \sum_{n=1}^{\infty} \left[ \frac{1}{m_{+}^{(n)}} - \frac{1}{m_{-}^{(n)}} \right] \approx -\frac{\alpha_s}{6\pi v} \sum_{n=1}^{\infty} \frac{m_{+}^{2}}{m_{-}^{2}}
\end{align}

(12)

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 due to the 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. The results are depicted in Fig. 3 as a function of the mass of the lightest KK mode (diagonal) mass eigenvalue ($m_1$). For the bulk fermion with the (half-)periodic boundary condition $m_1 = 1/R(1/(2R))$. 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\(^2\) 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 GHU, while

Fig. 1. The ratio of the Higgs boson production cross sections in the GHU and in the SM as a function of the KK mode mass $m_1$. The solid (dashed) line corresponds to the result including 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). We have taken $m_h = 120$ GeV.

it is increased in the UED scenario. This is a crucial point to distinguish the GHU from the UED scenario.

The contribution of top quark KK modes to the effective coupling between Higgs boson and photons are calculated similarly.

\[
\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{eff}}^{\gamma h} + \mathcal{L}_{\text{eff}}^{\gamma h},
\]

\[
C^{GH}_{\gamma h} = \frac{2m_t\alpha_{em}}{9\pi v} \sum_{n=1}^{\infty} \frac{m_t}{m_+^{(n)}} = \frac{4\alpha_{em}}{9\pi v} \sum_{n=1}^{\infty} \frac{m_t^2}{m_n^{(n)}}.
\]

(13)

For the effective coupling with photons, in addition to the KK fermion contributions, we also have the KK W-boson loop corrections as in the SM. However, we neglect such contributions compared to those from the KK top quark ones by the following plausible reasons.

- KK top ( KK W-boson) contributions are decoupling effects, and are proportional to mass squared of top (W-boson), respectively. This indicates that KK top quark contributions are likely to be dominant.
- In the GHU model on the flat space, a large dimensional representation in which the SM top quark is embedded must be introduced to reproduce a realistic top Yukawa coupling. Therefore, the effective 4D theory includes extra vector-like top-like quarks and its KK modes. Thus, KK top quark contributions are enhanced by a number of extra top-like quarks.
- In some GHU models, bulk top-like quarks with the half-periodic boundary condition are often introduced to realize the correct electroweak symmetry breaking and a viable Higgs boson mass. The lowest KK mass of the half-periodic fermions is half of the lowest KK mass of periodic ones, so that their loop contributions can dominate over those by periodic KK mode fields.
After these considerations, we see that the KK mode contributions to two photon decay is the same sign as those of the SM.

4. Effects on Higgs boson search at LHC

As we have shown, the KK mode loop contribution to the effective coupling between Higgs boson and gluons (photons) is subtractive (slightly constructive) to the top quark loop contribution in the SM. This fact leads to remarkable effects on Higgs boson search at the LHC. Since the main production process of Higgs boson at the LHC is through gluon fusion, and the primary discovery mode of Higgs boson is its two photon decay channel if Higgs boson is light $m_h < 150$ GeV. Therefore, the deviations of the effective coupling between Higgs boson and gluons or photons from the SM one give important effects on the Higgs boson production and the number of two photon events from Higgs boson decay.

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

$$\frac{\sigma(gg \to h; \text{SM} + \text{KK}) \times BR(h \to \gamma\gamma; \text{SM} + \text{KK})}{\sigma(gg \to h; \text{SM}) \times BR(h \to \gamma\gamma; \text{SM})} \simeq \left(1 + \frac{C_{g}^{KK(GH)}}{C_{g}^{SM}}\right)^2 \left(1 + \frac{C_{\gamma}^{KK(GH)}}{C_{\gamma}^{SM}}\right)^2.$$ (14)

where $\sigma$ is Higgs boson production cross section, BR denotes the branching ratio of two photon decay of Higgs boson. Fig. 2 shows the results for the periodic and half-periodic KK modes as a function of $m_1$ for the case of $n_t = 1, 3$ and $5$ extra top-like quark fermions. 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.

![Fig. 2. The ratio of the number of two photon events in the GHU scenario to those in the SM as a function of the lowest KK mass $m_1$. The solid (dashed) lines represent the results including the $n_t$ (half)periodic KK fermion contributions. $n_t = 1, 3, 5$ are shown from the top to the bottom at $m_1 = 1500$ GeV. Higgs mass is taken to be 120 GeV.](image)
5. Summary
We have calculated the one-loop KK fermion contributions to the Higgs effective couplings between Higgs boson and gluons or photons and found them to be finite. This finiteness is achieved by a non-trivial cancellations between two KK mass eigenstates, although each contribution 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 a clue to distinguish the GHU from the UED scenario. Our analysis have shown that even with the KK mode mass is around 1 TeV, the KK mode loop corrections provide O(10%) deviations from the SM results in Higgs boson phenomenology at the LHC. In a realistic GHU model, some extra top-like quarks would be introduced to reproduce the top Yukawa coupling in the SM. In such a case, the KK mode contributions are enhanced and the signal events of Higgs boson production at the LHC are quite different from those in the SM.

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