

Diphoton and Z photon Decays of Higgs Boson in Gauge-Higgs Unification: A Snowmass white paper

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Abstract

In the context of gauge-Higgs unification scenario in a 5-dimensional flat space-time, we investigate Higgs boson production via gluon fusion and its diphoton and $Z\gamma$ decay modes at the LHC. We show that the signal strength of the Higgs diphoton decay mode observed at ATLAS (and CMS), which is considerably larger than the Standard Model expectation, can be explained by a simple gauge-Higgs unification model with color-singlet bulk fermions to which a half-periodic boundary condition is assigned. The bulk fermions with mass at the TeV scale also play a crucial role in reproducing the observed Higgs boson mass of around 125 GeV. One naturally expects that the KK modes also contribute to the effective $H - Z - \gamma$ coupling. However, we show a very specific and general prediction of the gauge-Higgs unification scenario that KK-mode contributions to the $H - Z - \gamma$ coupling do not exist at the 1-loop level. If the excess of the Higgs to diphoton decay mode persists, its correlation with the Higgs to Z photon decay mode can be a clue to distinguish scenarios beyond the SM, providing a significant improvement of the sensitivity for the Higgs boson signals in the future.

As announced on July 4th 2012, the long-sought Higgs boson was finally discovered by ATLAS [1] and CMS [2] collaborations at the Large Hadron Collider. The discovery is based on the Higgs boson search with a variety of Higgs boson decay modes. Although the observed data were mostly consistent with the Standard Model (SM) expectations, the diphoton decay mode showed the signal strength considerably larger than the SM prediction. Since the effective Higgs-to-diphoton coupling is induced at the quantum level even in the SM, a certain new physics can significantly affect the coupling. Although the updated CMS analysis [3] gives a much lower value for the signal strength of the diphoton events than the previous one, the updated ATLAS analysis [4] is still consistent with their earlier result. The excess may persist in future updates.

Gauge-Higgs unification (GHU) [5] is one of the fascinating scenarios for physics beyond the SM, which can provide us a solution to the gauge hierarchy problem without invoking supersymmetry. In this scenario, the SM Higgs doublet is identified with an extra spatial component of a gauge field in higher dimensional gauge theory. Nevertheless the scenario is non-renormalizable, the higher dimensional gauge symmetry allows us to predict various finite physical observables such as Higgs potential [6], $H \rightarrow gg, \gamma\gamma$ [7, 8], the electric and magnetic moment of fermion [9].

We consider a simple GHU model based on the gauge group $SU(3) \times U(1)'$ in a 5-dimensional flat space-time with orbifolding on S^1/Z_2 with radius R of S^1 . In our setup of bulk fermions, we follow Ref. [10]: the up-type quarks except for the top quark, the down-type quarks and the leptons are embedded respectively into $\mathbf{3}$, $\bar{\mathbf{6}}$, and $\mathbf{10}$ representations of $SU(3)$. In order to realize the large top Yukawa coupling, the top quark is embedded into a rank 4 representation of $SU(3)$, namely $\bar{\mathbf{15}}$. The extra $U(1)'$ symmetry works to yield the correct Weinberg angle [11]. We assign appropriate $U(1)'$ charges for bulk fermions to give the correct hyper-charges for the SM fermions.

The boundary conditions should be suitably assigned to reproduce the SM fields as the zero modes. While a periodic boundary condition corresponding to S^1 is taken for all of the bulk SM fields, the Z_2 parity is assigned for gauge fields and fermions in the representation \mathcal{R} by using the parity matrix $P = \text{diag}(-, -, +)$ as

$$A_\mu(-y) = P^\dagger A_\mu(y) P, \quad A_y(-y) = -P^\dagger A_y(y) P, \quad \psi(-y) = \mathcal{R}(P)\psi(y) \quad (1)$$

where the subscripts μ (y) denotes the four (the fifth) dimensional component. With this choice of parities, the $SU(3)$ gauge symmetry is explicitly broken to $SU(2) \times U(1)$. A hypercharge is a linear combination of $U(1)$ and $U(1)'$. As a result, zero-mode vector bosons in the model are only the SM gauge fields.

Off-diagonal blocks in A_y have zero modes because of the overall sign in Eq. (1), which corresponds to an $SU(2)$ doublet. In fact, the SM Higgs doublet (H) is identified as

$$A_y^{(0)} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & H \\ H^\dagger & 0 \end{pmatrix}. \quad (2)$$

The KK modes of A_y are eaten by KK modes of the SM gauge bosons and enjoy their longitudinal degrees of freedom like the usual Higgs mechanism.

The parity assignment also provides the SM fermions as massless modes, but it also leaves exotic fermions massless. Such exotic fermions are made massive by introducing brane localized fermions with conjugate $SU(2) \times U(1)$ charges and an opposite chirality to the exotic fermions, allowing us to write mass terms on the orbifold fixed points. In the GHU scenario, the Yukawa interaction is unified with the gauge interaction, so that the SM fermions obtain the mass of the order of the W -boson mass after the electroweak symmetry breaking. To realize light SM fermion masses, one may introduce a Z_2 -parity odd bulk mass terms for the SM fermions, except for the top quark. Then, zero mode fermion wave functions with opposite chirality are localized towards the opposite orbifold fixed points and a resulting Yukawa coupling is exponentially suppressed by the overlap integral of the wave functions. In order to realize the top quark Yukawa coupling, we introduce a rank 4 tensor representation, namely, a symmetric $\overline{\mathbf{15}}$ without a bulk mass [10], which leads to $m_t = 2m_W$ at the compactification scale [11].

With the setup discussed above, we have estimated the ratio of the signal strength of the process $gg \rightarrow H \rightarrow \gamma\gamma$ in our model to the one in the SM [7, 12]. The result is depicted in Fig. 1 as a function of the KK mode mass/the compactification scale. The ratio R is found to be smaller than one, because of the destructive KK mode contribution to the gluon fusion channel and the accidental cancellation among the KK mode contributions to the Higgs-to-diphoton decay width. This fact has already been advocated in the previous paper by the present authors [7].

Now we extend the present GHU model to account for the signal strength measured by ATLAS (and CMS) for the process $gg \rightarrow H \rightarrow \gamma\gamma$ which is considerably larger than the SM expectation. The simplest extension is to introduce color-singlet bulk fermions with the half-periodic boundary condition in the bulk. In [12], we have considered two examples for the color-singlet bulk fermions of the representations $\mathbf{10}$ and $\mathbf{15}$ of $SU(3)$, with a suitable $U(1)'$ charge Q assignment and bulk mass M parametrized in the unit of the KK mass $m_{\text{KK}} = 1/R$ by $c_B \equiv M/m_{\text{KK}}$. For the two cases, we plot the ratio R as a function of the KK mode mass m_{KK} in Fig. 2. The left(right) panel corresponds to the case with the $\mathbf{10}(\mathbf{15})$ -plet bulk fermion, where we have fixed $Q = -1(-5)$ and

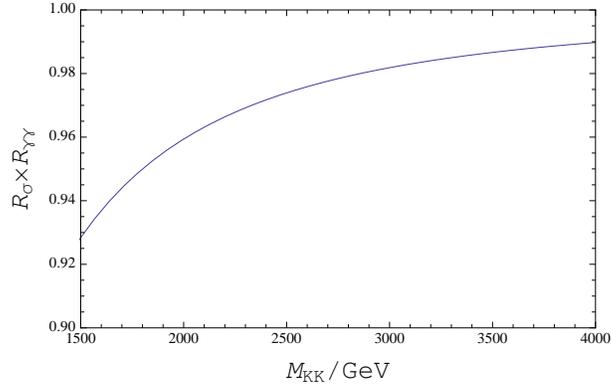


Figure 1: The ratio of diphoton events in the simple GHU model to those in the SM as a function of the compactification scale.

$c_B = 0.23(0.69)$. As we will see later, the Higgs boson mass around 125 GeV can be reproduced with the bulk mass $c_B = 0.23(0.69)$ for $m_{\text{KK}} = 3$ TeV. We have found that the Higgs-to-diphoton signal strength is considerably enhanced in the presence of the half-periodic bulk fermions with the TeV scale mass. The rate of the enhancement can be large as we like by adjusting a $U(1)'$ charge Q .

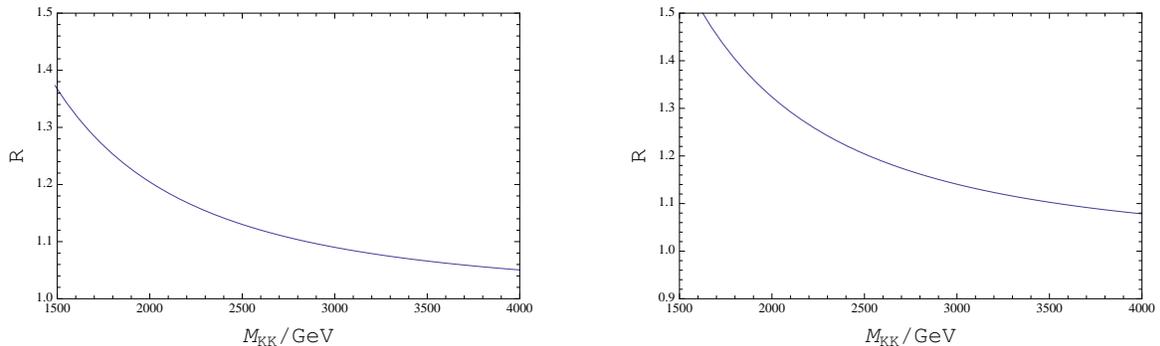


Figure 2: The diphoton signal strength (normalized by the SM prediction) in the GHU model with the **10**-plet (left) and **15**-plet (right) bulk fermions as a function of the compactification scale.

In Fig. 3, we plot the ratio of diphoton signal strength to the SM one as a function of the $U(1)'$ charge Q , for the two cases. For each plot, the bulk masses are fixed to be the same values as in the previous plots. We can see that $|Q| = \mathcal{O}(1)$ is enough to give rise to an order 10% enhancement of the diphoton signal.

Next, we discuss how the Higgs boson mass around 125 GeV is realized in our model. Realizing the 125 GeV Higgs boson mass is a quite non-trivial in 5-dimensional GHU scenario since the Higgs quartic coupling is generated at loop levels and a calculated Higgs boson mass is likely to be small. In estimating Higgs boson mass, we take a 4-dimensional

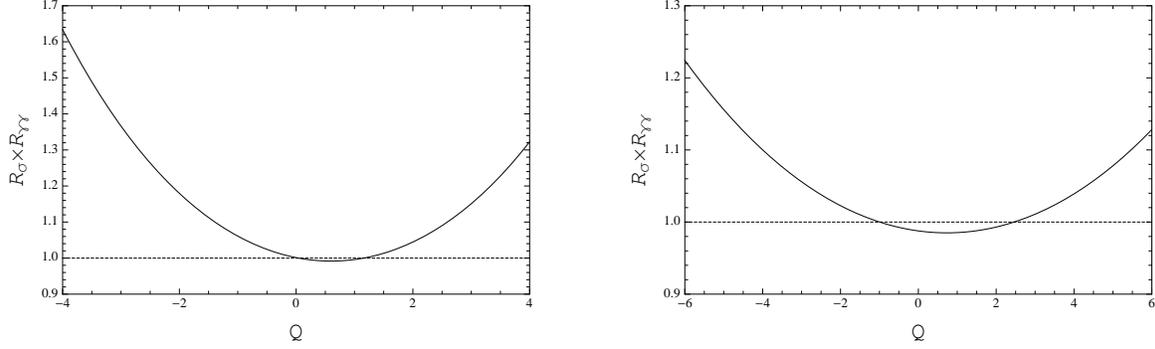


Figure 3: The diphoton signal strength (normalized by the SM prediction) in the GHU model with the **10**-plet (left) and **15**-plet (right) bulk fermions as a function of the $U(1)'$ charge Q , for $m_{\text{KK}} = 3$ TeV.

effective theory approach developed by Ref. [13], in which the low energy effective theory of the 5-dimensional GHU scenario is equivalent to the SM with the so-called “gauge-Higgs condition” on the Higgs quartic coupling, namely, we impose a vanishing Higgs quartic coupling at the compactification scale, which reflects the 5-dimensional gauge invariance restoration. The Higgs boson mass at low energies is easily calculated by solving the RGE of the Higgs quartic coupling with the gauge-Higgs condition and is mainly determined by light states below the compactification scale. In our model, we have introduced bulk fermions with the half-periodic boundary condition, and their first KK modes appear below the compactification scale. Therefore, not only the SM particles but also the first KK modes are involved in our RGE analysis with the gauge-Higgs condition.

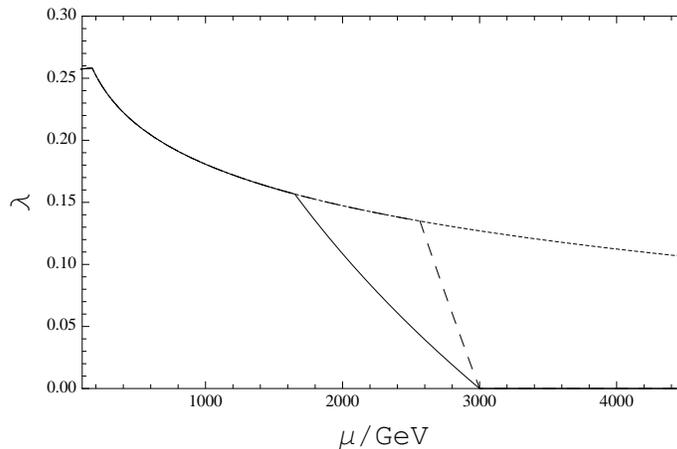


Figure 4: 1-loop RGE running of the Higgs quartic coupling.

The numerical results of 1-loop RGE of the Higgs quartic coupling are shown in Fig. 4. Here we have applied the gauge-Higgs condition ($\lambda(m_{\text{KK}}) = 0$) at the compactification scale $m_{\text{KK}} = 3$ TeV and numerically solve the RGE toward low energies. The bulk masses

of the $\mathbf{10(15)}$ -plet are fixed to be the values $c_B = 0.23(0.69)$, respectively, with which Higgs boson mass of $m_H = 125$ GeV (equivalently, $\lambda(\mu = m_H) = 0.258$) is realized. The solid (dashed) line represents the running Higgs quartic coupling for the case with the $\mathbf{10(15)}$ -plet bulk fermion, while the dotted line corresponds to the RGE running in the SM case with the boundary condition $\lambda(\mu = m_H) = 0.258$. As can be seen from Fig. 4, the existence of the half-periodic bulk fermions is essential to realize the Higgs mass around 125 GeV with the compactification at the TeV scale. Since the bulk fermions provide many first KK mode fermions in the SM decomposition, the running Higgs quartic coupling is sharply rising from zero toward low energies.

We naturally expect that the decay $H \rightarrow Z\gamma$ is also deviated from the SM prediction since the KK modes have electroweak charges. The correlation between the $\gamma\gamma$ and the $Z\gamma$ decays of Higgs boson is interesting since this property is model dependent and useful for distinguishing our model from other models beyond the SM. In [14], we have studied the KK mode contributions to the Higgs boson to $Z\gamma$ decay in the GHU and found a striking result that we have no KK mode contributions to it the at 1-loop level. This is because Z boson always has couplings over two different mass eigenstates corresponding to the mass splitting due to the electroweak symmetry breaking, while the Higgs boson and photon couple with the same mass eigenstates. This coupling manner originates from the basic structure of the GHU scenario and can be a clue to distinguish the GHU scenario from other scenarios beyond the SM, providing a significant improvement of the sensitivity for the Higgs boson signals in the future.

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References

- [1] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **716**, 1 (2012).
- [2] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **716**, 30 (2012).
- [3] The CMS Collaboration, CMS-PAS-HIG-13-001.
- [4] The ATLAS Collaboration, ATLAS-CONF-2013-012.

- [5] N. S. Manton, Nucl. Phys. B **158**, 141 (1979); D. B. Fairlie, Phys. Lett. B **82**, 97 (1979), J. Phys. G **5**, L55 (1979); Y. Hosotani, Phys. Lett. B **126**, 309 (1983), Phys. Lett. B **129**, 193 (1983), Annals Phys. **190**, 233 (1989).
- [6] I. Antoniadis, K. Benakli and M. Quiros, New J. Phys. **3**, 20 (2001); G. von Gersdorff, N. Irges and M. Quiros, Nucl. Phys. B **635**, 127 (2002); R. Contino, Y. Nomura and A. Pomarol, Nucl. Phys. B **671**, 148 (2003); C. S. Lim, N. Maru and K. Hasegawa, J. Phys. Soc. Jap. **77**, 074101 (2008); N. Maru and T. Yamashita, Nucl. Phys. B **754**, 127 (2006); Y. Hosotani, N. Maru, K. Takenaga and T. Yamashita, Prog. Theor. Phys. **118**, 1053 (2007).
- [7] N. Maru and N. Okada, Phys. Rev. D **77**, 055010 (2008);
- [8] N. Maru, Mod. Phys. Lett. A **23**, 2737 (2008).
- [9] Y. Adachi, C. S. Lim and N. Maru, Phys. Rev. D **76**, 075009 (2007); Phys. Rev. D **79**, 075018 (2009); Phys. Rev. D **80**, 055025 (2009).
- [10] G. Cacciapaglia, C. Csaki and S. C. Park, JHEP **0603**, 099 (2006).
- [11] C. A. Scrucca, M. Serone and L. Silvestrini, Nucl. Phys. B **669**, 128 (2003).
- [12] N. Maru and N. Okada, Phys. Rev. D **87**, 095019 (2013).
- [13] N. Haba, S. Matsumoto, N. Okada and T. Yamashita, JHEP **0602**, 073 (2006); Prog. Theor. Phys. **120**, 77 (2008).
- [14] N. Maru and N. Okada, arXiv:1307.0291 [hep-ph].