Testing Gauge-Higgs Unification Models by Measuring the Triple Higgs Boson Coupling at Future Collider Experiments

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Motivation

125 GeV Higgs boson was discovered at CERN LHC

➡ Success of the Standard Model (SM)

But, Higgs sector is not fully understood

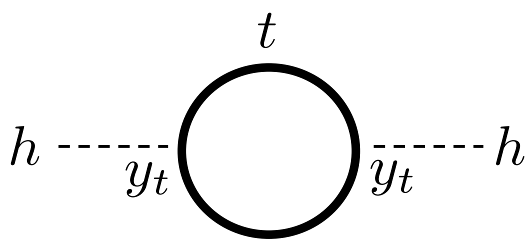
- Guiding principle
- Number of the Higgs particles
- Couplings of the Higgs boson
- Hierarchy problem

What is the true structure of the Higgs sector?

We need to investigate the Higgs sector from both of experimental and theoretical sides

Hierarchy problem

Mass squared of the Higgs boson



one-loop correction of the top quark

$$m_h^2 = m_{h,0}^2 + \Delta m_h^2 \quad \text{In the SM} \quad \Delta m_h^2 = -\frac{y_t^2}{8\pi^2}\Lambda^2 + \cdots$$

$(125\ \mathrm{GeV})^2$ $\quad \mathcal{O}(10^{34})\ \mathrm{GeV}^2$

Quadratic divergence of the order of the cut-off scale Λ

For $\Lambda = \mathcal{O}(10^{19})\ \mathrm{GeV}$, we need fine-tuning with accuracy of 10^{-30}

Paradigms of new physics at TeV scale

- Supersymmetry
- Composite Models
- Gauge-Higgs Unification (GHU)

The Higgs sector is extended by different way

Gauge-Higgs Unification

Features of Gauge-Higgs Unification

- TeV scale extra special dimension(s) is introduced
  - ➢ Kaluza-Klein (KK) particles appear

oscillation modes in the extra dimensional directions

$$\phi(x_\mu, x_m) = \sum_{n=0}^{\infty} f^{(\pm n)}(x_m)\phi^{(\pm n)}(x_\mu)$$

- Higgs is embedded in higher dimensional gauge fields

$$A_M = (A_\mu, \underline{A_m})$$

extra components ∊ SM like Higgs

  - ➢ Gauge transformation also imposes on Higgs

Model Classification

Earlier studies of gauge-Higgs unification

Flat space

- Minimal SU(3) model

  [e.g. Scrucca, et al., NPB 669 (2003), etc.]

- SU(3) model with large bulk representations

  [e.g. Cacciapaglia, Csaki, Park, JHEP 0603 (2006);Adachi, Maru, PRD 98 (2018), etc.]

- SU(3) model with 5D Lorentz symmetry relaxed

  [e.g. Panico, Serone, Wulzer, NPB 739 (2006), etc.]

  ← This talk

Warped space

- SO(5) X U(1) model

  [e.g. Funatsu, Hatanaka, Hosotani, Orikasa, Shimotani, PLB 722 (2013), etc.]

Higgs sector in Gauge-Higgs Unification

Modification of the Higgs sector

Higgs sector is also controlled by the gauge principle

(
- Higgs interaction is unified into the gauge interaction
- Higgs potential is only generated by the loop contribution

⇓

Testing the gauge-Higgs unification models

Mass of the Higgs boson
Mass of the top quark
$\rightarrow$ Strongly limit the models

Triple Higgs boson Coupling $\rightarrow$ Testable by Future experiments

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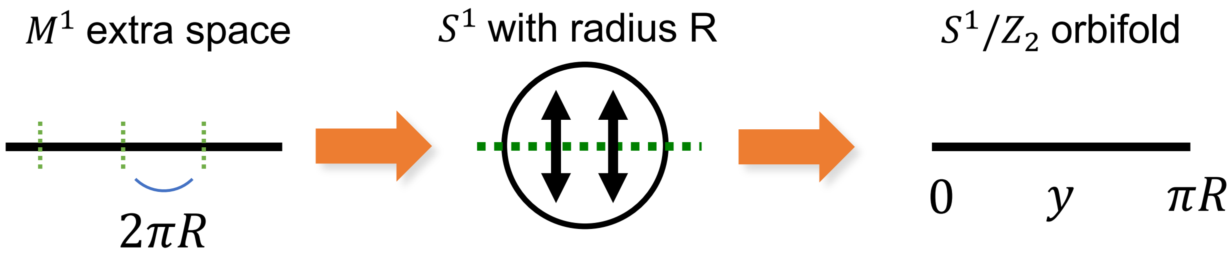
SU(3) Model

Space-time



Flat $M^4 \times S^1/Z_2$ with compactification scale 1/R

Symmetry breaking by Boundary conditions (BC)

$$SU(3)_w \times U(1)'$$

$$\left(\begin{array}{l} S^1 : A_M(y + 2\pi R) = A_M(y) \\ Z_2 : A_\mu(-y) = P^\dagger A_\mu(y) P\,,\ A_5(-y) = -P^\dagger A_5(y) P \end{array} \right.$$

BC with
$P = (-1, -1, +1)$

$$SU(2)_L \times U(1)_Y \times U(1)_X$$

Assignment of Z_2 parity

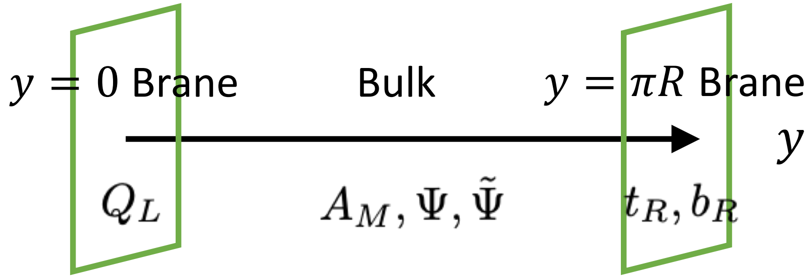
$$A_\mu = \begin{pmatrix} (+,+) & (+,+) & (-,-) \\ (+,+) & (+,+) & (-,-) \\ (-,-) & (-,-) & (+,+) \end{pmatrix} \quad A_5 = \begin{pmatrix} (-,-) & (-,-) & (+,+) \\ (-,-) & (-,-) & (+,+) \\ (+,+) & (+,+) & (-,-) \end{pmatrix}$$

Zero modes of the gauge fields

Higgs doublet

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

Field Configuration



Field configuration on the S^1/Z_2 orbifold

Field contents

- Bulk gauge fields : A_M
- Bulk fermion pairs : $\{\Psi_t, \tilde{\Psi}_t\}, \{\Psi_b, \tilde{\Psi}_b\}, \{\Psi_A, \tilde{\Psi}_A\}$
- Brane fermions : $Q_L = (t_L, b_L)^{\mathrm{T}}, t_R, b_R$

5D Matter Lagrangian (3rd generation quarks)

$$\mathcal{L}^{5D}_{\mathrm{mat}} = \sum_{j=t,b,A} \left\{ \bar{\Psi}_j \left(i\not{D}_4 - k_j D_5 \gamma^5\right) \Psi_j + \bar{\tilde{\Psi}}_j \left(i\not{D}_4 - \tilde{k}_j D_5 \gamma^5\right) \tilde{\Psi}_j + \frac{1}{\pi R}\left(\bar{\Psi}_j \lambda_j \tilde{\Psi}_j + \mathrm{h.c.}\right) \right\}$$
$$+ \delta(y-0) \left\{ \bar{Q}_L i\not{D}_4 Q_L + \sqrt{\frac{2}{\pi R}} \left(\epsilon_1^b \bar{Q}_L \psi_b + \epsilon_1^t \bar{Q}_R^c \psi_t + \mathrm{h.c.}\right) \right\}$$
$$+ \delta(y-\pi R) \left\{ \bar{t}_R i\not{D}_4 t_R + \bar{b}_R i\not{D}_4 b_R + \sqrt{\frac{2}{\pi R}} \left(\epsilon_2^b \bar{b}_R \chi_b + \epsilon_2^t \bar{t}_L^c \chi_t + \mathrm{h.c.}\right) \right\}$$

5D Lorentz invariance relaxed: $SO(4,1) \to SO(3,1)$

Model parameters

$\epsilon_1^t, \epsilon_2^t, \epsilon_1^b, \epsilon_2^b, \lambda_t, \lambda_b, \lambda_A, k_t, k_b, k_A$

For simplicity, $k_j = \tilde{k}_j$

Higgs Potential

The structure of Higgs potential in GHU

Higgs boson : $A_5^{6(0)} = \frac{2\alpha}{g_4 R}$

$$V_{\rm eff}^0 = 0$$ ← gauge symmetry

$$V_{\rm eff}^{\rm 1loop}(\alpha) = -3 \sum_{A=W^\pm,Z} \sum_{n=-\infty}^{\infty} \frac{i}{2} \int \frac{d^4p}{(2\pi)^4} \ln\left\{-p^2 + m_A^{(n)^2}(\alpha)\right\}$$ ← Bulk gauge field

$$+8 \sum_{j=t,b,A} \sum_q \sum_{n=-\infty}^{\infty} \frac{i}{2} c_j \int \frac{d^4p}{(2\pi)^4} \ln\left\{-p^2 + m_{\Psi_j}^{(n)^2}(q\alpha)\right\}$$ ← Bulk fermion

$$+4 \sum_{a=t,b} \frac{i}{2} c_a \int \frac{d^4p}{(2\pi)^4} \ln\left\{-Z_1^a(\alpha) Z_2^a(\alpha) p^2 + m_a^2(\alpha)\right\}$$ ← Brane fermion

Non-zero VEV is induced by suitable model parameter set

The mass and triple self-coupling reflect the above structure

$$m_h^2 = \left(\frac{g_4 R}{2}\right)^2 \frac{\partial^2 V_{\rm eff}(\alpha)}{\partial \alpha^2}\bigg|_{\alpha=\alpha_0} \quad , \quad \lambda_{hhh} = \left(\frac{g_4 R}{2}\right)^3 \frac{\partial^3 V_{\rm eff}(\alpha)}{\partial \alpha^3}\bigg|_{\alpha=\alpha_0}$$

➡ Difference from the SM appear in the λ_{hhh}

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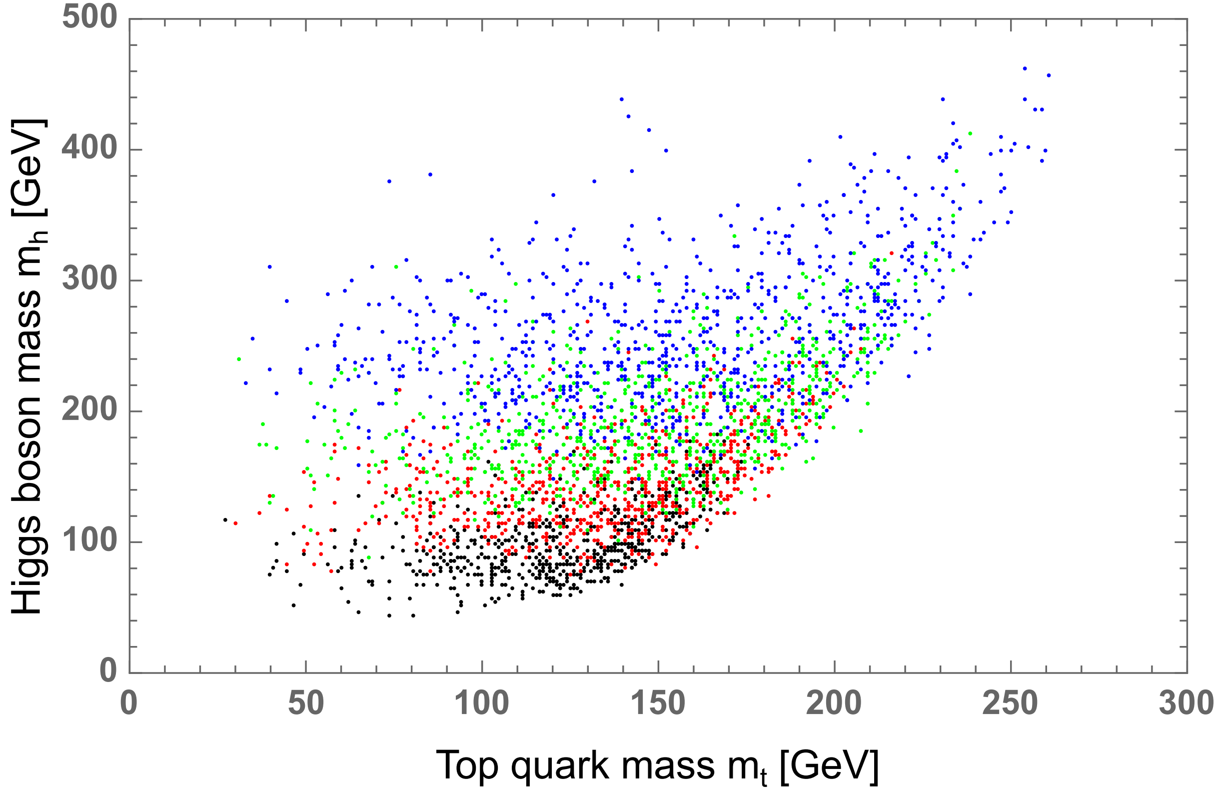
Top quark mass vs Higgs boson mass

The range of the input model parameters

$$\begin{cases} 1.5 < k_{\rm t} < 2.5 \\ 1.25 < k_{\rm b} < 2.25 \\ 1.1 \times k_{\rm t} < k_{\rm A} < 1.5 \times k_{\rm t} \end{cases} \quad \begin{cases} 0.5 < \lambda^{\rm t} < 1.5 \\ 5 < \lambda^{\rm b} < 7 \\ 0.75 < \lambda^{\rm A} < 3.5 \end{cases} \quad \begin{cases} 0.75 < \epsilon^{\rm t}_{1,2} < 7.5 \\ 2 < \epsilon^{\rm b}_{1,2} < 7 \end{cases}$$

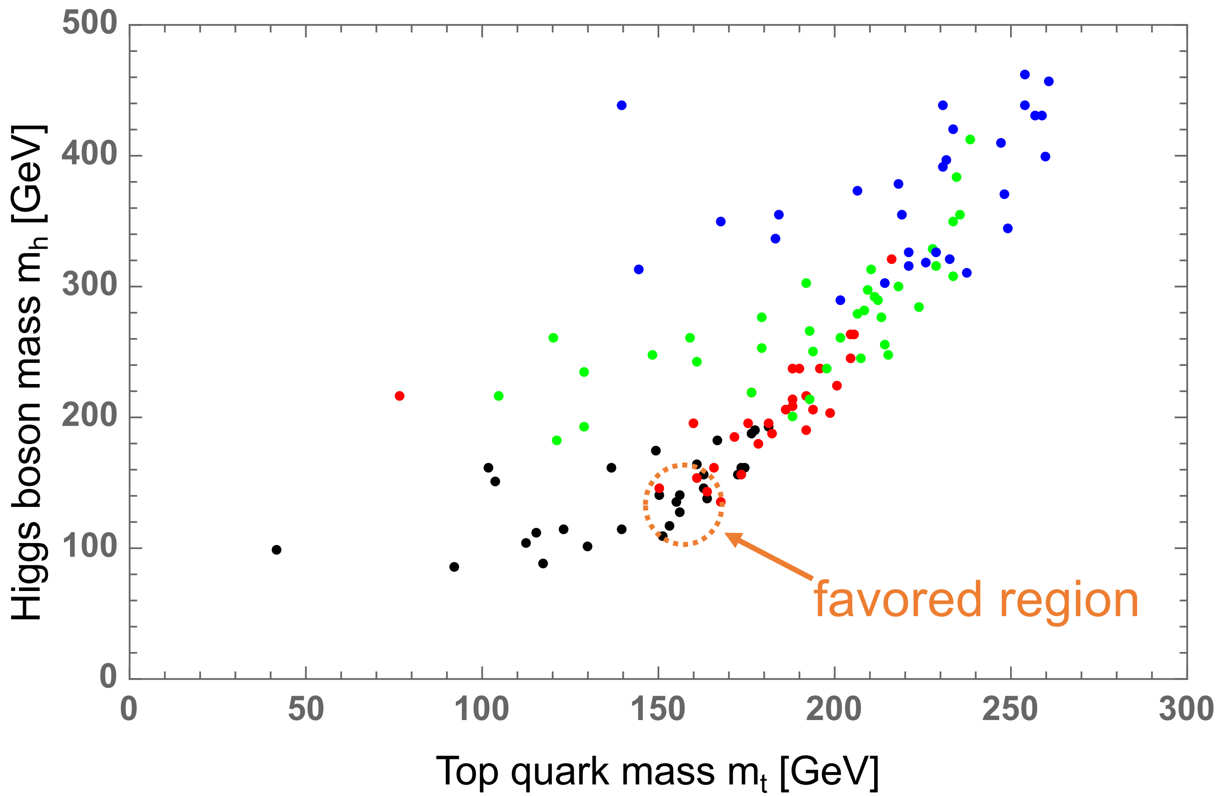


$1/R > 800$ [GeV]

- $2.25 < k_t < 2.5$ (blue)
- $2 < k_t < 2.25$ (green)
- $1.75 < k_t < 2$ (red)
- $1.5 < k_t < 1.75$ (black)

Top quark mass vs Higgs boson mass (contd.)

The mass of the Higgs boson, top quark and KK particles can be consistent with experimental data



$1/R > 800\,[\mathrm{GeV}]$

$1/R > 4\,[\mathrm{TeV}]$

(updated exp. bound)

$2.25 < k_t < 2.5$

$2 < k_t < 2.25$

$1.75 < k_t < 2$

$1.5 < k_t < 1.75$

Triple Higgs boson coupling

Deviation from the SM prediction

$$\Delta\lambda = \frac{\lambda_{hhh} - \lambda_{hhh}^{\mathrm{SM}}}{\lambda_{hhh}^{\mathrm{SM}}}$$

- Constraints:

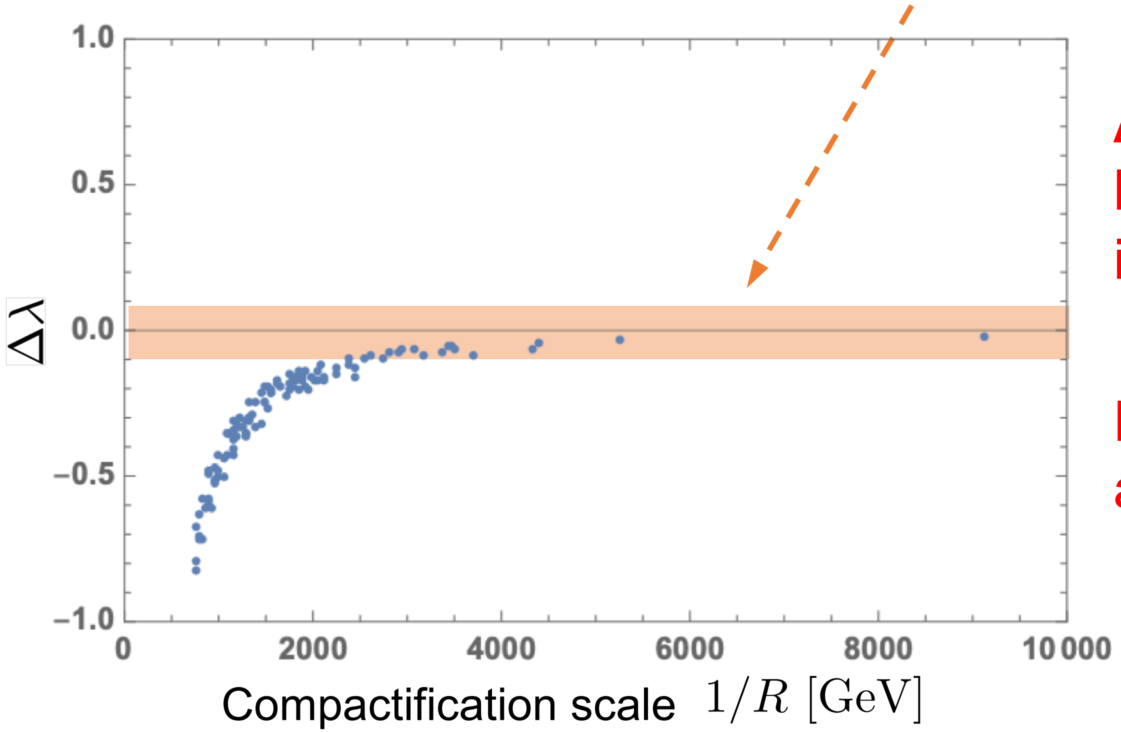
$$152\ \mathrm{GeV} < m_t < 182\ \mathrm{GeV}$$

$$110\ \mathrm{GeV} < m_h < 140\ \mathrm{GeV}$$

Future collider experiments

HL-LHC : $-1.8 \lesssim \Delta\lambda \lesssim 6.7$ (95% CL) [ATL-PHYS-PUB-2017-001]

ILC($\sqrt{s} = 1\,\mathrm{TeV}$, $L = 4\,\mathrm{ab}^{-1}$) : $\Delta\lambda$: 10% [K. Fujii et al. (2019)]



Δλ is characterized primarily by the compactification scale in this model

Deviation quickly disappear as increase of 1/R

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Summary

- We have revisited the SU(3) model with 5D Lorentz symmetry relaxed in Gauge-Higgs Unification

- In this model, the mass of the Higgs boson, top quark and KK particles can be consistent with experimental data

- The deviation of the triple Higgs boson coupling is characterized primarily by the compactification scale in this model

- The observation of a significant deviation in the triple Higgs boson coupling requires additional extension of the model