# Triple Higgs Boson Coupling in Gauge-Higgs Unification Models


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# Motivation

125 GeV Higgs boson was discovered at CERN LHC

- Success of the Standard Model

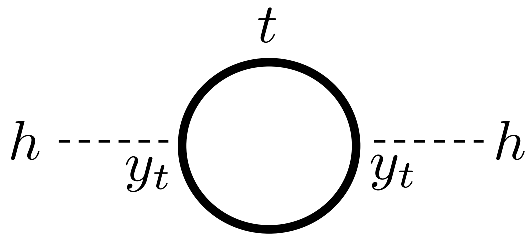
But, Higgs sector is not fully understood

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

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

What is the true structure of the Higgs sector?

# Hierarchy problem




one-loop correction of the top quark

## Mass squared of the Higgs boson

$$m_h^2 = m_{h,0}^2 + \Delta m_h^2$$

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

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

Quadratic divergence of the order of the cut-off scale $\Lambda$

For $\Lambda = \mathcal{O}(10^{19})$ 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
- SM like Higgs is the extra components of gauge fields
- Higgs sector is described by gauge principle
  - ✓ Interaction: yukawa interaction $\longrightarrow$ gauge interaction
  - ✓ Higgs Potential: Tree + loop effect $\longrightarrow$ loop induced

## Difficulties in gauge-Higgs unification

- The Higgs boson, top quark and KK particles are too light

# Attempts

## 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.]

This work
- Analysis of the Higgs potential in above model
- Estimation of the triple Higgs boson coupling

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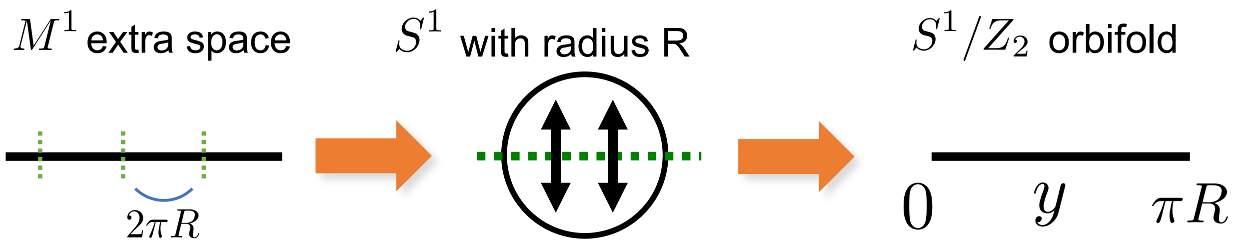
# SU(3) Model

## 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

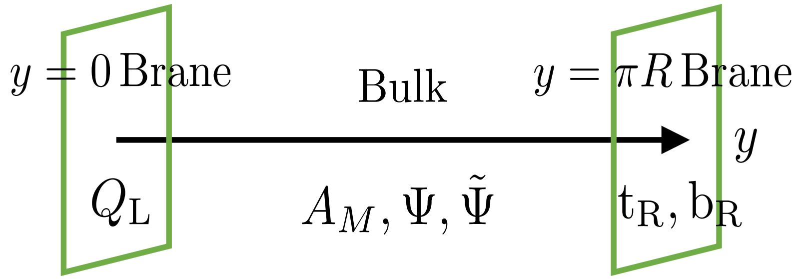
$$A_\mu = \begin{pmatrix} (+,+) & (+,+) & (-,-) \\ (+,+) & (+,+) & (-,-) \\ (-,-) & (-,-) & (+,+) \end{pmatrix} \quad A_5 = \begin{pmatrix} (-,-) & (-,-) & (+,+) \\ (-,-) & (-,-) & (+,+) \\ (+,+) & (+,+) & (-,-) \end{pmatrix}$$

## Zero modes of the gauge fields

Higgs doublet

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

# Field configuration




Field configuration on the $S^1/Z_2$ orbifold

## Field contents

- Bulk gauge fields : $A_M$
- Bulk fermion pairs : $\{\Psi_{\rm t}, \tilde{\Psi}_{\rm t}\}, \{\Psi_{\rm b}, \tilde{\Psi}_{\rm b}\}, \{\Psi_{\rm A}, \tilde{\Psi}_{\rm A}\}$
- Brane fermions : $Q_L = (\mathrm{t}_L, \mathrm{b}_L)^{\rm T}, \mathrm{t}_R, \mathrm{b}_R$

## 5D Matter Lagrangian (3rd generation quarks)

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

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

## VEV is induced by non-trivial way

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

$$V_{\rm eff}^{0} = 0 \quad \longleftarrow \text{ gauge symmetry}$$

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

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

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

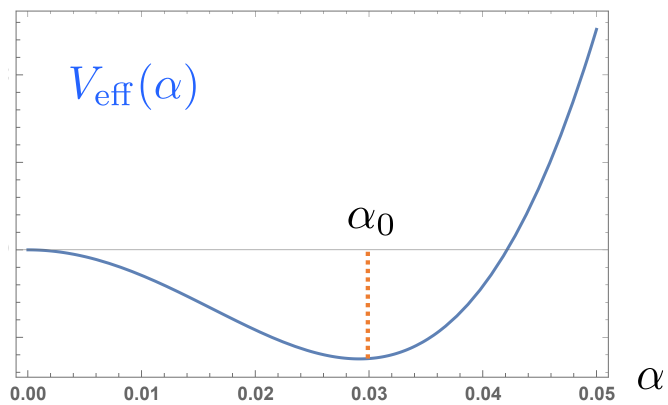
## Mass of the Higgs boson

$$m_h^2 = \left(\frac{g_4 R}{2}\right)^2 \left.\frac{\partial^2 V_{\rm eff}(\alpha)}{\partial \alpha^2}\right|_{\alpha=\alpha_0}$$

## Triple Higgs boson coupling

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

Illustration of the Higgs potential



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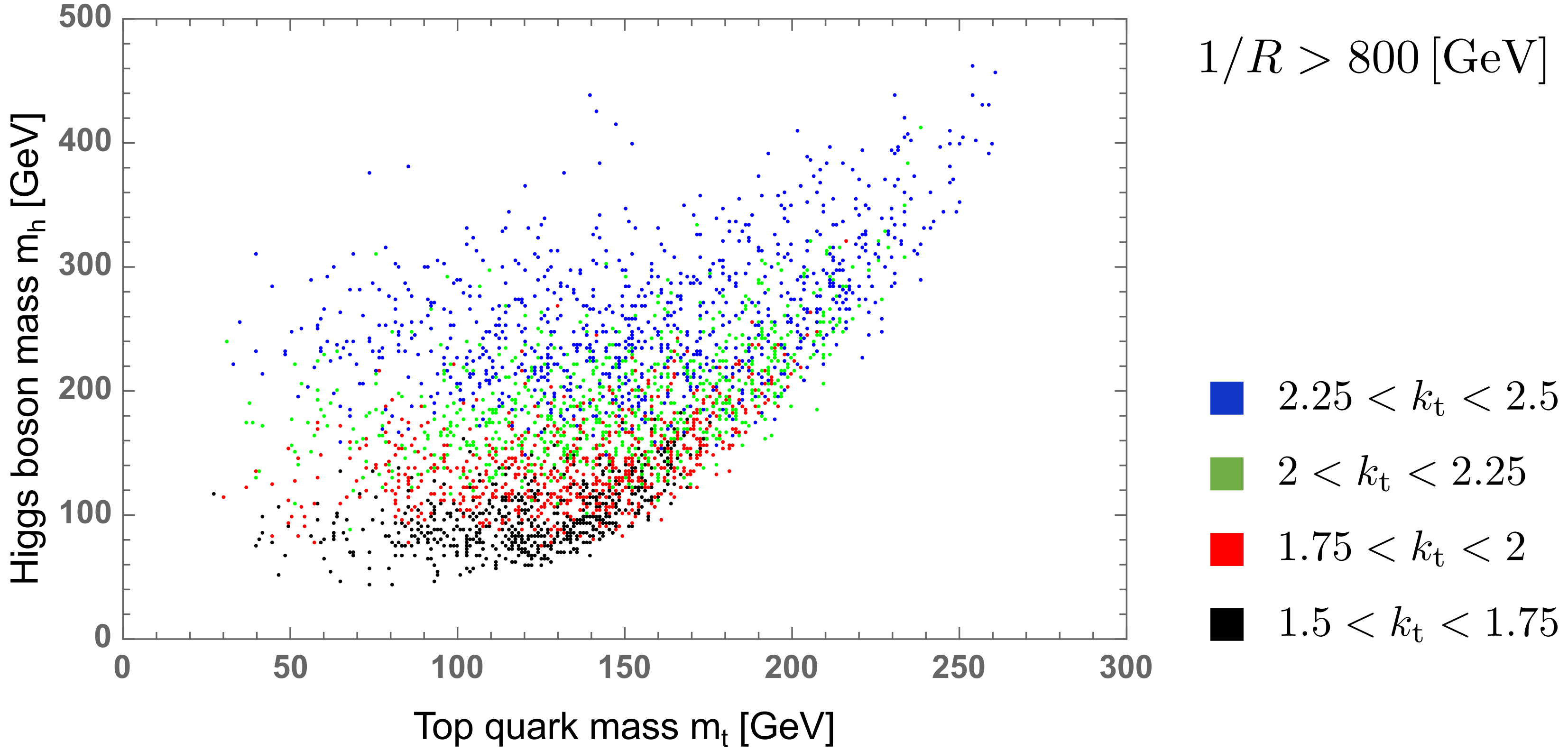
# Top quark mass vs Higgs boson mass

## The range of the input model parameters

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



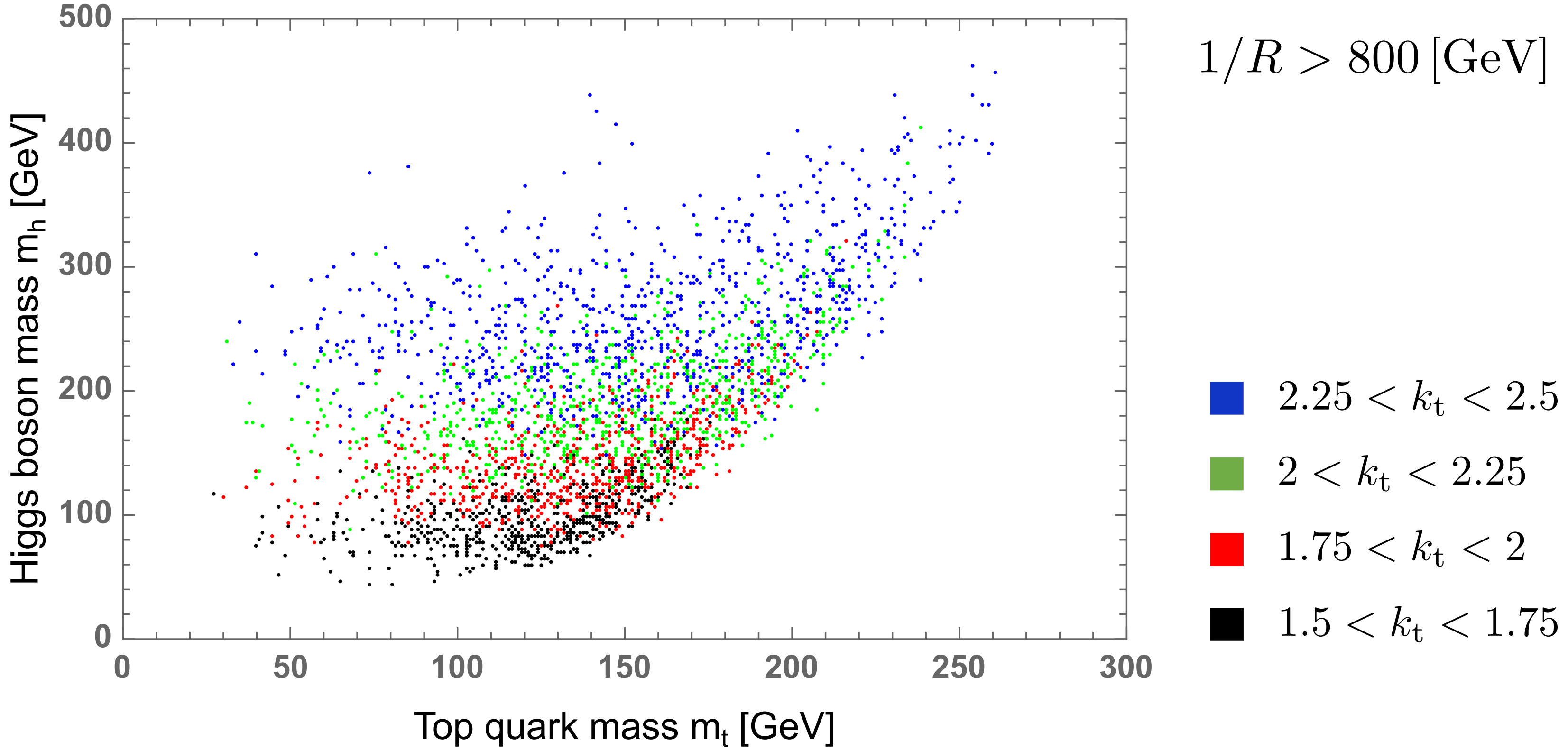
# Top quark mass vs Higgs boson mass

## Mass enhancement by k parameter

$$m_t \lesssim \sqrt{2} k_t m_W \quad , \quad m_h \propto k^2$$ ( Very rough approximation )

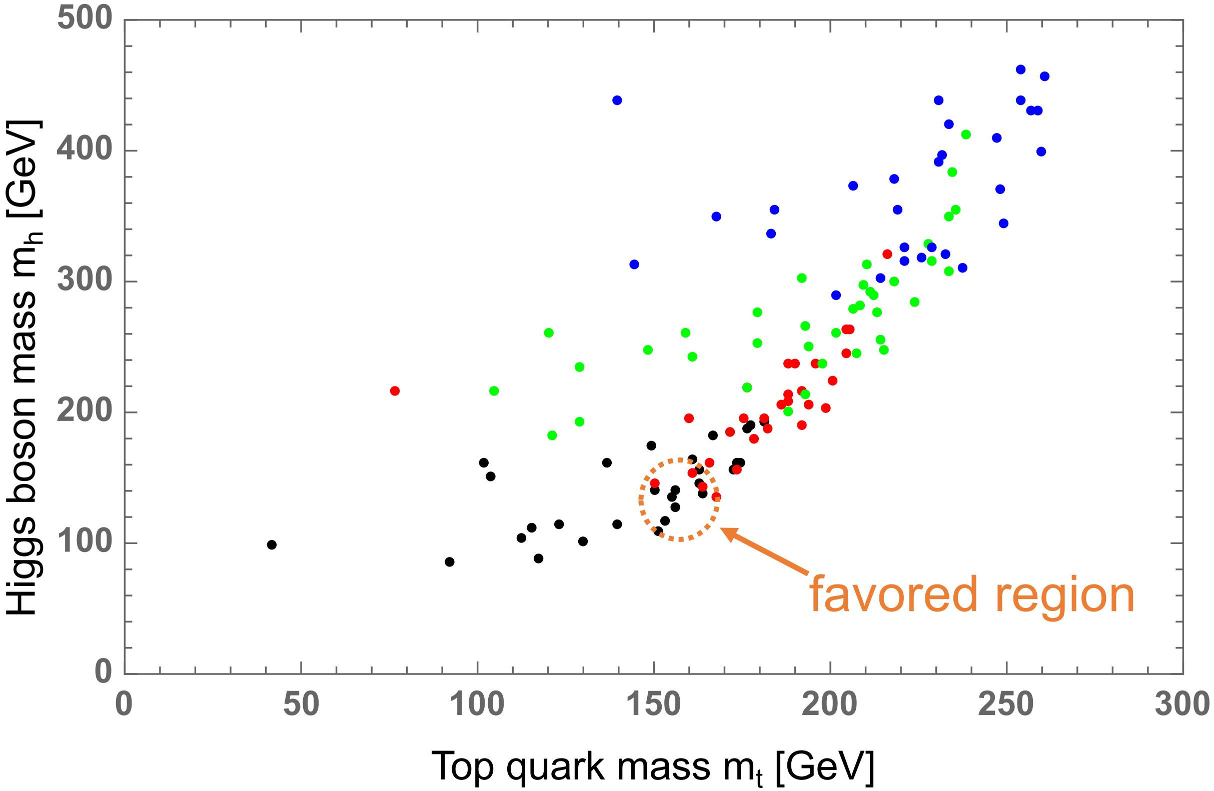
## Our results are consistent with earlier works

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



# 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

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

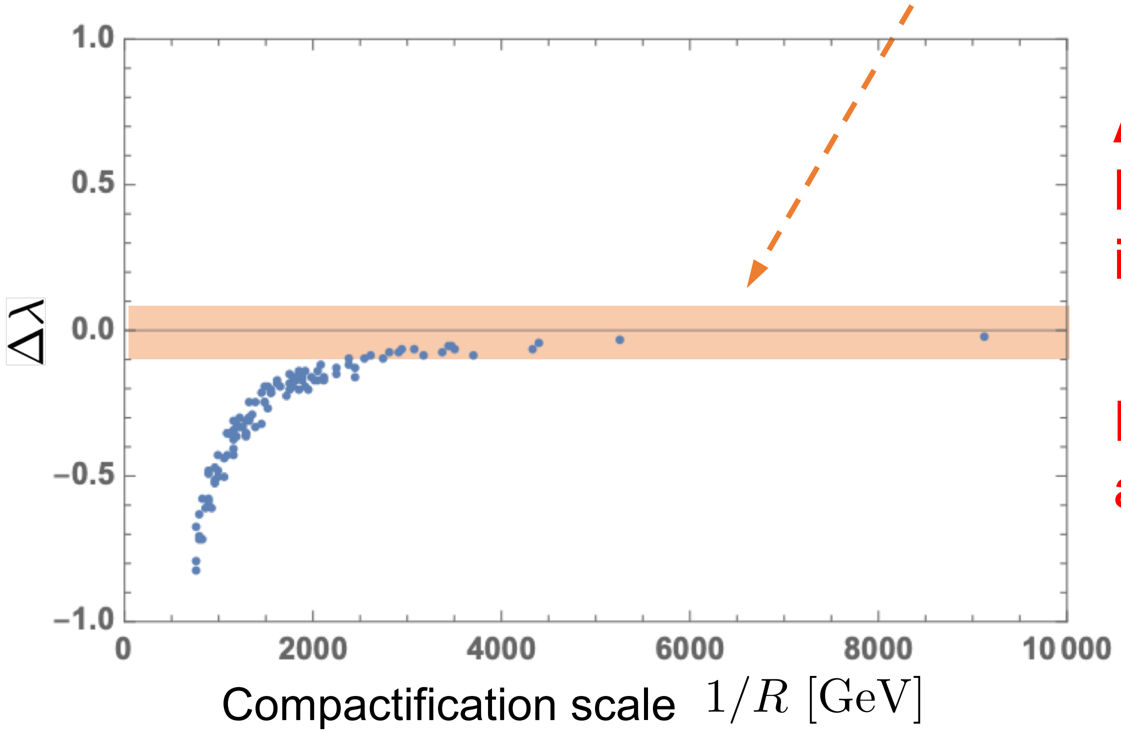
- Constraints:

$$152 \text{ GeV} < m_t < 182 \text{ GeV}$$
$$110 \text{ GeV} < m_h < 140 \text{ GeV}$$

## Future collider experiments

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

ILC($\sqrt{s} = 1\,\text{TeV}$ , $L = 4\,\text{ab}^{-1}$) : $\Delta\lambda$ : 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

# Back up