Structure of the Higgs potential in Gauge-Higgs Unification with a Flat Extra Dimension

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Introduction (Mystery in the Higgs Sector)

Hierarchy problem suggest the new physics at TeV scale

- Supersymmetry
- Composite Models
- Gauge-Higgs Unification

$$A_M = (A_\mu, A_m)$$

A_μ: 4D gauge, A_m: 4D Higgs

$$\Rightarrow V_{\rm eff}^{\rm GHU} = {\rm const.} + \sum_i \frac{n_i}{2}\int \frac{d^4 p_E}{(2\pi)^4} \ln\left(p_E^2 + m_i^2(\phi)\right)$$

one-loop correction

We analyze the Higgs potential and triple coupling in the SU(3) model with 5D Lorentz symmetry relaxed

SU(3) Model [Panico, Serone, Wulzer, NPB 739 (2006)]

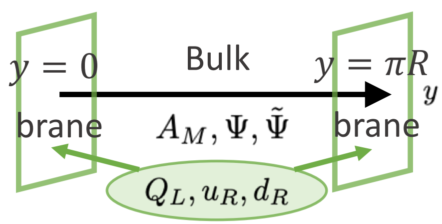
Space-time : Flat $M^4 \times S^1/Z_2$ with compactification scale $1/R$

Symmetry Breaking : $SU(3)_w \times U(1)'$

$$\xrightarrow{\rm BC} SU(2)_L \times U(1)_Y \times U(1)_X$$

Field contents

- Bulk gauge field : A_M
- Bulk fermion pair : $\{\Psi, \tilde{\Psi}\}$
- Brane fermion : Q_L, u_R, d_R



Effective Potential in the Flat SU(3) Model

Conventional notation : $\frac{g_4}{2}\phi = \frac{\alpha}{R}$

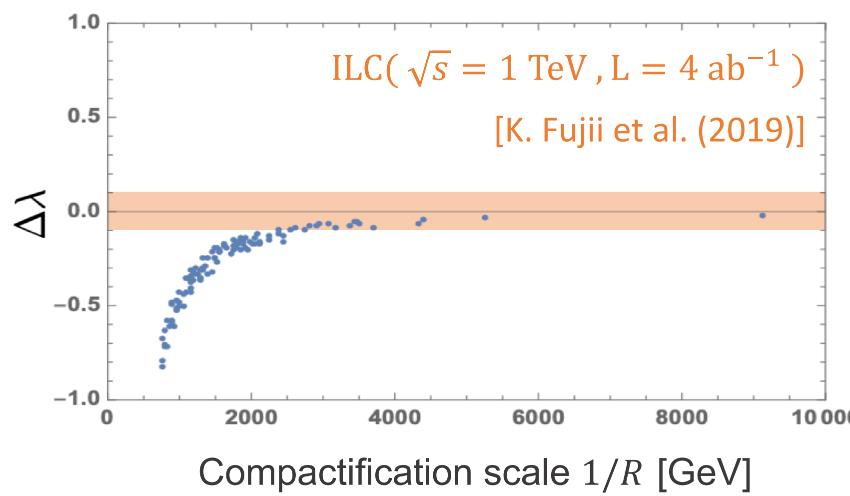
$$V_{\rm eff}(\alpha) = {\rm const.} + \sum V_A(q\alpha) + \sum V_\Psi(q\alpha) + \sum V_a$$

$$\xrightarrow{\alpha \ll 1} \left(\frac{1}{R}\right)^2 A\phi^2 + B\phi^4 + C\phi^4 \ln\frac{\phi^2}{v^2} + \left(\frac{1}{R}\right)^{-2} D\phi^6$$

$$V_{\rm SM}(\phi) = A'\phi^2 + B'\phi^4 + C\phi^4 \ln\frac{\phi^2}{v^2}$$

Deviation of the Triple Higgs Boson Coupling

$$\Delta\lambda \equiv \frac{\lambda_{hhh} - \lambda_{hhh}^{\rm SM}}{\lambda_{hhh}^{\rm SM}} \sim \left(\frac{1}{R}\right)^{-2} \quad : \quad \left.\frac{\partial V}{\partial \phi}\right|_{\phi=v} = 0 \ , \ \left.\frac{\partial^2 V}{\partial \phi^2}\right|_{\phi=v} = m_h^2$$



SU(3) Model [Panico, Serone, Wulzer, NPB 739 (2006)]

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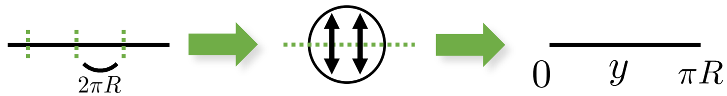


Boundary conditions (gauge field)

$$\begin{cases} S^1 : A_M(y+2\pi R) = A_M(y) \\ Z_2 : A_\mu(-y) = P^\dagger A_\mu(y) P \,,\; A_5(-y) = -P^\dagger A_5(y) P \end{cases}$$

symmetry : $SU(3)_c \times SU(3)_w \times U(1)' \xrightarrow{BC} SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$

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

→ SM gauge
Higgs doublet

Matter Lagrangian

5D Lorentz invariance relaxed

$$\mathcal{L}^{5D}_{\rm mat} = \sum_j \left\{ \bar\Psi_j \left(i\not{D}_4 - k_j D_5 \gamma^5 \right) \Psi_j + \bar{\tilde\Psi}_j \left(i\not{D}_4 - \tilde k_j D_5 \gamma^5 \right) \tilde\Psi_j + \frac{1}{\pi R} \left(\bar\Psi_j \lambda_j \tilde\Psi_j + \text{h.c.} \right) \right\} \quad ①$$

$$+ \delta(y-y_1) \left\{ \bar Q_L i\not{D}_4 Q_L + \sqrt{\frac{2}{\pi R}} \left(\epsilon_1^d \bar Q_L \psi_d + \epsilon_1^u \bar Q_R^c \psi_u + \text{h.c.} \right) \right\} \quad ②$$

$$+ \delta(y-y_2) \left\{ \bar u_R i\not{D}_4 u_R + \bar d_R i\not{D}_4 d_R + \sqrt{\frac{2}{\pi R}} \left(\epsilon_2^d \bar d_R \chi_d + \epsilon_2^u \bar u_L^c \chi_u + \text{h.c.} \right) \right\} \quad ②$$

① TeV scale bulk mass term

② Bulk-Brane mixing : Source of the brane fermion mass

→ Reproduce the mass scale of the SM fermions

1-loop effective potential

$$V_{\rm eff}(\alpha) = \text{const.} + \sum V_g(q\alpha) + \sum V_\Psi^\pm(q\alpha) + \sum V_a(\alpha)$$

bulk gauge — bulk fermion — brane fermion

$$V_g(q\alpha) = -\frac{9}{64\pi^6 R^4} \sum_{n=1}^{\infty} \frac{1}{n^5} \cos(2\pi n q \alpha)$$

$$V_\Psi^\pm(q\alpha) = \frac{3k^4}{8\pi^6 R^4} \sum_{n=1}^{\infty} \frac{(\pm 1)^n}{n^5} \left(1 + 2n\frac{\lambda}{k} + \frac{4}{3} n^2 \frac{\lambda^2}{k^2} \right) e^{-2n\frac{\lambda}{k}} \cos(2\pi n q \alpha)$$

$$V_a(\alpha) = \frac{c_a}{2} \int \frac{d^4 p_E}{(2\pi)^4} \ln \left\{ Z_1^a(\alpha) Z_2^a(\alpha) p_E^2 + m_a(\alpha)^2 \right\}$$

Matter configuration

	$SU(3)_c \times SU(3)_w$	η	Contribution to $V_{\rm eff}(\alpha)$
$\{\Psi_t, \tilde\Psi_t\}$	$(\mathbf{3}, \bar{\mathbf{6}})$	0	$3V_{\Psi_t}^+(2\alpha) + 3V_{\Psi_t}^+(\alpha)$
$\{\Psi_b, \tilde\Psi_b\}$	$(\mathbf{3}, \mathbf{3})$	0	$3V_{\Psi_b}^+(\alpha)$
$\{\Psi_A, \tilde\Psi_A\}$	$(\mathbf{1}, \mathbf{6})$	1/2	$V_{\Psi_A}^-(2\alpha) + V_{\Psi_A}^-(\alpha)$

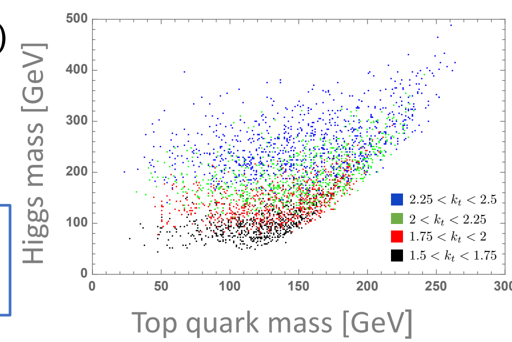
Brane fermion : $Q_L = (t_L, b_L)^{\rm T} \to y = 0$; $t_R, b_R \to y = \pi R$

Model parameters $\sim O(1)$

$\epsilon_1^t, \epsilon_2^t, \epsilon_1^b, \epsilon_2^b$

$\lambda_t, \lambda_b, \lambda_A$ k_t, k_b, k_A

By tuning them, we can reproduce the $m_h, m_t, m_{\rm KK}$



Analyze of the Higgs potential

GHU : $V_{\rm eff}^{\rm GHU} = {\rm const.} + \sum_i \frac{n_i}{2} \int \frac{d^4 p_E}{(2\pi)^4} \ln\left(p_E^2 + m_i^2(\phi)\right)$

$$\xrightarrow{1/R\to\infty} \left(\frac{1}{R}\right)^2 A\phi^2 + B\phi^4 + C\phi^4 \ln\frac{\phi^2}{v^2} + \left(\frac{1}{R}\right)^{-2} D\phi^6$$

SM : $V_{\rm SM}(\phi) = A'\phi^2 + B'\phi^4 + C\phi^4 \ln\frac{\phi^2}{v^2}$

Tadpole and mass conditions

$$\left.\frac{\partial V_{\rm eff}}{\partial\phi}\right|_{\phi=v} = 0 \quad\longrightarrow\quad B' = -\frac{2}{C} - \frac{A'}{2v^2} - \frac{3}{2}D\frac{v^4}{(1/R)^2}$$

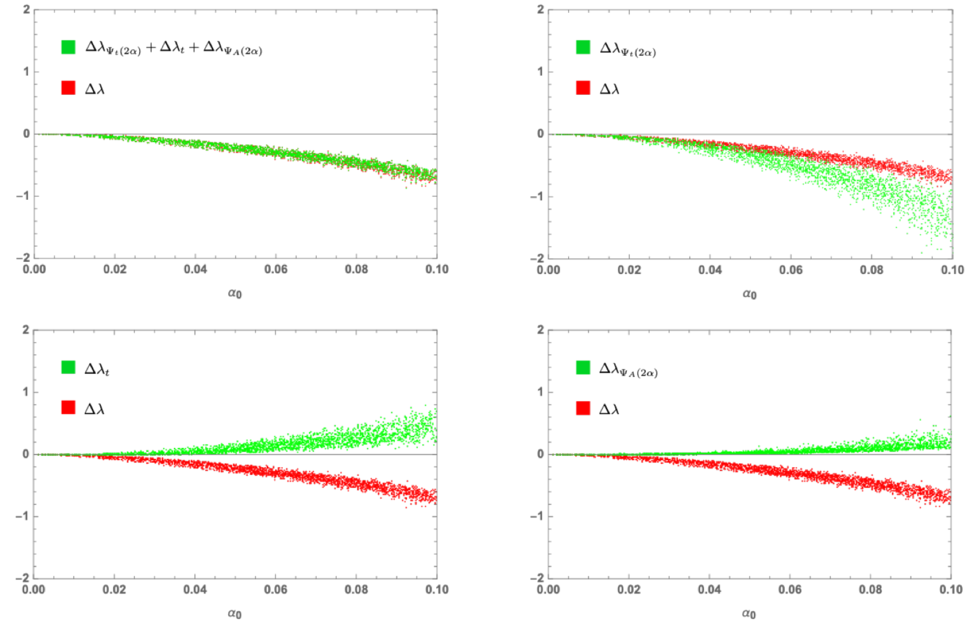
$$\left.\frac{\partial^2 V_{\rm eff}}{\partial\phi^2}\right|_{\phi=v} = m_h^2 \quad\longrightarrow\quad m_h^2 = -4A' + 8Cv^2 + 12\frac{v^4}{(1/R)^2}$$

Triple Higgs boson coupling In $1/R \to \infty$ limit

$$\lambda_{hhh} = \frac{3}{v}\left\{m_h^2 + \frac{16}{3}\left(C + 3D\frac{v^2}{(1/R)^2}\right)v^2\right\} \quad\rightarrow\quad \Delta\lambda \sim \left(\frac{1}{R}\right)^{-2}$$

This feature is not only found in this model but also models with bulk-brane mixing on flat S^1/Z_2 orbifold

Dominant contribution of $\Delta\lambda$

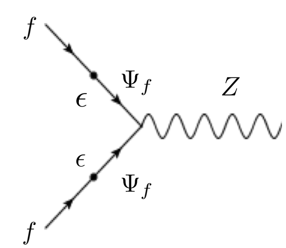


limitation of the compactification scale

G. Panico, M. Serone, A. Wulzer, NPB 739 (2006) , NPB 762 (2007)

Direct correction

- $Zb_L\bar{b}_L$: $\frac{\delta g_b}{g_b} \simeq \frac{1}{1-\frac{2}{3}\sin^2\theta_W} \frac{\epsilon_1^{t2} k_t^2}{\lambda_t^2 Z_1} \left(\frac{m_W}{M_t}\right)^2$
- FCNC : $g_{\rm FCNC} \sim \frac{\epsilon_1^u \epsilon_1^c}{\lambda_u \lambda_c}\left(\frac{m_W}{M_t}\right)^2$



Oblique correction

- $T = \hat{T}/\alpha_e = \alpha_0^2\pi^2/\alpha_e$ ⇨ $1/R \geq 5$ TeV