Analysis of the Higgs Potential in Extended Gauge-Higgs Unification Models

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- Paper in preparation

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Motivation

Discovery of the 125 GeV Higgs boson h at the CERN LHC

- The Standard Model (SM) has been established as a low-energy effective theory below $O(100)$ GeV

This is not the end of the story

Puzzles in the Higgs sector

- Guiding principle?
- Shape of the Higgs potential (multiplets, symmetries, ...)?
- Dynamics behind the electroweak symmetry breaking (EWSB)?

Phenomena beyond the SM (BSM)

- Baryon asymmetry of the Universe (BAU)
- Existence of dark matter
- Cosmic inflation
- Neutrino oscillations

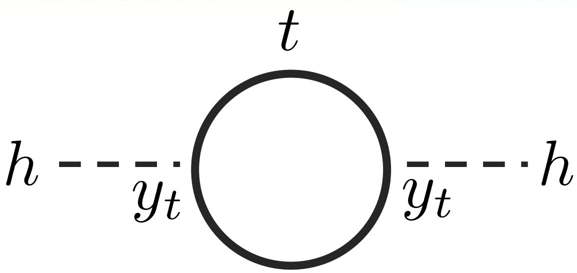
Idea: Higgs sector = Window to New Physics

- The structure of the Higgs sector is related to BSM models

Information on new physics can be obtained by investigating the properties of the Higgs sector

Hierarchy problem and paradigms

Mass squared of the Higgs boson



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

$(125\ \mathrm{GeV})^2$

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

Λ: Cutoff scale

Quadratic divergence

$\mathcal{O}(10^{34})\ \mathrm{GeV}^2$ for $\Lambda = 10^{18}\ \mathrm{GeV}$

Fine-tuning with accuracy of 10^{-30} is necessary

New paradigms at the TeV scale

- Supersymmetry
- Composite models
- Gauge-Higgs unification (GHU)

Gauge-Higgs unification

Features of gauge-Higgs unification

- TeV scale extra special dimension(s) is introduced
- The Higgs doublet is the extra component of a gauge field
- Higgs interactions are controlled by the gauge principle
- The Higgs potential is flat at the tree level and determined by loop effects
- The imprints of Kaluza-Klein (KK) particles are testable at colliders [See Hosotani's talk, Futatsu's talk]

Difficulties in gauge-Higgs unification

- The Higgs boson, top quark and KK particles are too light
- Weinberg angle is too large

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 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.]

Warped space

- SO(5) X U(1) model
  [e.g. Funatsu, Hatanaka, Hosotani, Orikasa, Shimotani, PLB 722 (2013), etc.]

- The masses of the Higgs boson and KK particles are determined by the Higgs potential

Goal of this work

- Analysis of the Higgs potential in the SU(3) model with 5D Lorentz symmetry relaxed

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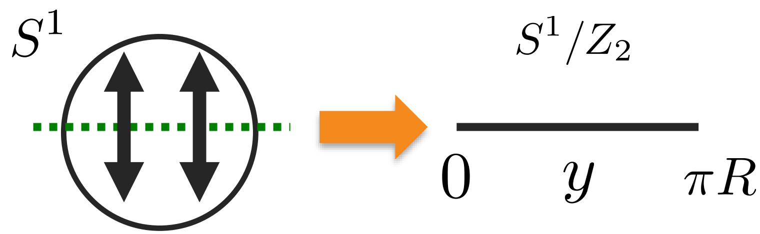
SU(3) model

Space-time

- Flat $M^4 \times S^1/Z_2$

  R^{-1}: compactification scale



Orbifold breaking to the electroweak gauge symmetry

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

Boundary conditions

$$A_M(y+2\pi R) = A_M(y)$$

$$A_\mu(-y) = P^\dagger A_\mu(y) P \qquad A_5(-y) = -P^\dagger A_5(y) P$$

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

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

Zero modes of the gauge fields

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

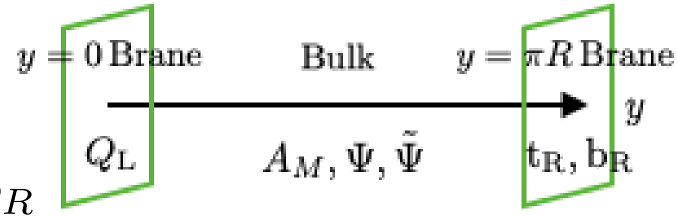
Higgs doublet

Field configuration

Fields

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

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



5D matter Lagrangian for the 3rd generation quarks

$$\mathcal{L}_{\rm mat} = \sum_{j=t,b,A} \left\{ \bar{\Psi}_j \left(i D_4 - k_j D_5 \gamma^5\right) \Psi_j + \bar{\tilde{\Psi}}_j \left(i D_4 - \tilde{k}_j D_5 \gamma^5\right) \tilde{\Psi}_j + \frac{1}{\pi R} \left(\bar{\Psi}_j \lambda_j \tilde{\Psi}_j + \text{h.c.}\right) \right\}$$
$$+ \delta(y-0) \left\{ \bar{Q}_L i D_4 Q_L + \sqrt{\frac{2}{\pi R}} \left(\epsilon_1^b \bar{Q}_L \psi_b + \epsilon_1^t \bar{Q}_R^c \psi_t + \text{h.c.}\right) \right\}$$
$$+ \delta(y-\pi R) \left\{ \bar{t}_R i D_4 t_R + \bar{b}_R i D_4 b_R + \sqrt{\frac{2}{\pi R}} \left(\epsilon_2^b \bar{b}_R \chi_b + \epsilon_2^t \bar{t}_L^c \chi_t + \text{h.c.}\right) \right\}$$

Model parameters

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

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

5D Lorentz invariance relaxed!

Mass of the top quark

$m_t \lesssim \sqrt{2} k_t m_W$

Larger top quark mass

Higgs sector

Higgs potential

$$V_{\text{eff}} = V_{\text{eff}}^{0} + V_{\text{eff}}^{1\text{loop}}$$

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

$$V_{\text{eff}}^{0} = 0$$

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

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

Mass of the Higgs boson

$$m_h^2 = \left(\frac{g_4 R}{2}\right)^2 \frac{\partial^2 V_{\text{eff}}(\alpha)}{\partial \alpha^2}\bigg|_{\alpha=\alpha_0} \qquad v = \frac{2\alpha_0}{g_4 R}$$

Very roughly

$$m_h \propto k^2$$

Larger Higgs boson mass

Triple Higgs boson coupling

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

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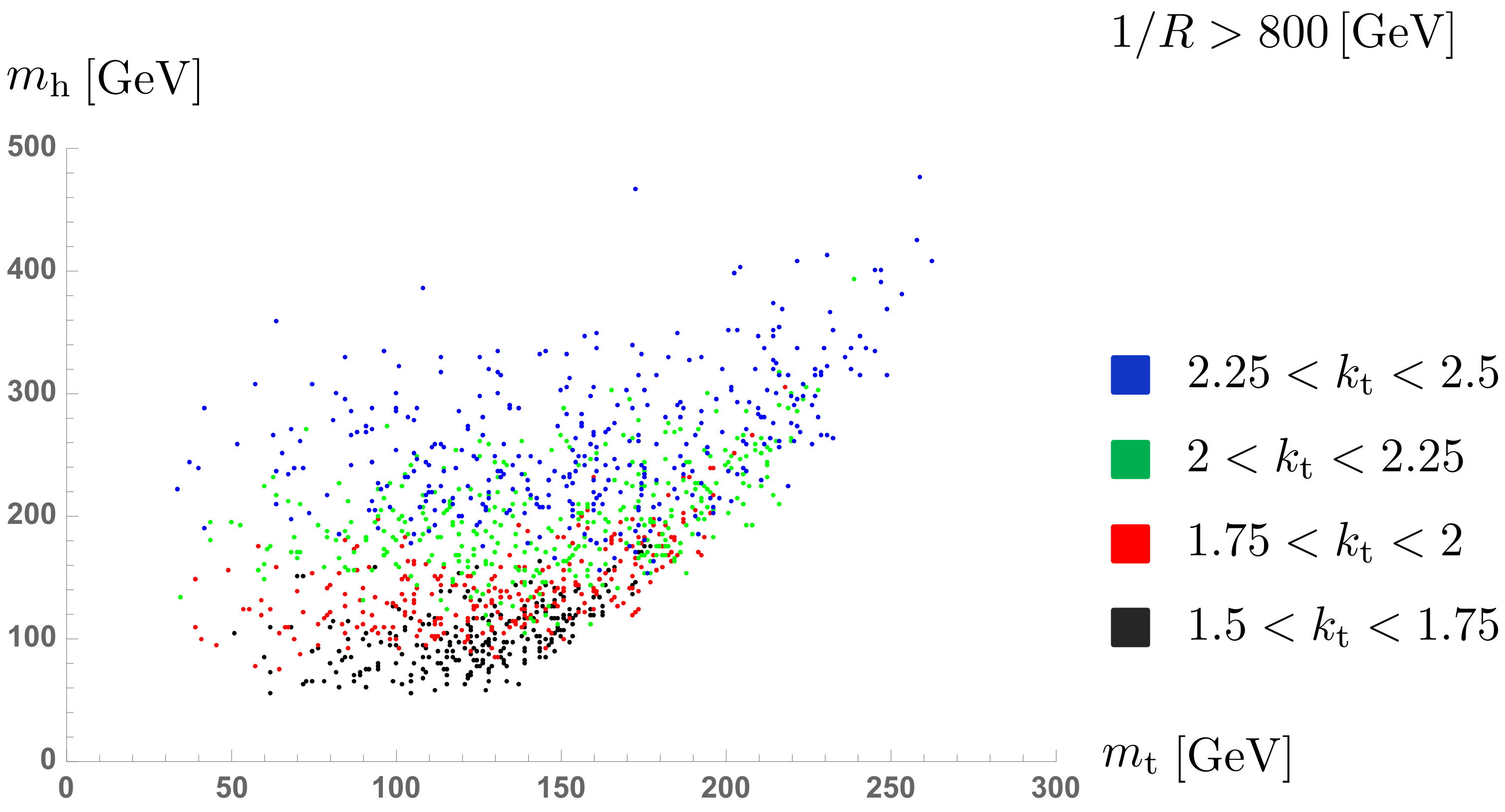
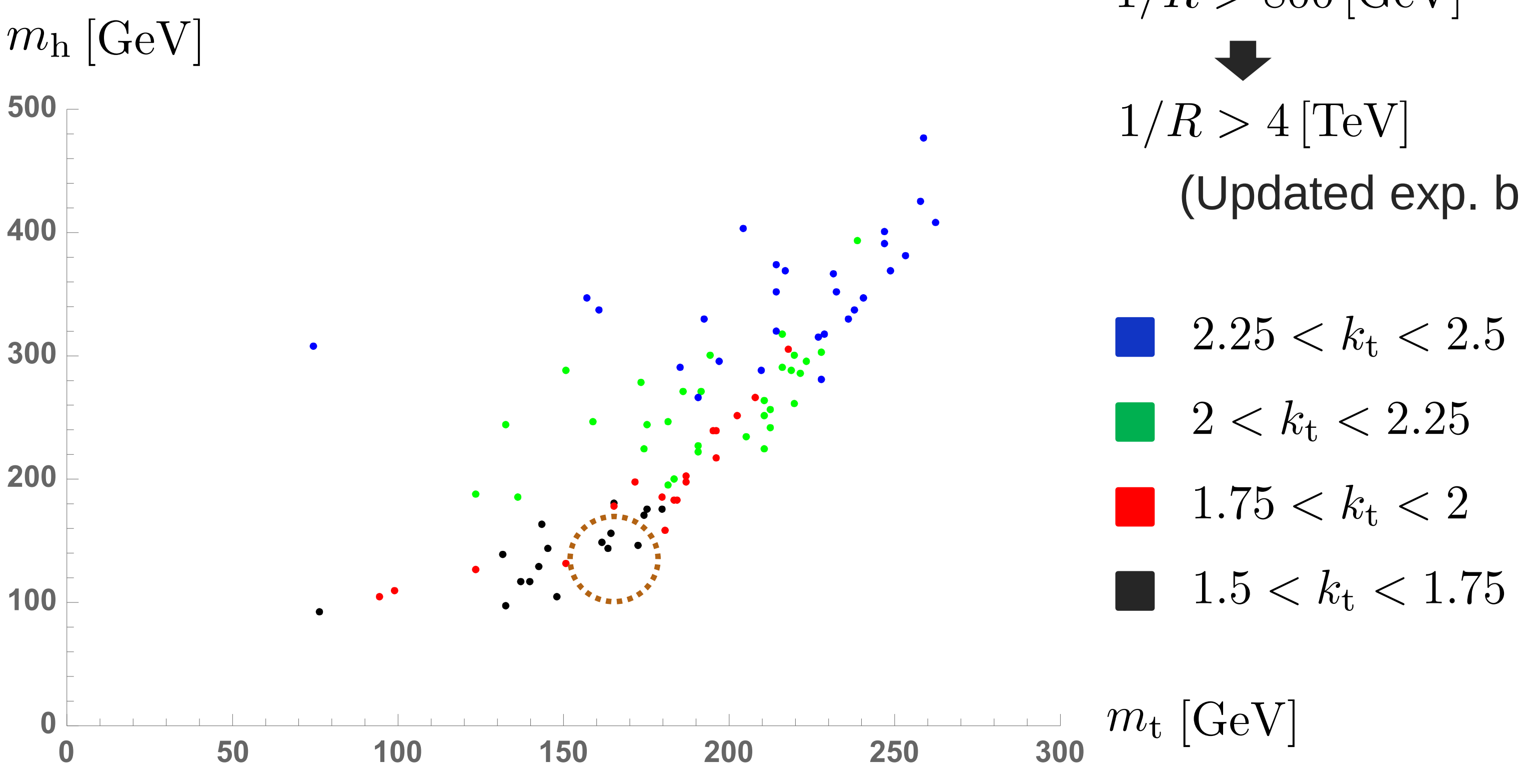
Top quark mass vs Higgs boson mass



Our results are consistent with earlier works

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

Top quark mass vs Higgs boson mass (contd.)



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

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

(Updated exp. bound)

Triple Higgs boson coupling

Deviation from the SM prediction

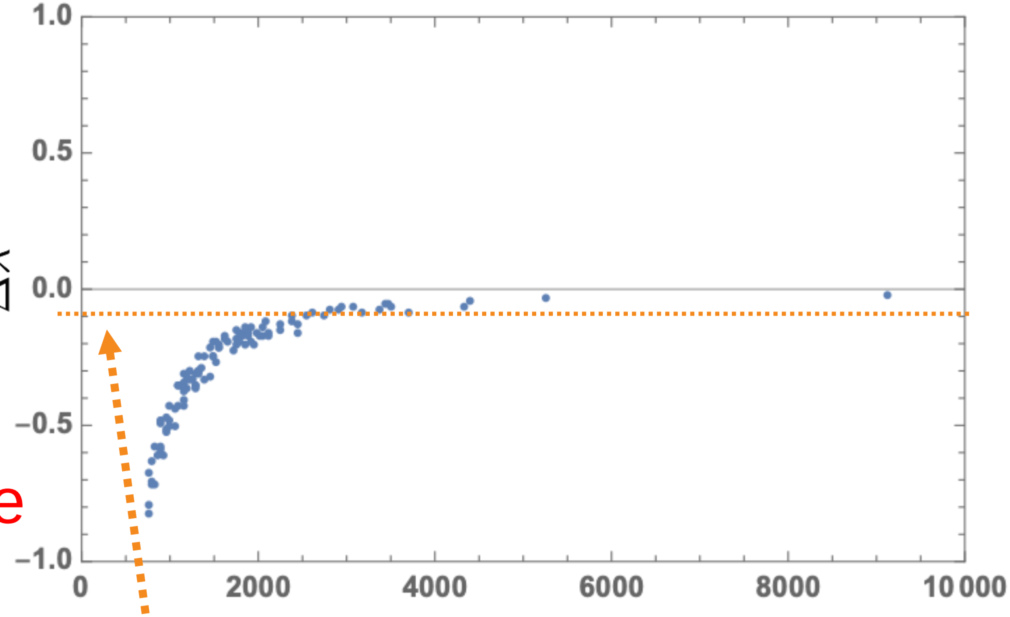
$$\Delta\lambda = \frac{\lambda_{hhh} - \lambda_{hhh}^{\rm SM}}{\lambda_{hhh}^{\rm SM}}$$

- Constraints:

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

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

- The effects of KK particles quickly decouple



Future colliders

- HL-LHC: $-1.3 \lesssim \Delta\lambda \lesssim 8.7$ [ATL-PHYS-PUB-2014-019]
- ILC ($\sqrt{s} = 1$ TeV $L = 5\ \text{ab}^{-1}$): $\Delta\lambda : 10\%$ [Fujii et al. (2015)]

The observation of a significant deviation requires additional extensions of the models

4. Summary

- We have revisited gauge-Higgs unification models with 5D Lorentz invariance relaxed
- In such models, the masses of the Higgs boson, top quark and KK particles can be consistent with experimental data
- The observation of a significant deviation in the triple Higgs boson coupling at future linear colliders with energy upgrades requires additional extensions of the models

Backup slides