Higgs boson decays and hierarchical quark masses in gauge-Higgs unification

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I. Introduction

The origin of the Higgs is still unclear, even after the success of LHC.
A great hint: the Higgs has turned out to be light !

$$M_H = \mathcal{O}(M_W)\,, \text{i.e.} \quad \lambda \sim g^2$$

⇒ Higgs self-coupling is governed by gauge principle:

Among the theories of BSM, having such desirable property,
we focus on the scenario

Gauge-Higgs Unification (GHU)

where the **origin of Higgs boson: gauge boson !**

(N.S. Manton ('79), Y. Hosotani ('83))

$$A_M = (A_\mu, A_y) \quad (D = 5) \qquad A_y^{(0)}(x) = H(x) : \text{ Higgs}$$

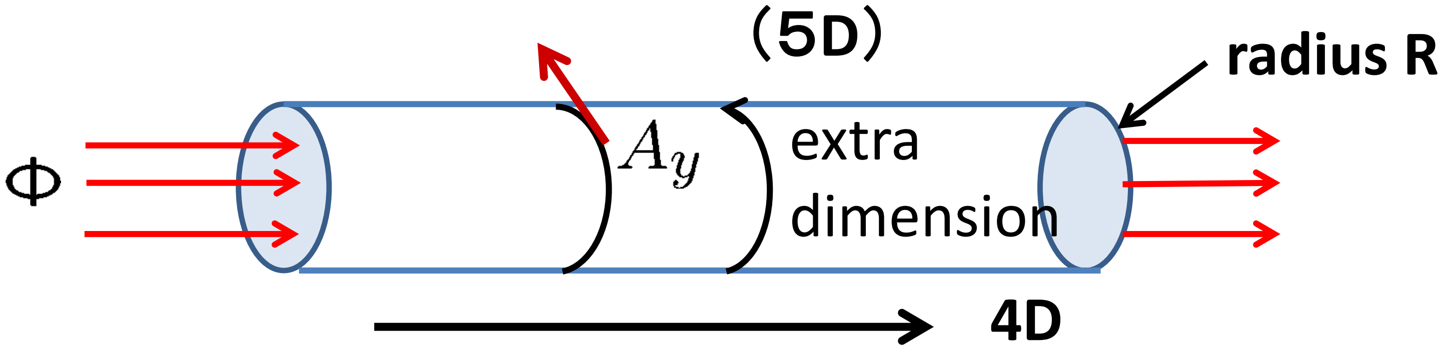
New avenue to solve the hierarchy problem without relying on SUSY, thanks to higher dimensional local gauge symmetry.
(H. Hatanaka, T. Inami, and C.S. L., Mod. Phys. Lett.A13('98)2601)

Is the VEV of the Higgs, which is nothing but a constant gauge field, physically meaningful ?
Yes ! it has a meaning as a Aharonov-Bohm (AB) or Wilson-loop phase:

$$W = \mathrm{Tr}(e^{i\frac{g}{2}\oint A_y dy}) = e^{i g_4 \pi R A_y^{(0)}} = e^{i\frac{g_4}{2}\Phi}$$

Higgs

(Circle : non-simply-connected)



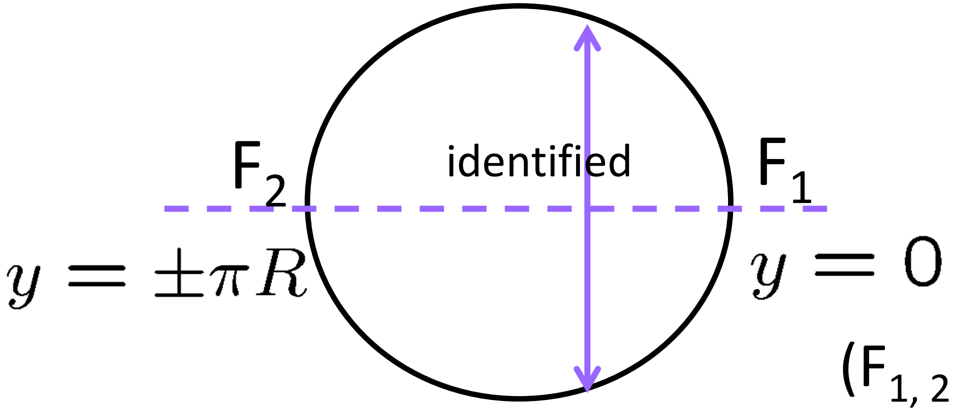
The minimal model of GHU

In GHU, gauge group should be inevitably enlarged.

5D SU(3) model of electro-weak unification on S^1/Z_2 orbifold (M. Kubo, C.S. L. and H. Yamashita, Mod. P. L. 17('02)2249; C.A. Scrucca, M. Serone and L. Silvestrini, Nucl. Phys. B669, ('03)128)

SU(3) → $SU(2)_L$ x $U(1)_Y$ by orbifolding S^1/Z_2 (Y. Kawamura):

$Z_2 : \quad y \rightarrow -y$



($F_{1, 2}$: fixed points)

(N.B.) Orbifolding is also useful to get a chiral theory

II. Few remarks on the Higgs decays in GHU

(K. Hasegawa & C.S. L., P.R.D94 (2016) 055021)

As another characteristic prediction on Higgs physics of GHU, we discuss Higgs decays, $H \to \gamma\gamma, \quad H \to Z\gamma.$

N. Maru & N. Okada have found that the contribution of non-zero Kaluza-Klein (KK) modes to $H \to Z\gamma$ in GHU just vanishes ! (in the minimal 5D electro-weak SU(3) GHU model, P.R.D 88 ('13) 037701)

(Operator analysis of $H \to \gamma\gamma, \quad H \to Z\gamma$)

Analysis by use of gauge invariant operator is helpful,

- to understand the deep reason of the vanishing contribution
- to see whether such result is genuine feature of GHU or not.

We have found:

- There does not exist any (bulk) local SU(3) invariant operator responsible for $H \to \gamma\gamma$ nor $H \to Z\gamma$!

- Taking into account the contribution of the Wilson-loop (global operator) we find a $d = 6$ operator for $H \to \gamma\gamma$, but not for $H \to Z\gamma$, which should be the reason why the decay amplitude just vanishes.

d = 6 local operator in the bulk

In the SM gauge invariant d = 6 operators are

$$\phi^\dagger\phi \mathrm{Tr}(W_{\mu\nu}W^{\mu\nu}), \ \phi^\dagger\phi B_{\mu\nu}B^{\mu\nu}, \ (\phi^\dagger W_{\mu\nu}\phi)B^{\mu\nu}$$

where $W_{\mu\nu}, \ B_{\mu\nu}$ are field strengths of SU(2) and U(1) gauge fields and ϕ denotes the Higgs doublet.

In GHU, both of 4D gauge and Higgs fields ← A_M
Thus the d = 6 gauge invariant local operator (in the bulk) turns out to be unique (thanks to the Bianchi identity):

$$\mathrm{Tr}\{(D_L F_{MN})(D^L F^{MN})\}$$

For instance,

- $\mathrm{Tr}\{(D_y F_{\mu\nu})(D^y F^{\mu\nu})\}$

$$D_y F_{\mu\nu} = igh(\partial_\mu Z_\nu - \partial_\nu Z_\mu)[T_h, T_Z]$$

, where $T_h,\ T_Z$ are generators associated with h and Z.
Thus, $(D_y F_{\mu\nu})(D^y F^{\mu\nu})$ does not contribute to $H \to \gamma\gamma$ or $H \to Z\gamma$.

III. Hierarchical quark masses in gauge-Higgs unification

(C.S. Lim, A work in progress)

The Yukawa coupling in GHU is gauge coupling to start with

→ to realize the hierarchical fermion masses is non-trivial

In higher dimensional theory on Z_2-orbifold (S^1/Z_2),

$$Z_2: \; y \to -y, \;\; x^\mu \to x^\mu \quad \to \quad Z_2: \; \psi \to \pm i\gamma_5\psi$$

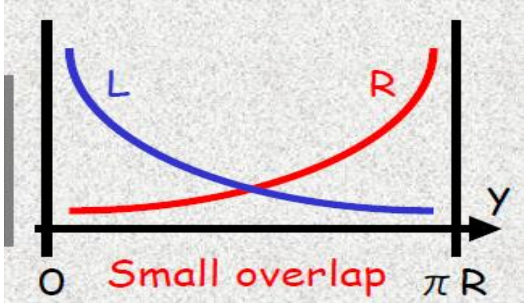
Z_2-odd bulk mass term

$$\epsilon(y)M\bar{\psi}\psi \quad (\epsilon(y): \text{sign function})$$

is allowed → localization of mode function of KK zero-mode

⇒ exponentially suppressed Yukawa coupling

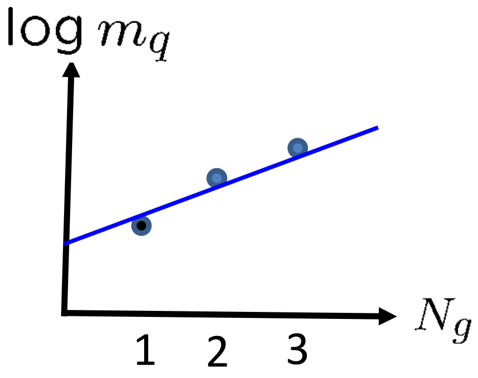
$$\sim g \; (\pi RM)e^{-\pi RM} \;\; (R: \text{the radius of } S^1)$$



Interestingly, the observed hierarchical quark masses, behaving as

$$\log m_q \sim \alpha N_g + \beta \leftrightarrow m_q = e^{\beta+3\alpha} e^{-(3-N_g)\alpha}$$

$$(N_g : \text{generation number})$$



may be naturally understood in GHU:

♠ Originally all quark masses are unique, M_W

⇒ provides good reasoning of the universal factor $e^{\beta+3\alpha}$

♠ hierarchical mass spectrum is naturally realized by the suppression factor $e^{-\pi RM}$

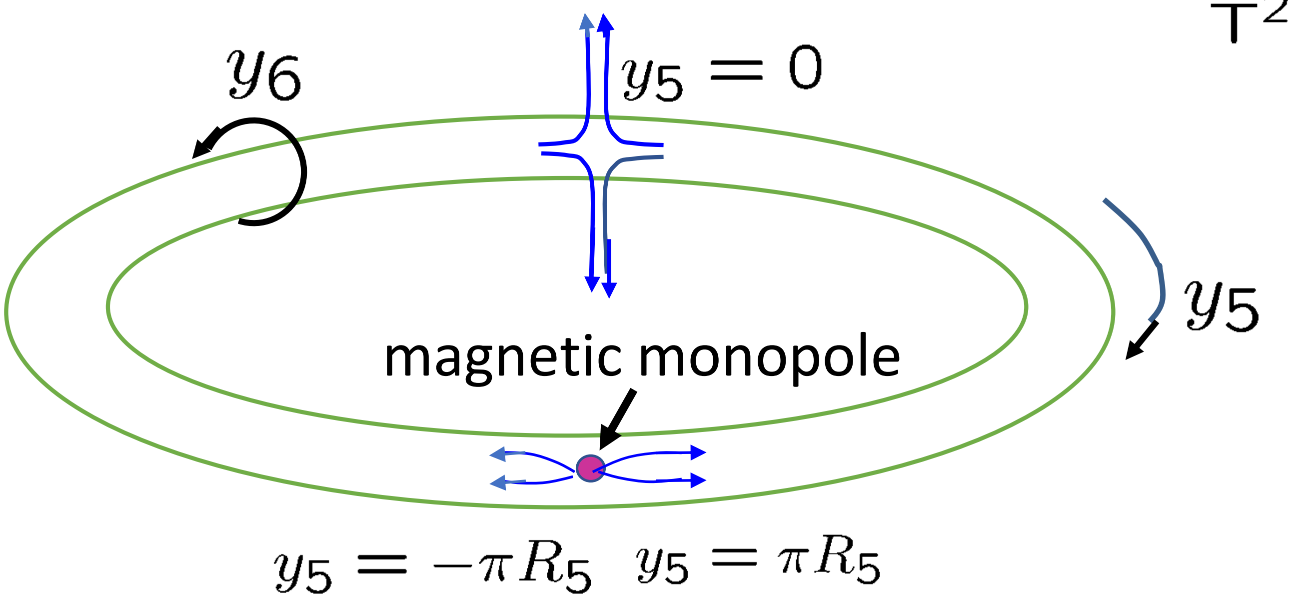
♠ It will be great if a natural mechanism to account for

$M \propto$ 0, 1, 2 (“quantized Z_2 – odd bulk mass”)

is found !!

It is natural to expect that such quantization is realized by invoking the flux quantization of some magnetic monopole.

【Model】6D GHU model with T^2 as extra space, where some magnetic monopole is placed inside the torus.



$$T^2 = \underset{\underset{R_5}{\uparrow}}{S^1} \times \underset{\underset{R_6}{\uparrow}}{S^1}$$

$$R_5 \gg R_6$$

$$\Rightarrow \quad A_6 = \epsilon(y)\frac{M}{2gR_6}$$

(N.B.) quantization condition:
M should be an integer.

(1) Z_2 – odd mass (in 5D theory) is now replaced by the configuration of A_6 produced by the magnetic monopole

(N.B.)

- Z_2 –odd mass is parity-odd quantity ⇒ Natural to replace it by the magnetic monopole, which is also parity-odd.
- In GHU, Higgs field can be regarded as a sort of AB phase ⇒ Natural to consider another magnetic configuration.

(2) Even if only 1 fermion (6D Weyl), we have M pieces of KK zero-modes ⇒ M generations of quarks

(D. Cremades, L.E. Ibanez, F. Marchesano ('04))

(3) Also, even if we do not impose orbifold condition, these M KK zero-modes become chiral ! (as the mode function of either chirality is not normalizable)

(4) The mode function of each KK zero mode is given by power series expansion:

$$\psi_{M,j}(y,z) \;=\; N_{M,j} \sum_{r=-\infty}^{\infty} e^{-\pi \frac{R_5}{R_6} M (r+\frac{j}{M})^2} \cdot e^{-\pi \frac{R_5}{R_6} M \{(r+\frac{j}{M})\hat{y} + \frac{1}{2}|\hat{y}|\}} \cdot e^{i\pi M (r+\frac{j}{M})\hat{z}} \quad (\hat{y} = \frac{y}{\pi R_5}, \hat{z} = \frac{z}{\pi R_6})$$

where $j = 0, 1, \ldots, M-1$: M generations.

It can be well-approximated by a single term as (under $R_5 \gg R_6$),

$$\psi_{M,j}(y,z) \propto e^{-\pi \frac{R_5}{R_6} \{(\frac{M}{2} - j)\hat{y}\}} \qquad (\text{for } 0 \leq j < \frac{M}{2}),$$
$$\propto e^{-\pi \frac{R_5}{R_6} \{(j - \frac{M}{2})\hat{y}|\}} \qquad (\text{for } \frac{M}{2} \leq j < M)$$

Thus, the desirable exponential suppression, with the ``quantized exponent”, is expected.