Flavor physics and anomalous interactions in Gauge-Higgs Unification

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C.S. Lim (Kobe University, Japan)

I. Introduction

The standard model has unsettled problems in its Higgs sector:

(1) The hierarchy problem (how to maintain $M_W \ll \Lambda$ naturally?) : Higgs mass gets "quadratic divergence" Λ^2
(2) The origin of hierarchical fermion masses and flavor mixings ?
(3) The origin of CP violation ?
(4) The origin of Higgs itself ?
← there is no guiding principle (symmetry) to restrict the interactions of Higgs

"Gauge-Higgs unification (GHU)" scenario (Manton, Hosotani)

unification of gauge (s=1) & Higgs (s=0) interactions

: realized in higher dimensional gauge theory

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

The quantum correction to m_H is finite because of the higher dimensional gauge symmetry, once all KK modes are summed up (H. Hatanaka , T. Inami and C.S. L., Mod. P. L. A13('98)2601)

→ A new avenue to solve the hierarchy problem without invoking SUSY and is expected to shed some lights on the problems in the Higgs sector.

(N.B.)

- Close relation to "Little Higgs"

Little Higgs ⇔ Dimensional Deconstruction ⇔ GHU

- The (bosonic part of) point particle limit of open superstring theory, 10D SUSY Y.-M. theory, is a sort of GHU.

The minimal model:

GHU SU(3) electro-weak model has been constructed

(M. Kubo, C.S. L. and H. Yamashita, Mod. P. L. 17('02)2249;
C. A. Scrucca, M. Serone and L. Silvestrini, N. P. B **669**, 128 (2003).)

If the origin of Higgs is gauge boson, the following are challenging and interesting issues:

- to realize fermion mass hierarchy
- to accommodate flavor mixing
- to break CP

II. Flavor Physics in GHU

(Y. Adachi, N. Kurahashi, C.S. L. and N. Maru,
JHEP 1011(2011)150; JHEP 1201 (2012) 047)

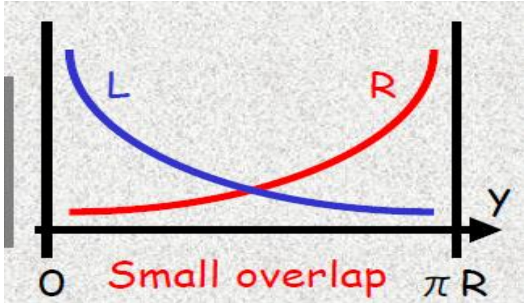
To achieve flavor violation is non-trivial in GHU.
In higher dimensional model with Z_2-orbifolding (S^1/Z_2),
Z_2-odd bulk masses

$$\epsilon(y) M_i \bar{\psi}_i \psi_i \quad (\epsilon(y) : \text{sign function})$$

are allowed $\rightarrow$ new source of the violation of flavor symmetry

Localization $\Rightarrow$ exponentially suppressed
Yukawa coupling

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



(N.B.)

- The observed hierarchical quark masses, behaving as

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

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

are 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 $e^{-\pi R M_i}$

Flavor mixing

Off-diagonal bulk mass matrix does not work

$$\epsilon(y) M_{ij} \bar{\psi}_i \psi_j \xrightarrow[\text{unitary transf.}]{} \epsilon(y) M'_i \bar{\psi}'_i \psi'_i$$

Invoke brane localized mass term
(G. Burdman and Y. Nomura, N. P. B **656**, 3(2003))

(N.B.) Still, bulk mass term controls flavor symmetry:
For degenerate bulk masses flavor mixing disappears in V_{KM}

FCNC

FCNC: touchstone for new physics (e.g. SUSY)
What about GHU ?

Different bulk masses
$\Rightarrow$ FCNC at tree level due to non-zero KK modes of gluon

We took $K^0 \leftrightarrow \bar{K}^0, \quad D^0 \leftrightarrow \bar{D}^0$ as FCNC.

For lighter generations, GIM-like mechanism is operative, especially for LR 4-fermi operator.
$\Rightarrow$ Obtained lower bound on the compactification scale is rather mild:

$$\mathcal{O}(10TeV) \quad \text{for } K^0 \leftrightarrow \bar{K}^0$$
$$\mathcal{O}(1TeV) \quad \text{for } D^0 \leftrightarrow \bar{D}^0$$

(N.B.) CP violation is also an interesting issue in GHU

CP violation due to the complex structure of the extra space
(C.S. L., N. Maru and K. Nishiwaki, P. R. D81:076006, 2010)

III. Anomalous interactions in GHU

(K. Hasegawa, C.S. L., N. Kurahashi and K. Tanabe, 1201.5001 [hep-ph])

In gauge theories with SSB fermion mass term is written as

$$m(v)\bar{\psi}\psi \qquad v = \langle H \rangle.$$

The interaction of physical Higgs field h with fermion is expected to be provided by $v \quad \to \quad v + h$

For instance, in the SM

$$m(v) = fv \ (f : \text{Yukawa coupling})$$

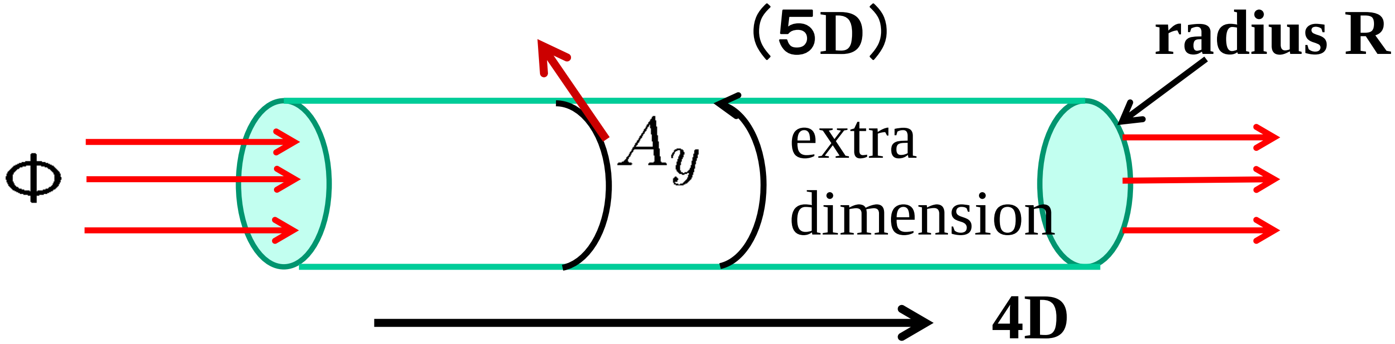
and the Yukawa interaction of h with ψ is given as

$$m(v+h)\bar{\psi}\psi = f(v+h)\bar{\psi}\psi,$$
$$f = \frac{dm(v)}{dv}$$

In GHU, $H(\leftarrow A_y^{(0)})$ has a physical meaning as
Wilson loop (AB phase):

$$W = P\ e^{i\frac{g}{2}\oint A_y dy} = e^{ig_4 \pi R A_y^{(0)}}$$

Circle : non-simply-connected



$$e^{ie\oint A_y dy} = e^{ie 2\pi R A_y} = e^{ie\Phi} \Rightarrow A_y = \frac{\Phi}{2\pi R}$$

↑ Wilson - loop

(Abelian case)

Thus we expect physical observables have periodicity in H

$$v \quad \rightarrow \quad v + \frac{2}{g_4 R} \quad (g_4 : \text{4D gauge coupling})$$

(N.B.) Effective potential of v is a typical example:

$$V(v) \propto \frac{3}{4\pi^2} \frac{1}{(2\pi R)^4} \sum_{n=1}^{\infty} \frac{\cos(n g_4 \pi R v)}{n^5}$$

Also for fermions masses, we will find for light quarks,

$$m(v) \propto \sin(\frac{g_4}{2}\pi R v)$$

$$\Downarrow$$

$$m(v+h) \propto \sin(\frac{g_4}{2}\pi R(v+h))$$: non-linear in h !

$$\Downarrow$$

$$f = \frac{dm(v)}{dv} \propto \cos(\frac{g_4}{2}\pi R v)$$

: even vanishes for $x \equiv \frac{g_4}{2}\pi R v = \frac{\pi}{2}$!

This kind of anomalous Higgs interaction has been pointed out for SO(5) x U(1) model on R-S 5D space-time

Y. Hosotani, K. Oda, T.Ohnuma, Y. Sakamura,
(P.R.D78('08)096002)

However, the Yukawa coupling should be linear in h as in SM:

After the replacement $v \rightarrow v + h$ of the free lagrangian

$$\bar{\psi}\{i\partial_\mu\gamma^\mu - \gamma_5\partial_y + i\gamma_5 g_4\frac{\lambda_6}{2}(v+h) - M\epsilon(y)\}\psi$$

At the first glance there seems to be contradiction.

(Our purpose)

To understand how these two "pictures" ("non-linear or linear") are reconciled each another in simple setting: SU(3) model on flat $M^4 \times S^1/Z_2$

How to reconcile two pictures ?

After the replacement $v \rightarrow v+h$, the operators of 4D mass & Yukawa coupling

$$\int_{-\pi R}^{\pi R} \bar{\psi}\{-\gamma_5 \partial_y + i\gamma_5 g_4 \frac{\lambda_6}{2}(v+h) - M\epsilon(y)\}\psi$$

is written in a matrix form

$$M_m + hM_Y$$: linear in h

in the base of physical quark states (including KK modes)

$$\psi_{L,R}^{(n)}(x) \ (n = 0, 1, \ldots)$$

where

$$M_m = \mathrm{diag}(m_0, m_1, m_2, \ldots)$$: diagonal mass matrix

M_Y : "Yukawa coupling matrix"

(N.B.)

- $m(v+h)$ is the eigenvalue for the whole matrix $M_m + hM_Y$, which may be non-linear in h, in general.

- In the case $m(v+h)$ is non-linear, M_Y should be off-diagonal, since otherwise the eigenvalues would be linear in h.

(wisdom in perturbation theory of quantum mechanics)

At 1-st order of perturbation H', the energy shift is given by $\langle n|H'|n\rangle$

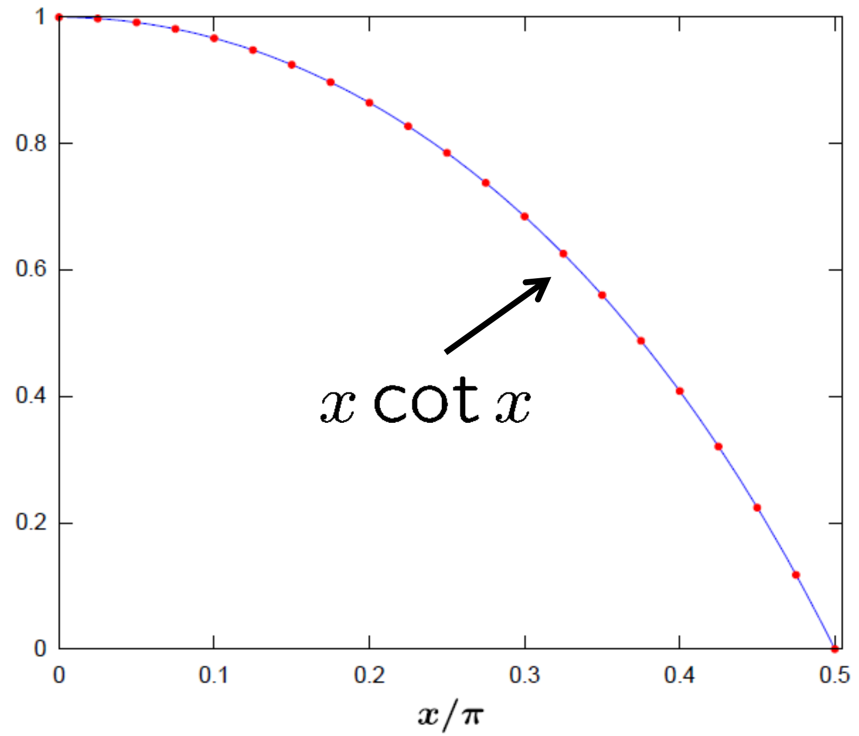
$\Rightarrow$ Treating hM_Y as a perturbation, $\frac{dm(v)}{dv} = m'(v)$

should be given by the diagonal element of M_Y : $(M_Y)_{nn}$

We calculated the both and confirmed they just coincide.
Especially, when $x \equiv \frac{g_4}{2}\pi R v = \frac{\pi}{2}$, M_Y is completely off-diagonal.

The anomalous Yukawa coupling with zero-mode light quark f_{GHU} is well approximated by the formula

$$\frac{f_{GHU}}{f_{SM}} \simeq x \cot x$$



(N.B.)
In the “decoupling limit”

$$x = \frac{g_4}{2} v \pi R \ll 1 \leftrightarrow M_W \ll \frac{1}{R}$$

SM prediction is recovered.

Then what about the quadratic Higgs interaction with quarks, $\bar{\psi}^{(0)}\psi^{(0)}h^2$?

The results in two pictures,

- direct calculation by use of off-diagonal Yukawa coupling
- $m''(v)h^2$

coincide only when $P_h \to 0$.

$\Rightarrow$ give different results for the processes testable at LHC.

(Anomalous gauge interactions)

We also have found anomalous gauge interaction of zero mode gauge bosons, which acquire masses from VEV, $W^{\pm}$, Z^0

$$\frac{g_W}{g_{SM}} \simeq 1 - \frac{x^2}{(2\pi RM)^2 + x^2}$$