CP Violation and Flavor Physics
in
Gauge-Higgs Unification

@ Goran Fest, Split

(June 10, '10)

C.S. Lim（Chong-Sa Lim）

(Kobe University, Japan)

I. Introduction

The standard model has unsettled problems in its Higgs sector:

(1) The hierarchy problem (how to guarantee $M_W \ll \Lambda$ naturally?) (SUSY, ADD, R-S, ..)

(2) In spite of the great success of the Kobayashi-Maskawa model, the origin of CP violation still seems to be not conclusive yet.

(3) The origin of flavor mixing ?
$\leftarrow$ there is no guiding principle (symmetry) to restrict the interactions of Higgs

We discuss
"**Gauge-Higgs Unification (GHU)**" scenario
as an attractive candidate of New Physics, which is expected to shed some lights on these problems relying on higher dimensional gauge symmetry.

"Gauge-Higgs unification" scenario

unified theory 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 idea of gauge-Higgs unification itself is not new:

- N.S. Manton, Nucl. Phys. 58('79)141.
- Y. Hosotani, Phys. Lett. B126 ('83) 309 : ``Hosotani mechanism"

The scenario was revived:

- **H. Hatanaka , T. Inami and C.S.L., Mod. Phys. Lett. A13('98)2601**

The quantum correction to m_H is finite because of the higher dimensional gauge symmetry → **A new avenue to solve the hierarchy problem** without invoking SUSY

Related scenarios

▪dimensional deconstruction: latticized 5D gauge theory. @ $N \to \infty$ limit, the effective potential for H just coincides with what we obtained.

▪little Higgs model : 4D theory, where G/H of global symmetry provides Higgs as a N-G, may be "dual" to 5D GHU, where A_y associated with G/H of higher dimensional local gauge symmetry provides Higgs ("holographic principle").

▪ The low energy limit of superstring theory, e.g. 10 dim. SUSY Y.-M. theory, is a sort of GHU.

Let us note that in GHU to break CP and to accommodate flavor mixing are non-trivial issues, as the gauge coupling is real and gauge interactions are universal among generations, to start with.

II. CP violation in GHU

Note that as long as higher dimensional gauge theory itself is CP invariant, without phase, CP violation should be a sort of “spontaneous” breaking.

We have discussed two possibilities:

1. **CP violation due to compactification**

(w./ **N. Maru and K. Nishiwaki**, Phys.Rev.D81:076006,2010)

One of a few possibilities to break CP symmetry is to invoke the manner of compactificaion, which determines the vacuum state of the theory.

C.S. Lim, Phys. Lett. B256('91)233 (A. Strominger and E. Witten, Commun. Math Phys. 101('85)231)

・Higher dimensional C, P transformations defined by, e.g. C matrix satisfying $C^\dagger \Gamma_M C = -(\Gamma_M)^t$, do not reduce to 4-dim. ones, in general, since they also act on the internal space of fermions.

・Interestingly, the modified CP transformation acts on the extra space coordinates non-trivially: it acts as a complex conjugation of the complex homogeneous coordinates for the extra space (in even dimensions).

Take D=6 case for an illustrative purpose.
In the base, where 6D spinor decomposes into two 4-D spinors,

$$\Psi_6 = \begin{pmatrix} \psi \\ \Psi \end{pmatrix}$$

gamma matrices are given as

$$\Gamma^\mu = \gamma^\mu \otimes I_2 = \begin{pmatrix} \gamma^\mu & 0 \\ 0 & \gamma^\mu \end{pmatrix}, \Gamma^y = \gamma^5 \otimes i\sigma_1 = \begin{pmatrix} 0 & i\gamma^5 \\ i\gamma^5 & 0 \end{pmatrix}, \Gamma^z = \gamma^5 \otimes i\sigma_2 = \begin{pmatrix} 0 & \gamma^5 \\ -\gamma^5 & 0 \end{pmatrix}$$

The C matrix satisfying $C^\dagger \Gamma_M C = -(\Gamma_M)^t$ is easily known to be

$$C = C_4 \otimes \sigma_2 \quad (C_4 = i\gamma_0\gamma_2) \;\; (\sigma_2^\dagger \sigma_i \sigma_2 = -(\sigma_i)^t)$$

Thus, we modify C and P as

$$P: \;\; \Psi_6 \;\to\; (\gamma^0 \otimes \sigma_3)\Psi_6, \;\; C: \;\; \Psi_6 \;\to\; (c_4 \otimes \sigma_3)\bar{\Psi}_6^t \;\; (c_4 = i\gamma_0\gamma_2).$$

Accordingly the transformation properties of a vector

$$V^M = \bar{\Psi}_6 \Gamma^M \Psi_6$$

is uniquely determined and we find:

$$P: \ (y, z) \to (y, z) \quad C, \ CP: \ (y, z) \to (y, -z)$$

Thus, introducing a complex coordinate

$$z = y + iz$$

CP transf. is nothing but a complex conjugation:

$$CP: \quad z \quad \to \quad z^*$$

(e.g.) Consider Type-I superstring theory with 6-dimensional Calabi-Yau manifold defined by

$$\sum_{a=1}^{5} (z^a)^5 - C(z^1 z^2 \cdots z^5) = 0$$

CP is broken if the coefficient C is complex (by "complex structure").

The purpose of our work: to realize CP violation in the framework of GHU (higher dimensional gauge theories), not string theory, with much simpler compact spaces, such as orbifold.

We discussed the CP violation in the 6-dimensional U(1) GHU model due to the compactification on the orbifold T^2/Z_4.

Easy to know that CP transfomation is not compatible with the condition of orbifolding.

In terms of a complex coordinate

$$\omega = y + iz \;\; (y, z : \text{extra space coordinates})$$

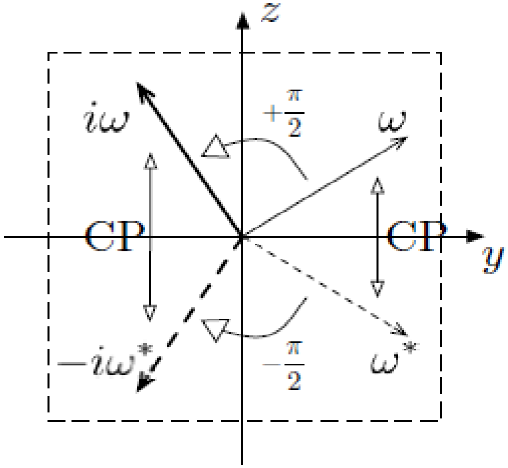
the orbifold condition is written as

$$i\omega \sim \omega$$

After the CP transf., the condition reads as

$$(-i)\omega^* \sim \omega^*$$: "orientation-changing operator" (Strominger and Witten)

Thus, CP tranf. is not compatible with orbifolding condition , and CP symmetry is expected to be broken.



Z_4 eigenvalue t for each field (t = $\pm 1, \ \pm i$):

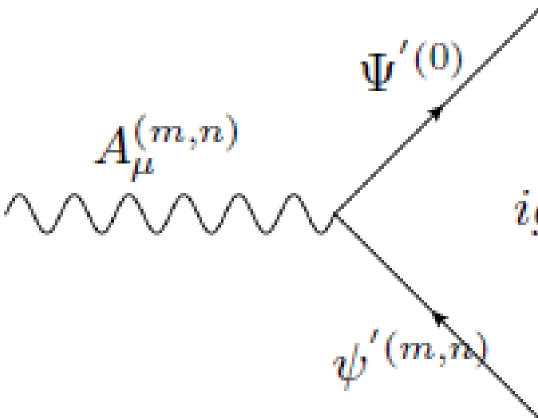
$$A_\mu(x, i\omega) = A_\mu(x, \omega) \quad (t = 1, \ \omega \equiv \frac{y + iz}{\sqrt{2}}).$$

$$A_\omega(x, i\omega) = (-i) A_\omega(x, \omega) \quad (t = -i).$$

$$(A_\omega = \frac{A_y - iA_z}{\sqrt{2}})$$

The mode functions with $t = \pm i$ signal the possibility of CP violation .

The interaction vertices for non-zero KK photons generally have CP violating phases:



CP violating phase

$$i g_4 \gamma^\mu \left(\frac{1}{m_f^{(m,n)}} \frac{m + in}{R} L \right)$$

The CP phases are confirmed to remain even after the re-phasing of fields.

2. CP violation due to the VEV of the Higgs
(w./ Y. Adachi and N. Maru, Phys. Rev. D 80('09)055025)

Another possibility to break CP is due to the VEV of some field which has odd CP eigenvalue. We argue that the VEV $\langle A_y \rangle$ of the Higgs , or the VEV of Wilson-loop plays the role.
We show that neutron EDM gets contribution already at 1-loop level in the model, though we assume the presence of only 1 generation.

(The model)
5-D SU(3) GHU model compactified on an orbifold S^1/Z_2 with a massive bulk fermion in a fundamental representation.

A Z_2-odd bulk mass term is introduced for the fermion:

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

In this case, the orbifold is too simple to break CP, thus only possibility seems to be due to $\langle A_y \rangle$.

(N.B.)

To get EDM, both P and CP have to be broken. P symmetry, however, is broken anyway by the orbifolding $(\{\gamma^0, \ \gamma^5\} = 0)$.

In 5D CP transf. can be defined just as in the 4D case:

$$CP: \quad \Psi(x^\mu, y) \to i\gamma^0\gamma^2\Psi(x_\mu, y)^*$$

Correspondingly, the transformations of space-time and fields are fixed as.

$$CP: \ x^\mu \to x_\mu, \ y \to y, \ A_\mu(x^\mu, y) \to -A^\mu(x_\mu, y)^t, \ A_y(x^\mu, y) \to -A_y(x_\mu, y)^t.$$

Thus we realize that the VEV of A_y has an odd CP-eigenvalue and leads to CP violation.

Actually, when the Z_2 – odd bulk mass is switched off , we can perform a chiral rotation for Ψ, so that the coupling of A_y becomes scalar type and therefore A_y has even CP eigenvalue.
Hence, to get physical CP violating effects, the interplay between the VEV $\langle A_y \rangle$ and the bulk mass is crucial.

(The neutron EDM)

EDM appears already at 1-loop level:

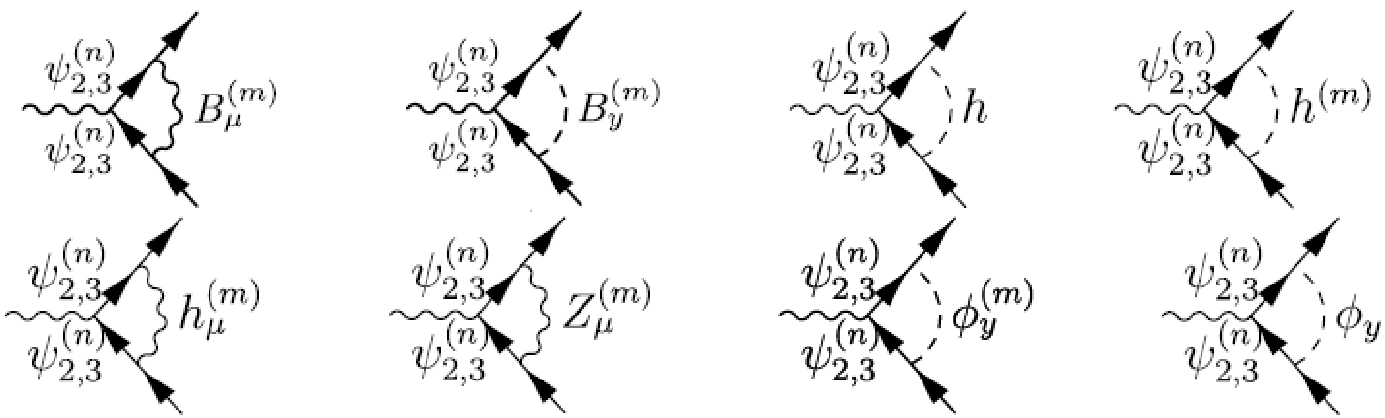


Figure 1: The diagrams contributing to EDM at one-loop by the neutral current

The experimental upper bound on the EDM imposes a meaningful lower Bound on the compactification scale,

$$M_c = \frac{1}{R} \geq 2.6(\mathrm{TeV}).$$

III. Flavor physics in GHU

(w./ **Y. Adachi, N. Kurahashi and N. Maru** , arXiv:1005.2455 [hep-ph])

To achieve flavor violation is non-trivial issue in GHU, as Yukawa couplings are originated form gauge coupling, which is universal for all flavors. As a new feature of higher dimensional model with Z_2-orbifolding, Z_2-odd bulk masses

$$\epsilon(y) M_i \bar{\psi}_i \psi_i$$

are allowed, which may be different depending on each flavor. This can be an important new source of the flavor violation.

Unfortunately, it cannot lead to flavor mixing: for each representation R of gauge group, a general form of the bulk mass terms

$$M(R)_{ij} \epsilon(y) \bar{\psi}(R)_i \psi(R)_j \ \ (i, j : \text{generation index})$$

can be diagonalized by a suitable unitary transformation.

We are led to introduce brane localized mass terms, which are needed anyway to make exotic states heavy and decouple from the low energy effective theory.

The Model

We consider a five dimensional $SU(3) \otimes SU(3)_{\text{color}}$ model compactified on S^1/Z_2.

As matter fields, we introduce n-generations of bulk fermion:

$$\psi^i(\mathbf{3}) = Q_3^i \oplus d^i,$$
$$\psi^i(\bar{\mathbf{6}}) = \Sigma^i \oplus Q_6^i \oplus u^i \ (i = 1, 2, \ldots, n)$$

To eliminate redundant quark doublets (and Σ^i), brane- localized mass term is introduced (G. Burdman and Y. Nomura, '03),

$$\int dy \sqrt{2\pi R}\delta(y)\bar{Q}_R^i(x)\left[\eta_{ij}Q_{3L}^j(x,y) + \lambda_{ij}Q_{6L}^j(x,y)\right] + \ldots$$

$\eta_{ij}, \ \lambda_{ij}$ may have off-fdiagonal elements and lead to flavor mixings.

(N.B.)

Still, the flavor violation due to the bulk masses handle the flavor mixings: in the limit of degenerate bulk masses $M_1 = M_2 = ...$ flavor mixings are known to disappear.

This type of flavor mixing is a genuine feature of GHU.

<u>Natural flavor conservation in GHU</u>

FCNC has played a crucial roles in the discussion of the viability of New Physics. We ask if "natural flavor conservation" is met, i.e. if FCNC processes at tree level are forbidden in GHU.

The condition by Glashow-Weinberg to guarantee natural flavor conservation

“ *fermions with the same electric charge and the same chirality should possess the same quantum numbers* ”

is satisfied in our model.

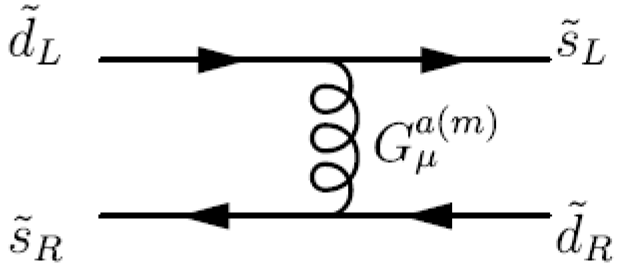
But, the new sauce of flavor violation , i.e. non-degenerate bulk masses, is known to lead to FCNC due to the exchanges of non-zero KK modes of gauge bosons already at the tree level.

(N.B.)

FCNC processes in pure zero-mode sector are still forbidden , as the mode functions for zero-mode gauge bosons are “flat” in extra-dimension. Thus the FCNC processes are suppressed by the inverse powers of the compactification scale, which are under control .

FCNC process: $K^0 \leftrightarrow \bar{K}^0$ mixing

We cosidered the dominant contribution due to the exchange of KK gluons:



We find

(1) There is a “chiral enhancement factor”, $(\frac{m_K}{m_s + m_d})^2$

(2) A lower bound of the compactification scale is obtained by comparing the SM prediction (T. Inami & C.S.L., Buras et al., ..) and the data:

$$\frac{1}{R} > 32\text{TeV}$$

Condratulation , Goran, for your
還暦 (“Kan-Reki”) !