ゲージ・ヒッグス統一模型におけるCP対称性の破れ

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Reference

- Y.A., C.S. Lim, N. Maru, Phys. Rev. D 80, 055025 (2009).

1 Introduction

- Gauge-Higgs unification
- Electric dipole moment (neutron EDM)

Gauge-Higgs unification

N. S. Manton, Nucl. Phys. B158, 141 (1979).
Y. Hosotani, Phys. Lett. 126B, 309 (1983); 129B, 193 (1983).
H. Hatanaka, T. Inami, C.S. Lim, Mod.Phys.Lett.A13:2601-2612,1998.

Higgs · · · extra component of higher dim'l gauge fields

$$A_M = \begin{pmatrix} A_\mu \\ A_y \\ \vdots \end{pmatrix}$$

A_μ ← 4D gauge fields

$A_y, \ldots$ ← Standard Model Higgs

operator $(A_y)^2$ is forbidden by local gauge symmetry.

Higgs(A_y) mass is protected from UV divergence

⇒ **Higgs mass is a predictable observable in the gauge-Higgs unification**

• Yukawa interaction (in 5D case)

$$g\bar{\psi}A_M\Gamma^M\psi \quad = \quad g\bar{\psi}_{L(R)}A_\mu\gamma^\mu\psi_{L(R)} \quad + \quad g\bar{\psi}_{L(R)}A_y\gamma^y\psi_{R(L)}$$

$\Uparrow$ **5D gauge interaction** — $\Uparrow$ **4D gauge interaction** — $\Uparrow$ **Yukawa interaction**

$$(\gamma^y = i\gamma^5)$$

$\Downarrow$

Yukawa couplings equal to gauge coupling

$\Rightarrow$
- various fermion masses? $(\mathcal{O}(1) \sim \mathcal{O}(10^{-5}))$
- CP violation? (complex yukawa coupling)

Electric Dipole Moment (EDM)

EDM ··· interaction between spin $\vec{\sigma}$ and electric field $\vec{E}$

described by dimension six operator: $\langle H^\dagger \rangle \bar{\psi}_R \sigma^{\mu\nu} \gamma^5 \psi_L F_{\mu\nu}$

$\Uparrow$

P and CP odd

$\Rightarrow$ nonzero EDM violates P, CP symmetry

- latest result of neutron EDM

2009@PDG.

X.-G. He, B. H. J. McKellar, S. Pakvasa, Int. J. Mod. Phys. A4(1989), 5011.

$$\begin{cases} |d_{\mathrm{N}}(\mathrm{EXP})| & < \quad 2.9 \times 10^{-26}[e \cdot \mathrm{cm}] \quad (\mathrm{CL} = 90\%) \\ d_{\mathrm{N}}(\mathrm{SM}) & = \quad 10^{-31} \sim 10^{-34}[e \cdot \mathrm{cm}] \quad (3\ \mathrm{loop}) \end{cases}$$

2 C,P transformation in 5D spacetime

4D C,P transformation in 5D spacetime

- **P transformation**

$$\begin{cases} \mathcal{P} : (x^\mu, y) = (x_\mu, -y), \\ \mathcal{P} : \psi(x^\mu, y) = \gamma^0 \psi(x_\mu, -y), \\ \mathcal{P} : (A^\mu, A^y)(x^\mu, y) = (A_\mu, -A^y)(x_\mu, -y). \end{cases}$$

$$\psi(x^\mu, y) = f^{(0)}(y)\psi^{(0)}(x^\mu) + \sum_{n\neq 0} f^{(n)}(y)\psi^{(n)}(x_\mu)$$

$$\xrightarrow{\mathcal{P}} \gamma^0\psi(x_\mu, -y) = f^{(0)}(y) \underbrace{\gamma^0\psi^{(0)}(x_\mu)}_{\text{4D P transformation}} + \sum_{n\neq 0} f^{(n)}(-y)\gamma^0\psi^{(n)}(x_\mu)$$

[$f^{(0)}(-y) = f^{(0)}(y)$ for massless mode]

- **C transformation**

$$\begin{cases} C : (x^\mu, y) = (x^\mu, -y), \\ C : \psi(x^\mu, y) = i\gamma^2\psi^*(x^\mu, -y), \\ C : (A^\mu, A^y)(x^\mu, y) = (-A^\mu, A^y)^{\mathrm{T}}(x^\mu, -y). \end{cases}$$

- **CP transformation**

CP transformation ⇒ combining C,P transformation

$$\begin{cases} C\mathcal{P} : (x^\mu, y) = (x_\mu, y), \\ C\mathcal{P} : (A^\mu, A^y) = (-A_\mu, -A^y)^{\mathrm{T}}, \\ C\mathcal{P} : \psi = i\gamma^0\gamma^2\psi^*. \end{cases}$$

⇓

A_y behaves as CP odd scalar

⇓

CP symmetry breaks down when A_y takes VEV

3 P,CP violation in 5D G-H U

- **Model**
- **EDM**
- **Constraint on compactification scale**

The Model

- (4+1)-dim $SU(3)$ gauge theory on S^1/Z_2 with Z_2 odd bulk mass term

$$\mathcal{L} = -\frac{1}{2}\mathrm{Tr}F_{MN}F^{MN} + \bar{\psi}\left[i\not{D} - M\epsilon(y)\right]\psi$$

$$F_{MN} = \partial_M A_N - \partial_N A_M - ig_5[A_M, A_N], \not{D} = (\partial_L - ig_5 A_L)\Gamma^L, \psi = (\psi_1, \psi_2, \psi_3)^{\mathrm{T}}$$

- Boundary Conditions

$$A_\mu = \begin{pmatrix} (+,+) & (+,+) & (-,-) \\ (+,+) & (+,+) & (-,-) \\ (-,-) & (-,-) & (+,+) \end{pmatrix}, A_y = \begin{pmatrix} (-,-) & (-,-) & (+,+) \\ (-,-) & (-,-) & (+,+) \\ (+,+) & (+,+) & (-,-) \end{pmatrix}, \psi = \begin{pmatrix} \psi_{1L}(+,+) + \psi_{1R}(-,-) \\ \psi_{2L}(+,+) + \psi_{2R}(-,-) \\ \psi_{3L}(-,-) + \psi_{3R}(+,+) \end{pmatrix}$$

(+,+) has massless mode.

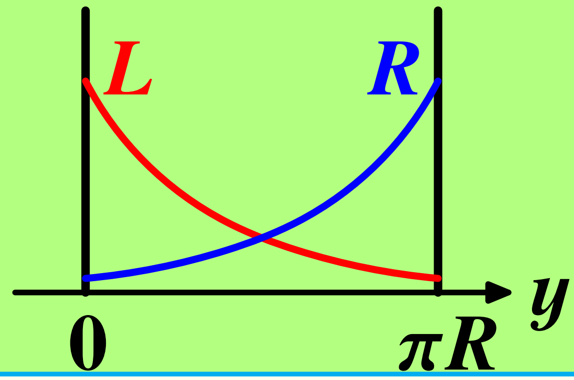
- massless mode

$SU(3)$ breaks into $SU(2)\times U(1)$ and chiral fermion appear.

$$A_\mu = \begin{pmatrix} \gamma, Z & W^+ & 0 \\ W^- & \gamma, Z & 0 \\ 0 & 0 & \gamma, Z \end{pmatrix}_\mu, A_y = \begin{pmatrix} 0 & 0 & \phi^- \\ 0 & 0 & h + i\phi^0 \\ \phi^+ & h - i\phi^0 & 0 \end{pmatrix}_y, \psi = \begin{pmatrix} \begin{pmatrix} u \\ d \end{pmatrix}_L \\ d_R \end{pmatrix}$$

Yukawa coupling

$$\begin{cases} f_L^{(0)}(y) \propto \mathrm{e}^{-My} \\ f_R^{(0)}(y) \propto \mathrm{e}^{My} \end{cases}$$



Yukawa coupling is obtained by an overlap integral of zero mode wave functions.

$$Y = g \int_{-\pi R}^{\pi R} \mathrm{d}y\, f_L^{(0)} f_R^{(0)} = \frac{2\pi RM}{\sqrt{(1-\mathrm{e}^{-2\pi RM})(\mathrm{e}^{2\pi RM}-1)}} g \sim 2\pi RM \mathrm{e}^{-\pi RM} g$$

d quark Yukawa coupling $Y_d = Y|_{\pi RM\sim 12.5} \sim 10^{-5}$

P,CP violation in 5D G-H U

Y.A., C.S. Lim, N. Maru, Phys. Rev. D 80, 055025 (2009).

- CP violation

$$A_M = \begin{pmatrix} A_\mu \\ A_y \end{pmatrix} \begin{matrix} \leftarrow \text{ 4D gauge fields} \\ \leftarrow \text{ CP odd scalar } \Longleftrightarrow \text{ VEV} \end{matrix}$$

$\Downarrow$

naive guess

A_y VEV breaks $\mathcal{CP}$ symmetry

• Source of CP violation

$$\bar{\psi}\left[i\partial\!\!\!/ - \underbrace{M\epsilon(y)}_{\mathcal{CP}\text{even}} + g_5 \underbrace{\langle A_y \rangle}_{\mathcal{CP}\text{odd}} \gamma^5\right]\psi$$

1. $\langle A_y \rangle = 0$ case

   There are no $\mathcal{CP}$ odd “source”$\Rightarrow$ $\mathcal{CP}$ conserved

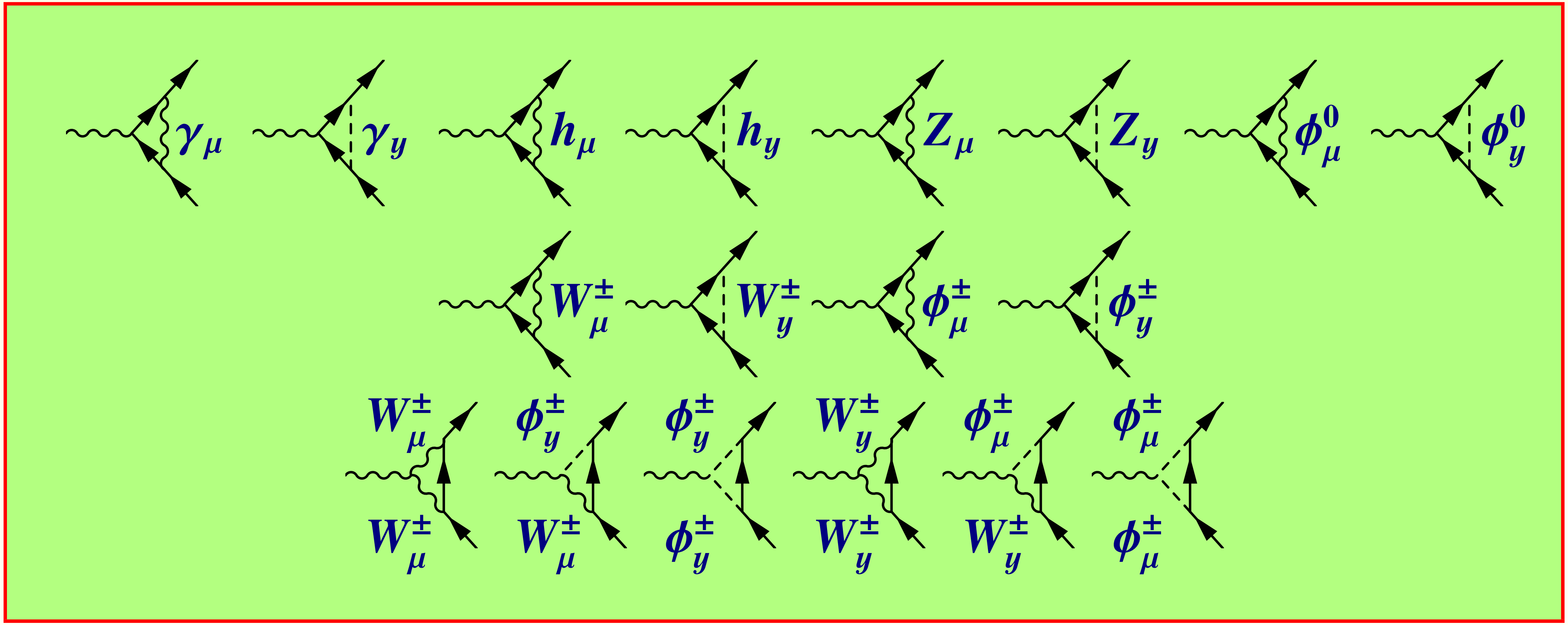
2. $M = 0$ case

   chiral rotation $\psi \rightarrow e^{i\frac{\pi}{4}\gamma^5}\psi \Rightarrow A_y : \mathcal{CP}$ even $\Rightarrow$ $\mathcal{CP}$ conserved

$$\Downarrow$$

Both M and A_y VEV is necessary to break $\mathcal{CP}$ symmetry.

- **EDM**



Zero mode (SM particle) has no contributions to EDM,

KK particle has nonzero contribution up to order 1-loop.

Contributions of KK particle

The contributions of KK particles $d_{\mathrm{N}}(\mathrm{KK})$ are obtained:

$$d_{\mathrm{N}}(\mathrm{KK}) = d_{\mathrm{N}}(\gamma^{(n)}) + d_{\mathrm{N}}(Z^{(n)}) + \cdots$$

$$= -\frac{2}{9} e^3 \frac{(MR)^3}{\pi^3} R^2 m_W \cdot 2.1 \times 10^{-5} \qquad (m_W = g_5 \langle A_y \rangle)$$

Both nonzero M and m_W is significant

$\Uparrow$

$\mathcal{CP}$ symmetry recovers if we take $M = 0$ or $m_W = 0$

Constraint on compactification scale R

Assuming that neutron EDM $d_{\mathrm{N}}(\mathrm{KK})$ is less than the differences between experimental results and theoretical expectation:

$$d_{\mathrm{N}}(\mathrm{KK}) = -\frac{2}{9}e^3\frac{(MR)^3}{\pi^3}R^2 m_W \cdot 2.1 \times 10^{-5}$$

$$= -2.3 \times 10^{-23}(Rm_W)^2[e \cdot \mathrm{cm}] < d_{\mathrm{N}}(\mathrm{EXP}) - d_{\mathrm{N}}(\mathrm{SM})$$

$$\Rightarrow \boxed{\frac{1}{R} > 33m_W \simeq 2.6\ \mathrm{TeV}}$$

4 Summary

- CP violation occurs in the 5D G-H U. by nonzero bulk mass and A_y VEV.

⇒ Fermion (odd) bulk mass realize yukawa coupling and CP violation.

- Fermion EDM appears in the order 1-loop.

- Comparing Neutron EDM experimental result, we obtain the constraint of compactification scale: $M_{\mathrm{KK}} = \frac{1}{R} > 2.6$TeV.

Backup

- **neutron EDM**

neutron $\cdots$ composite state of quarks (udd)

$$|n_\uparrow\rangle = \sqrt{\frac{2}{3}}|d_\uparrow\rangle|d_\uparrow\rangle|u_\downarrow\rangle - \frac{1}{\sqrt{6}}\left(|d_\uparrow\rangle|d_\downarrow\rangle|u_\uparrow\rangle + |u_\downarrow\rangle|u_\uparrow\rangle|d_\downarrow\rangle\right)$$

$$\Rightarrow d_{\mathrm{N}} = \langle n_\uparrow|\sigma^{\mu\nu}\gamma^5|n_\uparrow\rangle F_{\mu\nu} = \frac{4}{3}d_d - \frac{1}{3}d_u$$

- **latest result of neutron EDM (2009 @ PDG)**

$$\begin{cases} |d_{\mathrm{N}}(\mathrm{EXP})| & < \quad 2.9\times 10^{-26}[e\cdot\mathrm{cm}] \quad (\mathrm{CL}=90\%) \\ d_{\mathrm{N}}(\mathrm{SM}) & = \quad 10^{-31}\sim 10^{-34}[e\cdot\mathrm{cm}] \quad (\text{3 loop}) \end{cases}$$

$\mathcal{CP}$ transformation

$$\begin{cases} x^\mu \to x_\mu, y \to y \\ \psi(x^\mu, y) \to i\gamma^0\gamma^2\psi^*(x_\mu, y) \\ A^\mu(x^\mu, y) \to -A_\mu^{\mathrm{T}}(x_\mu, y), A_y(x^\mu, y) \to -A_y^{\mathrm{T}}(x_\mu, y) \end{cases}$$

$$\mathcal{P} : \bar{\psi}(i\partial_\mu\gamma^\mu + i\partial_y\gamma^y)\psi \Rightarrow \bar{\psi}(i\partial_\mu\gamma_\mu - i\partial_y\gamma^y)\psi$$

$$\mathcal{C} : \bar{\psi}(i\partial_\mu\gamma^\mu + i\partial_y\gamma^y)\psi \Rightarrow (-i\partial_\mu\bar{\psi})\gamma^\mu\psi + (i\partial_y\bar{\psi})\gamma^y\psi = \bar{\psi}(i\partial_\mu\gamma^\mu - i\partial_y\gamma^y)\psi$$