Anomalous Higgs couplings in gauge-Higgs unification scenario in warped spacetime

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Introduction

標準模型：　ゲージ理論

（ゲージ場、ヒッグス、クォーク、レプトン）

$$SU(3)_C \times SU(2)_W \times U(1)_Y$$

$$\Big\downarrow \quad \text{自発的対称性の破れ}$$

$$SU(3)_C \times U(1)_{EM}$$

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電弱対称性の破れ

$$SU(2)_W \times U(1)_Y \Rightarrow U(1)_{\mathrm{EM}}$$

ヒッグス二重項

$$H = \begin{pmatrix} \varphi^1 \\ \varphi^2 \end{pmatrix} \Rightarrow \langle H \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix} \quad (v = 246 \text{ GeV})$$

ヒッグス機構

$$\begin{aligned} \mathcal{L} &= \left| \left(\partial_\mu - igA_\mu^a \frac{\sigma^a}{2} - \frac{ig'}{2} B_\mu \right) H \right|^2 + \left\{ y_e \bar{e}_R H^\dagger \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \text{h.c.} \right\} \\ &\quad + \cdots \\ &\Rightarrow \frac{g^2 v^2}{2} W^{\mu\dagger} W_\mu + \frac{(g^2 + g'^2) v^2}{4} Z^\mu Z_\mu + y_e v (\bar{e}_R e_L + \text{h.c.}) \\ &\quad + \cdots \end{aligned}$$

電弱対称性の破れ

$$SU(2)_W \times U(1)_Y \Rightarrow U(1)_{\text{EM}}$$

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$$\Rightarrow \frac{g^2 v^2}{2} W^{\mu\dagger} W_\mu + \frac{(g^2 + g'^2) v^2}{4} Z^\mu Z_\mu + y_e v (\bar{e}_R e_L + \text{h.c.}) + \cdots$$

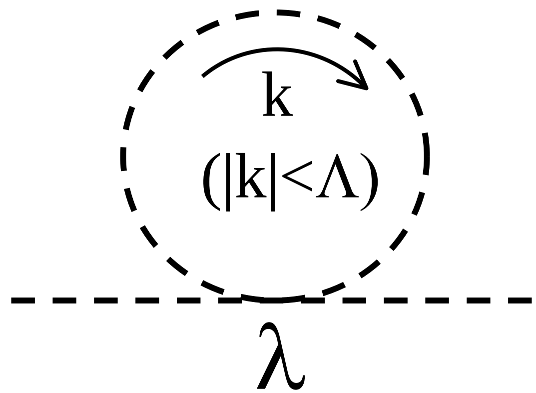
$$m_W \qquad \frac{m_Z}{2} \qquad m_e$$

ゲージ階層性の問題

ヒッグス質量の量子補正

$$m_H^2 = (m_H^0)^2 + \delta m_H^2$$

$$\delta m_H^2 = $$



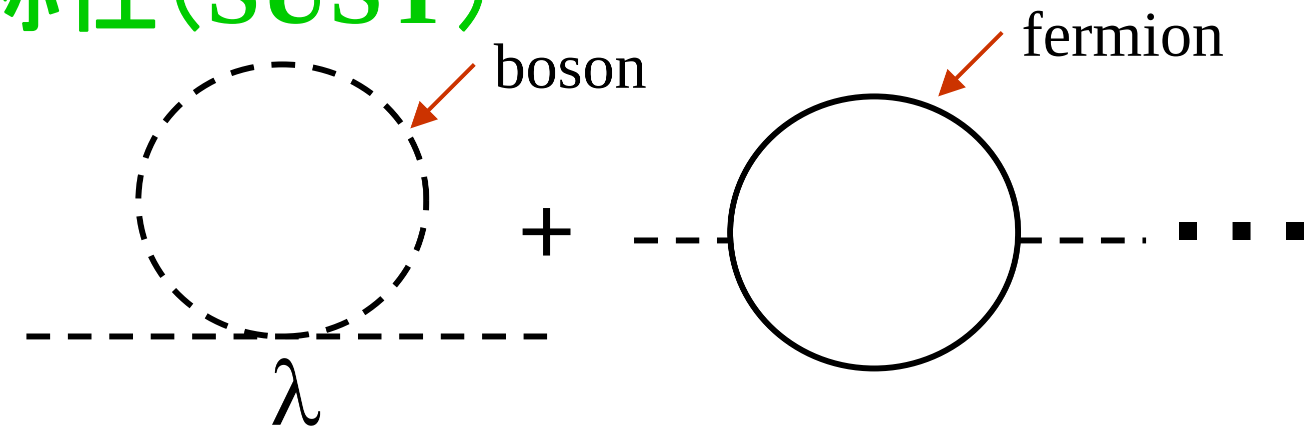
$$+ \cdots$$

$$= O(\Lambda^2) + \cdots$$

$$\begin{cases} m_H = O(10^2 \text{ GeV}) \\ \Lambda = O(10^{18} \text{ GeV}) \end{cases} \Rightarrow 10^{32} \text{ の fine tuning!}$$

超対称性(SUSY)

$\delta m_H^2 =$



$= O(\ln \Lambda) + \cdots$

テクニカラー模型

スカラー場を導入しない ⇨ ２次発散なし

$$\langle \bar{\psi}\psi \rangle = v \neq 0$$

ψ: techni-quark

ゲージヒッグス統合模型

ヒッグス場＝高次元ゲージ場の余剰次元成分

$$A_M = (A_\mu, A_y)$$

$\|$

Higgs

Tree levelでは、ヒッグス場はpotentialを持たない。

i.e., $m_H = 0$

One-loop levelで、$m_H \neq 0$。

高次元ゲージ対称性 ⇒ ヒッグス質量を量子補正から保護

Plan of talk

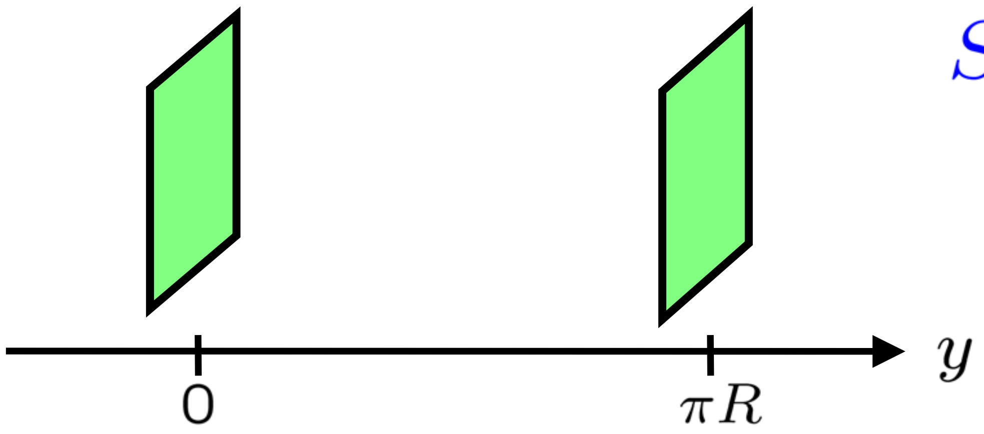
1. **Introduction**
2. **Simplest model (SU(3) model)**
   flat case
   warped case
3. **SO(5)xU(1) model**
4. **Summary**

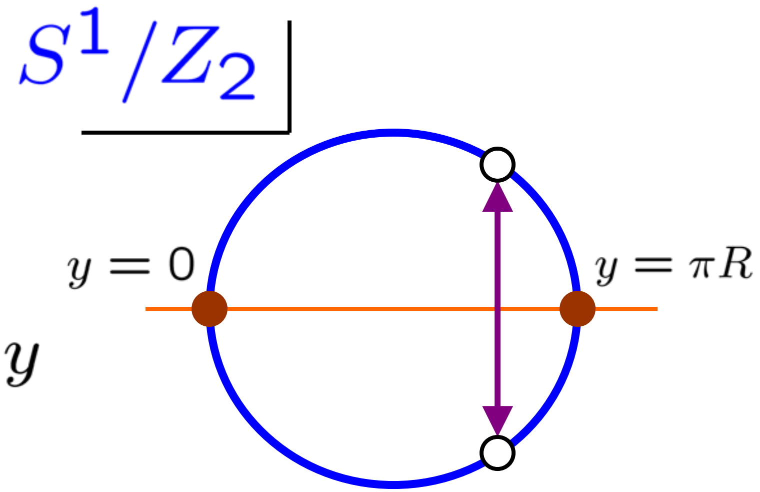
Simplest model

５次元SU(3)ゲージ理論

時空:　$M_4 \times S^1/Z_2$

$$ds^2 = \eta_{\mu\nu}dx^\mu dx^\nu + dy^2 \quad (0 \le y \le \pi R)$$





ゲージ対称性: $SU(3) \supset SU(2) \times U(1)$

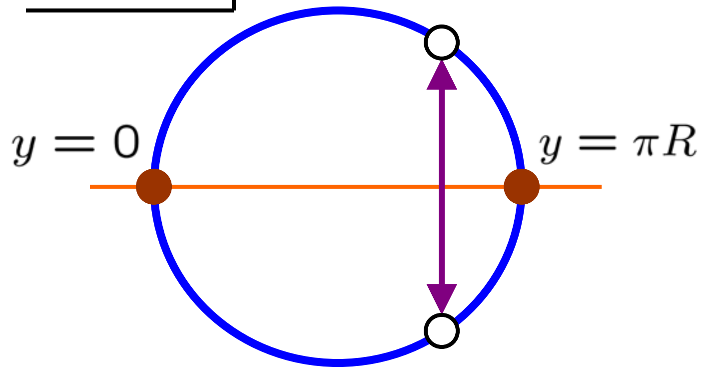
ゲージ場

$$A_M = \sum_{a=1}^{8} A_M^a \frac{\lambda^a}{2} \quad (M = 0, 1, 2, 3, 4)$$

$$= \frac{1}{2} \begin{pmatrix} A_M^3 + \frac{1}{\sqrt{3}} A_M^8 & A_M^1 - iA_M^2 & A_M^4 - iA_M^5 \\ A_M^1 + iA_M^2 & -A_M^3 + \frac{1}{\sqrt{3}} A_M^8 & A_M^6 - iA_M^7 \\ A_M^4 + iA_M^5 & A_M^6 + iA_M^7 & -\frac{2}{\sqrt{3}} A_M^8 \end{pmatrix}$$

Orbifold Parity

S^1/Z_2



$$(x^\mu, -y) \sim (x^\mu, +y)$$
$$(x^\mu, \pi R + y) \sim (x^\mu, \pi R - y)$$

Orbifold conditions:

$$\begin{pmatrix} A_\mu \\ A_y \end{pmatrix} (x, -y) = P_0 \begin{pmatrix} A_\mu \\ -A_y \end{pmatrix} (x, y) P_0^\dagger$$
$$\begin{pmatrix} A_\mu \\ A_y \end{pmatrix} (x, \pi R + y) = P_\pi \begin{pmatrix} A_\mu \\ -A_y \end{pmatrix} (x, \pi R - y) P_\pi^\dagger$$

where

$$P_0, P_\pi \in SU(3).$$

If we take P_0, P_π as

$$P_0 = P_\pi = \begin{pmatrix} -1 & & \\ & -1 & \\ & & +1 \end{pmatrix},$$

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

gauge symmetry: $SU(3) \to SU(2) \times U(1)$

$$A_y = \begin{pmatrix} (-,-) & (-,-) & (+,+) \\ (-,-) & (-,-) & (+,+) \\ (+,+) & (+,+) & (-,-) \end{pmatrix}$$

If we take P_0, P_π as

$$P_0 = P_\pi = \begin{pmatrix} -1 & & \\ & -1 & \\ & & +1 \end{pmatrix},$$

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$$A_y = \begin{pmatrix} (-,-) & (-,-) & (+,+) \\ (-,-) & (-,-) & (+,+) \\ (+,+) & (+,+) & (-,-) \end{pmatrix}$$

Higgs doublet

- **Higgs doublet**

$$A_y = \frac{1}{2}\begin{pmatrix} & & A_y^4 - iA_y^5 \\ & & A_y^6 - iA_y^7 \\ A_y^4 + iA_y^5 & A_y^6 + iA_y^7 & \end{pmatrix}$$

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- **(gauge-invariant) Wilson line phase**

$$\theta_H \equiv g_5 \int_0^{\pi R} dy\ A_y^7(y) \quad (= \text{Higgs field})$$

$$\theta_H \neq 0 \Rightarrow SU(2) \times U(1) \rightarrow U(1)$$

determined by quantum effect

Relations among mass scales

$$m_{KK}\left(\equiv\frac{1}{\pi R}\right)=2\pi\frac{m_W}{\theta_H}$$

$$m_H\sim\frac{g_W}{\sqrt{4\pi}}\frac{m_W}{\theta_H}$$

Relations among mass scales

If $\theta_H = \mathcal{O}(1)$,

$$m_{KK}\left(\equiv\frac{1}{\pi R}\right) = 2\pi\frac{m_W}{\theta_H} \sim \mathcal{O}(300\ \text{GeV})$$

$$m_H \sim \frac{g_W}{\sqrt{4\pi}}\frac{m_W}{\theta_H} \sim \mathcal{O}(10\ \text{GeV})$$

$\Rightarrow$ contradict experimental limits!

Relations among mass scales

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$$m_H \sim \frac{g_W}{\sqrt{4\pi}} \frac{m_W}{\theta_H} \sim \mathcal{O}(10 \text{ GeV})$$

$\Rightarrow$ contradict experimental limits!

To improve,

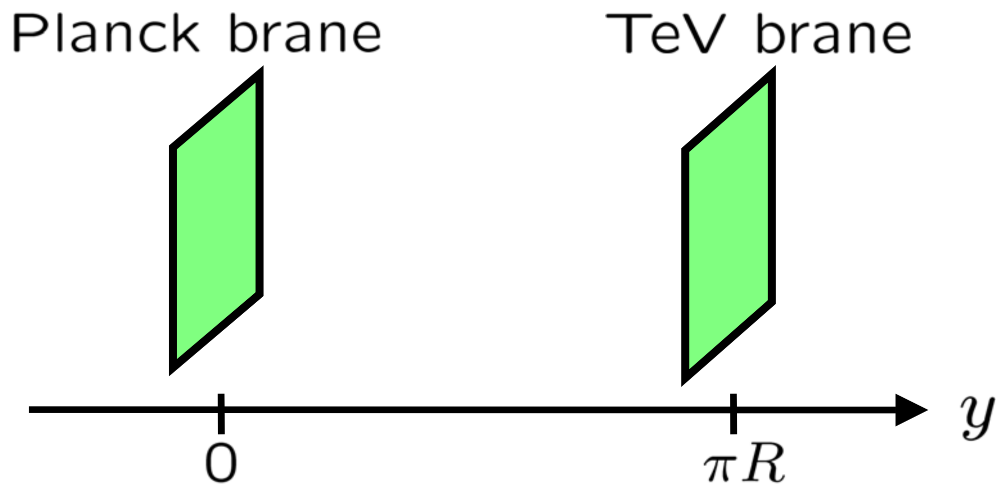
- small θ_H
- warped spacetime

Warped spacetime (Randall, Sundrum, PRL83 (1999) 3370)

$$ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$

$$(0 \leq y \leq \pi R)$$

$$\left(\frac{m_{\text{Planck}}}{m_{\text{weak}}} \sim 10^{15} \quad \Rightarrow \quad k\pi R \sim 35\right)$$



Relations among mass scales (warped case)

(Hosotani, Mabe, PLB615 (2005) 257)

$$m_{KK} \left(\equiv \frac{k\pi}{e^{k\pi R} - 1} \right) = \frac{\pi m_W}{\sin \frac{\theta_H}{2}} \cdot \sqrt{\frac{k\pi R}{2}} \sim \mathcal{O}(\text{TeV})$$

$$m_H \sim \frac{g_W}{\sqrt{4\pi}} \frac{m_W}{\sin \frac{\theta_H}{2}} \cdot \frac{k\pi R}{2} \sim \mathcal{O}(200 \text{ GeV})$$

Problem of SU(3) model

- Wrong value of the Weinberg angle θ_W

$$\sin^2\theta_W \equiv \frac{e_{EM}^2}{g_W^2} \simeq \frac{3}{4} \neq 0.23$$

- Rho parameter deviates from one.

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W}$$

$$\simeq \frac{4\sin^2\frac{\theta_H}{2}}{\sin^2\theta_H} = \frac{1}{\cos^2\frac{\theta_H}{2}} \neq 1$$

Problem of SU(3) model

- Wrong value of the Weinberg angle θ_W

$$\Rightarrow \text{extra } U(1) \text{ gauge group}$$

- Rho parameter deviates from one.

$$\begin{aligned} \rho &\equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} \\ &\simeq \frac{4\sin^2\frac{\theta_H}{2}}{\sin^2\theta_H} = \frac{1}{\cos^2\frac{\theta_H}{2}} \neq 1 \end{aligned}$$

Problem of SU(3) model

- Wrong value of the Weinberg angle θ_W

$$\Rightarrow \text{extra } U(1) \text{ gauge group}$$

- Rho parameter deviates from one.

$$\Rightarrow \text{custodial symmetry}$$

SO(5)xU(1)$_{B-L}$ model

Agashe,Contino,Pomarol, NPB719(2005)165

Gauge fields: $(A_M, B_M) \quad (M = 0,1,2,3,4)$

$SO(5) \quad U(1)_{B-L}$

$$SO(5) \supset SO(4) \simeq SU(2)_L \times SU(2)_R$$

$$A_M = \sum_{a_L=1}^{3} A_M^{a_L} T^{a_L} + \sum_{a_R=1}^{3} A_M^{a_R} T^{a_R} + \sum_{\hat{a}=1}^{4} A_M^{\hat{a}} T^{\hat{a}},$$

where

$$T^{a_L} \in SU(2)_L, \quad T^{a_R} \in SU(2)_R, \quad T^{\hat{a}} \in SO(5)/SO(4).$$

5D action

$$S = \int d^5x \sqrt{-G} \left[-\frac{1}{2g_A^2} \mathrm{tr} \left(F^{(A)MN} F^{(A)}_{MN} \right) \right.$$
$$\left. - \frac{1}{4g_B^2} F^{(B)MN} F^{(B)}_{MN} + \cdots \right],$$

where

$$F^{(A)}_{MN} \equiv \partial_M A_N - \partial_N A_M - i[A_M, A_N],$$
$$F^{(B)}_{MN} \equiv \partial_M B_N - \partial_N B_M.$$

Symmetry breaking

$$SO(5) \times U(1)_{B-L} \xrightarrow{\text{orbifold}} SO(4) \times U(1)_{B-L}$$

$$\wr\!|$$

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$A_\mu^{a_L}$	$A_\mu^{a_R}$	B_μ	$A_\mu^{\hat{a}}$
(N,N)	(N,N)	(N,N)	(D,D)

$A_y^{a_L}$	$A_y^{a_R}$	B_y	$A_y^{\hat{a}}$
(D,D)	(D,D)	(D,D)	(N,N)

Symmetry breaking

$$SO(5) \times U(1)_{B-L} \xrightarrow{\text{orbifold}} SO(4) \times U(1)_{B-L}$$

$$\wr|$$

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$A_\mu^{a_L}$	$A_\mu^{a_R}$	B_μ	$A_\mu^{\hat{a}}$
(N,N)	(N,N)	(N,N)	(D,D)

$A_y^{a_L}$	$A_y^{a_R}$	B_y	$A_y^{\hat{a}}$
(D,D)	(D,D)	(D,D)	(N,N)

Higgs doublet

Symmetry breaking

$$SO(5) \times U(1)_{B-L} \xrightarrow{\text{orbifold}} SO(4) \times U(1)_{B-L}$$

$$\cong$$

$$SU(2)_L \times \underline{SU(2)_R \times U(1)_{B-L}}$$

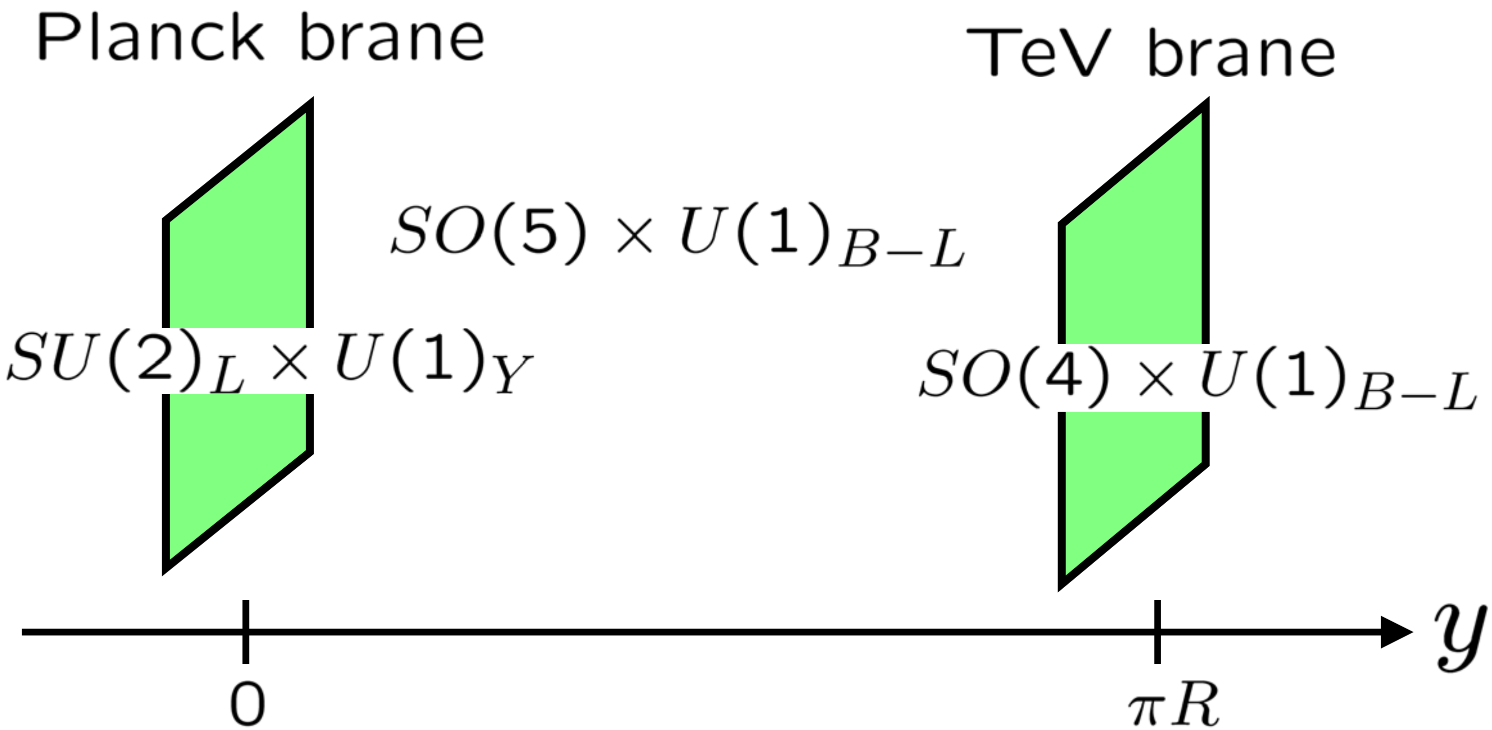
$$\Big\downarrow \quad \text{spontanenously on Planck brane at } M \gg (\text{TeV})$$

$$U(1)_Y$$

$$Y = T^{3_R} + \frac{B-L}{2}$$

$$\begin{pmatrix} A'^{3_R}_M \\ A^Y_M \end{pmatrix} = \begin{pmatrix} c_\phi & -s_\phi \\ s_\phi & c_\phi \end{pmatrix} \begin{pmatrix} A^{3_R}_M \\ B_M \end{pmatrix},$$

$$c_\phi \equiv \frac{g_A}{\sqrt{g_A^2 + g_B^2}}, \qquad s_\phi \equiv \frac{g_B}{\sqrt{g_A^2 + g_B^2}}$$



$A_\mu^{a_L}$	$A_\mu^{1,2_R}$	$A'^{3_R}_\mu$	A_μ^{Y}	$A_\mu^{\hat{a}}$
(N,N)	(D,N)	(D,N)	(N,N)	(D,D)

$A_y^{a_L}$	$A_y^{1,2_R}$	$A'^{3_R}_y$	A_y^{Y}	$A_y^{\hat{a}}$
(D,D)	(D,D)	(D,D)	(D,D)	(N,N)

Higgs doublet:

$$A_y^{\hat{a}} \ (\hat{a} = 1, 2, 3, 4)$$

By using residual symemtry, $\langle A_y^{\hat{a}} \rangle \propto \delta_{\hat{a},4}.$

Wilson line phase:

$$\theta_H \equiv \frac{g_A}{\sqrt{2}} \int_0^{\pi R} dy \ A_y^{\hat{4}}(y)$$

$$\theta_H \neq 0 \Rightarrow SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$$

Kaluza Klein analysis

4D fields

$$A^I_\mu(x,y) = \sum_n h^I_{A,n}(y) A^{(n)}_\mu(x),$$
$$A^I_y(x,y) = \sum_n h^I_{\varphi,n}(y) \varphi^{(n)}(x).$$

mode functions

flat case:三角関数
warped case:ベッセル関数

Mass spectrum $(m_n = k\lambda_n)$

W boson:

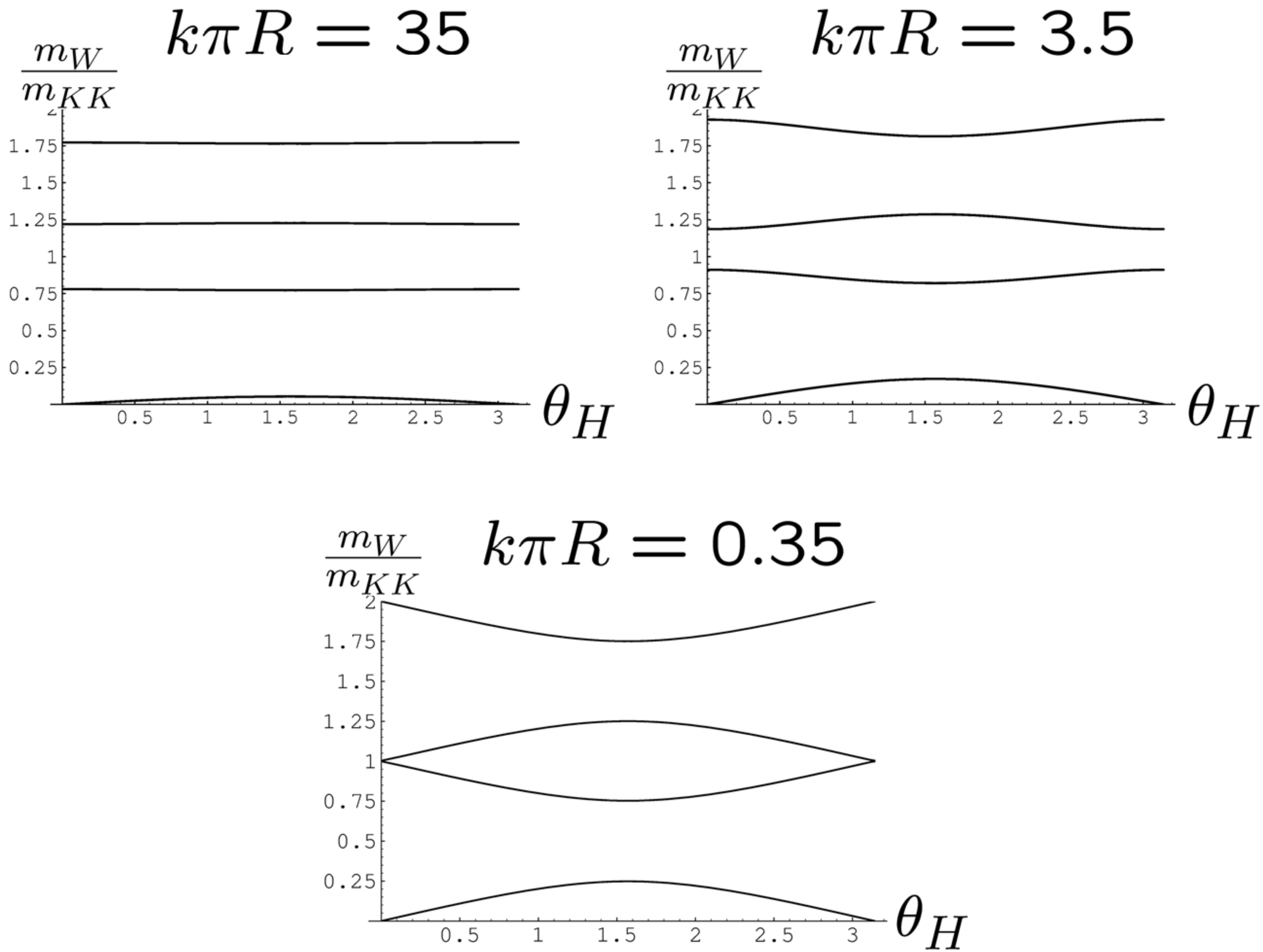
$$F_{0,0}(\lambda_n)F_{1,1}(\lambda_n) = \frac{2\sin^2\theta_H}{\pi^2\lambda_n^2 e^{k\pi R}}$$

Z boson:

$$F_{0,0}(\lambda_n)F_{1,1}(\lambda_n) = \left(\frac{g_A^2 + 2g_B^2}{g_A^2 + g_B^2}\right)\frac{2\sin^2\theta_H}{\pi^2\lambda_n^2 e^{k\pi R}}$$

where

$$F_{\alpha,\beta}(\lambda_n) \equiv J_\alpha(\lambda_n)Y_\beta(\lambda_n e^{k\pi R}) - Y_\alpha(\lambda_n)J_\beta(\lambda_n e^{k\pi R})$$


$k\pi R = 35$
$\frac{m_W}{m_{KK}}$
θ_H
$k\pi R = 3.5$
$\frac{m_W}{m_{KK}}$
θ_H
$k\pi R = 0.35$
$\frac{m_W}{m_{KK}}$
θ_H

Weak gauge boson masses

$$m_W \simeq \frac{m_{KK}}{\pi}\frac{|\sin\theta_H|}{\sqrt{k\pi R}},$$

$$m_Z \simeq \frac{m_{KK}}{\pi}\sqrt{\frac{g_A^2+2g_B^2}{g_A^2+g_B^2}}\frac{|\sin\theta_H|}{\sqrt{k\pi R}}.$$

$$\left(m_{KK} \equiv \frac{k\pi}{e^{k\pi R}-1}\right)$$

Coupling constants

mode functions

Kaluza-Klein expansion:

$$A^I_\mu(x,y) = \sum_n h^I_{A,n}(y) A^{(n)}_\mu(x),$$
$$A^I_y(x,y) = \sum_n h^I_{\varphi,n}(y) \varphi^{(n)}(x).$$

$$\boxed{\text{coupling constant} = (\text{overlap integral of mode functions})}$$

Gauge couplings

$$e_{EM} = \frac{g_A g_B}{\sqrt{\pi R(g_A^2 + 2g_B^2)}}, \qquad g \simeq \frac{g_A}{\sqrt{\pi R}}$$

Weinberg angle

$$\sin^2\theta_W \equiv \frac{e_{EM}^2}{g^2} \simeq \frac{g_B^2}{g_A^2 + 2g_B^2}$$

調整可能！

Rho parameter

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} \simeq 1$$

実験と無矛盾！

WWZ Coupling

$$\mathcal{L}^{(4)} = i g_{WWZ} \Big\{ (\partial_\mu W_\nu^{(0)} - \partial_\nu W_\mu^{(0)})^\dagger W^{(0)\mu} Z^{(0)\nu} \\ -(\partial_\mu W_\nu^{(0)} - \partial_\nu W_\mu^{(0)}) W^{(0)\dagger\mu} Z^{(0)\nu} \\ + W_\mu^{(0)\dagger} W_\nu^{(0)} (\partial^\mu Z^{(0)\nu} - \partial^\nu Z^{(0)\mu}) \Big\} + \cdots$$

SM value

Ratio of g_{WWZ} to $g \cos\theta_W$

$k\pi R$ \ θ_H	$\pi/10$	$\pi/4$	$\pi/2$
35	0.9999987	0.999964	0.99985
0.35	0.9994990	0.979458	0.83378

WWH, ZZH couplings

$$\mathcal{L}^{(4)} = -\lambda_{WWH} H^{(0)} W^{(0)\mu\dagger} W_\mu^{(0)} \\ -\frac{1}{2}\lambda_{ZZH} H^{(0)} Z^{(0)\mu} Z_\mu^{(0)} + \cdots$$

$$\lambda_{WWH} \simeq g m_W \cos\theta_H,$$

$$\lambda_{ZZH} \simeq \frac{g m_Z}{\cos\theta_W} \cos\theta_H,$$

SM values

WWHH, ZZHH couplings

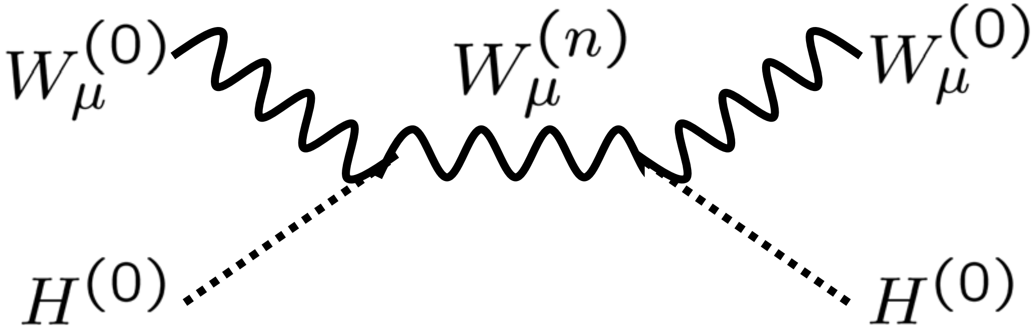
$$\mathcal{L}^{(4)} = -\frac{\lambda_{WWHH}^{(0)2}}{4} W_\mu^{(0)\dagger} W^{(0)\mu} H^{(0)} H^{(0)} - \frac{\lambda_{ZZHH}^{(0)2}}{8} Z_\mu^{(0)} Z^{(0)\mu} H^{(0)} H^{(0)} + \cdots$$

$$\lambda_{WWHH}^{(0)2} \simeq g^2 \left(1 - \frac{2}{3}\sin^2\theta_H\right),$$

$$\lambda_{ZZHH}^{(0)2} \simeq \frac{g^2}{\cos\theta_W} \left(1 - \frac{2}{3}\sin^2\theta_H\right),$$

SM values

Effective WWHH, ZZHH couplings



$$= -4 \times \sum_{n=1}^{\infty} \frac{\lambda^2_{WW_nH}}{m^2_{W_n}} \simeq -\frac{4g^2}{3} \sin^2\theta_H$$

Thus,

$$\lambda^2_{WWHH} \simeq g^2\left(1 - 2\sin^2\theta_H\right) = g^2 \cos 2\theta_H,$$

$$\lambda^2_{ZZHH} \simeq \frac{g^2}{\cos\theta_W}\left(1 - 2\sin^2\theta_H\right) = \frac{g^2 \cos 2\theta_H}{\cos\theta_W},$$

Effective Lagrangian

$$m_W = C_W \sin\theta_H$$

$$\mathcal{L}_{\text{eff}} = -\left\{ m_W^2 + g m_W \cos\theta_H H + \frac{g^2 \cos 2\theta_H}{4} H^2 \right\} W^{\mu\dagger} W_\mu + \cdots$$

$$= -C_W^2 \left\{ \sin^2\theta_H + 2\sin\theta_H \cos\theta_H \cdot \frac{gH}{2C_W} + \cos 2\theta_H \left(\frac{gH}{2C_W} \right)^2 + \cdots \right\} W^{\mu\dagger} W_\mu + \cdots$$

$$\Rightarrow -C_W^2 \underline{\sin^2\left(\theta_H + \frac{gH}{2C_W} \right)} W^{\mu\dagger} W_\mu + \cdots$$

非線形表現 Lagrangian と同じ形！

Analogy to Higgs as pseudo-NG bosons

4D theory:

Global symmetry

$$G = SO(5) \times U(1)$$

4 NG bosons

$$H = SO(4) \times U(1)$$

Analogy to Higgs as pseudo-NG bosons

4D theory:

Global symmetry

$$G = SO(5) \times U(1)$$

$\Downarrow$ $\Rightarrow$ **4 PNG bosons (Higgs doublet)**

$$H = SO(4) \times U(1) \supset SU(2) \times U(1)$$

ゲージ化

Analogy to Higgs as pseudo-NG bosons

4D theory:

Global symmetry

$$G = SO(5) \times U(1)$$

$\Rightarrow$ 4 PNG bosons (Higgs doublet)

$$H = SO(4) \times U(1) \supset SU(2) \times U(1)$$

ゲージ化

5D theory: Gauge-Higgs unification

Summary

SO(5)xU(1)$_{B-L}$ model in warped spacetime

ρ	$\simeq 1$
m_{KK}	$\dfrac{\pi m_W}{\sin\frac{\theta_H}{2}}\sqrt{\dfrac{k\pi R}{2}}$
m_H	$\sim \dfrac{g}{\sqrt{4\pi}}\dfrac{m_W}{\sin\frac{\theta_H}{2}}\dfrac{k\pi R}{2}$
WWZ $WWWW$, $WWZZ$	almost SM values
WWH, ZZH	suppressed by $\cos\theta_H$
$WWHH$, $ZZHH$	suppressed by $\cos 2\theta_H$

今後の課題

- 現実的なfermionセクターの構築
- 量子補正の考慮
- 有効ポテンシャルを求めてθ_Hの値を決定

$$\vdots$$