Gauge couplings in SO(5)xU(1) Gauge-Higgs unification

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Standard Model

W boson　up　charm

Z boson　down　bottom　top

光子　strange

グルーオン　電子　タウレプトン

ニュートリノ x3　ミューオン

ヒッグス粒子（まだ見つかっていない）

SO(5)xU(1) ゲージ・ヒッグス

W boson up charm

Z boson down bottom top

光子 strange

グルーオン xSU(3)c 電子 タウレプトン

ニュートリノ x3 ミューオン

ヒッグス粒子

＋非常に重い粒子

Custodial symmetry

Standard Model Higgs H $SU(2)_L$ doublet

ϵH^* transforms in the same way as H

$$\begin{pmatrix} \epsilon H^* & H \\ & \end{pmatrix}$$

Custodial symmetry

Standard Model Higgs H SU(2)$_L$ doublet

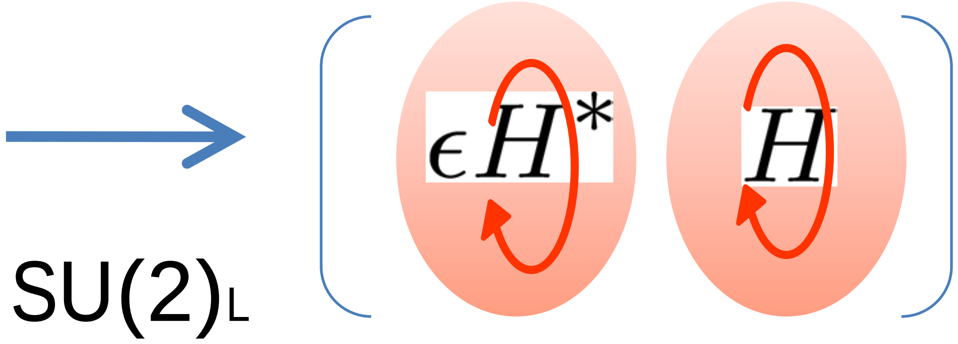
ϵH^* transforms in the same way as H

$$\xrightarrow{SU(2)_L} \begin{pmatrix} \epsilon H^* & H \end{pmatrix}$$

Custodial symmetry

Standard Model Higgs H SU(2)L doublet

ϵH^* transforms in the same way as H



Custodial symmetry

Standard Model Higgs H SU(2)$_L$ doublet

ϵH^* transforms in the same way as H

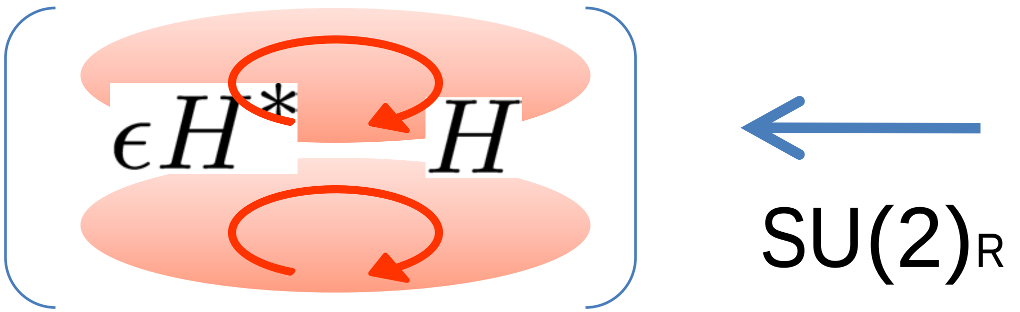
$$\begin{pmatrix} \epsilon H^* & H \end{pmatrix} \longleftarrow$$

SU(2)$_R$

Custodial symmetry

Standard Model Higgs H SU(2)$_L$ doublet

ϵH^* transforms in the same way as H



Custodial symmetry

Standard Model Higgs H SU(2)$_L$ doublet

ϵH^* transforms in the same way as H

$$\begin{pmatrix} \epsilon H^* & H \end{pmatrix}$$

SU(2)$_L$ X SU(2)$_R$

Custodial symmetry

Standard Model Higgs H $SU(2)_L$ doublet

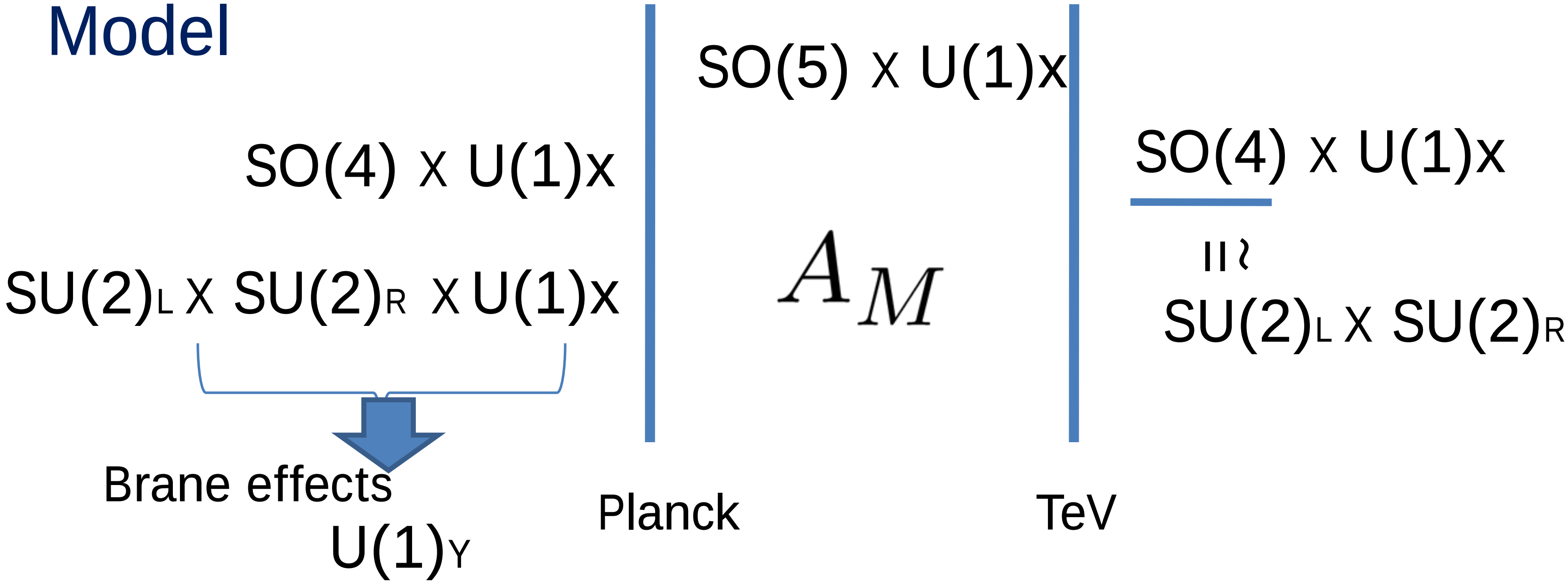
ϵH^* transforms in the same way as H

$$\begin{pmatrix} v & \\ & v \end{pmatrix}$$

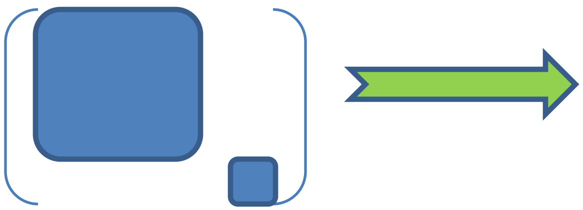
$SU(2)_L$ X $SU(2)_R$

$SU(2)_V$

Model

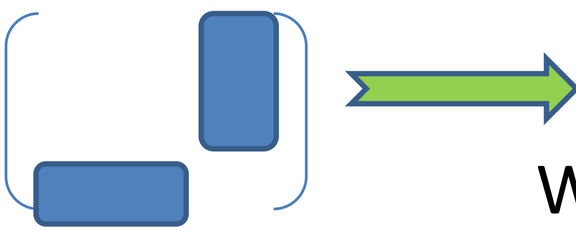


A_μ



W boson, Z boson, 光子

A_5



ヒッグス場

Wilson line phase θ_H

Model

$SO(5) \times U(1)_X$

$SO(4) \times U(1)_X$

$SU(2)_L \times SU(2)_R \times U(1)_X$

Brane effects

$U(1)_Y$

Planck

TeV

$SO(4) \times U(1)_X$

$\cong$

$SU(2)_L \times SU(2)_R$

$$Q_X = 2/3 \qquad \begin{pmatrix} T & t \\ B & b \end{pmatrix}, \qquad t'$$

$$Q_X = -1/3 \qquad \begin{pmatrix} U & X \\ D & Y \end{pmatrix}, \qquad b'$$

Model

$SO(5) \times U(1)_X$

$SO(4) \times U(1)_X$

$SU(2)_L \times SU(2)_R \times U(1)_X$

Brane effects

$U(1)_Y$

Planck

TeV

$SO(4) \times U(1)_X \cong SU(2)_L \times SU(2)_R$

$$Q = T_L^3 + T_R^3 + Q_X$$

$Q_X = 2/3$ $\begin{pmatrix} T & t \\ B & b \end{pmatrix}$, t' $Q = 2/3$

$Q_X = -1/3$ $\begin{pmatrix} U & X \\ D & Y \end{pmatrix}$, b' $Q = -1/3$

bulk	Q_X		$\frac{1}{2}Y$	Q_E	on the brane	$Q_X, \frac{1}{2}Y$	Q_E
Ψ_1	$2/3$	$Q_1 = \begin{pmatrix} T \\ B \end{pmatrix}$	$7/6$	$5/3$ $2/3$	$\hat{\chi}_{1R} = \begin{pmatrix} \hat{T}_R \\ \hat{B}_R \end{pmatrix}$	$7/6$	$5/3$ $2/3$
		$q = \begin{pmatrix} t \\ b \end{pmatrix}$	$1/6$	$2/3$ $-1/3$			
		t'	$2/3$	$2/3$			
Ψ_2	$-1/3$	$Q_2 = \begin{pmatrix} U \\ D \end{pmatrix}$	$1/6$	$2/3$ $-1/3$	$\hat{\chi}_{2R} = \begin{pmatrix} \hat{U}_R \\ \hat{D}_R \end{pmatrix}$	$1/6$	$2/3$ $-1/3$
		$Q_3 = \begin{pmatrix} X \\ Y \end{pmatrix}$	$-5/6$	$-1/3$ $-4/3$	$\hat{\chi}_{3R} = \begin{pmatrix} \hat{X}_R \\ \hat{Y}_R \end{pmatrix}$	$-5/6$	$-1/3$ $-4/3$
		b'	$-1/3$	$-1/3$			
Ψ_3	-1	$\ell = \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$	$-1/2$	0 -1			
		$L_1 = \begin{pmatrix} L_{1X} \\ L_{1Y} \end{pmatrix}$	$-3/2$	-1 -2	$\hat{\chi}^\ell_{1R} = \begin{pmatrix} \hat{L}_{1XR} \\ \hat{L}_{1YR} \end{pmatrix}$	$-3/2$	-1 -2
		τ'	-1	-1			
Ψ_4	0	$L_2 = \begin{pmatrix} L_{2X} \\ L_{2Y} \end{pmatrix}$	$1/2$	1 0	$\hat{\chi}^\ell_{2R} = \begin{pmatrix} \hat{L}_{2XR} \\ \hat{L}_{2YR} \end{pmatrix}$	$1/2$	1 0
		$L_3 = \begin{pmatrix} L_{3X} \\ L_{3Y} \end{pmatrix}$	$-1/2$	0 -1	$\hat{\chi}^\ell_{3R} = \begin{pmatrix} \hat{L}_{3XR} \\ \hat{L}_{3YR} \end{pmatrix}$	$-1/2$	0 -1
		ν'_τ	0	0			

SU(2)L x SU(2)R x U(1)x anomaly free

Quark

bulk	Q_X		$\frac{1}{2}Y$	Q_E	on the brane	$Q_X, \frac{1}{2}Y$	Q_E
Ψ_1	$2/3$	$Q_1 = \begin{pmatrix} T \\ B \end{pmatrix}$	$7/6$	$5/3$, $2/3$	$\hat{\chi}_{1R} = \begin{pmatrix} \hat{T}_R \\ \hat{B}_R \end{pmatrix}$	$7/6$	$5/3$, $2/3$
		$q = \begin{pmatrix} t \\ b \end{pmatrix}$	$1/6$	$2/3$, $-1/3$			
		t'	$2/3$	$2/3$			
Ψ_2	$-1/3$	$Q_2 = \begin{pmatrix} U \\ D \end{pmatrix}$		$2/3$, $-1/3$	$\hat{\chi}_{2R} = \begin{pmatrix} \hat{U}_R \\ \hat{D}_R \end{pmatrix}$	$1/6$	$2/3$, $-1/3$
		$Q_3 = \begin{pmatrix} X \\ Y \end{pmatrix}$	$-5/6$	$-1/3$, $-4/3$	$\hat{\chi}_{3R} = \begin{pmatrix} \hat{X}_R \\ \hat{Y}_R \end{pmatrix}$	$-5/6$	$-1/3$, $-4/3$
		b'	$-1/3$	$-1/3$			
Ψ_3	-1	$\ell = \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$		0, -1			
		$L_1 = \begin{pmatrix} L_{1X} \\ L_{1Y} \end{pmatrix}$	$-3/2$	-1, -2	$\hat{\chi}^\ell_{1R} = \begin{pmatrix} \hat{L}_{1XR} \\ \hat{L}_{1YR} \end{pmatrix}$	$-3/2$	-1, -2
		τ'	-1	-1			
Ψ_4	0	$L_2 = \begin{pmatrix} L_{2X} \\ L_{2Y} \end{pmatrix}$	$1/2$	1, 0	$\hat{\chi}^\ell_{2R} = \begin{pmatrix} \hat{L}_{2XR} \\ \hat{L}_{2YR} \end{pmatrix}$	$1/2$	1, 0
		$L_3 = \begin{pmatrix} L_{3X} \\ L_{3Y} \end{pmatrix}$	$-1/2$	0, -1	$\hat{\chi}^\ell_{3R} = \begin{pmatrix} \hat{L}_{3XR} \\ \hat{L}_{3YR} \end{pmatrix}$	$-1/2$	0, -1
		ν'_τ	0	0			

$\tilde{\mu}$

μ_2

$\tilde{\mu}^\ell$

μ^ℓ_3

Lepton

SU(2)L x SU(2)R x U(1)x anomaly free

4次元ラグランジアン

b クォークの　Z boson coupling

$$\mathcal{L}_{Zb\bar{b}} = \frac{g_A Z_\mu}{\cos\theta_W}\left(\mathcal{B}_L \bar{b}_L \gamma^\mu b_L + \mathcal{B}_R \bar{b}_R \gamma^\mu b_R\right)$$

$$\mathcal{B}_{L,R} = -\tfrac{1}{2}\mathcal{B}^3_{L,R} + \tfrac{1}{3}\mathcal{B}^Q_{L,R}\sin^2\theta_W$$

$$\begin{aligned}\mathcal{B}^3_L &= \int_1^{z_L} dz\,[N_Z(z)(C_L(z;\lambda_b))^2\left(a_b^2 + 2\cos\theta_H a_{D+X} a_{D-X}\right)\\ &\quad +2\sin\theta_H D_Z(z) C_L(z;\lambda_b) S_L(z;\lambda_b) a_{D+X} a_{b'}],\\ \mathcal{B}^Q_L &= \int_1^{z_L} dz\, N_Z(z)[(C_L(z;\lambda_b))^2(a_b^2 + a_{D+X}^2 + a_{D-X}^2) + (S_L(z;\lambda_b))^2 a_{b'}^2].\end{aligned}$$

4次元ラグランジアン

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$$\mathcal{L}_{Zb\bar{b}} = \frac{g_A Z_\mu}{\cos\theta_W}\left(\mathcal{B}_L \bar{b}_L \gamma^\mu b_L + \mathcal{B}_R \bar{b}_R \gamma^\mu b_R\right)$$

$$\mathcal{B}_{L,R} = -\tfrac{1}{2}\mathcal{B}^3_{L,R} + \tfrac{1}{3}\mathcal{B}^Q_{L,R}\sin^2\theta_W$$

$$\mathcal{B}^3_L = \int_1^{z_L} dz\,[N_Z(z)(C_L(z;\lambda_b))^2 + 2\sin\theta_H D_Z(z) C_L(z;\lambda_b) S$$

$$\mathcal{B}^Q_L = \int_1^{z_L} dz\, N_Z(z)[(C_L(z;\lambda_b))^2$$

$$\mathcal{B}_L \xrightarrow{\text{SM}} -\frac{1}{2} + \frac{1}{3}\sin^2\theta_W$$

$$\mathcal{B}_R \xrightarrow{\text{SM}} \frac{1}{3}\sin^2\theta_W$$

Standard Modelからのずれ

$Z t_L \bar{t}_L$	$Z t_R \bar{t}_R$	$Z b_L \bar{b}_L$	$Z b_R \bar{b}_R$
7%	18%	0.3%	0.9%

$$\frac{\text{coupling in SO(5)}\times\text{U(1) model}}{\text{coupling in standard model}} - 1$$

そのほかも、1%以下

universality の破れ (W boson coupling)

μ-e	τ-e	t-e
10^{-8}	10^{-6}	2.3%

Currents and custodial symmetry

$$\frac{g}{\cos\theta_w} Z_\mu \; \bar{f}\gamma^\mu (I_f^3 - Q_f \sin^2\theta_w) f$$

Currents and custodial symmetry

$$\frac{g}{\cos\theta_w} Z_\mu \; \bar{f}\gamma^\mu (I^3_f - Q_f \sin^2\theta_w) f$$

non-universal? ↑ conserved ↑

after EWSB

Symmetry and conserved charges

- $SU(2)_L \times SU(2)_R \times P_{LR}$ ⇒ $SU(2)_V \times P_{LR}$
- subgroup $U(1)_L \times U(1)_R \times P_{LR}$ ⇒ $U(1)_V \times P_{LR}$

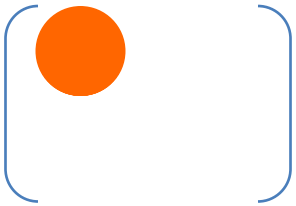
U(1)v $Q_V = Q_L + Q_R$ ⇒ Q_L → I^3_f

P_{LR}

L ⇔ R　入れ替え対称なら、
non-universal なずれは小さいはず

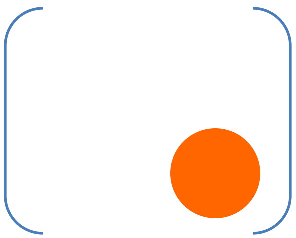
Agashe, Contino, Da Rold, Pomarol 06

$$\left(\text{Isopin}_L, T_L^3; \text{ Isospin}_R, T_R^3\right)$$

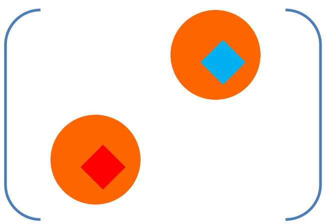


o $\left(\frac{1}{2}, +; \frac{1}{2}, +\right)$

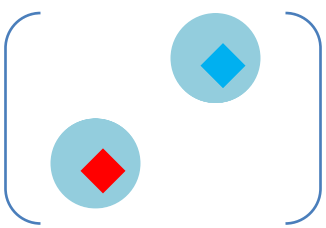
$(0; 0)$



o $\left(\frac{1}{2}, -; \frac{1}{2}, -\right)$



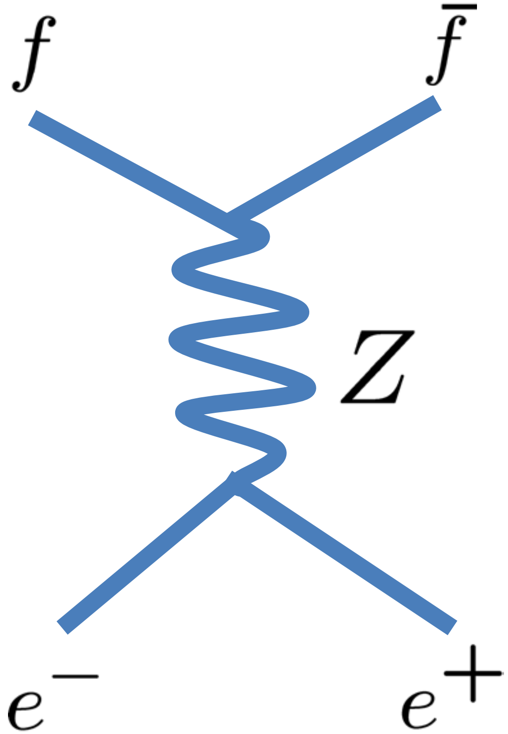
o $\left(\frac{1}{2}, -; \frac{1}{2}, +\right) + \left(\frac{1}{2}, +; \frac{1}{2}, -\right)$



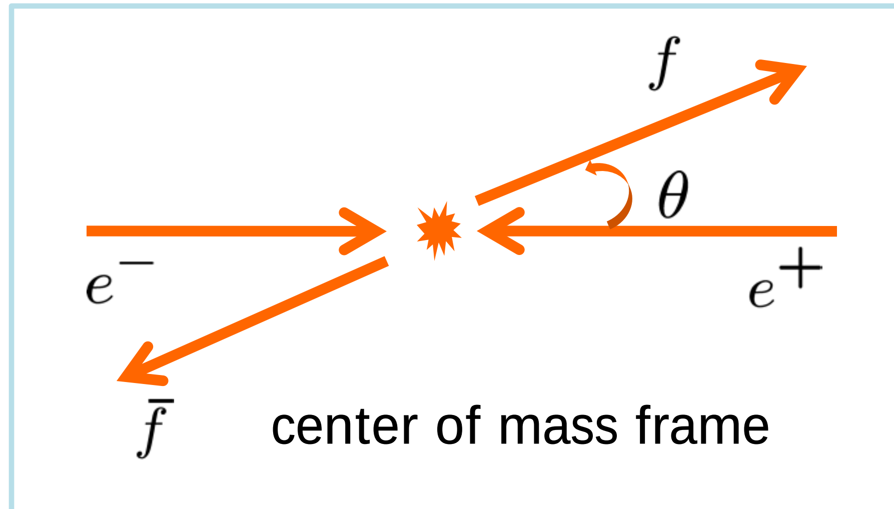
o $\left(\frac{1}{2}, -; \frac{1}{2}, +\right) - \left(\frac{1}{2}, +; \frac{1}{2}, -\right) \quad \propto \cos\theta_H$

$\theta_H = \frac{\pi}{2}$

L ⟷ R 非対称 部分がゼロ



散乱過程で引き出す物理量

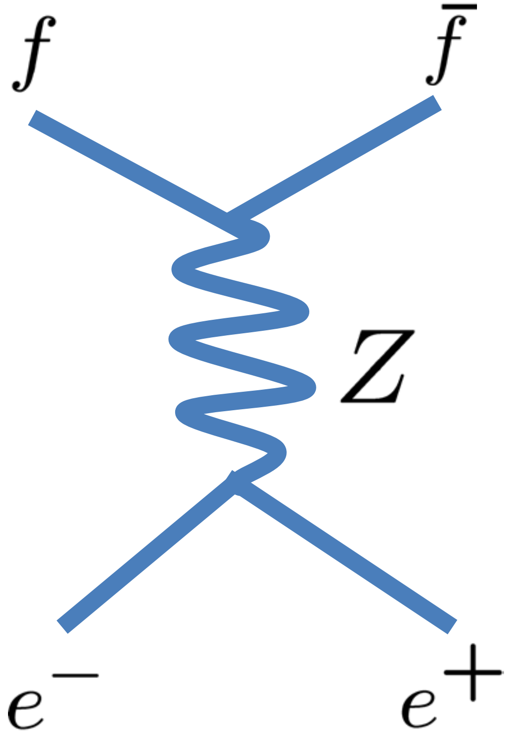


$$\frac{d\sigma}{d\Omega}(e^-_R e^+_L \to f_R \bar{f}_L) = \frac{\alpha^2}{4E_{cm}^2}(1+\cos\theta)^2 (g^e_R)^2 (g^f_R)^2$$

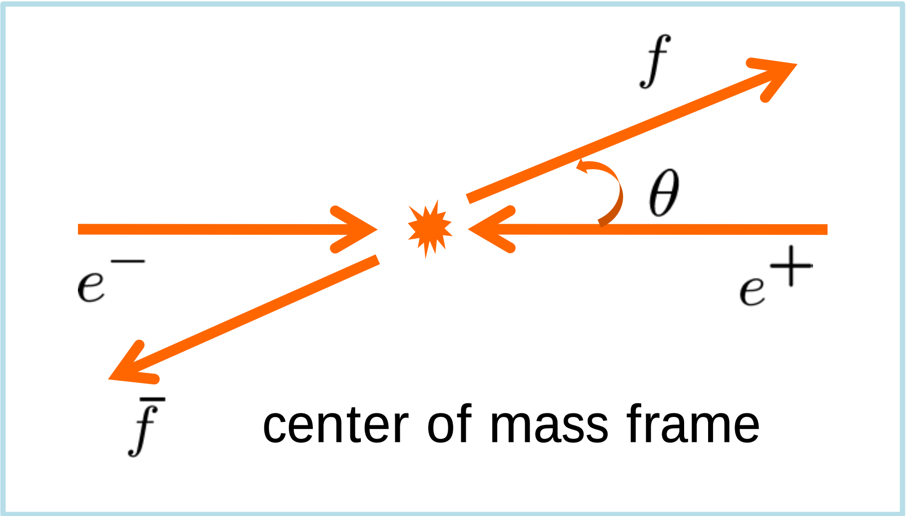
$$\frac{d\sigma}{d\Omega}(e^-_R e^+_L \to f_L \bar{f}_R) = \text{''}\,(1-\cos\theta)^2 (g^e_R)^2 (g^f_L)^2$$

$$\frac{d\sigma}{d\Omega}(e^-_L e^+_R \to f_R \bar{f}_L) = \text{''}\,(1-\cos\theta)^2 (g^e_L)^2 (g^f_R)^2$$

$$\frac{d\sigma}{d\Omega}(e^-_L e^+_R \to f_L \bar{f}_R) = \text{''}\,(1+\cos\theta)^2 (g^e_L)^2 (g^f_L)^2$$



散乱過程で引き出す物理量



Forward-backward asymm

$$A_{FB}^{f} = \frac{\left(\int_0^1 - \int_{-1}^0\right) d\cos\theta \, \frac{d\sigma(e^-e^+ \to f\bar{f})}{d\cos\theta}}{\left(\int_0^1 + \int_{-1}^0\right) d\cos\theta \, \frac{d\sigma(e^-e^+ \to f\bar{f})}{d\cos\theta}} = \frac{3}{4} A_{LR}^{e} A_{LR}^{f}$$

Polarization asymmetry of decay Z → $f\bar{f}$

$$A_{LR}^{f} = \frac{(g_L^f)^2 - (g_R^f)^2}{(g_L^f)^2 + (g_R^f)^2}$$

16コパラメータがある。

- バルク質量パラメータ　c

  計6コ　クォーク3、レプトン3

- 相対的なブレイン結合パラメータ

  $|\tilde{\mu}/\mu_2|, \ |\mu_3^\ell/\tilde{\mu}^\ell|$

  計6コ　クォーク3、レプトン3

- ゲージ結合定数

  計2コ　SO(5)とU(1)

- 時空の曲率 k, 余剰次元長さ L

16コパラメータがある。

- バルク質量パラメータ　c
  - クォーク3、レプ
- イン結合パラ
  - クォーク3、レプ
- ゲージ結合定数
  - 計2コ　SO(5)とU(1)
- 時空の曲率　k,　余剰次

クォークの
質量
6コ

レプトンの
質量
6コ

$\sin\theta_W, m_Z$

$k,$

ワープ因子
$z_L = e^{kL}$

Xing-Zhang-Zhou ’07, Fusaoka-Koide ’97, Particle Data Group ’08 (in unit of MeV)

	m_u	m_d	m_s	m_c	m_b	m_t	m_e	m_μ	m_τ
XZZ	1.27	2.90	55	619	2890	171700	0.486570161	102.7181359	1746.24
FK	2.33	4.69	93.4	677	3000	181000	0.48684727	102.75138	1746.69
PDG	2.4	4.75	104	1270	4200	171200	0.510998910	105.658367	1776.84

$$\sin^2\theta_W = 0.2312 \ (\overline{\mathrm{MS}} \text{ in PDG})$$

$$m_Z = 91.1876\mathrm{GeV}$$

$$z_L = (10^{18}\mathrm{GeV})/(1\mathrm{TeV}) = 10^{15}$$

$$k = 4.7 \times 10^{17}\mathrm{GeV}$$

such that the value of m_W is appropriately reproduced

$$A^b_{FB}$$

実験データ	**0.0992** ± 0.0016
Standard Model (PDG review)	0.1033 ± 0.0007
Standard Model	0.10496 (tree)
XZZ, FK	**0.09952**
PDG	**0.09941**

中心値に近い!

$$A^c_{FB}$$

実験データ	**0.0707** ± 0.0035
Standard Model (PDG review)	0.0738 ± 0.0006
Standard Model	0.07500 (tree)

XZZ, FK	**0.07073**	**中心値に近い!**
PDG	**0.07065**	

$z_L = 10^{15}$ → (100倍) $z_L = 10^{17}$

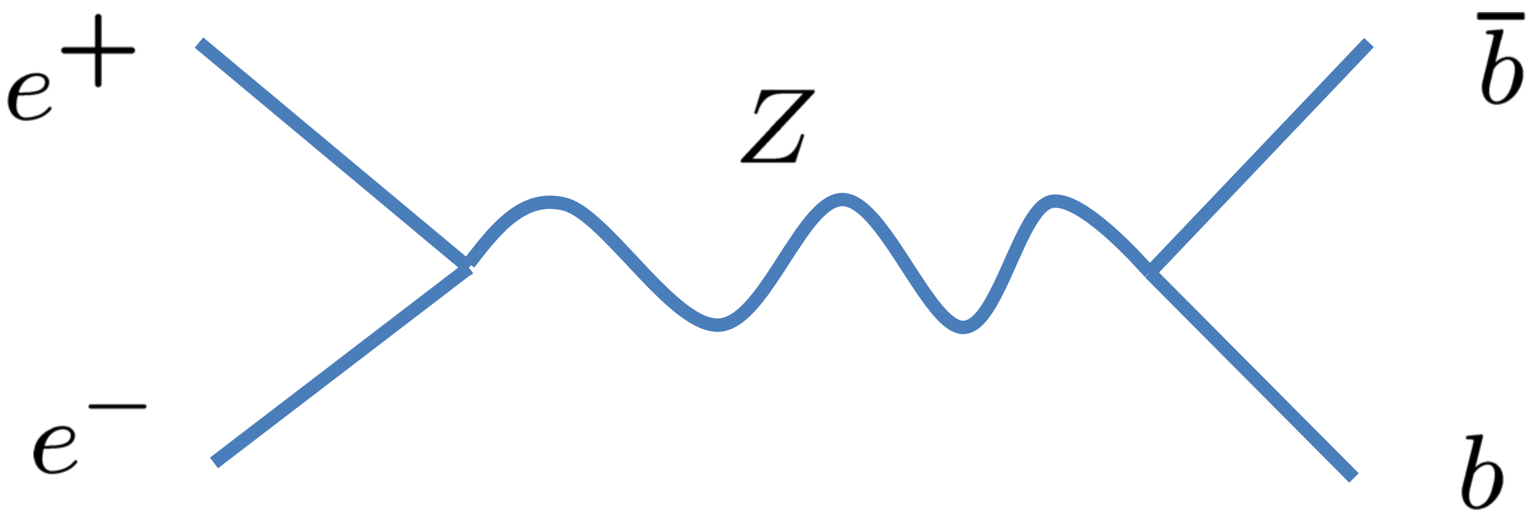
$k = 4.7 \times 10^{17}$ GeV → $k = 5.0 \times 10^{19}$ GeV

	A^b_{FB}	
0.09952		0.10019

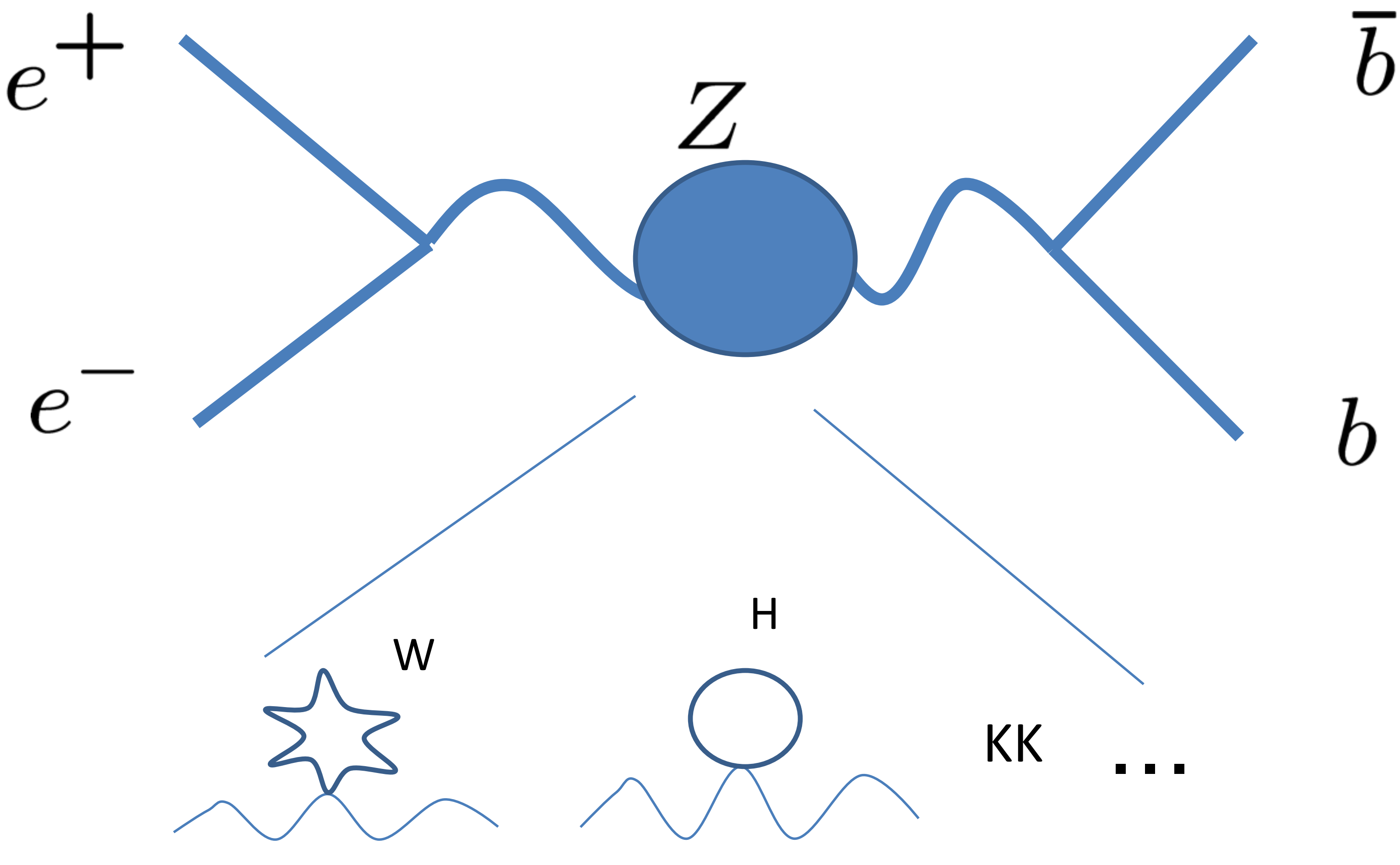
	A^c_{FB}	
0.07073		0.07125

パラメータを100倍しても、Standard Modelより中心値に近い

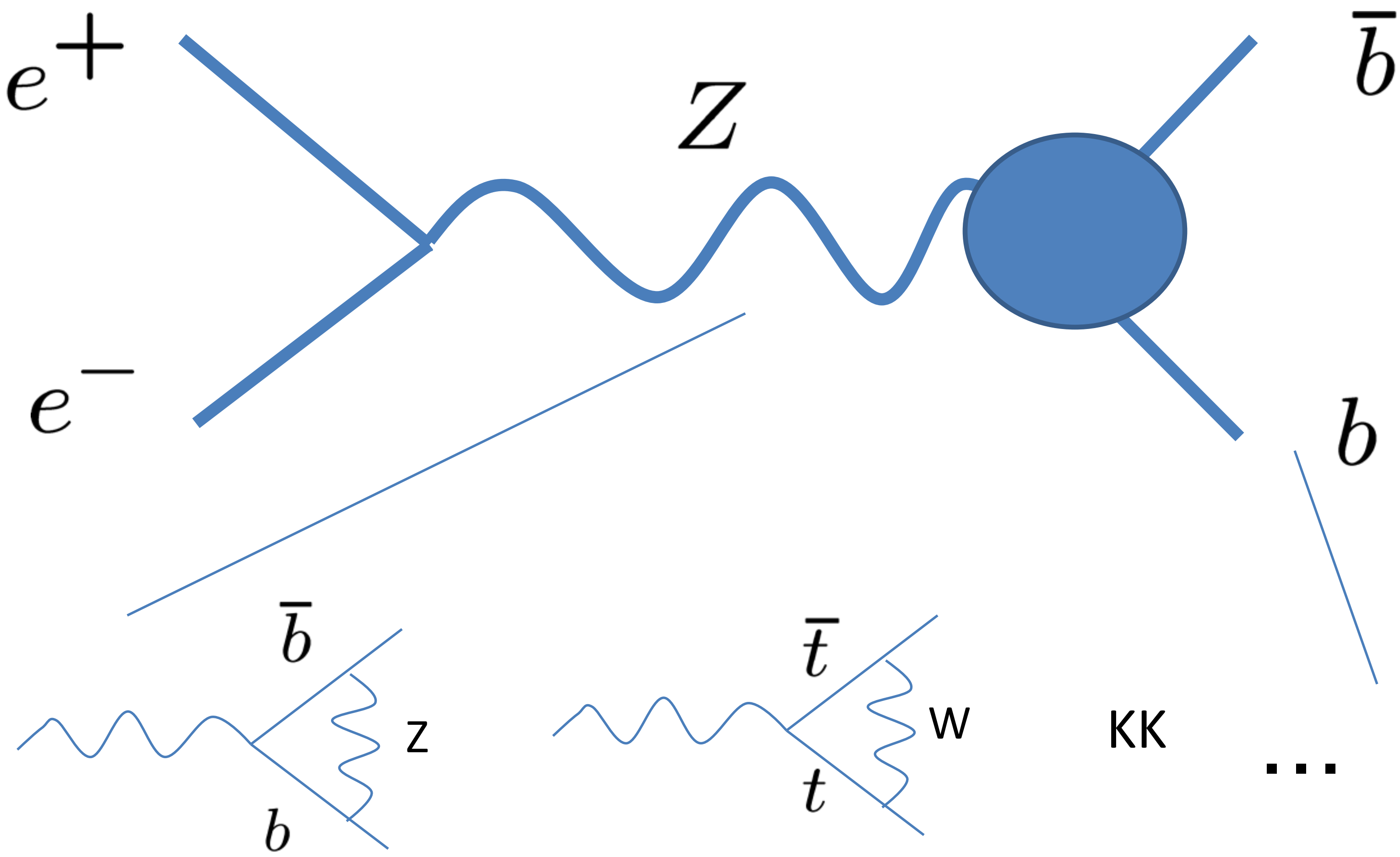
Radiative corrections



Radiative corrections



Radiative corrections



SUMMARY

	実験データ 中心値	SO(5)xU(1) tree-level 予言
A^b_{FB}	0.0992	0.09952
A^c_{FB}	0.0707	0.07073

- top はStandard Modelから最もずれる

$Zt_L\bar{t}_L$	$Zt_R\bar{t}_R$	そのほか、	μ-e	τ-e	t-e
7%	18%	1%以下	10^{-8}	10^{-6}	2.3%