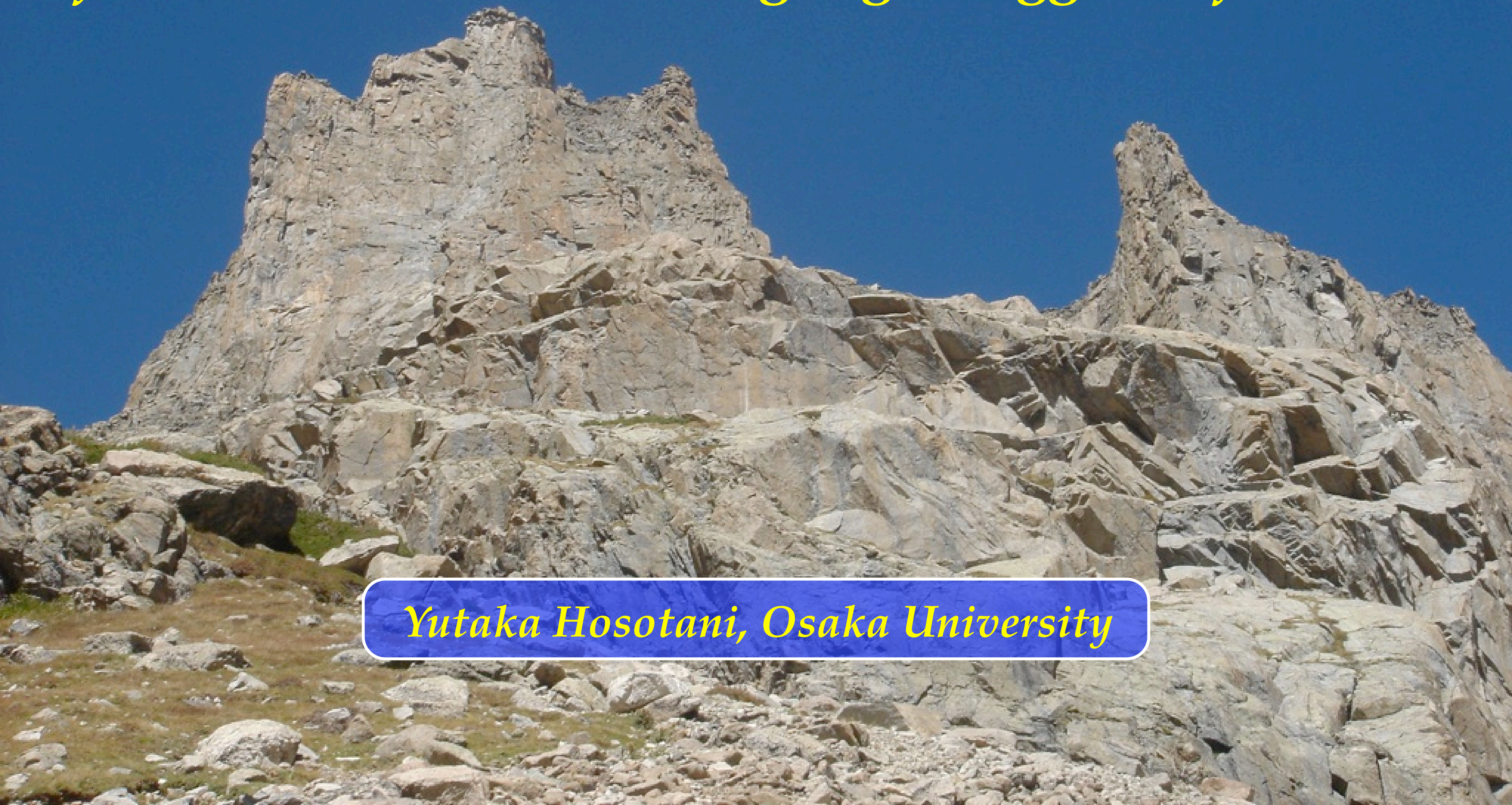
Predictions for LHC physics from extra-dimensional gauge-Higgs unification



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Higgs particles

To be discovered at LHC.

symmetry breaking $SU(2)_L \times U(1)_Y \to U(1)_{EM}$

$m_H^2 \sim 2\lambda v^2$

Yukawa couplings $g_j \, \phi_H \, \overline{\psi}_j \psi_j$

⇨ *fermion masses* $m_j \sim g_j \, v$

many "g_j" , λ

No principle

Mass hierarchy

Ugly.

Gauge-Higgs unification

Fairlie 1979, Manton 1979
Hosotani 1983, 1989

In higher-dimensional gauge theory

$$A_M = (A_\mu , A_{y_j})$$

extra-dimensional components

A_{y_j} *serve as 4-d Higgs fields.*

Higgs fields are unified with gauge fields.

on $M^4 \times S^1$ $\quad A_y(x,y) = \sum_{n=-\infty}^{\infty} A_y^{(n)}(x)\, e^{iny/R}$

$A_y^{(0)}(x)$ *Higgs fields in the adjoint rep.*

Dynamical gauge-Higgs unification

1. $SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$

   Higgs doublet $\subset$ gauge fields

   → larger group

   $SU(3), SO(5), G_2, \cdots$

   Fairlie 1979, Manton 1979

2. *Chiral fermions* → orbifolds

   Pomarol, Quiros 1998

3. *Wilson line phases* → *dynamical gauge sym. breaking*

   finite Higgs mass

   Hosotani mechanism, 1983, 1989

4. *Warped space* for *realistic Higgs & fermions*

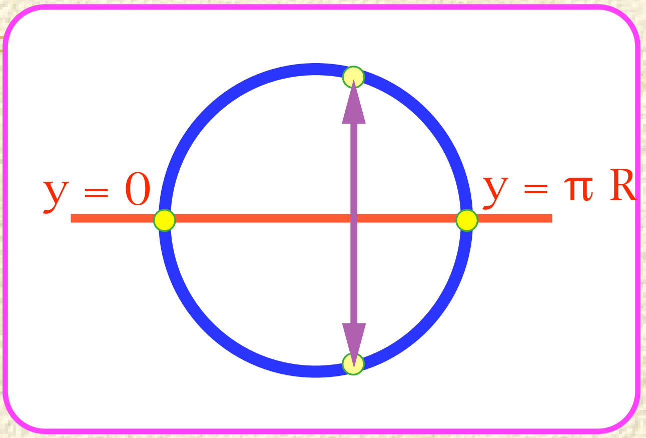
   YH, Mabe, Sakamura, Noda, Shimasaki (2005)

Orbifolds ··· extra dimensional space

Pomarol, Quiros 1998

$M^4 \times S^1$ ⇨ $M^4 \times (S^1/Z_2)$

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



Restriction - boundary conditions

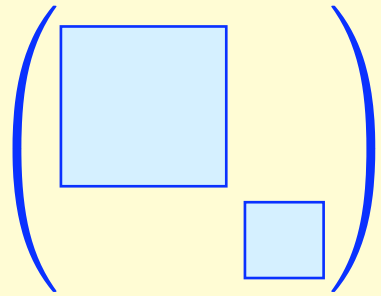
$$\begin{pmatrix} A_\mu \\ A_y \end{pmatrix}(x, -y) = P_0 \begin{pmatrix} A_\mu \\ -A_y \end{pmatrix}(x, y) P_0^\dagger \qquad P_0 = \begin{pmatrix} -1 & & \\ & -1 & \\ & & +1 \end{pmatrix}$$

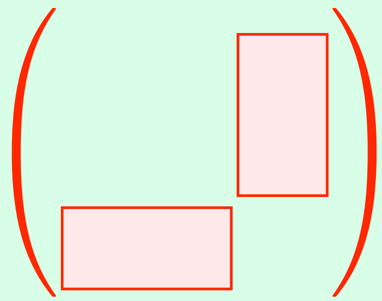
⇨

Low energy gauge symmetry

Chiral fermions

Low energy theory

$A_\mu =$  $\Rightarrow \frac{1}{\sqrt{\pi R}} \left\{ W_\mu(x), Z_\mu(x), A_\mu^{EM}(x) \right\}$

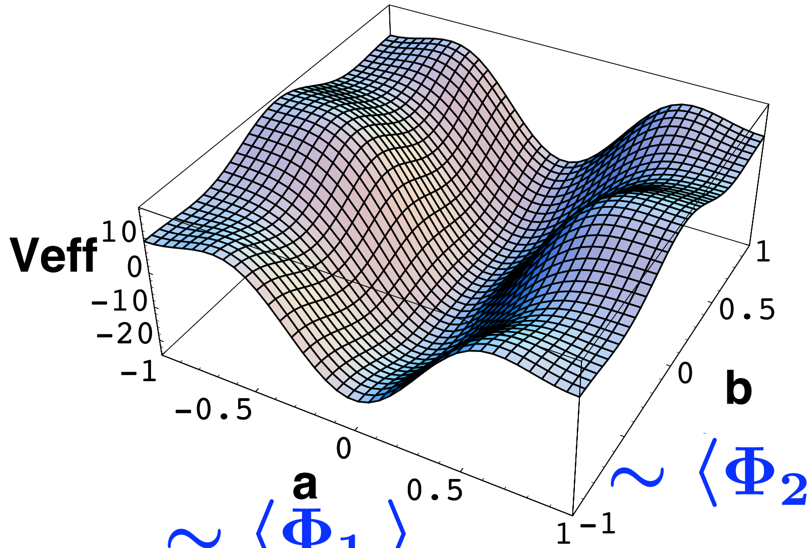
$A_y =$  $\Rightarrow \frac{1}{\sqrt{\pi R}} \Phi(x)$ *(Higgs)*

Chiral quarks and leptons $\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} \begin{pmatrix} u_L \\ d_L \end{pmatrix} \begin{matrix} e_R \\ u_R \ , d_R \end{matrix}$

Example in flat space $U(3)_S \times U(3)_W$ *model*

Antoniadis, Benakli, Quiros, NJP (2001)
Hosotani, Noda, Takenaga, PLB (2005)

$N_{Ad} = 1 \ , \ N_F = 3$



$\sim \langle \Phi_1 \rangle$ $\sim \langle \Phi_2 \rangle$

Dynamical gauge-Higgs unification is achieved.

W

$$m_W = 0.135 \times \frac{1}{R}$$

too small $M_{KK} = \dfrac{1}{R} \sim 10 \, m_W$

Higgs

$$m_H = 0.871 \times \sqrt{\frac{g_4^2}{4\pi}} \, m_W$$

too small $m_H \sim \sqrt{\dfrac{g_4^2}{4\pi}} \, m_W$

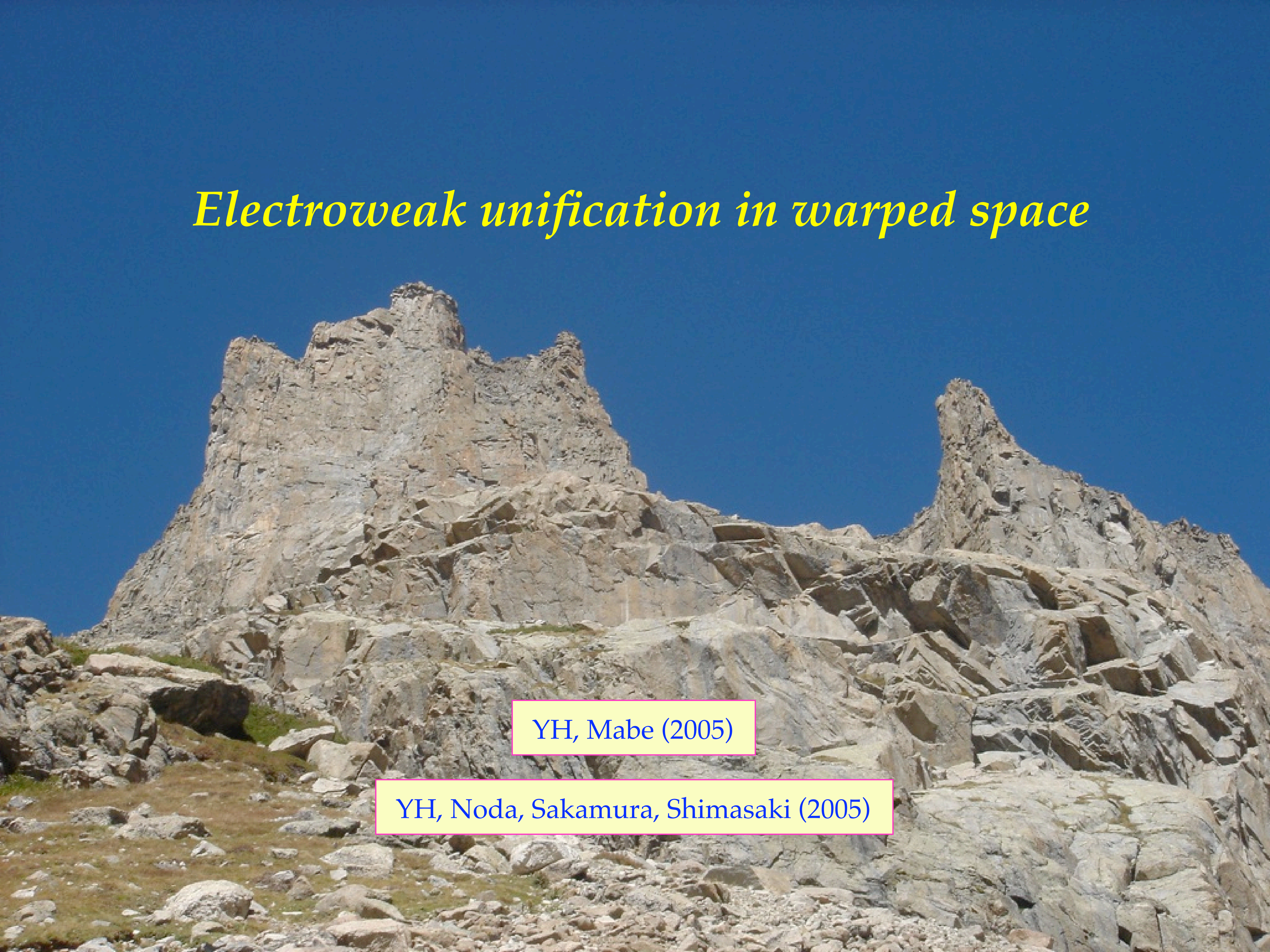
4 ***Warped space*** **for** *realistic Higgs & fermions*

YH, Mabe, Sakamura, Noda, Shimasaki (2005)

The situation drastically changes for the better,

if the extra-dimensional space is curved and warped.

Electroweak unification in warped space

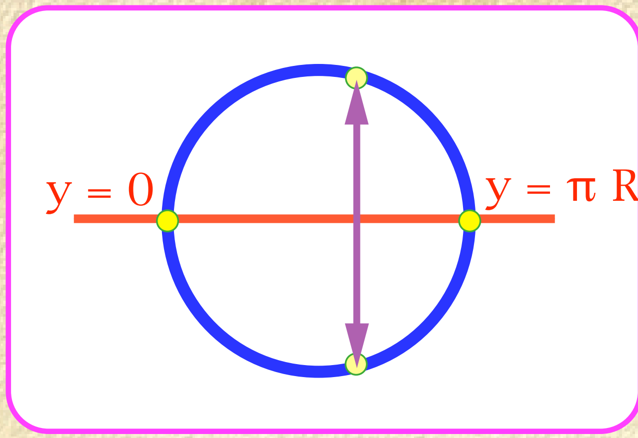


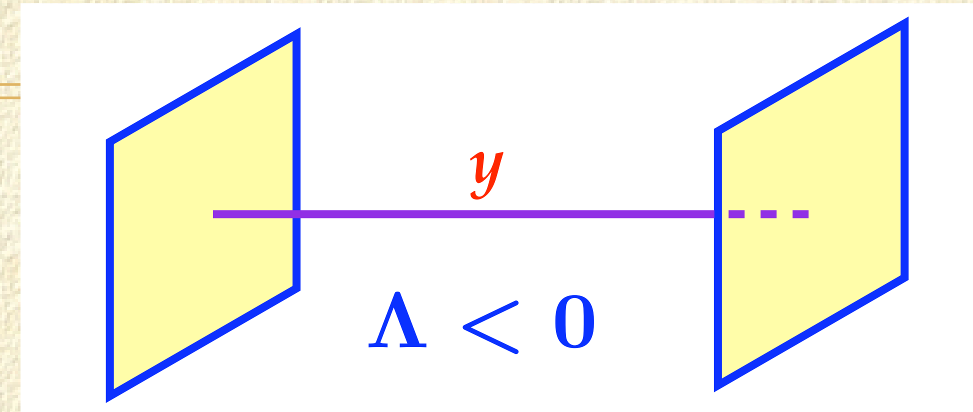
YH, Mabe (2005)

YH, Noda, Sakamura, Shimasaki (2005)

$M^4 \times (S^1/Z_2)$

Randall-Sundrum





$$ds^2 = dx_\mu dx^\mu + dy^2 \quad \Rightarrow \quad ds^2 = e^{-2k|y|} dx_\mu dx^\mu + dy^2$$

$$M_{KK} \sim \frac{1}{R} \quad \Rightarrow \quad ?$$

$$M_{KK} \sim 10\, m_W \quad \Rightarrow \quad ?$$

too small !

$$m_H \sim \sqrt{\alpha_w}\, m_W \quad \Rightarrow \quad ?$$

too small !

KK mass scale

$$m_n \sim M_{KK}\, n \quad \text{for } m_n \gg k$$

$$M_{KK} \sim \frac{\pi k}{e^{\pi k R} - 1} = \begin{cases} 1/R & \text{as } k \to 0 \\ \pi k\, e^{-\pi k R} & \text{for } kR > 2 \end{cases}$$

Wilson line phase

$(F_{MN} = 0\ ,$ but nontrivial$)$

$$A_w = \begin{pmatrix} & a \\ a & \end{pmatrix} : \quad 2g \int_{w_0}^{w_1} dw\, A_w \ \Rightarrow \ \theta_W = 2ga(w_1 - w_0)$$

$$(\ w = e^{2ky} = z^2\ ,\ w_0 = 1\ ,\ w_1 = e^{2\pi kR} \ )$$

W-boson mass

$$\int d^4x dw\, (-2k)\, \mathrm{Tr}\, F_{\mu w} F^{\mu}{}_w \ \Rightarrow \ m_W = \sqrt{\frac{2k}{\pi R}}\, e^{-\pi kR} \ \sin\frac{\theta_W}{2}$$

m_W , $\theta_W = (0.2 \sim 0.4)\pi$ $\quad k \sim M_{Pl}$ $\quad \Rightarrow \quad kR \sim 12$

Higgs field

$$\theta_W \leftrightarrow 2gA_w(w_1 - w_0) \Rightarrow g_4\sqrt{\frac{\pi R(w_1 - w_0)}{2k}}\,(v + \phi)$$

$\cdots$ *fluctuations in* θ_W

$$V_{\text{eff}}(\theta_W) = \text{const} + \frac{1}{2}m_H^2\phi^2 + \frac{1}{3}\eta\phi^3 + \frac{1}{4}\lambda\phi^4 + \cdots$$

	flat R	*Randall-Sundrum* $R\ ,\ kR$
M_{KK}	$2\,\dfrac{\pi}{\theta_W}\,m_W$	$\dfrac{\pi}{\sin(\theta_W/2)}\sqrt{\dfrac{\pi kR}{2}}\,m_W$
m_H	$\sqrt{\dfrac{3}{32\pi}f^{(2)}(\theta_W)\sqrt{\alpha_W}}\;\dfrac{m_W}{\frac{1}{2}\theta_W}$	$\sqrt{\dfrac{3}{32\pi}f^{(2)}(\theta_W)\sqrt{\alpha_W}}\;\dfrac{\pi kR}{2}\;\dfrac{m_W}{\sin\frac{1}{2}\theta_W}$
λ	$\dfrac{\alpha_W^2}{16}\,f^{(4)}(\bar{\theta}_W)$	$\dfrac{\alpha_W^2}{16}\,f^{(4)}(\bar{\theta}_W)\,\left(\dfrac{\pi kR}{2}\right)^2$

	flat R	Randall-Sundrum $R\ ,\ kR = 12$
M_{KK}	$2\,\dfrac{\pi}{\theta_W}\,m_W$ $400 \sim 800$ GeV	$\dfrac{\pi}{\sin(\theta_W/2)}\,\sqrt{\dfrac{\pi k R}{2}}\,m_W$ $1.8 \ \sim\ 3.5$ TeV
m_H	$\sqrt{\dfrac{3}{32\pi} f^{(2)}(\theta_W)\sqrt{\alpha_W}}\ \dfrac{m_W}{\frac{1}{2}\theta_W}$ 7.5 GeV ~ 15 GeV	$\sqrt{\dfrac{3}{32\pi} f^{(2)}(\theta_W)\sqrt{\alpha_W}}\ \dfrac{\pi k R}{2}\ \dfrac{m_W}{\sin\frac{1}{2}\theta_W}$ $150\ \sim\ 285$ GeV
λ	$\dfrac{\alpha_W^2}{16}\ f^{(4)}(\bar{\theta}_W)$ 0.0008	$\dfrac{\alpha_W^2}{16}\ f^{(4)}(\bar{\theta}_W)\ \left(\dfrac{\pi k R}{2}\right)^2$ 0.3

θ_W^{min} : $0.2\,\pi \sim 0.4\,\pi$

Quarks and leptons

$$\mathcal{L} = -\bar{\psi}\, i\, \Gamma^a e_a^{\ M} \Big\{ \partial_M + \frac{1}{8}\omega_{bcM}[\Gamma^b, \Gamma^c] - igA_M \Big\} \psi$$

$$- i\, c\, \sigma'\, \bar{\psi}\, \psi$$

bulk (kink) mass

Gherghetta-Pomarol (2000)

Zero (massless) modes exist only for `quarks/leptons'.

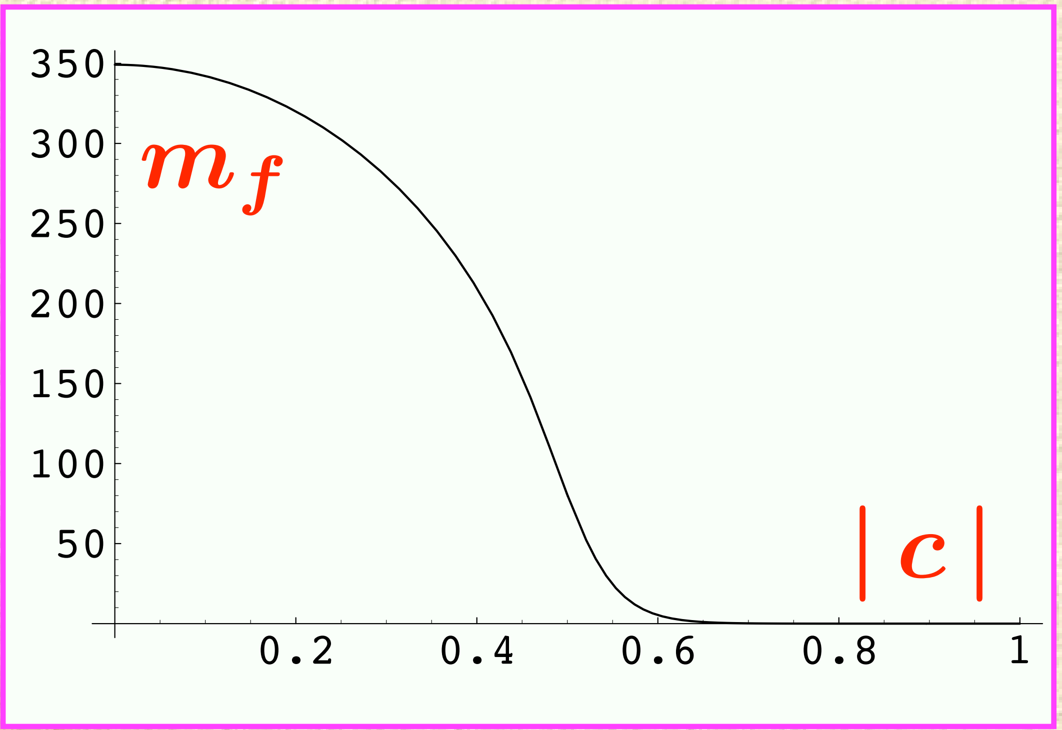
$$\begin{pmatrix} \nu_L \\ e_L \\ \tilde{e}_L \end{pmatrix} \begin{pmatrix} \tilde{\nu}_R \\ \tilde{e}_R \\ e_R \end{pmatrix} \quad \begin{pmatrix} b_R^c \\ t_R^c \\ \tilde{t}_R^c \end{pmatrix} \begin{pmatrix} \tilde{b}_L^c \\ \tilde{t}_L^c \\ t_L^c \end{pmatrix}$$

$$f_0^{(\pm)}(z) = \sqrt{\frac{1 \mp 2c}{e^{(1 \mp 2c)\pi kR} - 1}}\; z^{\mp c}$$

Fermion masses

Gauge interactions $g\,\overline{\psi}\,\Gamma^5 e_5{}^z \langle A_z \rangle\,\psi$

$$m_f = \sqrt{\frac{\pi k R}{2} \cdot \frac{(1-4c^2)(z_1^2-1)}{(z_1^{1-2c}-1)(z_1^{1+2c}-1)}}\; m_W$$



	$\lvert c \rvert$
m_e	0.87
m_μ	0.71
m_τ	0.63
m_u	0.81
m_c	0.64
m_t	0.43

Explains the hierarchy.

preliminary

Non-universality of weak interactions

Gauge interactions $g\,\overline{\psi}\,\Gamma^a e_a{}^\mu A_\mu\,\psi(x,z)$

$$g_4(\theta_W, c)\,\bar{e}_L(x)\,\gamma^\mu\,\nu_L(x)\,W_\mu(x)$$

$$\frac{g_4(\theta_W, c)}{g_4(\theta_W, c_e)}$$

θ_W	μ	τ	t
0	1	1	1
π	1.00000	0.999988	0.951

When SU(2)$_L$ is broken,
weak interactions are not universal in 4-d effective theory.

Summary

Dynamical gauge-Higgs unification is promising.

M_{KK}	$1.8 \sim 3.5$ TeV
m_H	$150 \sim 285$ GeV
λ	0.3

$$\frac{m_H^2}{2v^2} = (1.9 \sim 7.6)\,\lambda$$

Higgs predicted at the LHC energies !!

Natural fermion-mass hierarchy

mass	m_e	m_t
c	0.87	0.43

Non-universality

	e	τ	t
g_{weak}	1.00000	0.999988	0.951


We might be able to see the EXTRA dimensions !