New dimensions from gauge-Higgs unification

Yutaka Hosotani

Physics
OSAKA UNIVERSITY

Summer School and Workshop
on the Standard Model and Beyond

1 September 2016, Corfu, Greece

Explore new dimensions through gauge-Higgs unification

1. What is gauge-Higgs unification?

2. Gauge-Higgs EW unification

   success and predictions

3. Why grand unification?

4. Gauge-Higgs grand unification

   5d unification

5. Realistic gauge-Higgs grand unification

   6d unification

Physics
OSAKA UNIVERSITY

References

Review of gauge-Higgs unification

YH, 1606.08108

Gauge-Higgs EW unification

Funatsu, Hatanaka, YH, 1510.06550

Gauge-Higgs grand unification

YH, Yamatsu, 1504.03817
Furui, YH, Yamatsu, 1606.07222

Physics
OSAKA UNIVERSITY

1. What is gauge-Higgs unification ?

A_M

A_μ A_y

gauge principle

γ , W , Z

$Higgs$

Aharonov-Bohm phase

θ_H

Hosotani mechanism

dynamical
EW sym breaking

Finite Higgs mass generated.
Solves the gauge-hierarchy prob.

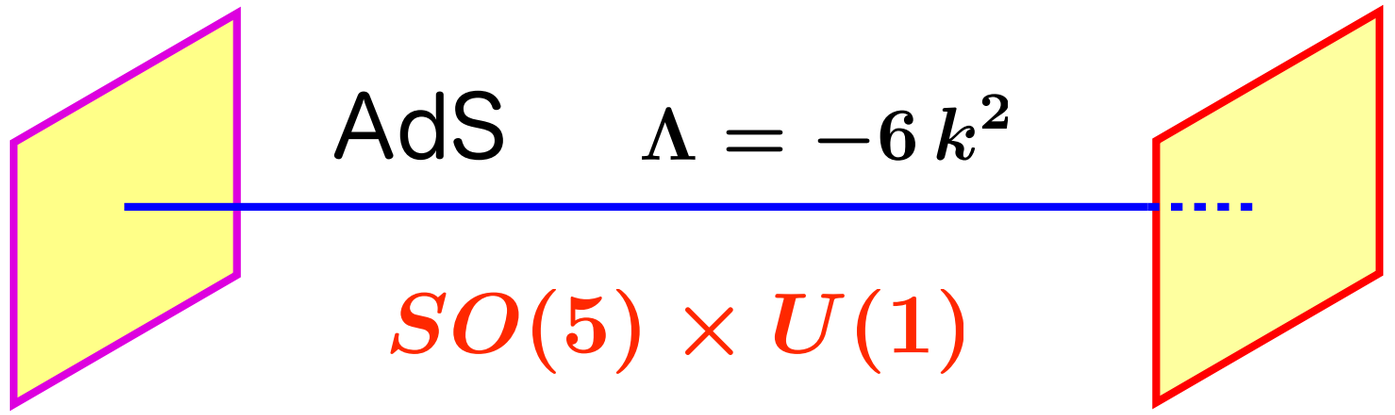
Physics
OSAKA UNIVERSITY

2. Gauge-Higgs EW unification

SO(5)xU(1) GHU in Randall-Sundrum

Agashe, Contino, Pomarol 2005
YH, Sakamura 2006
YH, Oda, Ohnuma, Sakamura 2008

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



$$\begin{pmatrix} A_\mu \\ A_y \end{pmatrix}(x, y_j - y) = P_j \begin{pmatrix} A_\mu \\ -A_y \end{pmatrix}(x, y_j + y) P_j^\dagger$$

$$(y_0, y_1) = (0, L)$$

Orbifold BC : P_0 , P_1

4D gauge bosons and Higgs

Orbifold BC : P_0 , P_1

$$P_0 = P_1 = \begin{pmatrix} -1 & & & & \\ & -1 & & & \\ & & -1 & & \\ & & & -1 & \\ & & & & +1 \end{pmatrix}$$

W Z γ

$$A_\mu \sim \begin{pmatrix} \square & \\ & \end{pmatrix}$$

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

Higgs

$$SU(2)_L \text{ doublet}$$

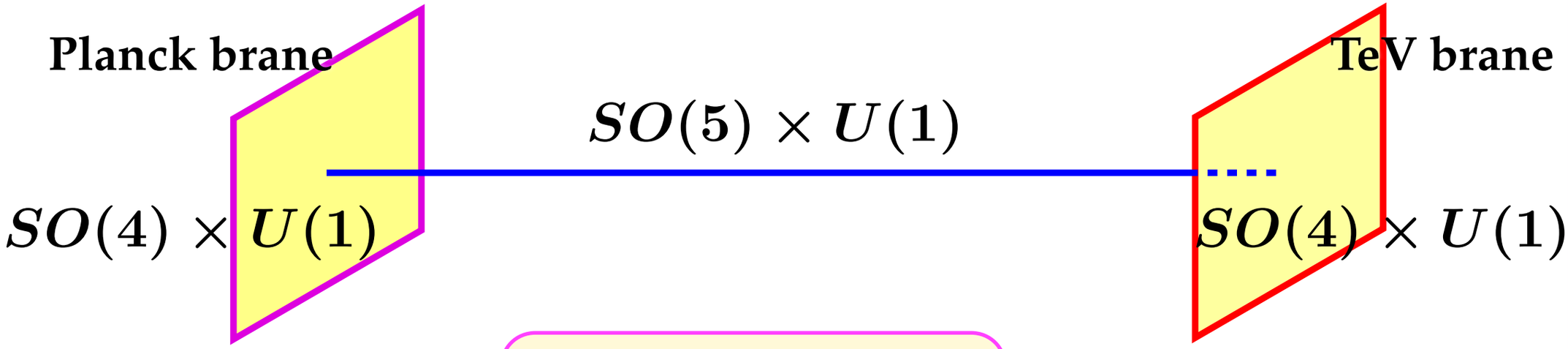
$$A_y \sim \begin{pmatrix} & \phi_1 \\ & \phi_2 \\ & \phi_3 \\ \square & \phi_4 \end{pmatrix}$$

AB phase

$$e^{i\hat{\theta}_H(x)} \sim P \exp\left\{ ig \int dy\, A_y \right\}$$

Physics
OSAKA UNIVERSITY

SO(5)xU(1) EW GH



Brane fermion

$(\frac{1}{2}, 0)$

Brane scalar

$\hat{\Phi}\ (0, \frac{1}{2})$

quarks/leptons

vector rep

dark fermions

spinor rep

$SU(2)_L \times U(1)_Y \xrightarrow{\theta_H} U(1)_{EM}$

Success

Gauge principle for Higgs boson

m_H : generated at 1 loop, and finite

Gauge-hierarchy prob. solved.

"**Almost**" **SM** at low energies for $\theta_H < 0.1$

No vacuum instability

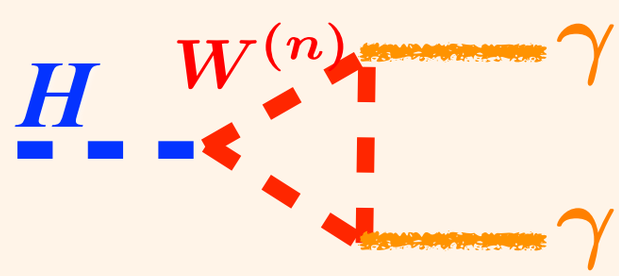
$$V_{\rm eff}(\theta_H + 2\pi) = V_{\rm eff}(\theta_H)$$

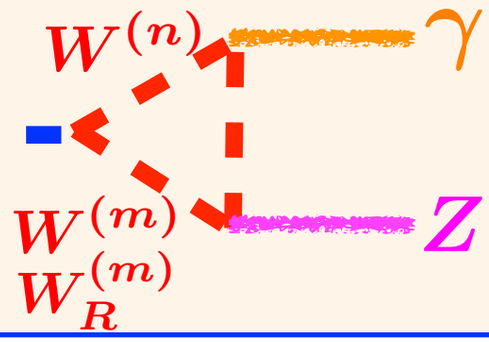
Dynamical EW sym. breaking

Physics
OSAKA UNIVERSITY

Predictions

Higgs decay : $\mu \sim \mu_{\rm SM} \cdot \cos^2\theta_H$

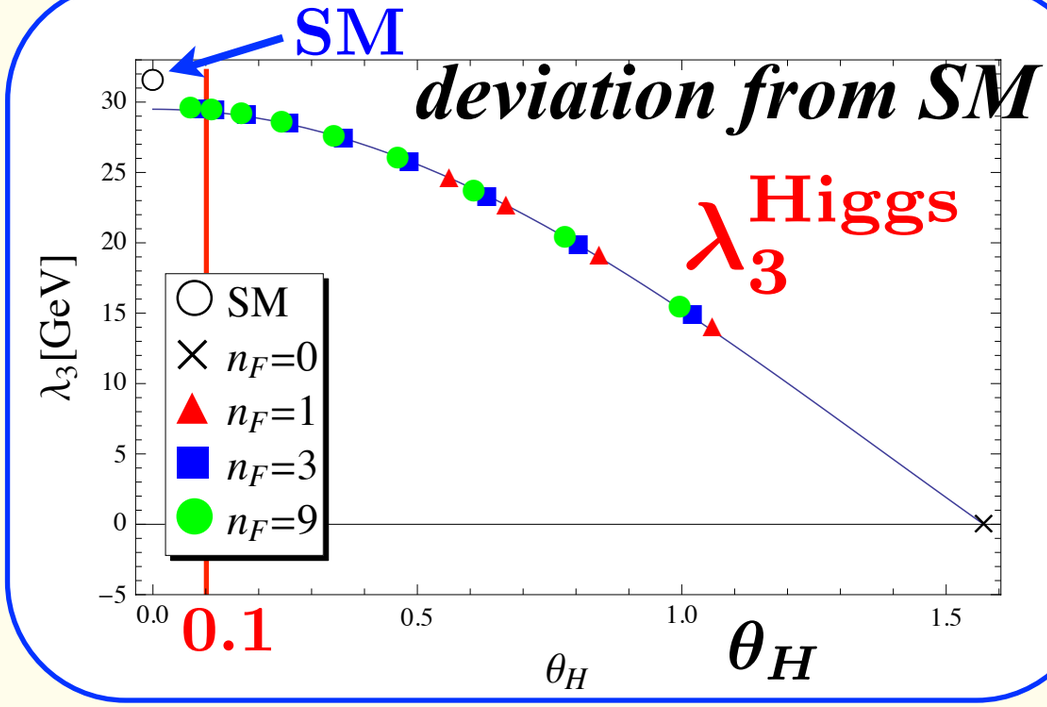
$\sum_n$ 

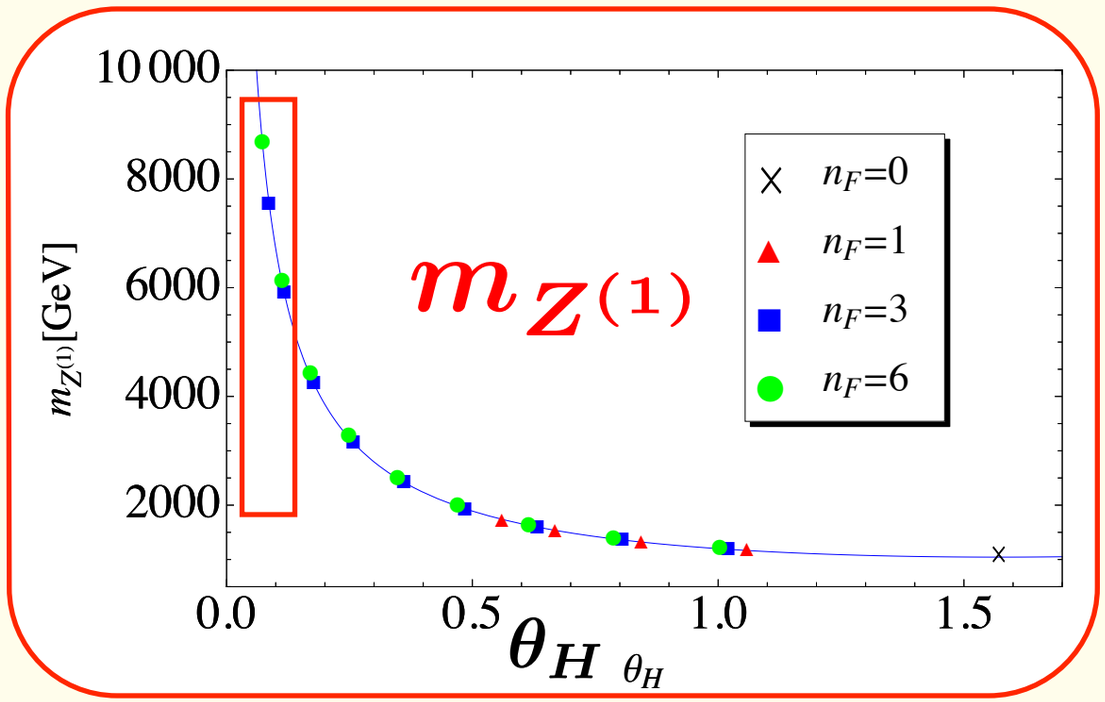
$\sum_{n,m}$ 

: finite

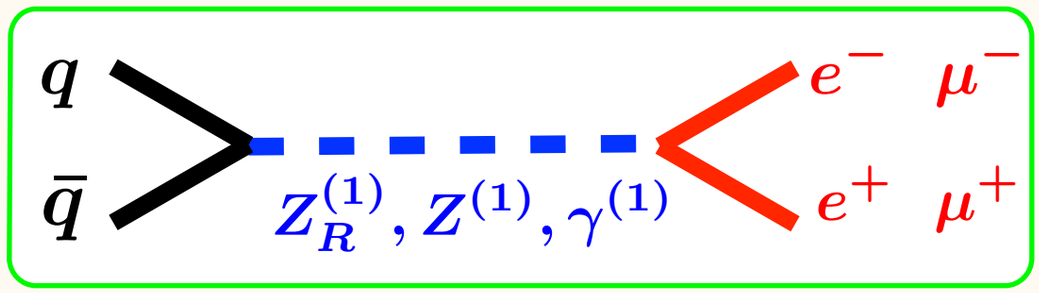
Funatsu, Hatanaka, YH, Orikasa, Shimotani 1301.1744 Funatsu, Hatanaka, YH, 1510.06550

Universality $m_{KK}(\theta_H),\ m_{Z^{(1)}}(\theta_H),\ \lambda_3^H(\theta_H),\ \lambda_4^H(\theta_H)$

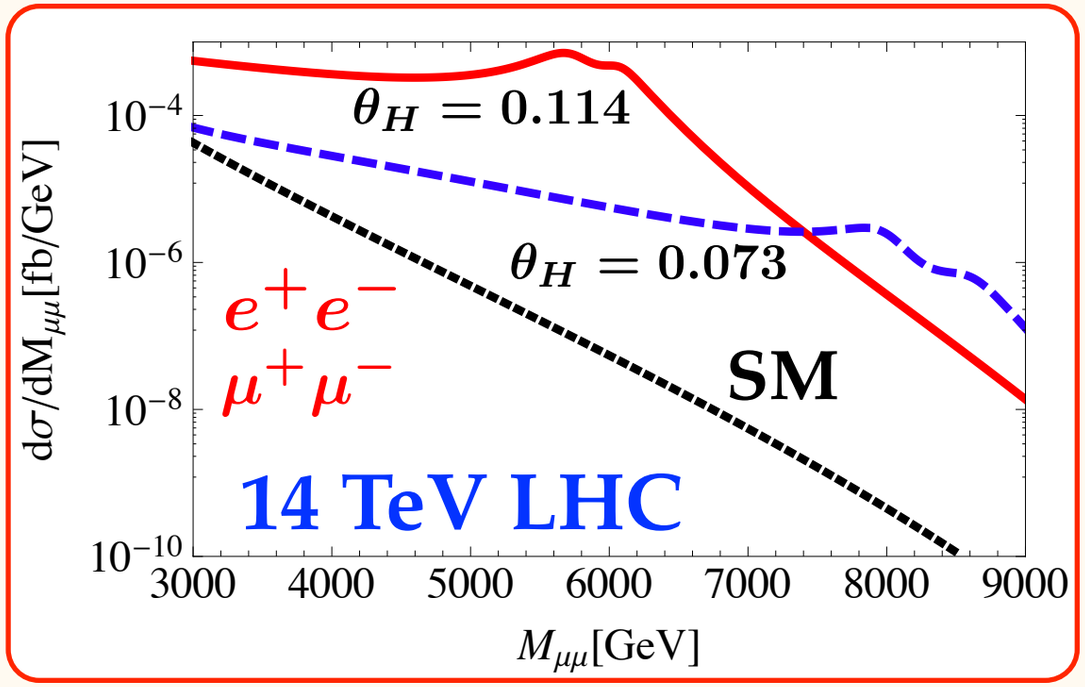




Z'



FHHOS 1404.2748



	$\theta_H = 0.114$		$\theta_H = 0.073$	
Z'	m (TeV)	Γ (GeV)	m (TeV)	Γ (GeV)
$Z_R^{(1)}$	5.73	482	8.00	553
$Z^{(1)}$	6.07	342	8.61	494
$\gamma^{(1)}$	6.08	886	8.61	1040

3. Why grand unification ?

Electroweak + Strong

charge quantization

requirements

Unification of forces

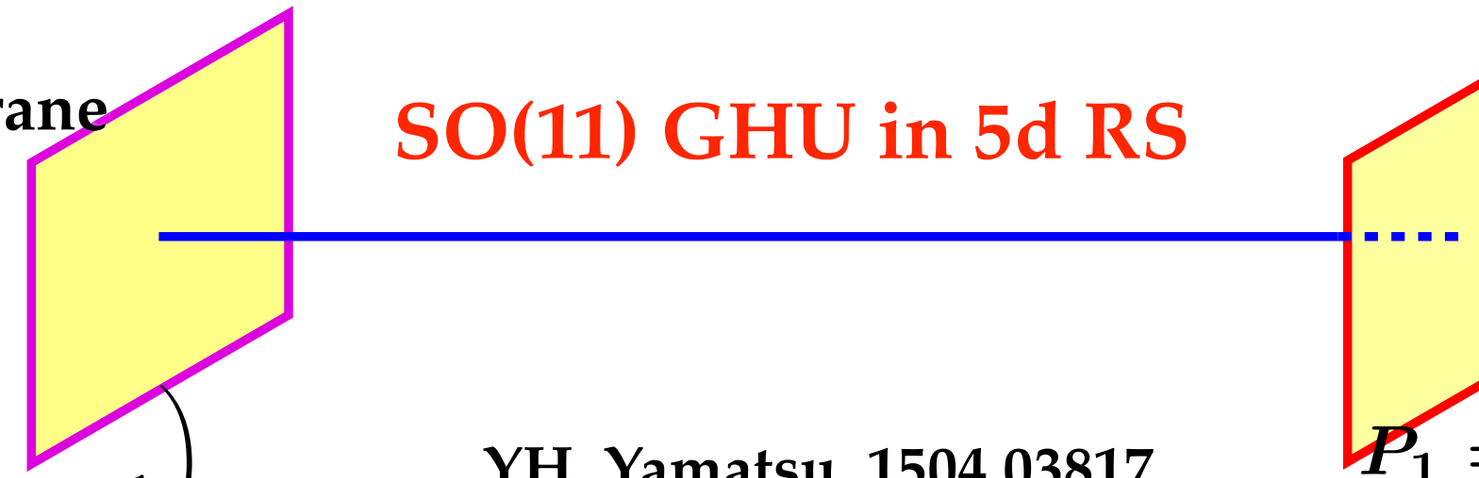
Reproduce quark-lepton spectrum

No exotic particles

Burdman, Nomura 2003 Haba, YH, Kawamura, Yamashita 2004
Lim, Maru 2007 Kojima, Takenaga, Yamashita 2011
Frigerio, Serra, Varagnolo 2011

Physics
OSAKA UNIVERSITY

4. Gauge-Higgs grand unification in 5d



$$P_0 = \begin{pmatrix} I_{10} & \\ & -1 \end{pmatrix}$$

YH, Yamatsu, 1504.03817
Furui, YH, Yamatsu, 1606.07222

$$P_1 = \begin{pmatrix} I_4 & \\ & -I_7 \end{pmatrix}$$

$$A_\mu : \begin{array}{c|c|c} (+,+) & (+,-) & (-,-) \\ \hline & (+,+) & (-,+) \\ \hline & & \end{array} \quad \begin{matrix} SO(4) \\ \\ \\ SO(6) \end{matrix}$$

Higgs doublet

$$A_y : \begin{array}{c|c|c} (-,-) & (-,+) & (+,+) \\ \hline & (-,-) & (+,-) \\ \hline & & \end{array}$$

Physics
OSAKA UNIVERSITY

EW unification

$$SO(5) \times U(1)_X \times SU(3)_C$$

$$\downarrow P_0 = P_1$$

$$SO(4) \times U(1)_X \times SU(3)_C$$

$$\downarrow \Phi_{(1,2)}$$

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

$$\downarrow \theta_H$$

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

5d grand unification

$$SO(11)$$

$$\downarrow P_0 \neq P_1$$

$$SO(4) \times SO(6)$$

$$\downarrow \Phi_{16}$$

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

$$\downarrow \theta_H$$

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

BC

brane scalar

Hosotani mech.

Physics
OSAKA UNIVERSITY

Quarks & Leptons

$$\Psi_{32} \quad \Psi_{11} \quad \Psi'_{11}$$

$$\Psi_{32} = \begin{pmatrix} \Psi_{16} \\ \Psi_{\overline{16}} \end{pmatrix}$$

$$\Psi_{16} = \begin{pmatrix} \nu \\ e \\ \hat{e} \\ \hat{\nu} \\ u_j \\ d_j \\ \hat{d}_j \\ \hat{u}_j \end{pmatrix} \begin{matrix} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \\ \textit{zero modes} \\ \begin{pmatrix} u_{jL} \\ d_{jL} \end{pmatrix} \end{matrix}$$

$$\Psi_{\overline{16}} = \begin{pmatrix} \nu' \\ e' \\ \hat{e}' \\ \hat{\nu}' \\ u'_j \\ d'_j \\ \hat{d}'_j \\ \hat{u}'_j \end{pmatrix} \begin{matrix} \begin{pmatrix} \nu_R \\ e_R \end{pmatrix} \\ \textit{zero modes} \\ \begin{pmatrix} u_{jR} \\ d_{jR} \end{pmatrix} \end{matrix}$$

$$\Psi_{11} = \begin{pmatrix} \hat{E} & N \\ \hat{N} & E \\ D_j & \hat{D}_j \\ S \end{pmatrix} D_{jR}\, \hat{D}_{jR} \qquad \Psi'_{11} = \begin{pmatrix} \hat{E}' & N' \\ \hat{N}' & E' \\ D'_j & \hat{D}'_j \\ S' \end{pmatrix} D'_{jL}\, \hat{D}'_{jL}$$

Quark/lepton spectrum

SO(10) inv. brane interactions

↓

Mass splitting

However, light exotic fermions $\hat{u}, \hat{d}, \hat{e}$ appear.

↑

$P_0 \neq P_1$ in RS.

$$p \not\to \pi^0 \, e^+$$

$N_\Psi = 3 \quad N_\Psi = -1$

no proton decay

Physics
OSAKA UNIVERSITY

5. Realistic gauge-Higgs grand unification

SO(11) GHU in 6d hybrid-warped space

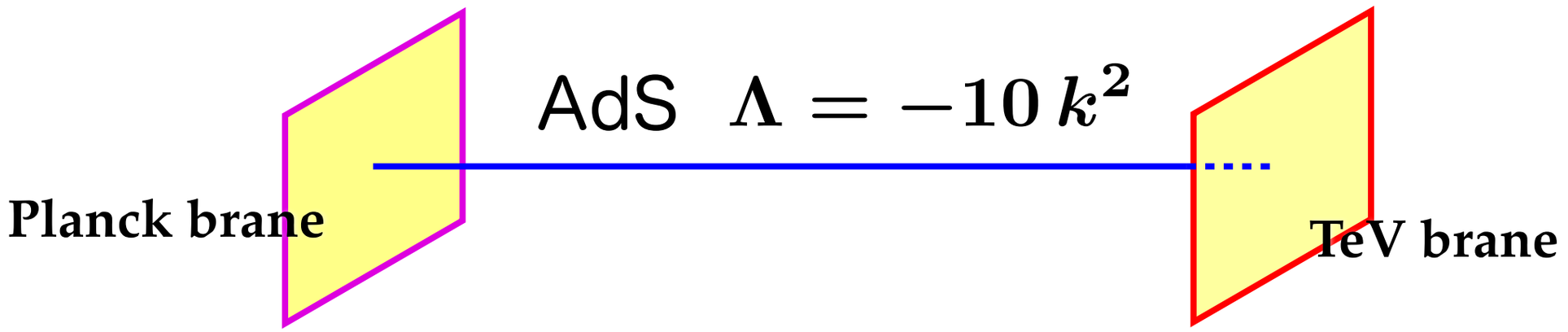
work in progress, with N. Yamatsu

$$ds^2 = e^{-2k|y|}(dx^\mu dx_\mu + dv^2) + dy^2$$

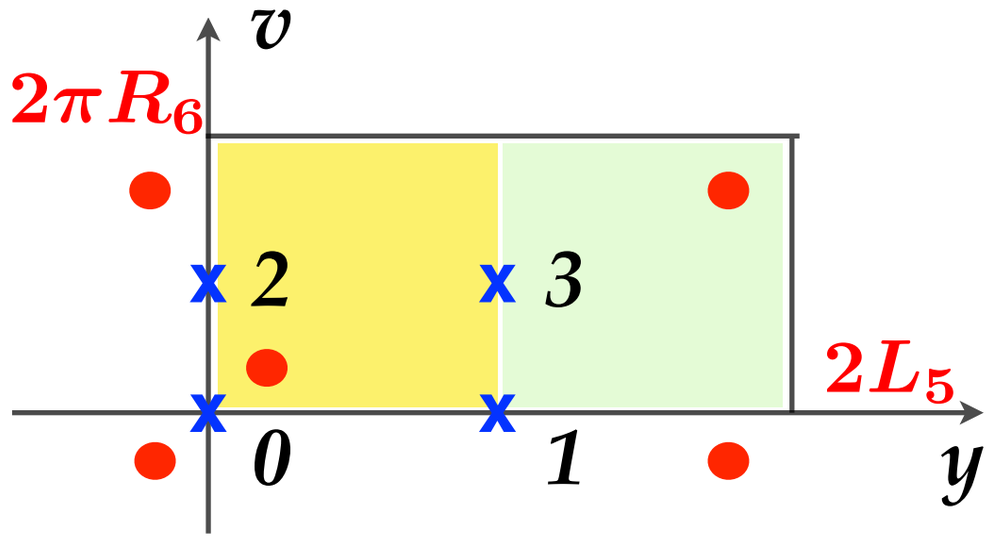
6th dim *5th dim*

$$v \sim v + 2\pi R_6 \qquad y \sim y + 2L_5$$

$$(-y, -v) \sim (y, v)$$



Physics
OSAKA UNIVERSITY



Parity around 4 fixed points

$$P_0, P_1, P_2, P_3$$

$$P_3 = P_1 P_0 P_2 = P_2 P_0 P_1$$

$$P_0 = P_1 = \begin{pmatrix} I_4 & \\ & -I_7 \end{pmatrix}$$

$$P_2 = P_3 = \begin{pmatrix} I_{10} & \\ & -1 \end{pmatrix}$$

$$m_{KK}^{(5)} = \pi k\, e^{-kL_5} \ll \frac{1}{R_6}$$

6 - 10 TeV　　GUT scale

No exotic light particles

5d grand unification

$$SO(11)$$

$$\downarrow \quad P_0 \neq P_1$$

$$SO(4) \times SO(6)$$

$$\downarrow \quad \Phi_{16}$$

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

$$\downarrow \quad \theta_H$$

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

6d grand unification

$$SO(11)$$

$$\downarrow \quad P_2 = P_3$$

$$SO(10)$$

$$\downarrow \quad P_0 = P_1$$

$$SO(4) \times SO(6)$$

$$\downarrow \quad \Phi_{32}$$

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

$$\downarrow \quad \theta_H$$

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

Summary

SO(5)xU(1) gauge-Higgs EW unification

Higgs phenomenology, Z', W' (KK modes)

SO(11) gauge-Higgs grand unification

More than 5 dimensions

5th dim : EW

6th dim : GUT

Physics
OSAKA UNIVERSITY