Gauge-Higgs seesaw mechanism in six-dimensional grand unification

Yutaka Hosotani

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YH, N. Yamatsu, arXiv:1706.03503

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Gauge-Higgs unification

A_M

A_μ

γ , W , Z

A_y

$Higgs$
Aharonov-Bohm phase
θ_H

Finite Higgs mass
generated.
Gauge-hierarchy problem
is solved.

Hosotani mechanism

Dynamical
EW sym breaking

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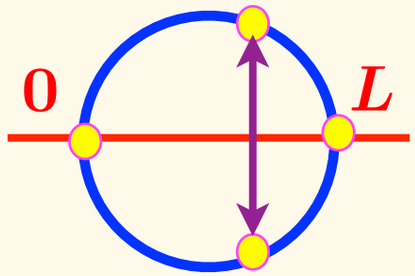
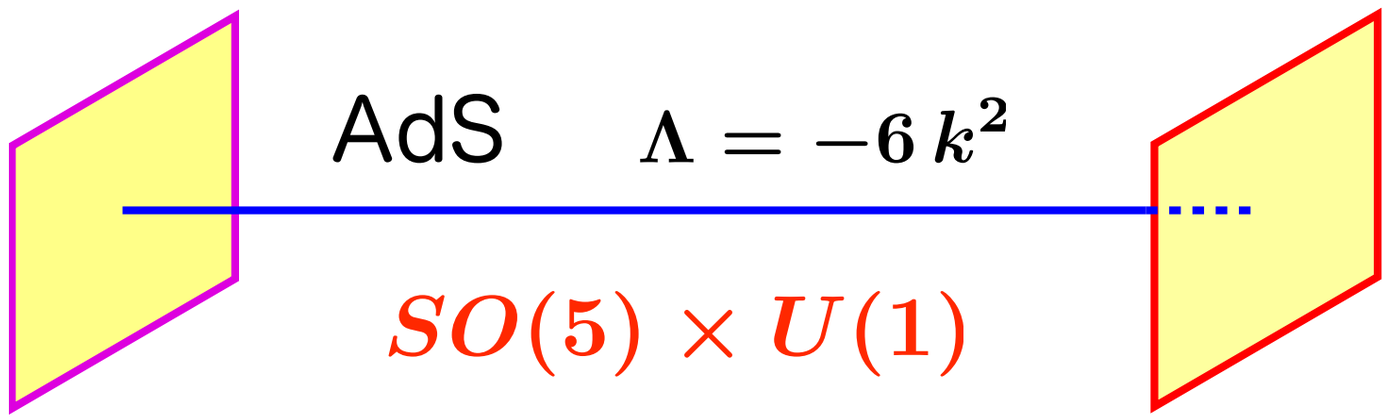
EW: SO(5)xU(1) GHU in Randall-Sundrum

Agashe, Contino, Pomarol 2005
YH, Sakamura 2006
Medina, Shah, Wagner 2007
YH, Oda, Ohnuma, Sakamura 2008
Funatsu, Hatanaka, YH, Orikasa, Shimotani 2013



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



UV brane

IR brane

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

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

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4D gauge bosons and Higgs

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

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

$$A_\mu \sim \begin{pmatrix} W\ Z\ \gamma & \\ & \end{pmatrix} \qquad A_y \sim \begin{pmatrix} \text{Higgs} & \\ & \end{pmatrix}$$

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

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At low energies

Nearly the same as SM

gauge couplings of quarks/leptons~ SM

	g_{GHU}/g_{SM} $(\theta_H = 0.115)$
W to $\ell\nu$, ud , cs	1.00019
$t\,b$	0.9993
WWZ	0.9999998

Higgs couplings to W, Z, quarks/leptons ~ $(SM) \times \cos\theta_H$

$$\cos\theta_H \sim 0.995 \quad \text{for } \theta_H = 0.1$$

Higgs decays:

$$\Gamma(H \to \gamma\gamma), \mu(H \to \gamma\gamma) \sim (SM) \times \cos^2\theta_H$$

corrections due to KK modes < 0.2%

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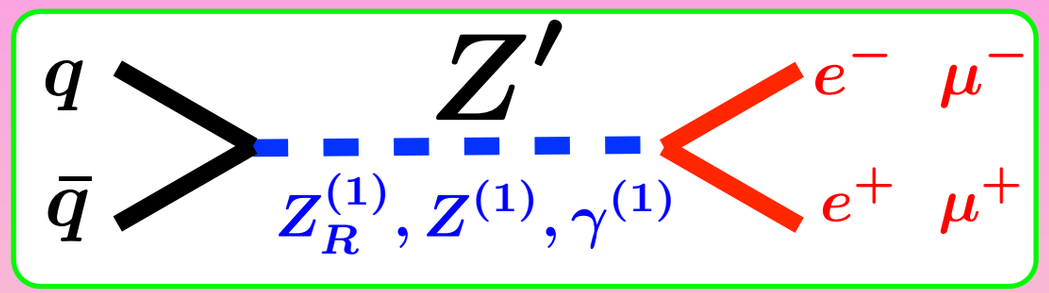
Predictions

LHC

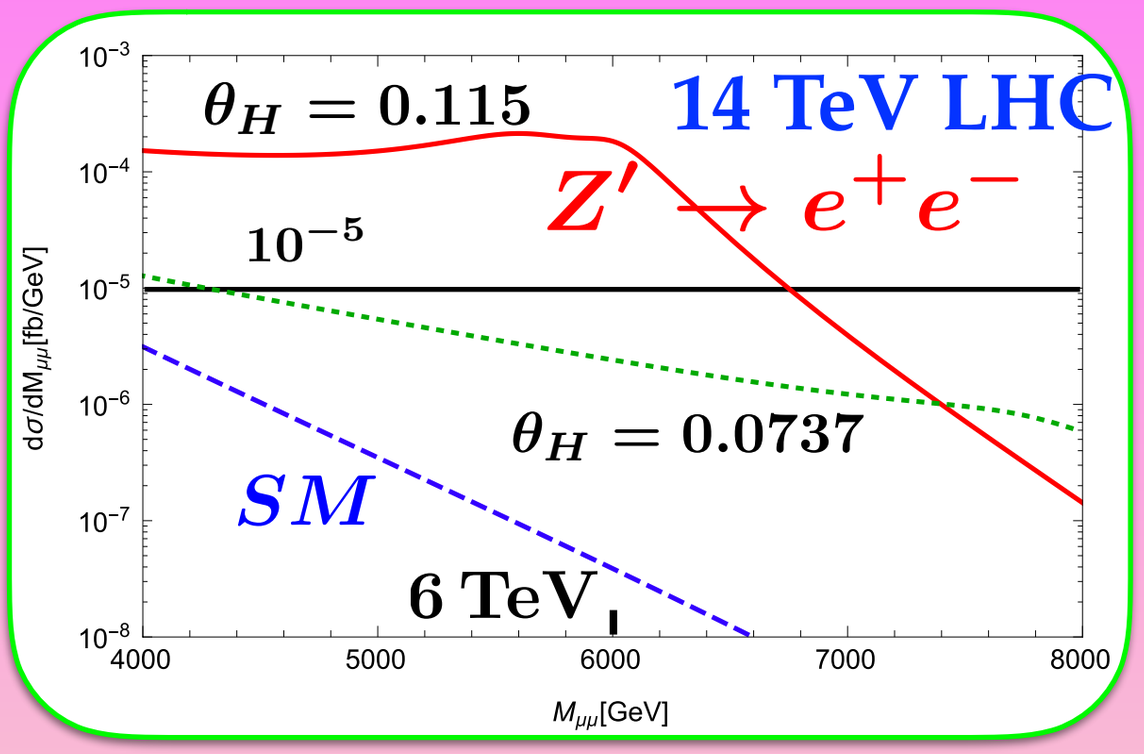


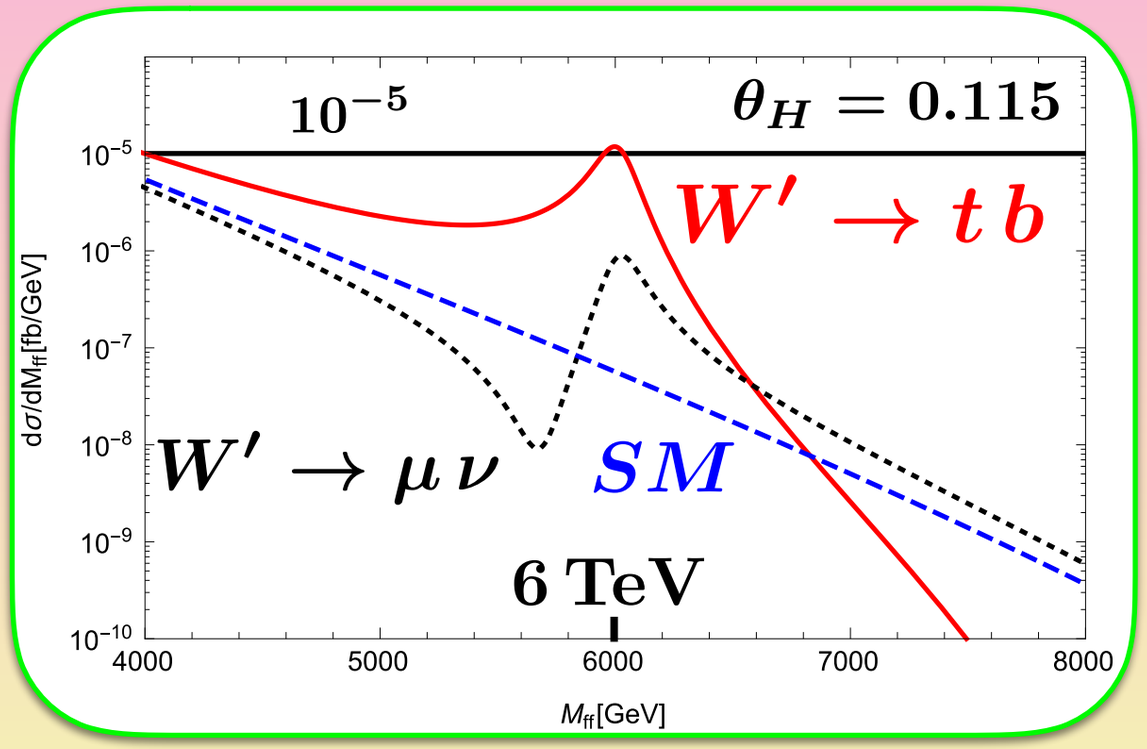
ATLAS-CONF-2017-027
(9 April 2017)

$\sqrt{s} = 13\,\text{TeV}, \quad 36.1\,\text{fb}^{-1}$

no event for > 3000 GeV

$\Rightarrow \quad \theta_H < 0.1$





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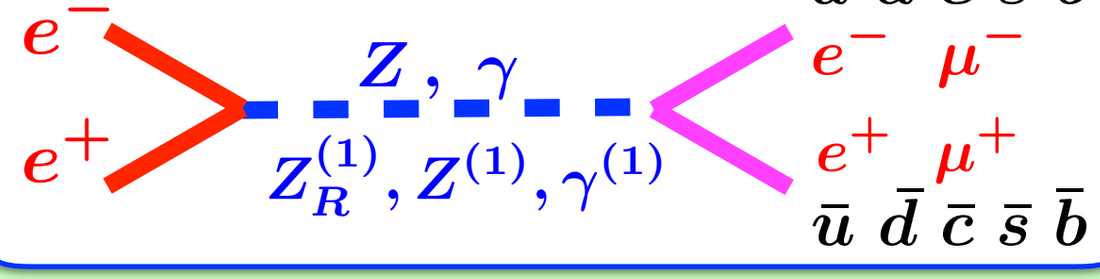
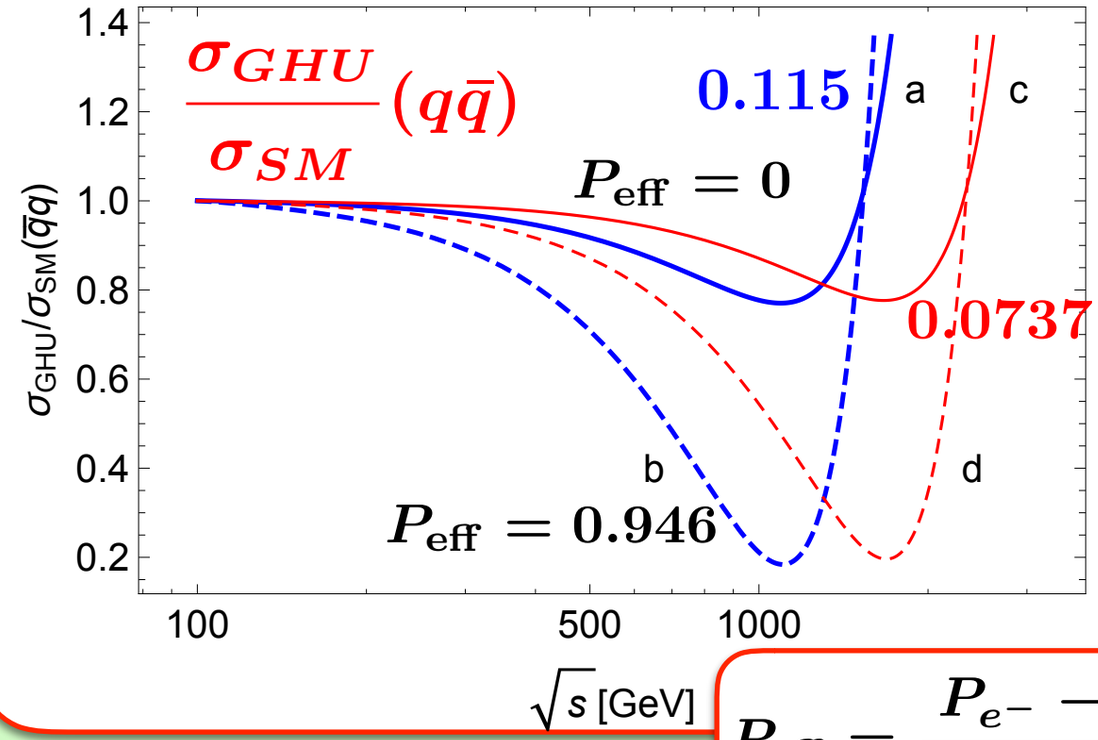
Funatsu, Hatanaka, YH, Orikasa, 1612.03378 (PRD)

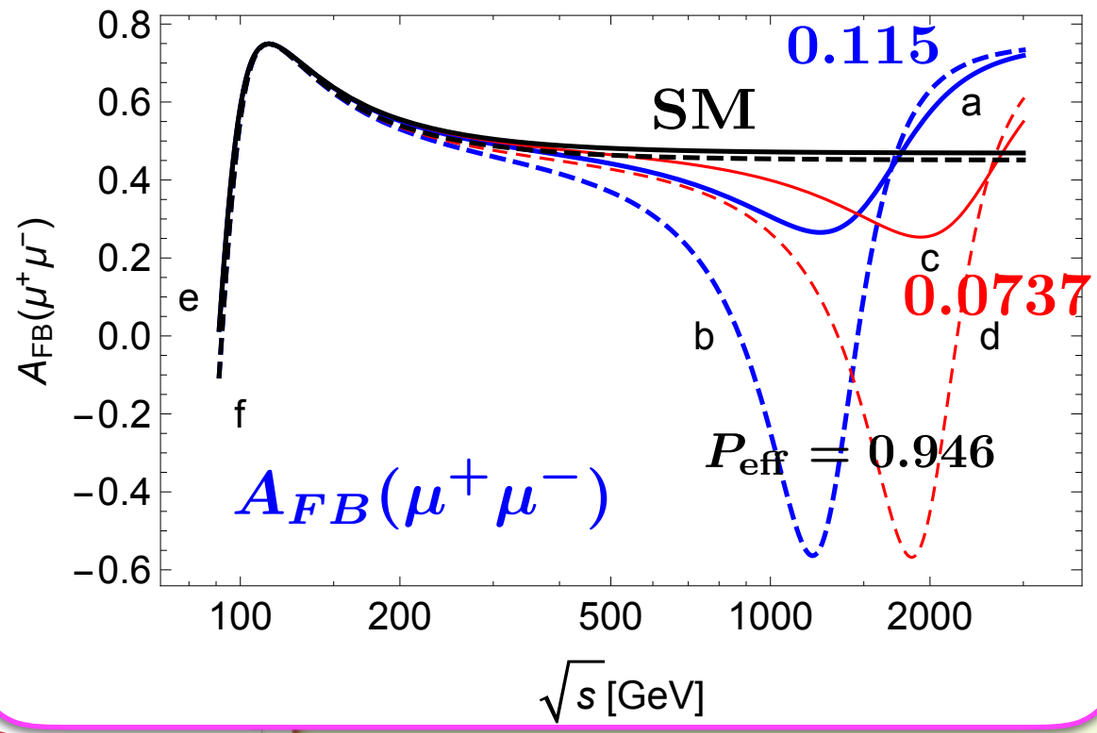
ILC

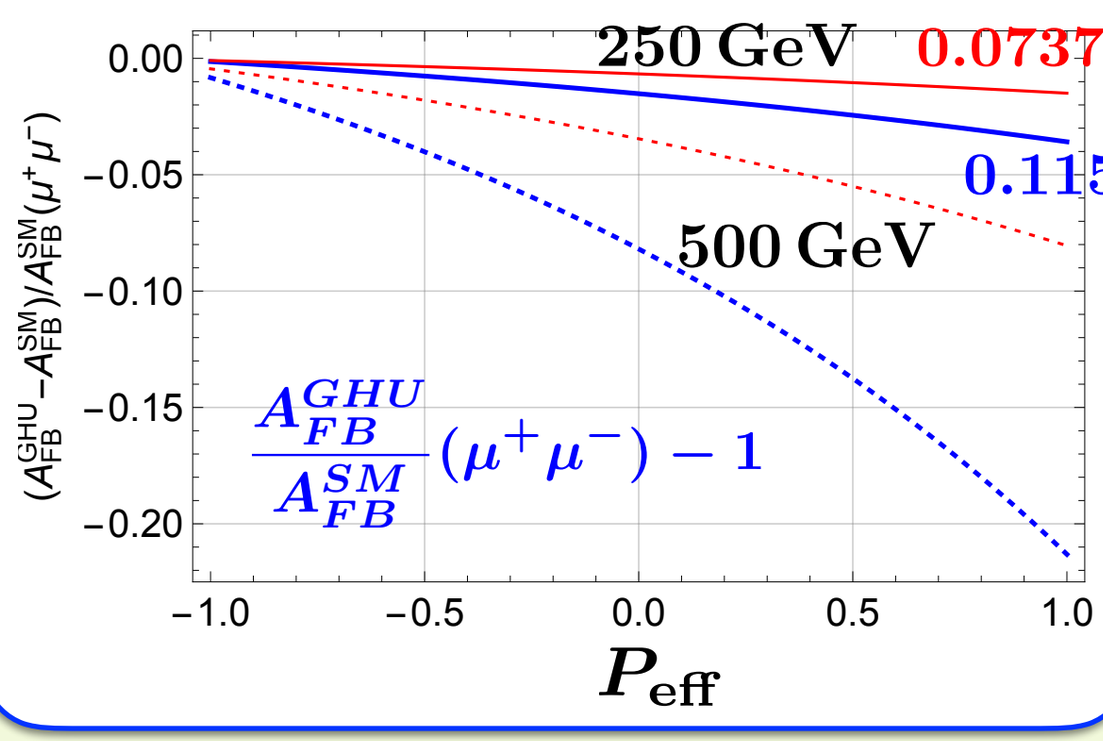


Distinct deviations



$$P_{\rm eff} = \frac{P_{e^-} - P_{e^+}}{1 - P_{e^-} P_{e^+}}$$





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Funatsu, Hatanaka,YH, Orikasa, 1705.05282

Next

Grand unification

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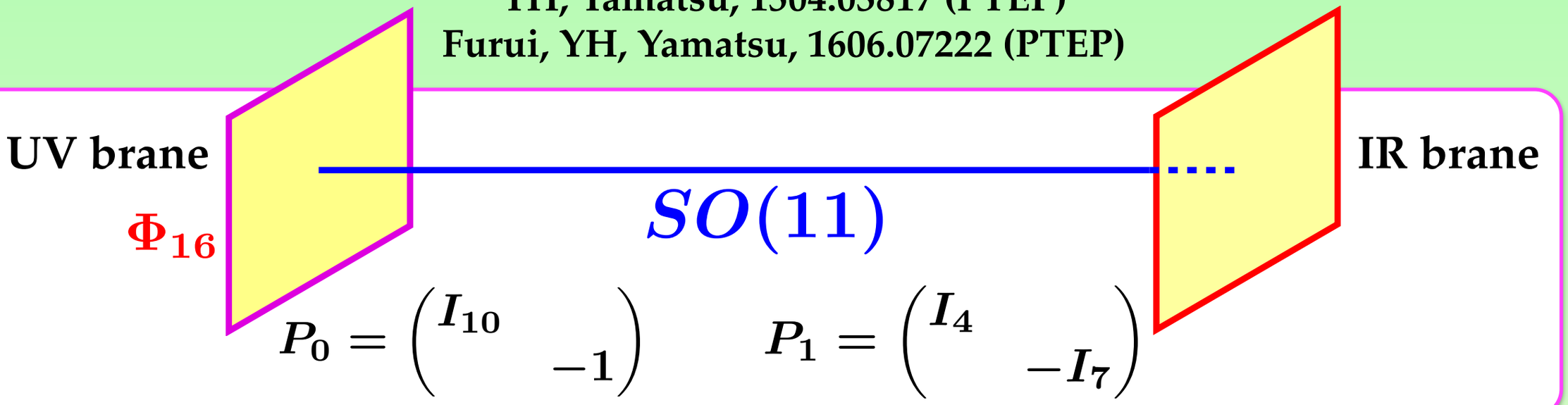
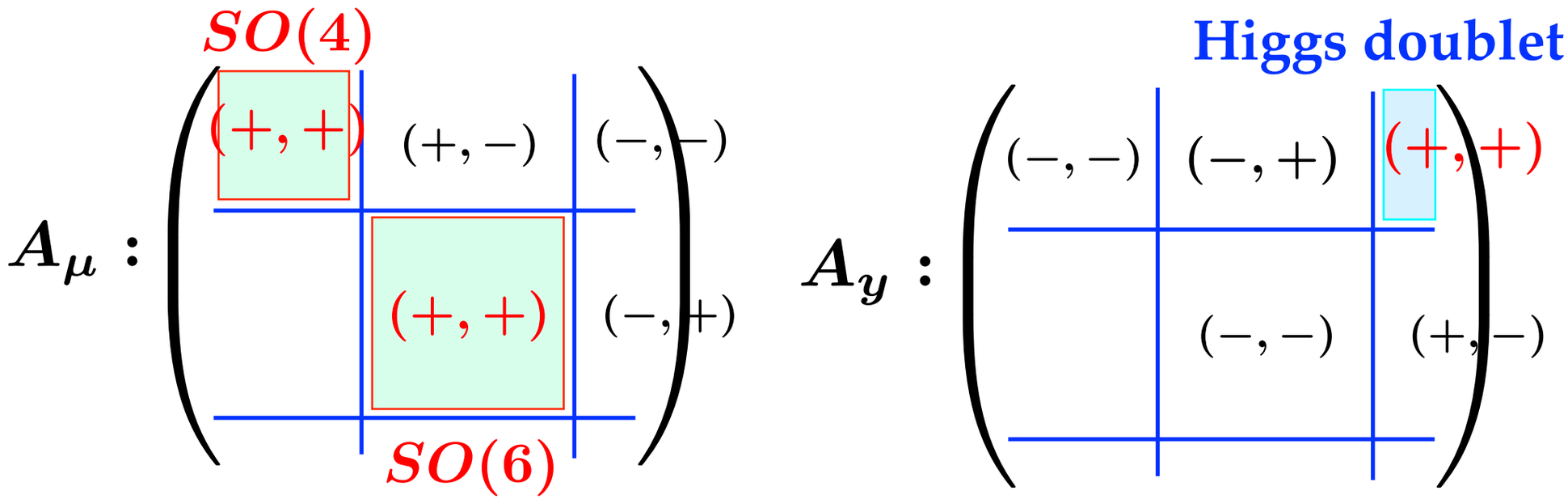
Gauge-Higgs grand unification in 5d RS

YH, Yamatsu, 1504.03817 (PTEP)
Furui, YH, Yamatsu, 1606.07222 (PTEP)





$$SO(4) \times SO(6) \xrightarrow[\langle \Phi_{16} \rangle]{} SU(2)_L \times SU(3)_C \times U(1)_Y$$

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Quarks & Leptons

$$\Psi_{32} \quad \Psi_{11}$$

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

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

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

exotic light particles

$$\Psi_{11} = \begin{pmatrix} \hat{E} & N \\ \hat{N} & E \\ D_j & \hat{D}_j \\ S & \end{pmatrix}$$

unavoidable in 5d theory

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Gauge-Higgs grand unification in 6d

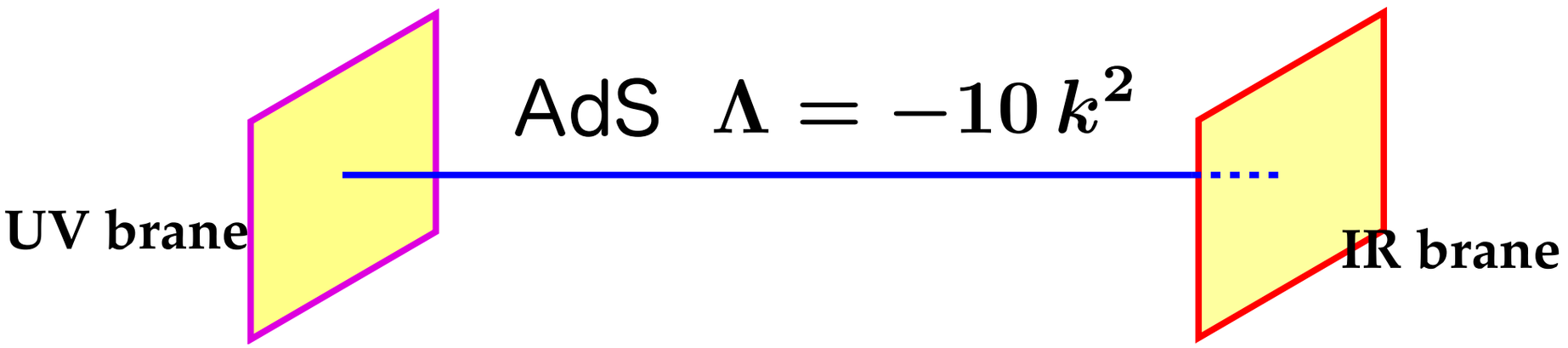
6d hybrid-warped space: compactified $RS_6 \equiv \overline{RS_6}$

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

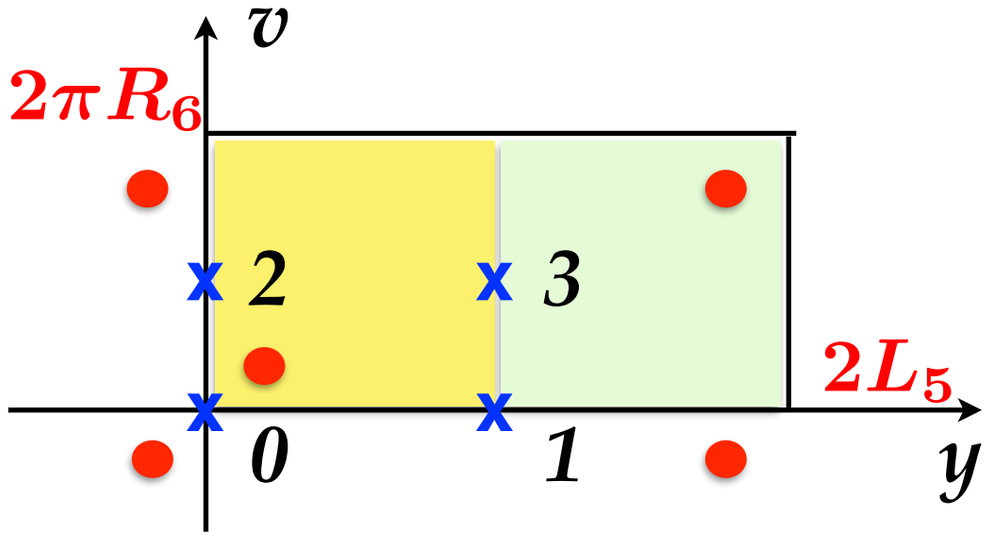
6th dim *5th dim*

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

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



Einstein eqs. solved with 5d branes



Parity around 4 fixed points

$$P_0, P_1, P_2, P_3$$

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

$SO(11)$ GHU in $\overline{RS_6}$

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

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

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

6 - 10 TeV　　GUT scale

No exotic light particles

Chiral fermions in $\overline{RS_6}$

$$\{\Gamma^M, \Gamma^N\} = 2\eta^{MN}$$

$$\gamma_{6d}^{7} = \begin{pmatrix} I_4 & \\ & -I_4 \end{pmatrix} = \gamma_{4d}^{5}\,(-i\Gamma^5\Gamma^6) \qquad \gamma_{4d}^{5} = \begin{pmatrix} I_2 & & & \\ & -I_2 & & \\ & & I_2 & \\ & & & -I_2 \end{pmatrix}$$

$$\Psi(x, y_j - y, v_j - v) = -i\Gamma^5\Gamma^6\, P_j \Psi(x, y_j + y, v_j + v)$$

$$\gamma_{6d}^{7}\,\gamma_{4d}^{5}$$

6d Weyl + orbifold BC ⇨ chiral fermions

Action

$$I = \int d^6x \sqrt{-\det G}\ \overline{\Psi}\left\{\Gamma^A E_A{}^M \mathcal{D}_M + \boxed{ic\,k\,\Gamma^6}\right\}\Psi$$

bulk vector mass

$$\Psi_{32}(x, y, v)\ ,\ \ \Psi_{11}(x, y, v)$$

On the UV brane (y=0)

$\Psi_1(x, v)$ simplectic Majorana

$\Phi_{32}(x, v)$ $SO(11) \to SU(5)$

Neutrinos

$$m_\nu \ll m_e$$

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Seesaw mechanism in 4d

$$\mathcal{L}_m \sim \frac{i}{2}(\nu_L^{c\dagger}, \nu_R^{\dagger}) \begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} + h.c.$$

$$\Rightarrow \quad |mass| = \begin{cases} \dfrac{m_D^2}{M} \sim m_\nu \\ M \end{cases}$$

P. Minkowski, Phys. Lett. B67 (1977) 421

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Gauge-Higgs seesaw

resulting 4d effective theory

6d bulk $\Psi_{32} \to \nu_L, \nu'_R$

5d UV brane $\Psi_1 \to \eta$ **(simplectic Majorana)**

$$\mathcal{L}_m \sim \frac{i}{2}(\nu_L^{c\dagger}, \nu_R^{\prime\dagger}, \eta_L^{c\dagger}) \begin{pmatrix} 0 & m_D & 0 \\ m_D & 0 & \tilde{m}_B \\ 0 & \tilde{m}_B & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \\ \eta_L \end{pmatrix} + h.c.$$

$$\Rightarrow |mass| = \begin{cases} \dfrac{m_D^2 M}{\tilde{m}_B^2} \sim m_\nu \\ \dfrac{1}{2}\left\{\sqrt{M^2 + 4\tilde{m}_B^2} \pm M\right\} \end{cases}$$

Simplectic Majorana condition

Mirabelli, Peskin, PRD58 (1998) 065002

on the 5d UV brane at y=0

$$\Psi_1(x,v) = \begin{pmatrix} \xi_{R+} \\ \eta_{L+} \\ \xi_{R-} \\ \eta_{L-} \end{pmatrix} \begin{matrix} (++) \\ \\ \\ (++) \end{matrix}$$

orbifold BC $\quad \Psi_1(x, v_j - v) = -i\Gamma^5\Gamma^6\Psi_1(x, v_j + v)$

simplectic Majorana

$$\Psi_1^{C_{6d}} = i\gamma_{4d}^5\Gamma^6\,\Psi_1 \quad (\leftarrow \text{5d spinor})$$

$$\Rightarrow \xi_{R+} = \eta_{L-}^c$$

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Gauge-Higgs seesaw mechanism

$$m_D:\ \nu-\nu' \ \leftarrow\ g\overline{\Psi}_{32}\Gamma^5 A_y \Psi_{32}$$ Hosotani mechanism

Dirac mass

$$\delta(y)\kappa_B\left\{\overline{\Psi}_{32}\Phi_{32}\Psi_1+h.c.\right\} \ \rightarrow \frac{m_B}{\sqrt{k}}(\overline{\chi}\nu'+\overline{\nu}'\chi)|_{y=0}$$

mixing

$$\delta(y)\frac{1}{2}M\overline{\Psi}_1\Psi_1 \ \rightarrow\ \frac{1}{2}M\overline{\chi}\chi \ \rightarrow\ \frac{i}{2}M(\eta_L^{c\dagger}\eta_L-\eta_L^{\dagger}\eta_L^c)$$

Majorana mass

Neutrino mass

$$m_\nu = -\frac{m_u^2 M z_L^{2c+1}}{(c+\frac{1}{2})m_B^2}$$

$$m_u = \sqrt{4c^2-1}\, k z_L^{-c-\frac{1}{2}} \sin\tfrac{1}{2}\theta_H$$

4d effective theory

$$\begin{pmatrix} 0 & m_D & 0 \\ m_D & 0 & \tilde{m}_B \\ 0 & \tilde{m}_B & M \end{pmatrix} \qquad m_\nu = \frac{m_D^2 M}{\tilde{m}_B^2}$$

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Summary

SO(11) gauge-Higgs grand unification

in 6-dim hybrid warped space

Gauge-Higgs seesaw mechanism

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