Gauge-Higgs Unification
- LHC and beyond -

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Particles, Cosmology and String
Hsinchu, Taiwan, 8 December 2016

Standard Model is successful.

$$\mathcal{L}_{\text{gauge}} \quad -\frac{1}{2}\mathrm{Tr}\, G_{\mu\nu}G^{\mu\nu} - \frac{1}{2}\mathrm{Tr}\, F_{\mu\nu}F^{\mu\nu} - \frac{1}{4} B_{\mu\nu}B^{\mu\nu}$$

$+$

$$\mathcal{L}_{\text{Higgs}} \quad \left|D_\mu \Phi\right|^2 - V[\Phi]$$

$+$

$$\mathcal{L}_{\text{fermion}} \quad \overline{\psi}_j i\gamma^\mu D_\mu \psi_j$$

$+$

$$\mathcal{L}_{\text{Yukawa}} \quad y_{jk}\, \overline{\psi}_j \Phi\, \psi_k$$

Beautiful

No principle

Standard Model

$\mathcal{L}_{\rm gauge}$

$+$

$\mathcal{L}_{\rm Higgs}$

$\mathcal{L}_{\rm fermion}$

$+$

$\mathcal{L}_{\rm Yukawa}$

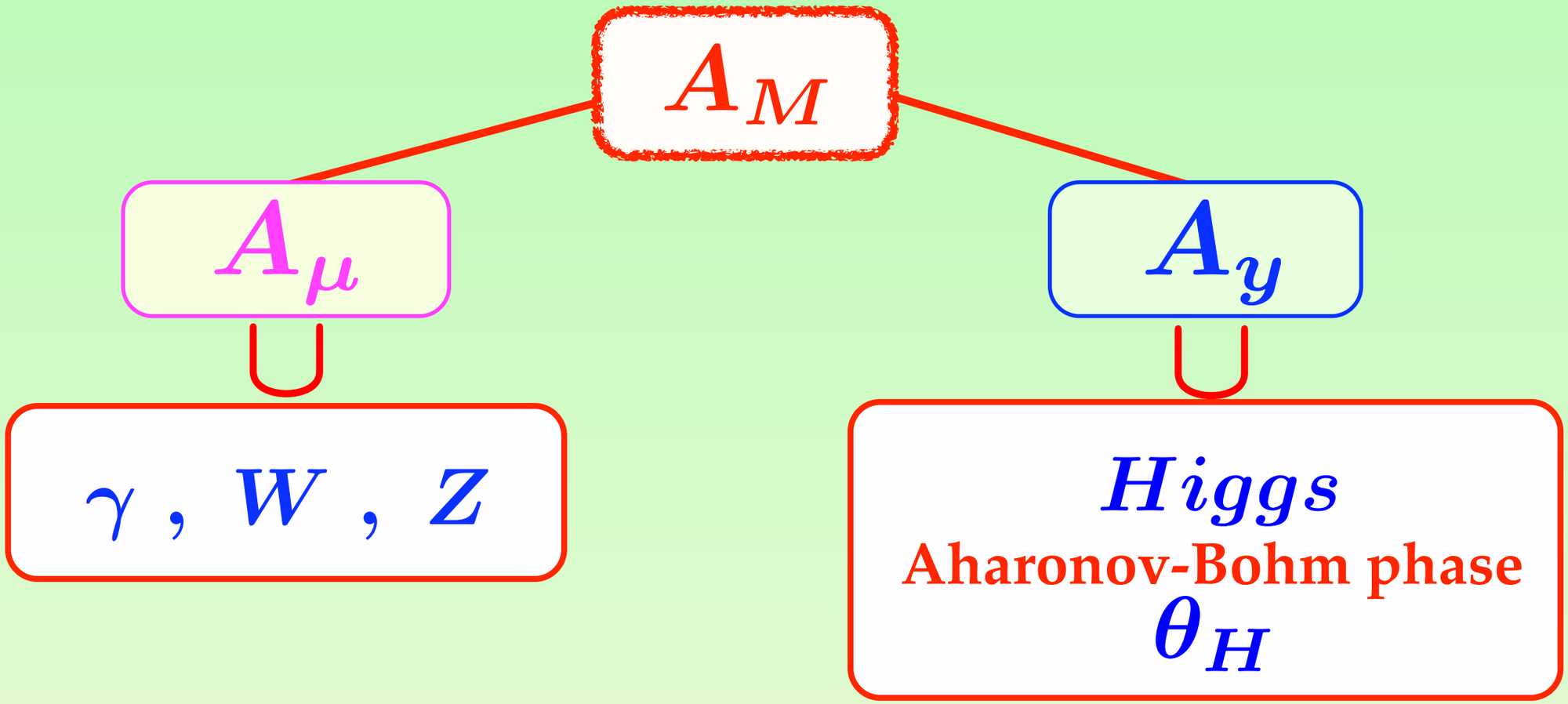
Gauge-Higgs Unification

$\mathcal{L}^{\rm 5d}_{\rm gauge}$

gauge principle

$\mathcal{L}^{\rm 5d}_{\rm fermion}$

Gauge-Higgs unification



Gauge-Higgs unification

A_M

A_y

$Higgs$

Aharonov-Bohm phase

θ_H

Finite Higgs mass generated.

Gauge-hierarchy prob. solved.

Hosotani mechanism

Dynamical
EW sym breaking

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Hosotani mechanism

$$\langle P e^{ig \oint dy A_y} \rangle = e^{i\theta_H}$$

AB phase in the 5th dim

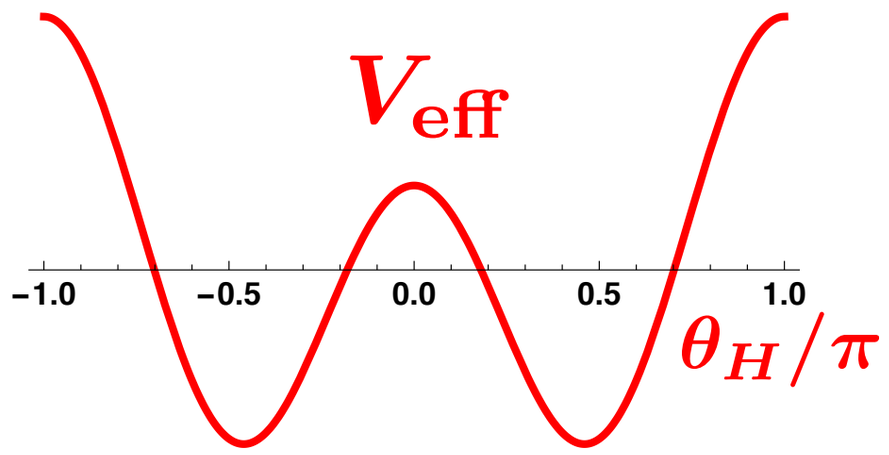
Higgs mechanism

$$\langle \Phi \rangle$$

Gauge sym breaking by gauge inv quantities

$$V_{\rm eff}(\theta_H)^{\rm classical} = 0$$

$$V_{\rm eff}(\theta_H)^{\rm quantum} \neq 0$$



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Hosotani mechanism

$$\theta_H \neq 0 \qquad \mathcal{G} \to \mathcal{H}$$

gauge bosons
fermions → massive

$$A_y(x,y) = \left\{ f_H \theta_H + H(x) \right\} u_0(y) + \cdots$$

4D Higgs

Finite Higgs mass generated.

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Gauge-Higgs EW unification

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

Higgs : SU(2) doublet → $\mathcal{G} \supset SU(2) \times U(1)$

Chiral fermions → orbifold

$SU(3)$ on $M^4 \times (S^1/Z_2)$

Kubo, Lim, Yamashita 2002

$SU(3) \times U(1)_X$

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

Agashe, Contino, Pomarol 2005

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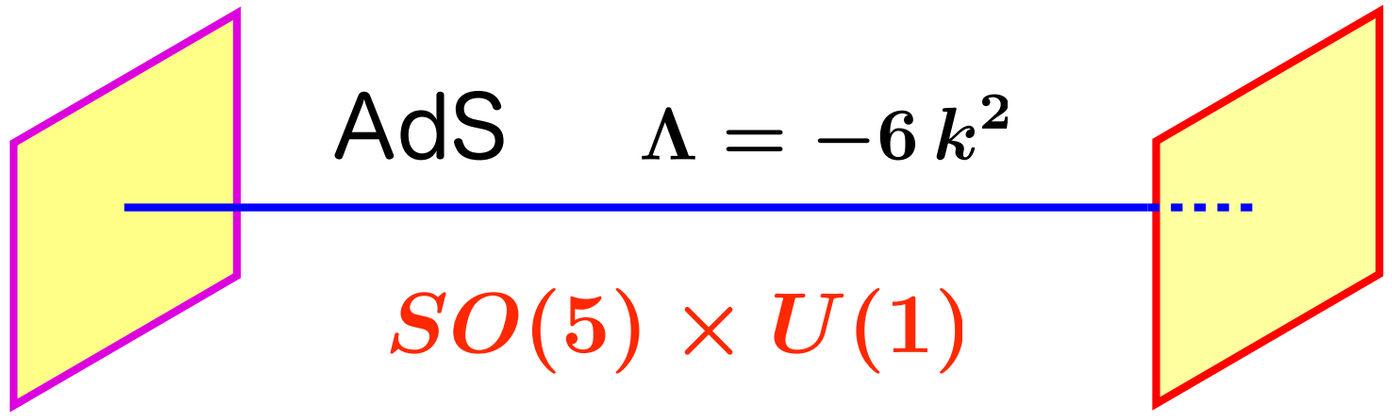
SO(5)xU(1) GHU in Randall-Sundrum

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

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



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

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

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4D gauge bosons and Higgs

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

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

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

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

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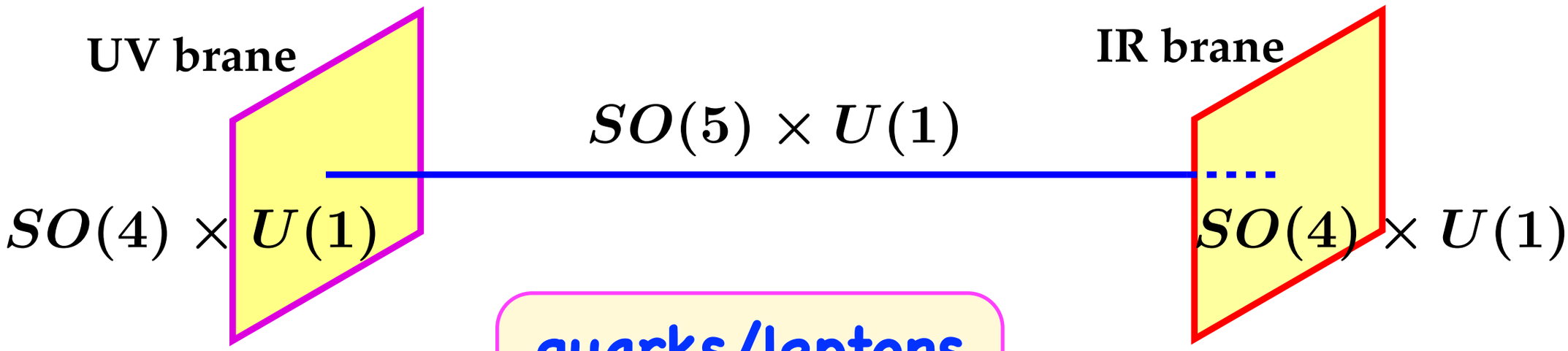

Brane fermion

quarks/leptons

vector rep

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

dark fermions

Brane scalar

spinor rep

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

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

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

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Scales

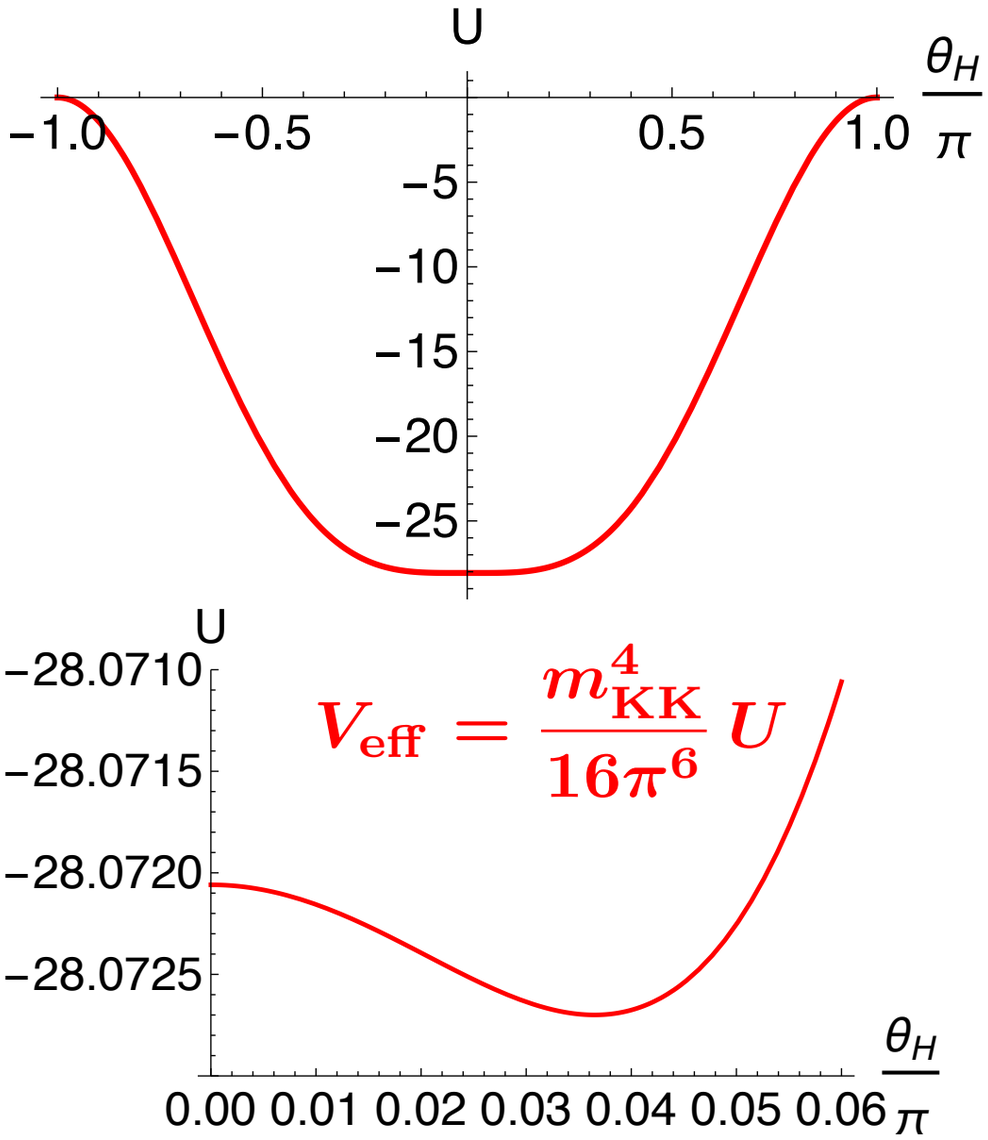
KK scale $m_{\rm KK} = \pi k e^{-kL} \sim \dfrac{\pi\sqrt{kL}}{\sin\theta_H}\, m_W$

$\sim 7 - 10\,\mathrm{TeV}$

Weak scale $m_W \sim 80\,\mathrm{GeV}$

QCD scale $m_p \sim 0.9\,\mathrm{GeV}$

EW sym breaking



$z_L = 10^5,\ \theta_H = 0.115$
$n_F = 4$

$\theta_H = 0.115$ (example)

$m_Z,\ \alpha,\ \sin^2\theta_W$

$\rightarrow m_{\rm KK} = 7.41\,{\rm TeV}$

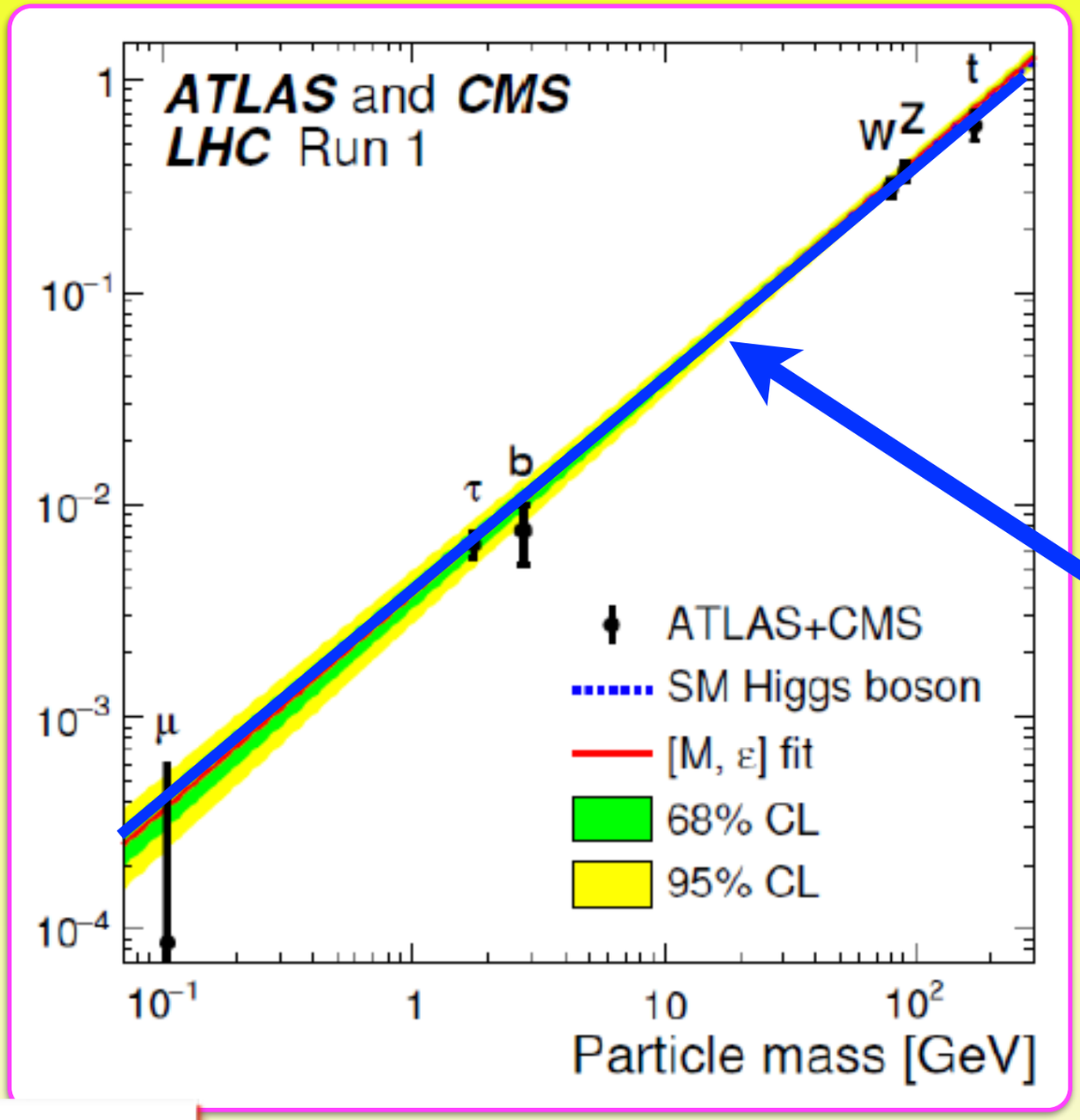
$m_t = 171\,{\rm GeV},\ m_H = 125\,{\rm GeV}$

$\rightarrow c_t = 0.227,\ c_F = 0.332$

$m_\tau,\ m_e = 0.511\,{\rm MeV}$

$\rightarrow c_\tau = 0.950,\ c_e = 1.72$

Predictions



Hff, HWW, HZZ couplings

$$\sim (\mathrm{SM}) \times \cos\theta_H$$

Gauge-Higgs

$$(\theta_H \sim 0.1)$$

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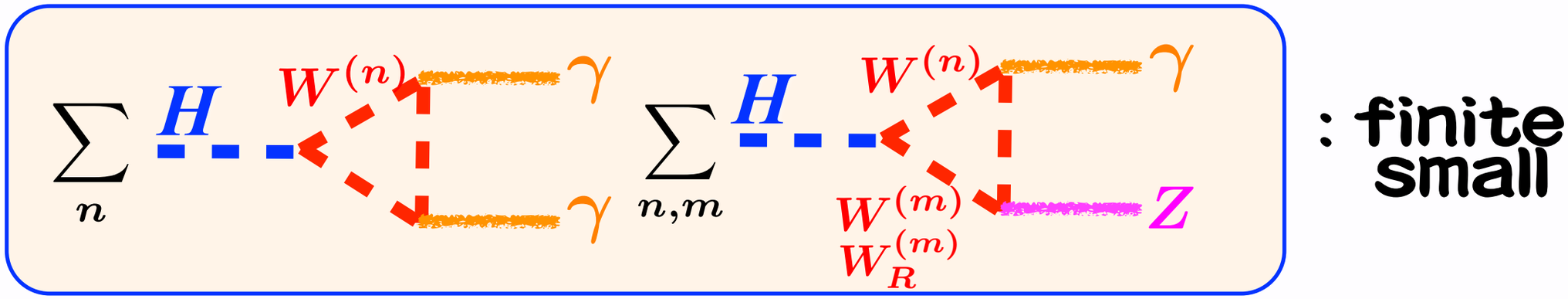
Higgs decay $H \to j$

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

$$BR \sim BR_{\rm SM}$$



: finite small

Funatsu, Hatanaka, YH, Orikasa, Shimotani 2013
Funatsu, Hatanaka, YH 2015

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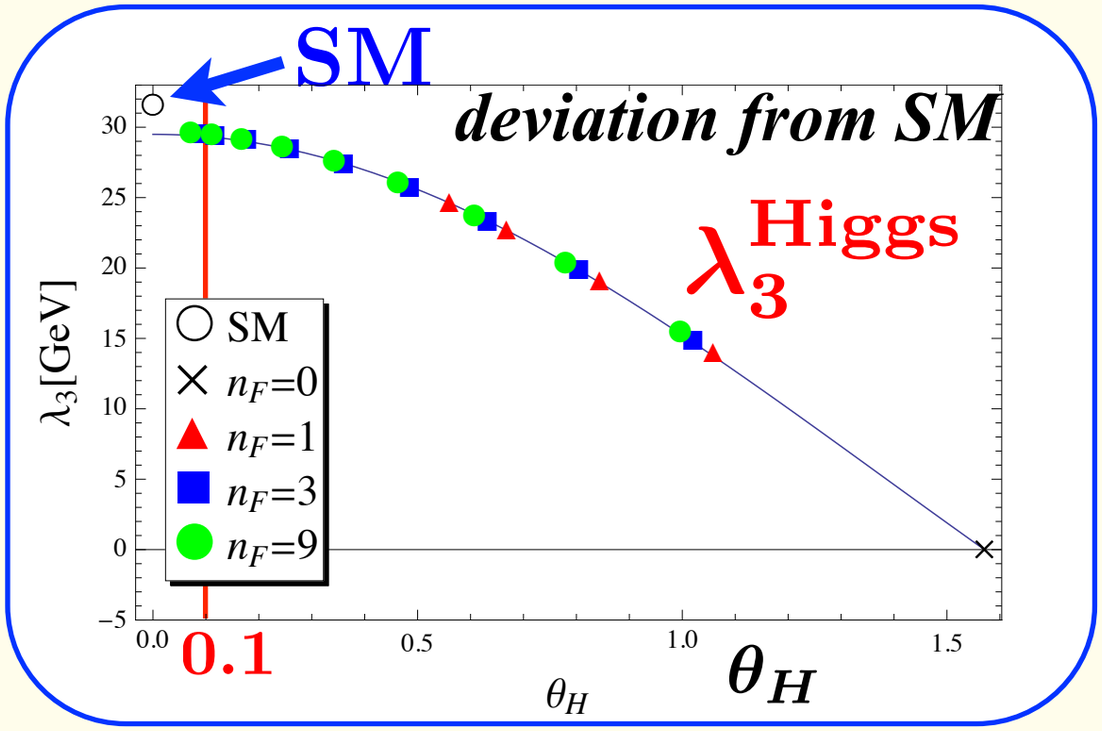
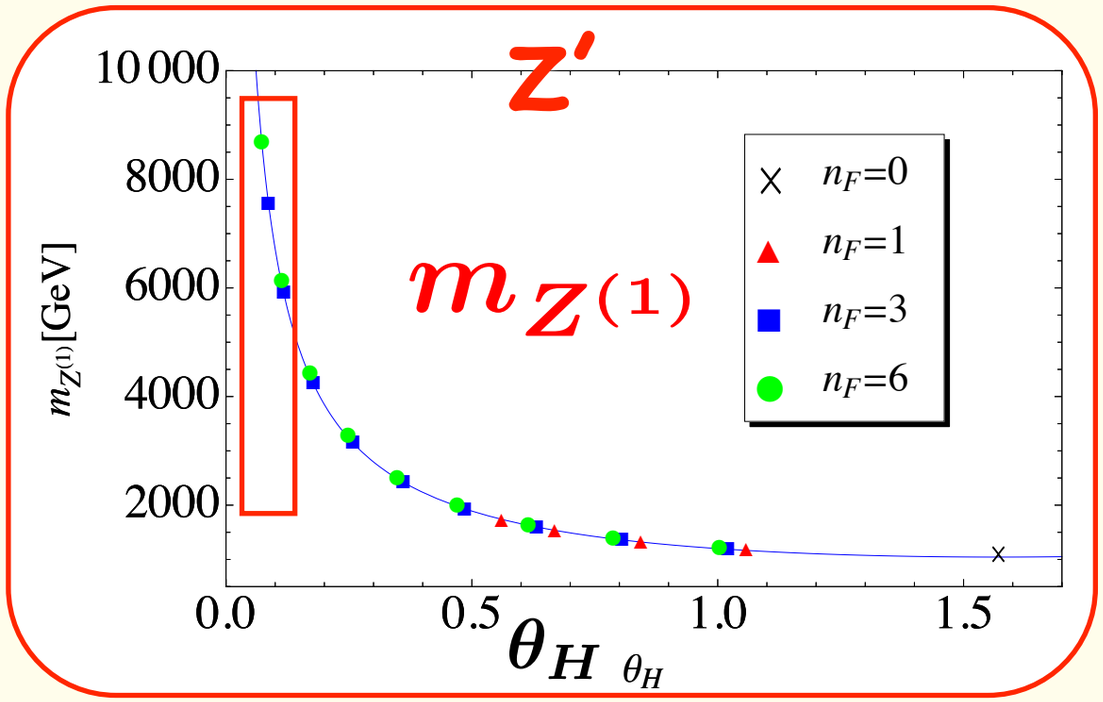
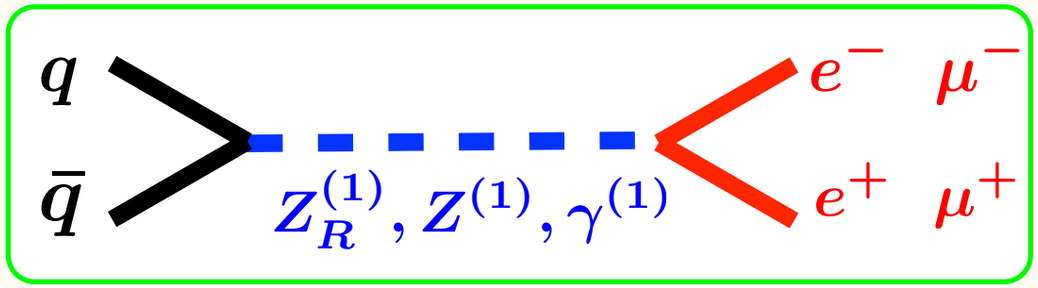
Universality

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

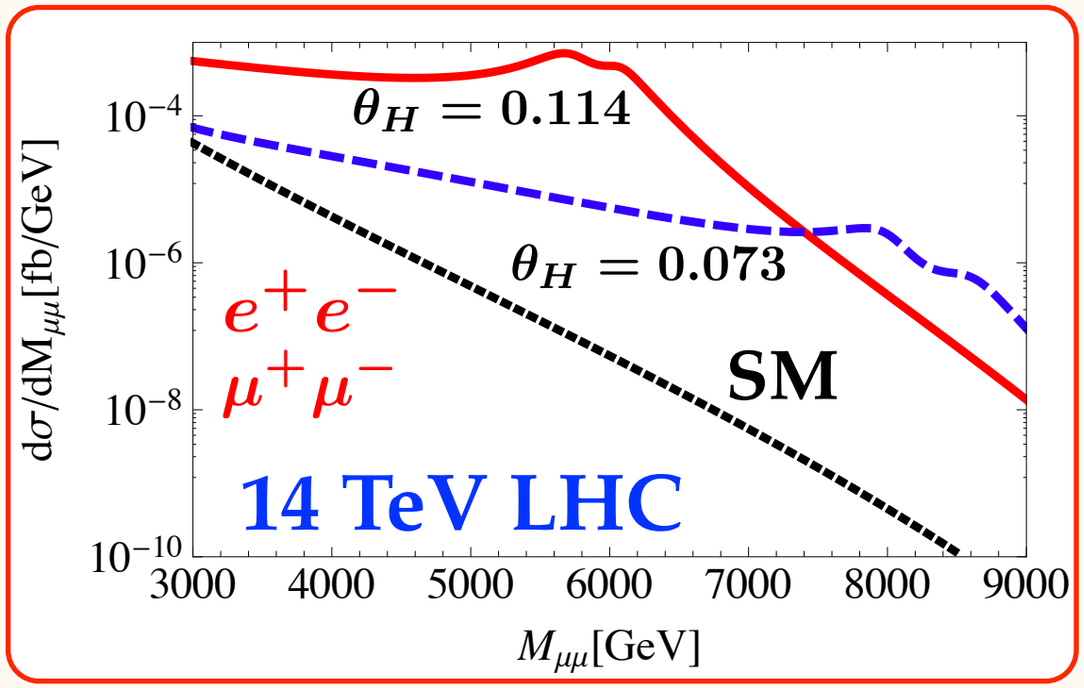




Z'



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

Funatsu, Hatanaka, YH, Orikasa, Shimotani 2014

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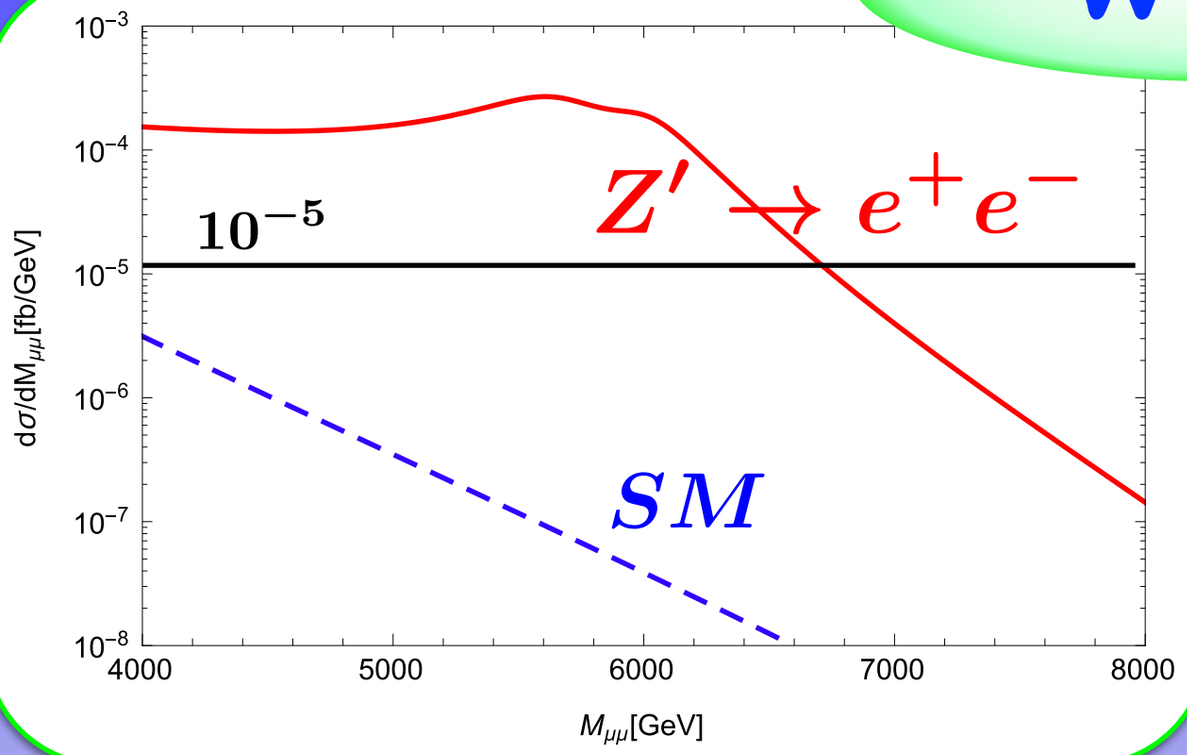
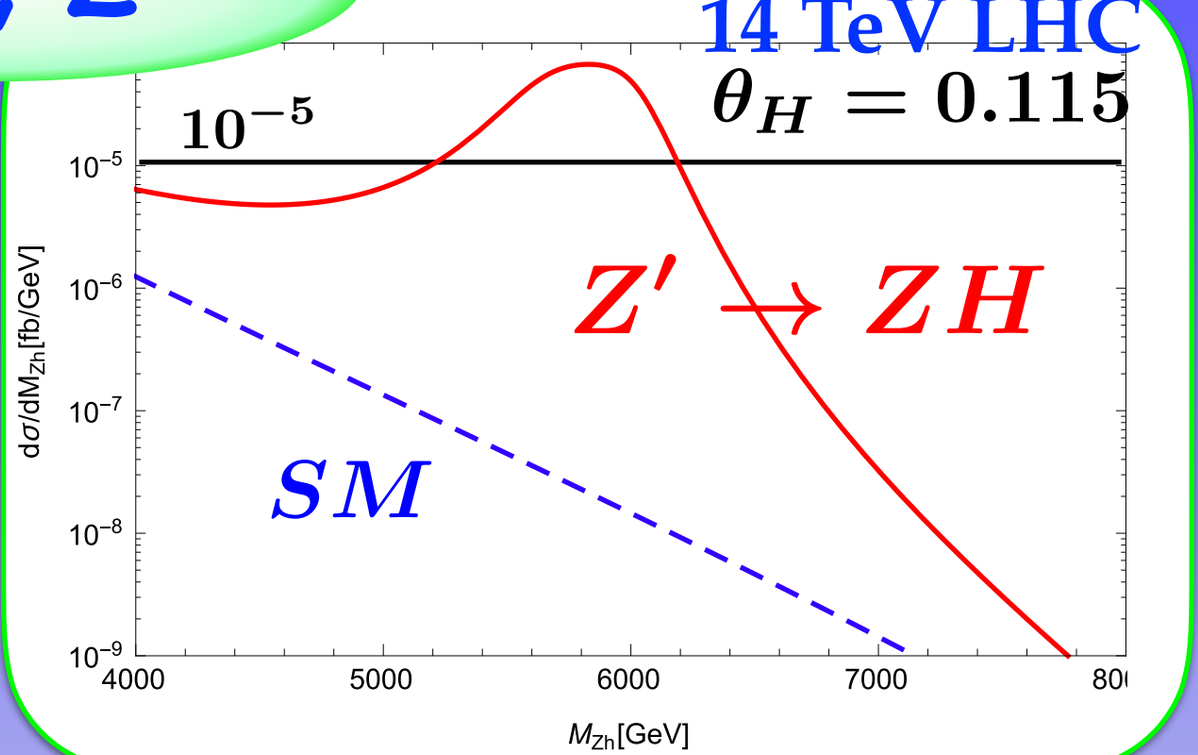
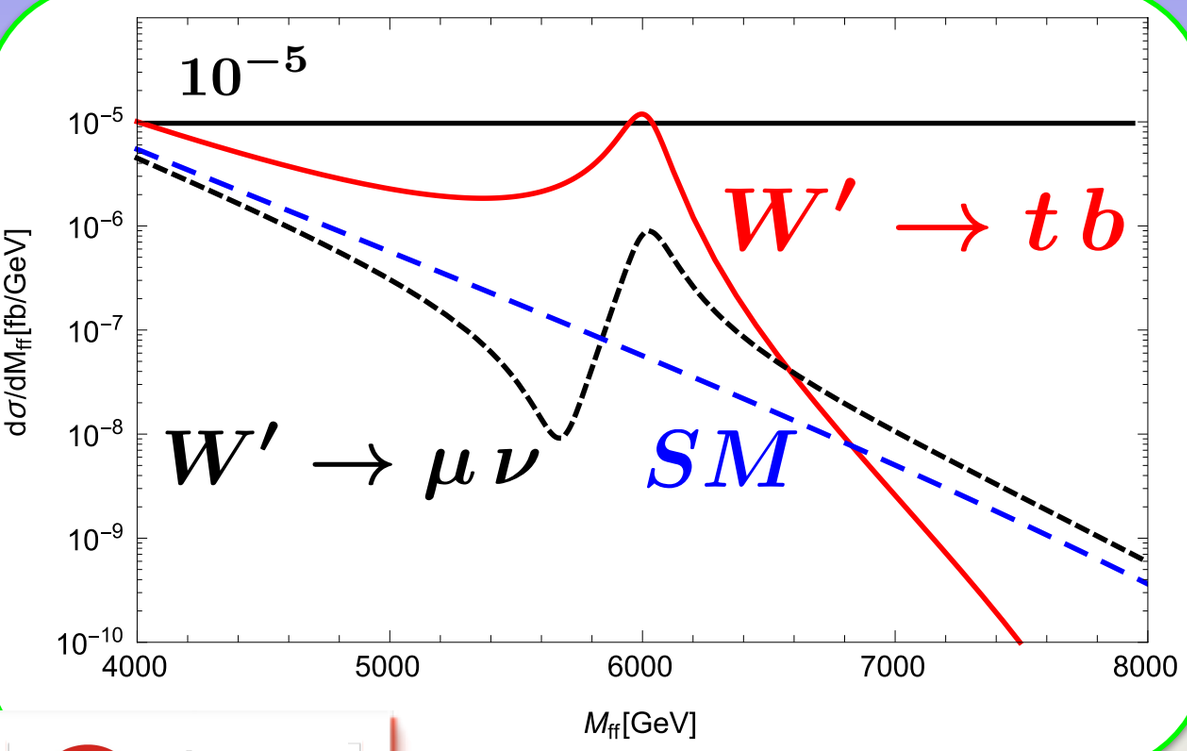
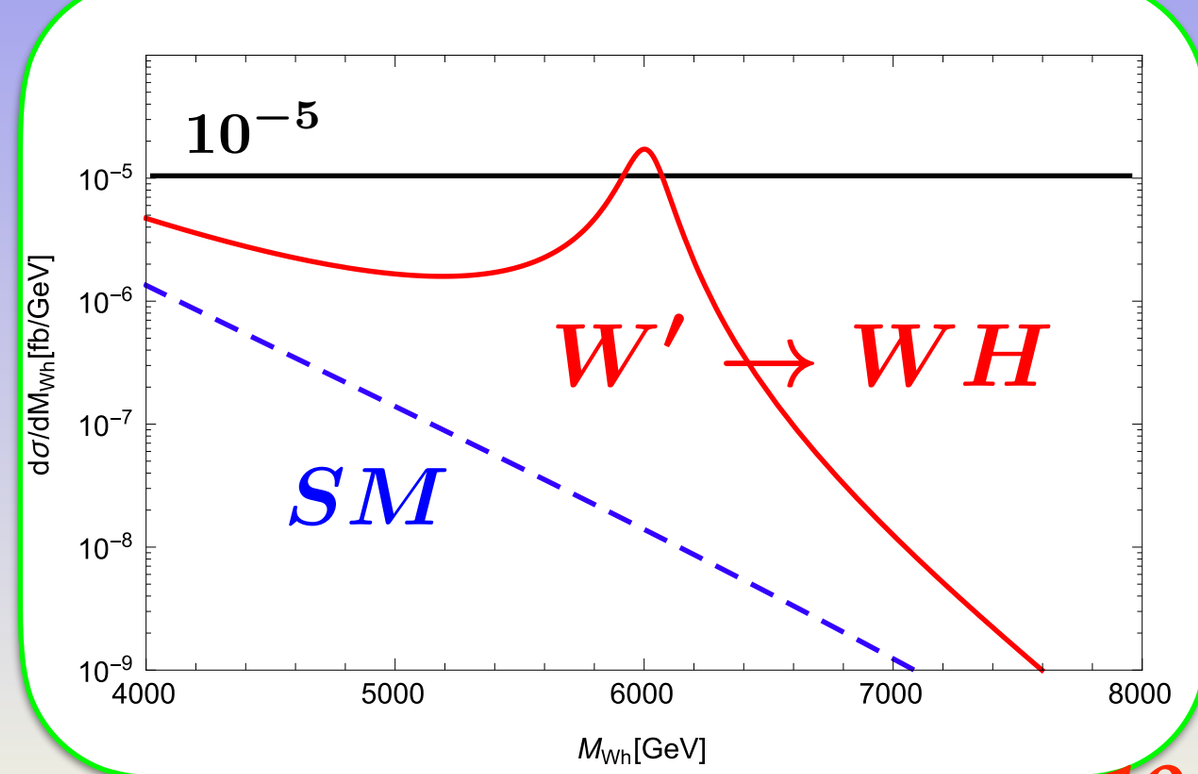
W′, Z′









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Funatsu, Hatanaka, YH, Orikasa (in preparation)

What is next?

Beyond LHC

Gauge-Higgs grand unification

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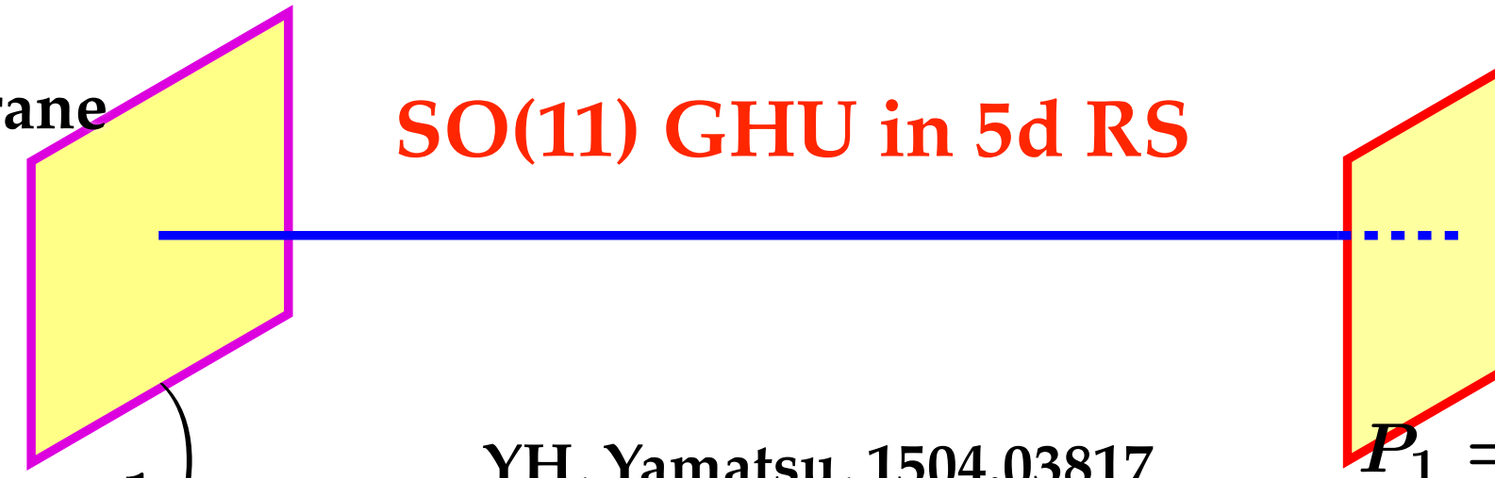
Gauge-Higgs grand unification in 5d



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

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

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

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

$SO(4)$ $SO(6)$

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

Higgs doublet

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Quarks & Leptons

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

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

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

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

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

$$\Psi'_{11} = \begin{pmatrix} \hat{E}' & N' \\ \hat{N}' & E' \\ D'_j & \hat{D}'_j \\ S' \end{pmatrix} \quad D'_{jL}\, \hat{D}'_{jL}$$

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

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

no proton decay

But

exotic light particles

appear.

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Gauge-Higgs grand unification in 6d

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

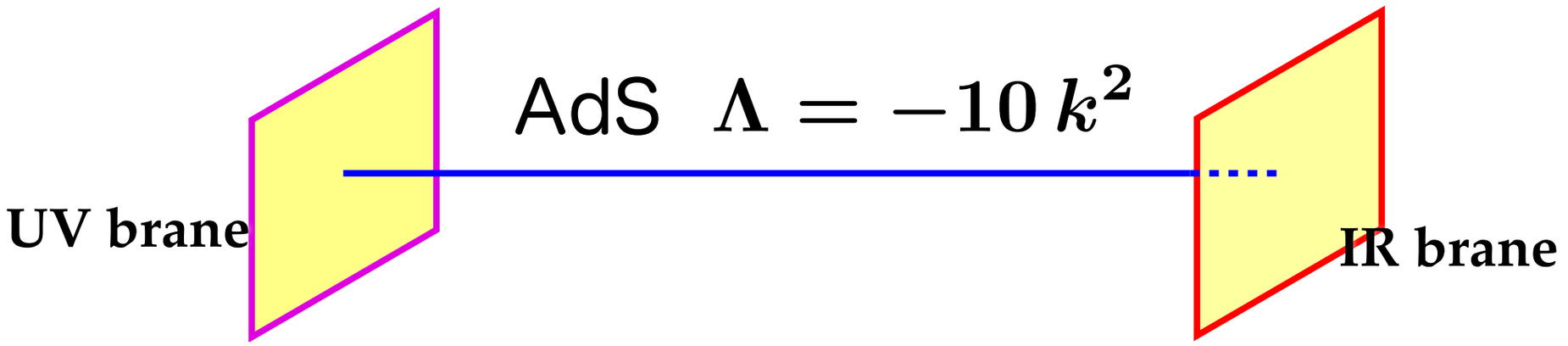
work in progress, with N. Yamatsu

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

6th dim *5th dim*

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

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



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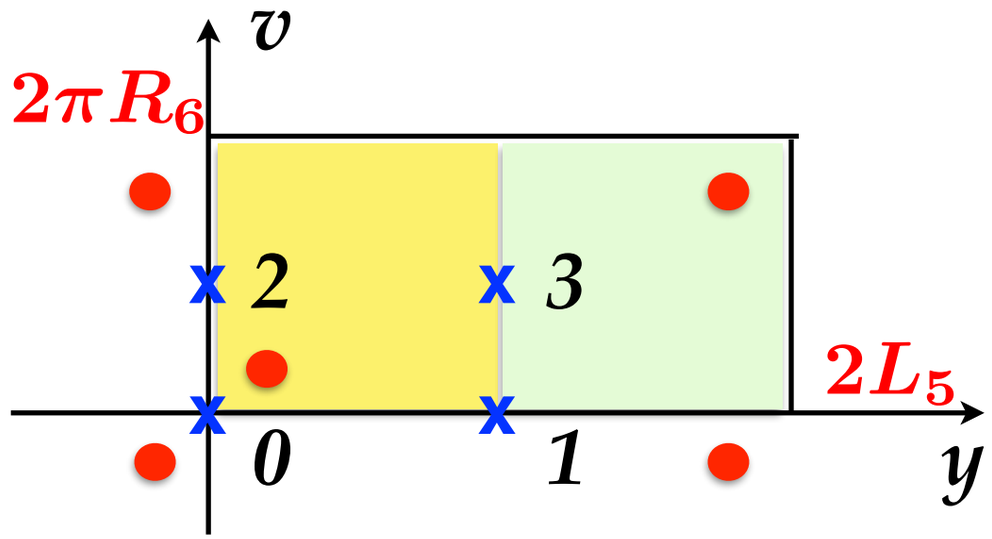

Parity around 4 fixed points

$$P_0, P_1, P_2, P_3$$

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

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

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

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

6 - 10 TeV　　GUT scale

No exotic light particles

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Fermions in 6d hybrid warped space

$$\Psi(x,-y,-v) = P_0 \bar{\gamma}\, \Psi(x,y,v)\ , \quad \bar{\gamma} = -i\Gamma^5\Gamma^6$$

$$\gamma^5_{\rm 4D} = \begin{pmatrix} I_2 & & & \\ & -I_2 & & \\ & & I_2 & \\ & & & -I_2 \end{pmatrix},\ \Gamma^7_{\rm 6D} = \gamma^5_{\rm 4D}\bar{\gamma} = \begin{pmatrix} I_2 & & & \\ & I_2 & & \\ & & -I_2 & \\ & & & -I_2 \end{pmatrix}$$

6D-Weyl + orbifold BC ⇒ zero modes : chiral

Dirac eq. $z = e^{ky}\ \ (0 \le y \le L_5)$

$$\left\{ \Gamma^\mu D_\mu + \Gamma^6 D_v + \Gamma^5 D_z + i\frac{c}{z}\Gamma^6 \right\} \frac{1}{z^{5/2}}\Psi = 0$$

bulk vector mass

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Summary

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

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

SO(11) gauge-Higgs grand unification

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