The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2400-3

Workshop on Strongly Coupled Physics Beyond the Standard Model

25 - 27 January 2012

Gauge-Higgs unification and the LHC

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Gauge-Higgs Unification and the LHC

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Strongly coupled physics BSM
ICTP, Trieste, 26 January 2012

If the Higgs boson

is 124 or 126 or ? GeV

with SM couplings, → Explain “SM Higgs”.

with non-SM couplings,

is not seen at LHC,

→ { Higgs is stable.
Higgs does not exist.

If the Higgs boson

is 124 or 126 or ? GeV

with SM couplings,

with non-SM couplings,

is not seen at LHC,

→ { Higgs is stable.
Higgs does not exist.

} → **gauge-Higgs**

Discovery

of

un-discovery

of

the Higgs boson

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It's no surprise

in gauge-Higgs unification.

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Gauge-Higgs Unification

A_M

4-dim. components A_μ	extra-dim. component A_y
$\cup$	$\cup$
4D gauge fields γ , W , Z	4D Higgs fields H Aharonov-Bohm phase
	⇓
	Symmetry breaking Hosotani mechanism

Higgs boson as an AB phase in extra dim

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

$$\hat{\theta}_H(x) = \theta_H + \frac{H(x)}{f_H}$$

$$\theta_H = \frac{\langle \mathrm{Higgs} \rangle}{f_H}$$

⇒

- symmetry breaking
- masses for quarks/leptons/W,Z

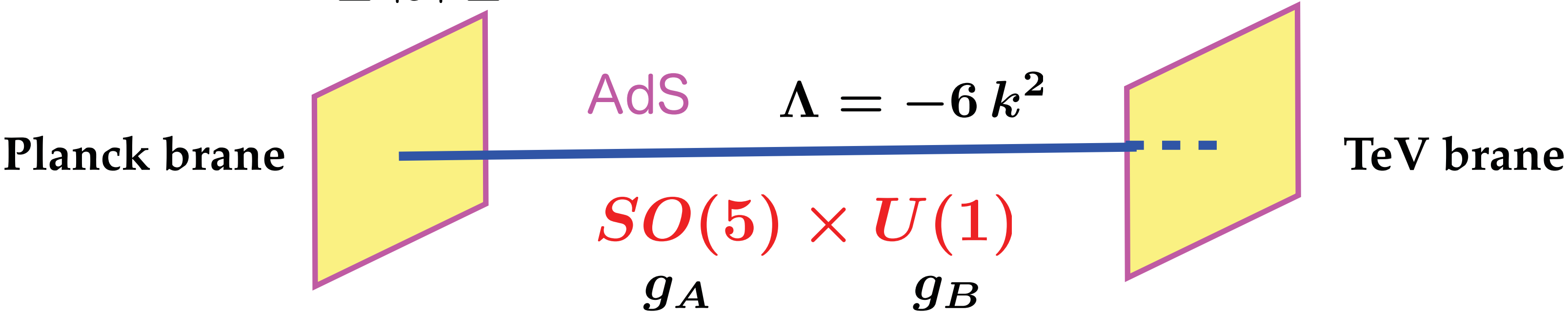
$$\theta_H \sim \theta_H + 2\pi$$

differs from SM.

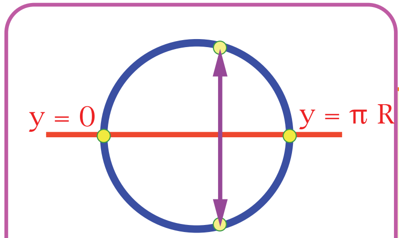
$SO(5) \times U(1)$ in Randall-Sundrum warped space

$$ds^2 = e^{-2k|y|} dx_\mu dx^\mu + dy^2$$
$$0 \le |y| \le L = \pi R$$

Agashe, Contino, Pomarol, 2005
YH, Oda, Ohnuma, Sakamura 2008
YH, Noda, Uekusa 2009



brane fermions — **quarks, leptons**
brane scalar



Orbifold BC

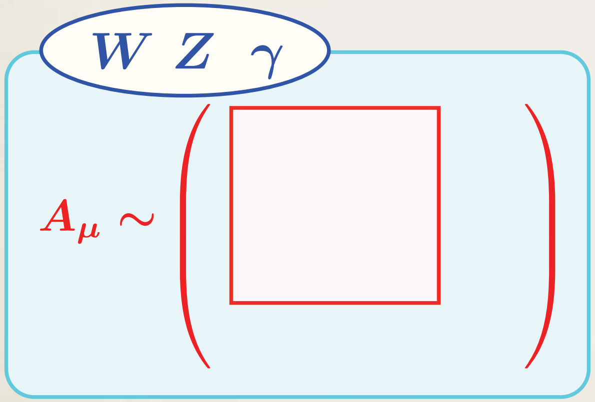
$$\begin{pmatrix} A_\mu \\ A_y \end{pmatrix} (x, -y) = P_0 \begin{pmatrix} A_\mu \\ -A_y \end{pmatrix} (x, y) P_0^\dagger$$

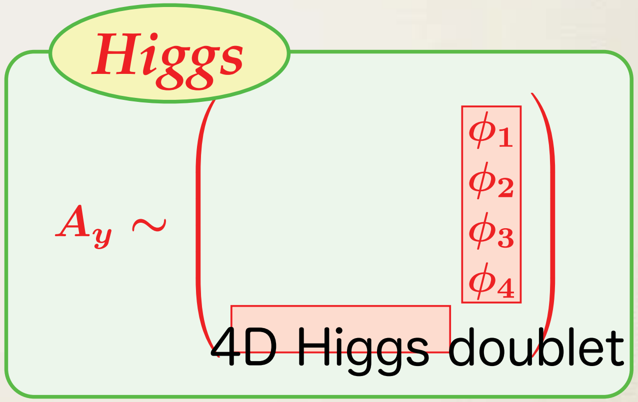
$$\begin{pmatrix} A_\mu \\ A_y \end{pmatrix} (x, \pi R - y) = P_1 \begin{pmatrix} A_\mu \\ -A_y \end{pmatrix} (x, \pi R + y) P_1^\dagger$$

4D gauge bosons and Higgs

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

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





brane scalar $SO(4) \times U(1) \rightarrow SU(2)'_L \times U(1)'$

$\neq SU(2)_L \times U(1)_Y$

$\theta_H \neq 0$ $\rightarrow U(1)_{EM}$

parameters

RS: k , $z_L = e^{kL}$

g_A , g_B

fermions

inputs

α_w , $\sin^2\theta_W$

m_Z

quark/lepton masses

⇒ One free parameter z_L

Warped space

☺ Planck scale — input

$m_{\rm KK}$ TeV scale — output

Weak scale m_W — input

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

$kL = 30 \sim 40$ for $z_L = 10^{13} \sim 10^{17}$

☺ Symmetry breaking

Effective interactions

in SM

$f_H \sin\hat\theta_H \to v + H$

$$\mathcal{L}_{\rm eff} \sim \; -\Big(\frac{1}{2} g f_H \sin\hat\theta_H\Big)^2 \Big\{ W_\mu^\dagger W^\mu + \frac{1}{2\cos^2\theta_W} Z_\mu Z^\mu \Big\}$$

$$- y_f f_H \sin\hat\theta_H \, \overline{\psi}_f \psi_f$$

$$\hat\theta_H = \theta_H + \frac{H}{f_H} \qquad f_H = \frac{2}{\sqrt{kL}} \frac{m_{KK}}{\pi g}$$

WWH
ZZH
Yukawa
= SM × $\cos\theta_H$

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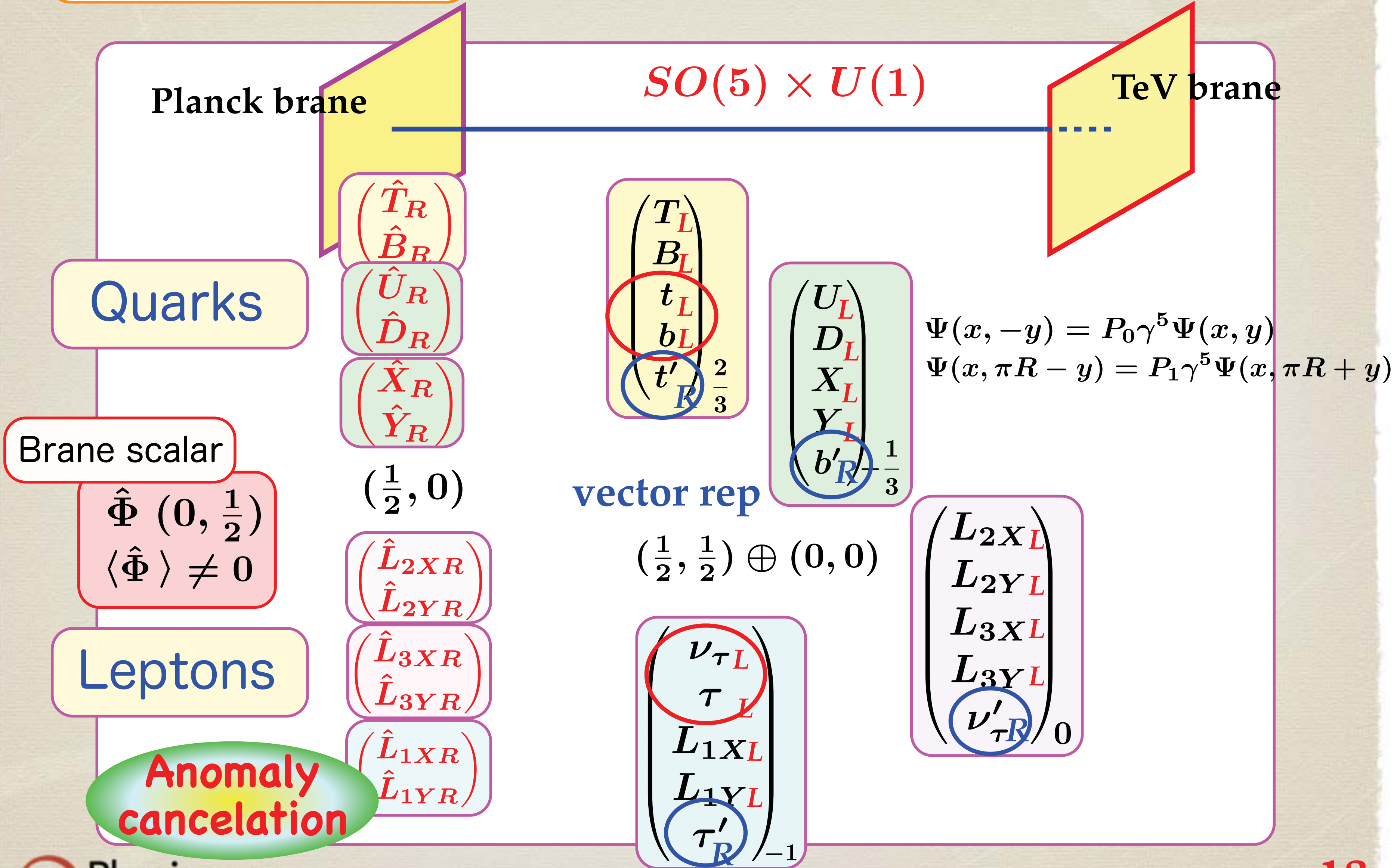
Matter content

YH, Oda, Ohnuma, Sakamura 2008

YH, Noda, Uekusa 2009



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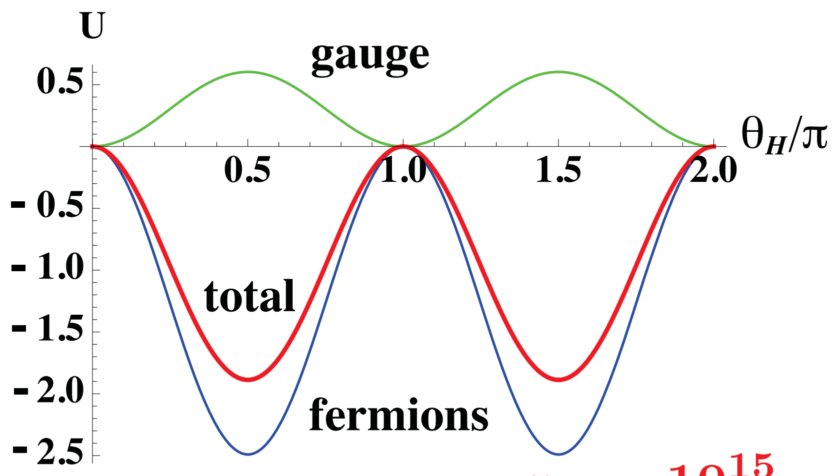
EW symmetry breaking by Hosotani mechanism

$V_{\rm eff}(\theta_H)/m_{\rm KK}^4$



$z_L = 10^{15}$

$\Rightarrow$ $\theta_H = \dfrac{\pi}{2}$

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

$m_H = 135\,{\rm GeV}\ (z_L = 10^{15})$

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

H parity

YH, Ko, Tanaka, 2009

YH, Tanaka, Uekusa, 2010

$$\theta_H + \frac{H}{f_H} = \frac{\pi}{2} + \frac{H}{f_H} \longrightarrow \frac{\pi}{2} - \frac{H}{f_H}$$

$$H : -$$

$$\text{all other SM particles} : +$$

Stable Higgs

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H parity

$$SO(5): \quad SO(4) \simeq SU(2)'_L \times SU(2)'_R \quad SO(5)/SO(4)$$

$$\{ T^{\alpha} \} = \{ T^{a_L}, T^{a_R}, \quad T^{\hat{a}}, T^{\hat{4}} \}$$

$$P_H: \quad SU(2)'_L \leftrightarrow SU(2)'_R \qquad T^{\hat{4}} \rightarrow -T^{\hat{4}}$$

↔ **Agashe, Contino, Da Rold, Pomarol 2006**

T parameter $Zb\bar{b}$

Where is $SU(2)_L \times U(1)_Y$ in $SO(5) \times U(1)$?

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

B.C. $\rightarrow SO(4) \times U(1)_X \simeq SU(2)'_L \times SU(2)'_R \times U(1)_X$

Brane scalar $\langle \hat{\Phi} \rangle \neq 0$ $\rightarrow SU(2)'_L \times U(1)'$ $\neq SU(2)_L \times U(1)_Y$

$\theta_H \neq 0$ $\rightarrow U(1)_{EM}$

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SO(5) $\{\, T_L^a,\ T_R^a,\ \hat{T}^a,\ \hat{T}^4 \,\}$ $\{\, I_L^a,\ I_R^a,\ \hat{I}^a,\ \hat{I}^4 \,\}$

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

$$\begin{pmatrix} I_L^a \\ I_R^a \end{pmatrix} = \frac{1 \pm \cos\theta_H}{2} T_L^a + \frac{1 \mp \cos\theta_H}{2} T_R^a \mp \frac{\sin\theta_H}{\sqrt{2}} \hat{T}^a$$

Note: $T_L^a + T_R^a = I_L^a + I_R^a$: custodial $SU(2)_V$

$W^\pm$ couples to $I_L^1 \pm i I_L^2$

Z $c_W I_L^3 - s_W Q_Y$ // $c_\phi Q_X + s_\phi I_R^3$, $s_\phi = t_W$

γ $Q_{EM} = I_L^3 + I_R^3 + Q_X = T_L^3 + T_R^3 + Q_X$

Higgs $\hat{I}^4 = \hat{T}^4$

YH, Sakamura 2007
Contino, Marzocca, Pappadopulo, Rattazzi 2011
Hatanaka, YH, Shimotani

$$W_\mu^\pm \qquad W_\mu^1,\ W_\mu^2 \quad \Big\} \quad SU(2)_L$$

$$\begin{pmatrix} Z_\mu \\ \gamma_\mu \\ \tilde{Z}_\mu \end{pmatrix} \qquad \begin{pmatrix} W_\mu^3 \\ B_\mu^X \\ W_\mu'^3 \end{pmatrix} \qquad \begin{matrix} \\ U(1)_X \\ SU(2)_R \end{matrix}$$

Furthermore

$$\sum W_\mu^{(n)}(x)\Big\{C(z;\lambda_W^{(n)})I_L^+(\theta_H) - \frac{\sin\theta_H}{\sqrt{2}}[\hat{S}(z;\lambda_W^{(n)}) - C(z;\lambda_W^{(n)})]\hat{T}^+\Big\}$$

All KK modes participate.

Collider signatures

◇ $\theta_H = \frac{1}{2}\pi$ ⇨ Absence of single-Higgs production

Higgs pair production

Higgs = missing energy, momentum

hard to confirm at LHC/ILC

← $\nu, \bar{\nu}$ **background**

Cheung, Song, 1004.2783, Alves, 1008.0016
YH, Tanaka, Uekusa, 1103.6076

Gauge couplings precision measurements

- Forward-backward asymmetry in $e^+e^- \to Z \to \ell\bar{\ell}\ ,\ q\bar{q}$
- Z-decay branching fractions

	No. data	SM	$z_L : 10^{15}$	$z_L : 10^{10}$	$z_L : 10^5$
$\sin^2\theta_W$		0.2312	0.2309	0.2303	0.2284
$\chi^2(AFB)$	6	10.8	6.3	6.4	7.1
$\chi^2(Z\ decay)$	8	13.6	16.5	37.7	184.5

⇒ $z_L \geq 10^{15}$

YH, Tanaka, Uekusa, 2011

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KK $Z^{(1)}$ & $\gamma^{(1)}$

$Z^{(1)}$

z_L	10^5	10^{15}
m	653	1130
Γ	104	422

in GeV

$\gamma^{(1)}$

z_L	10^5	10^{15}
m	678	1144
Γ	446	1959

in GeV

Large widths

Larger couplings for right-handed quarks and lepton

$\sim \quad \times 10$ "strong couplings at TeV"

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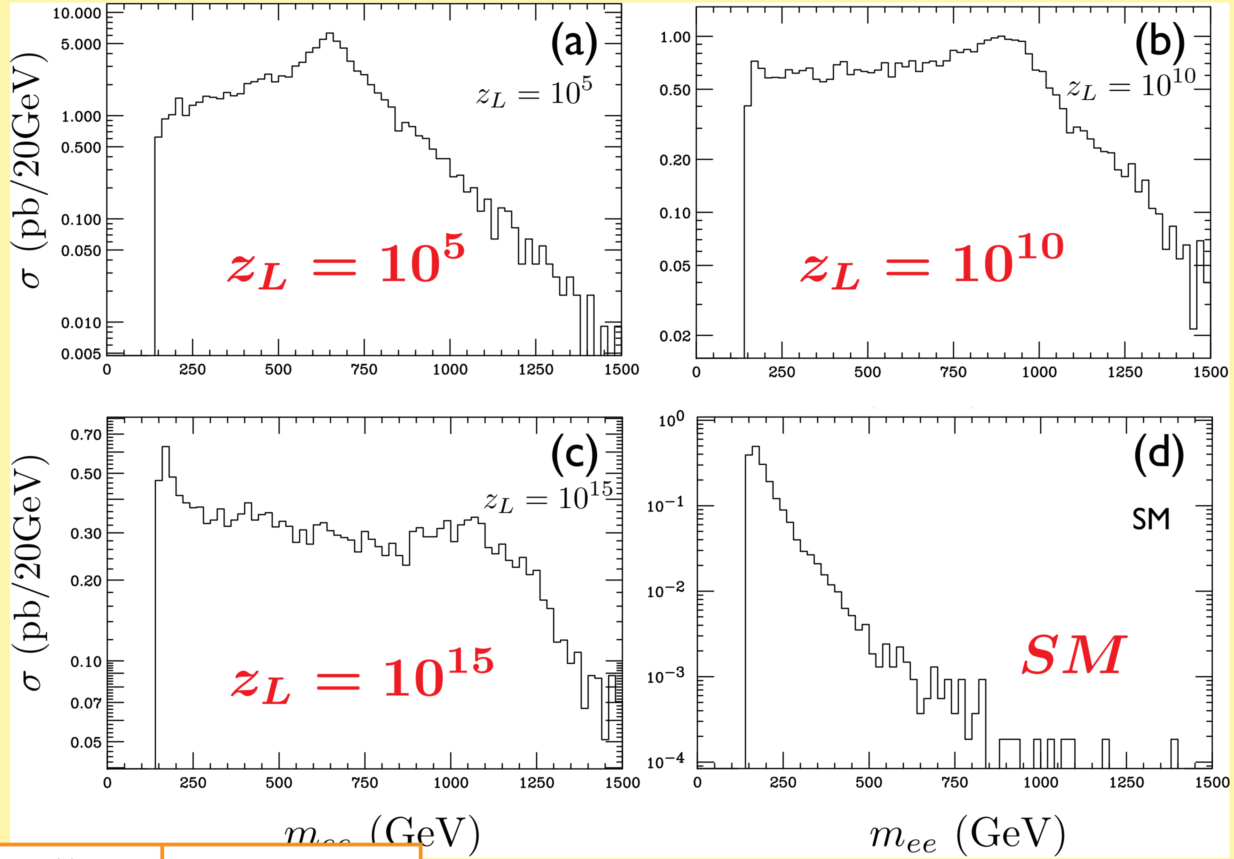
LHC (3.5 + 3.5 TeV)

$$q\bar{q} \to Z^{(1)}, \gamma^{(1)} \to e^+e^-$$



$Z^{(1)}$

z_L	10^5	10^{15}
m	653	1130
Γ	104	422

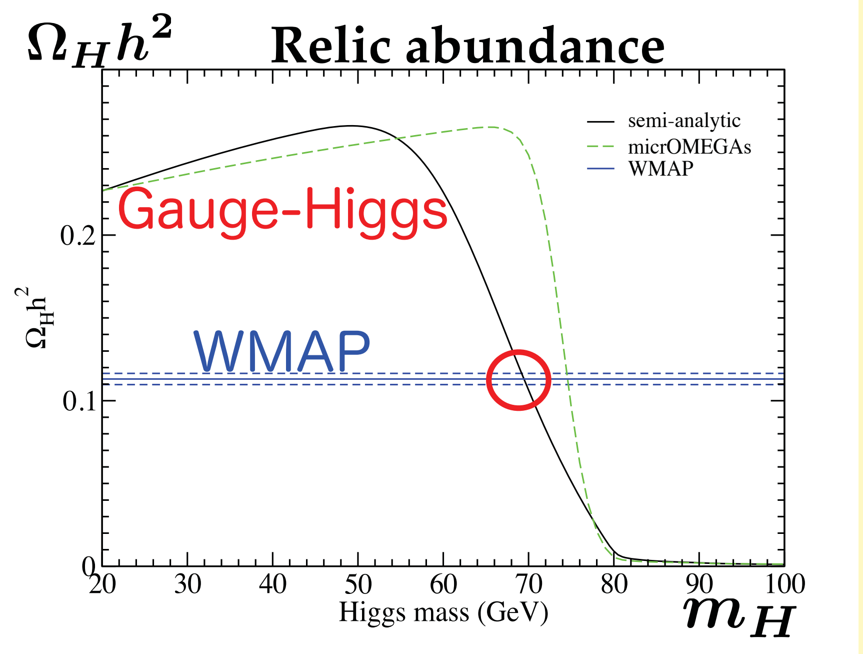
in GeV

Large BG from $\gamma^{(1)}$

⇒ $z_L > 10^{15}$

Stable Higgs ⇒ Dark Matter

YH, Ko, Tanaka, 2009



WMAP data

⇓

$$m_H = 70 \sim 75\,\text{GeV}$$

z_L	10^5	10^{10}	10^{15}
m_H	72 GeV	108	135

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Collider signatures → $z_L > 10^{15}$ → $m_H = 135\,\mathrm{GeV}$

Dark matter → $m_H = 70 \sim 75\,\mathrm{GeV}$ → $z_L \sim 10^5$

$m_H = 70 \sim 75\,\mathrm{GeV}$ compatible with $z_l > 10^{15}$?

Yes

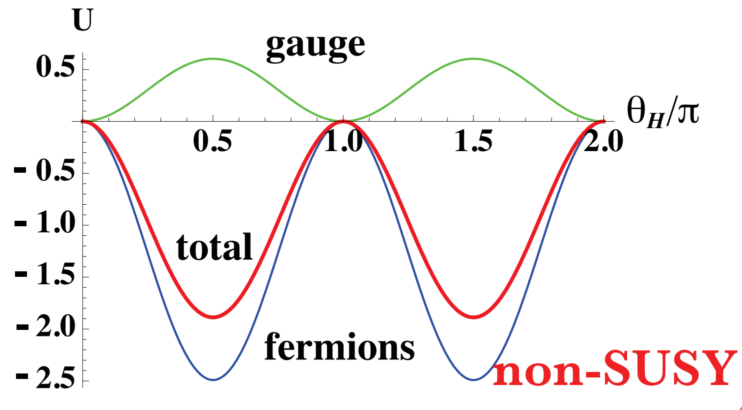
Hatanaka, YH, 2011

SUSY

exact → $m_H = 0$

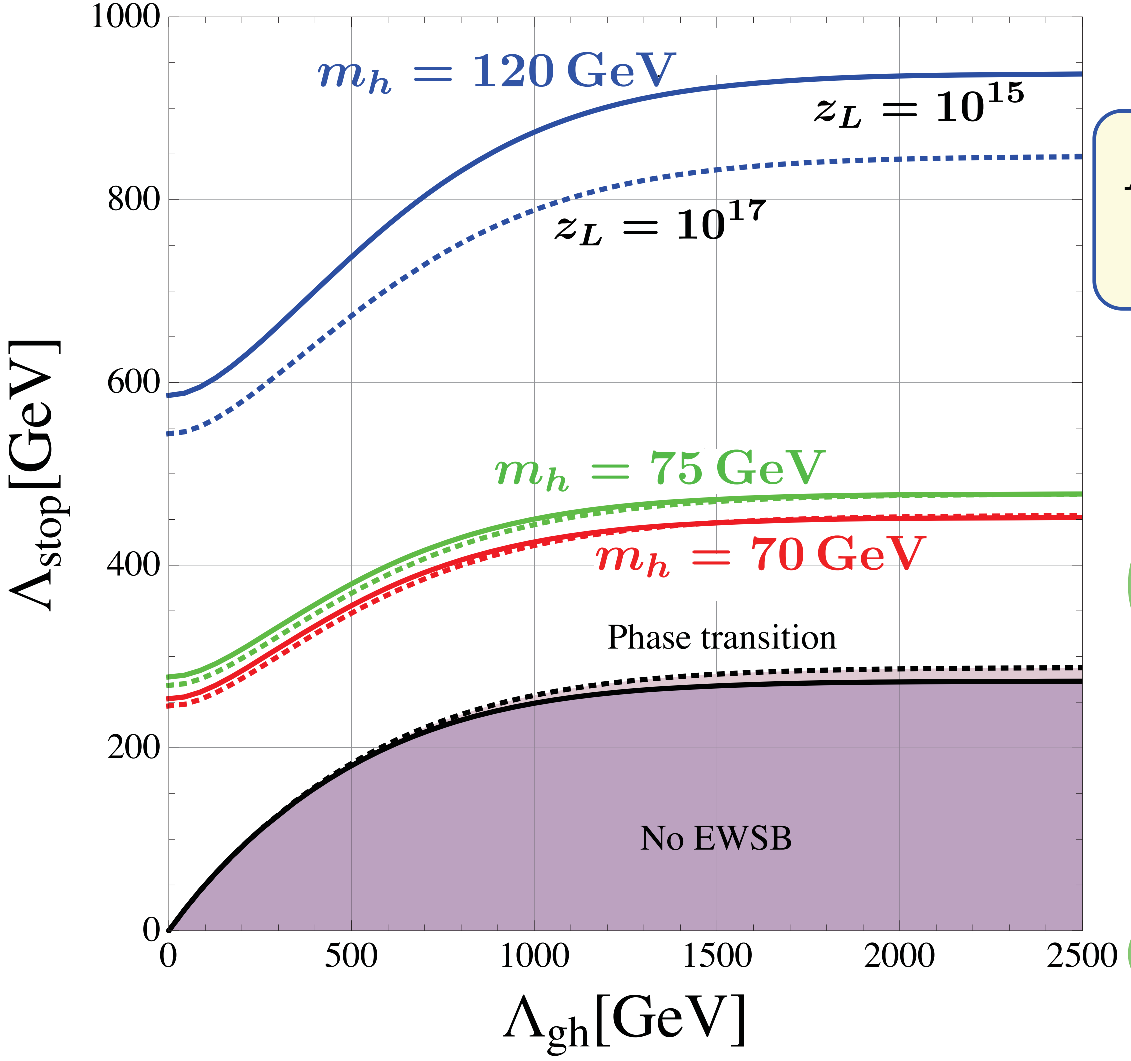
broken → $70 \sim 75\,\mathrm{GeV}$

$$V_{\rm eff} = \pm\frac{1}{2}\int\frac{d^4p}{(2\pi)^4}\sum_n \ln\left\{p^2 + m_n(\theta_H)^2\right\}$$



SUSY

$W, Z, Higgs$	$\tilde{W}, \tilde{Z}, \tilde{H}iggs$
$\{\ m_n\ \}$	$\tilde{m}_n = \sqrt{m_n^2 + \Lambda_{\rm gh}^2}$
t	$\tilde{t}$
$\{\ m_n\ \}$	$\left\{\ \tilde{m}_n = \sqrt{m_n^2 + \Lambda_{stop}^2}\ \right\}$



$$\Lambda_{\rm stop} = 450 - 475 \,\text{GeV}$$
$$\Lambda_{\rm gh} > 1 \,\text{TeV}$$

stop mass

480 - 505 GeV

for $m_h = 70 \sim 75$ GeV

800 - 900 GeV

for $m_h \sim 120$ GeV

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Summary

If the Higgs boson

is 124 or 126 or ? GeV with non-SM couplings,

or

is not seen at LHC (as Higgs is stable),

⇒ **gauge-Higgs** (extra dimensions).