Gauge-Higgs Unification
H parity and LHC/ILC signals

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Gauge-Higgs Unification in 5 dimensions

4-dim. components A_μ

extra-dim. component A_y

Hosotani 1983, 1989
Davies, McLachlan 1988, 1989
Hatanaka, Inami, Lim, 1998

AB phase in extra dim

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

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

Higgs field = gauge field

stable Higgs
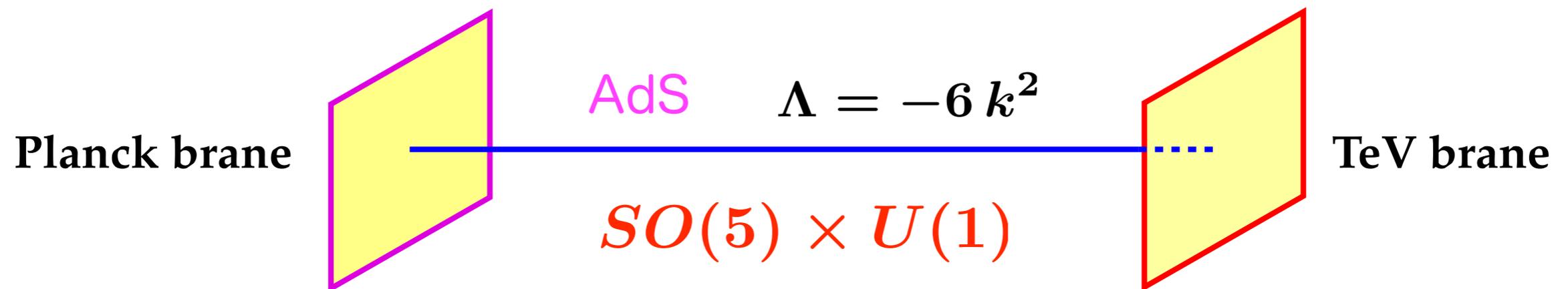
precision measurements

KK modes

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

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

$$0 \leq |y| \leq L = \pi R$$

Agashe, Contino, Pomarol 2005
Hosotani, Sakamura 2006
Medina, Shah, Wagner 2007

Planck brane

AdS $\quad \Lambda = -6\,k^2$

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

TeV brane

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

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

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

W Z γ

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

Higgs

$$A_y \sim \begin{pmatrix} & & \phi_1 \\ & & \phi_2 \\ & & \phi_3 \\ & & \phi_4 \\ & & \end{pmatrix} \qquad \Phi = \begin{bmatrix} \phi_1 + i\phi_2 \\ \phi_4 - i\phi_3 \end{bmatrix}$$

4D Higgs doublet

Matter content

Planck brane

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

TeV brane

Quarks

$$\begin{pmatrix} \hat{T}_R \\ \hat{B}_R \end{pmatrix}$$

$$\begin{pmatrix} \hat{U}_R \\ \hat{D}_R \end{pmatrix}$$

$$\begin{pmatrix} \hat{X}_R \\ \hat{Y}_R \end{pmatrix}$$

Brane scalar

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

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

$$\begin{pmatrix} T_L \\ B_L \\ t_L \\ b_L \\ t' \end{pmatrix}_{R \ \frac{2}{3}}$$

$$\begin{pmatrix} U_L \\ D_L \\ X_L \\ Y_L \\ b'_R \end{pmatrix}_{-\frac{1}{3}}$$

$\Psi(x, -y) = P_0 \gamma^5 \Psi(x, y)$

vector rep

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

$$\begin{pmatrix} \hat{L}_{2XR} \\ \hat{L}_{2YR} \end{pmatrix}$$

$$\begin{pmatrix} \hat{L}_{3XR} \\ \hat{L}_{3YR} \end{pmatrix}$$

$$\begin{pmatrix} \hat{L}_{1XR} \\ \hat{L}_{1YR} \end{pmatrix}$$

Leptons

$$\begin{pmatrix} \nu_{\tau L} \\ \tau_L \\ L_{1XL} \\ L_{1YL} \\ \tau'_R \end{pmatrix}_{-1}$$

$$\begin{pmatrix} L_{2XL} \\ L_{2YL} \\ L_{3XL} \\ L_{3YL} \\ \nu'_{\tau R} \end{pmatrix}_0$$

Matter content

YH, Noda, Uekusa 2009

Planck brane

TeV brane

$$\begin{pmatrix} \hat{T}_R \\ \hat{B}_R \end{pmatrix}$$

$$\begin{pmatrix} \hat{U}_R \\ \hat{D}_R \end{pmatrix}$$

$$\begin{pmatrix} \hat{X}_R \\ \hat{Y}_R \end{pmatrix}$$

$$\begin{pmatrix} T_L \\ B_L \\ t_L \\ b_L \\ t'_R \end{pmatrix}_{\frac{2}{3}}$$

$$\begin{pmatrix} U_L \\ D_L \\ X_L \\ Y_L \\ b'_R \end{pmatrix}_{-\frac{1}{3}}$$

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

$\langle \hat{\Phi} \rangle \neq 0$

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

$$\left(\frac{1}{2}, \frac{1}{2} \right) \oplus (0, 0)$$

$$\begin{pmatrix} \hat{L}_{2XR} \\ \hat{L}_{2YR} \end{pmatrix}$$

$$\begin{pmatrix} \hat{L}_{3XR} \\ \hat{L}_{3YR} \end{pmatrix}$$

$$\begin{pmatrix} \hat{L}_{1XR} \\ \hat{L}_{1YR} \end{pmatrix}$$

$$\begin{pmatrix} L_{2X\,L} \\ L_{2Y\,L} \\ L_{3X\,L} \\ L_{3Y\,L} \\ \nu'_{\tau R} \end{pmatrix}_0$$

$$\begin{pmatrix} \nu_{\tau L} \\ \tau_L \\ L_{1X L} \\ L_{1Y L} \\ \tau'_R \end{pmatrix}_{-1}$$

SM spectrum

Anomaly cancellation

Effective interactions

AB phase $\quad \hat{\theta}_H = \theta_H + \dfrac{H}{f_H} \qquad f_H = \dfrac{2}{\sqrt{kL}} \dfrac{m_{KK}}{\pi g}$

$$\mathcal{L}_{\mathrm{eff}} \sim \quad -V_{\mathrm{eff}}(\hat{\theta}_H)$$

YH 1983, Oda-Weiler 2005

Falkowski 2007

$$-m_W(\hat{\theta}_H)^2 W_\mu^\dagger W^\mu - \frac{1}{2} m_Z(\hat{\theta}_H)^2 Z_\mu Z^\mu$$

Sakamura-YH 2006, 2007

$$-m_f(\hat{\theta}_H)\,\overline{\psi}_f \psi_f$$

YH-Kobayashi 2008

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

Gauge-Higgs   **SM**

$$m_W(\hat{\theta}_H) \sim \frac{1}{2} g f_H \sin \hat{\theta}_H \qquad \frac{1}{2} g(v+H)$$

$$m_Z(\hat{\theta}_H) \sim \frac{1}{2\cos\theta_W} g f_H \sin \hat{\theta}_H \qquad \frac{1}{2\cos\theta_W} g(v+H)$$

periodic
nonlinear

$$m_f(\hat{\theta}_H) \sim y_f f_H \sin \hat{\theta}_H \qquad y_f(v+H)$$

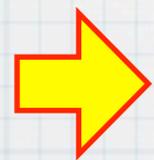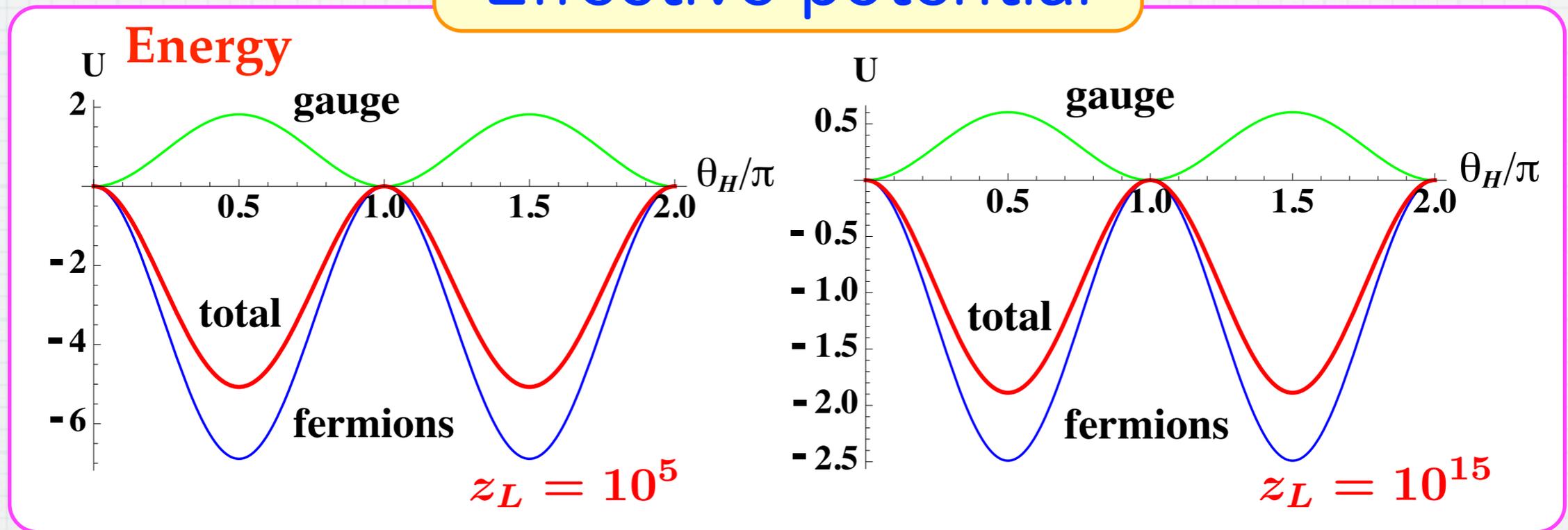$$\hat{\theta}_H = \theta_H + \frac{H}{f_H}$$

⟹

| WWH ZZH Yukawa | $= SM \times \cos\theta_H$ |

| WWHH ZZHH | $= SM \times \cos 2\theta_H$ |

Effective potential

EW symmetry breaking by Hosotani mechanism

$$m_H : 70\,\mathrm{GeV} \sim 135\,\mathrm{GeV}$$

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

WWH, ZZH, Yukawa = 0

LEP2 bound is evaded.

H parity

$$H : -$$
all other SM particles : $+$

Proof (1) **YH, Ko, Tanaka, 0908.0212**

Proof (2) **YH, Tanaka, Uekusa, 1010.6135**

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

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

Algebra is invariant under

$$\Rightarrow \{\, T'^\alpha \,\} = \quad \{\, T^{a_R}\,,\, T^{a_L}\,, \quad T^{\hat{a}}\,,\, -T^{\hat{4}} \,\}$$

$$T'^\alpha = \Omega_H T^\alpha \Omega_H^{-1} \qquad \Omega_H = \begin{pmatrix} 1 & & & & \\ & 1 & & & \\ & & 1 & & \\ & & & -1 & \\ & & & & 1 \end{pmatrix}$$

$$P_H : \quad \begin{aligned} SU(2)_L &\leftrightarrow SU(2)_R \\ T^{\hat{4}} &\rightarrow -T^{\hat{4}} \end{aligned}$$

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

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

bulk action   invariant under $A_M \rightarrow \Omega_H A_M \Omega^{-1}$

⟹ P_H -inv

brane interactions P_H odd fields do not couple.

⟹ Theory is H parity invariant.

$$P_H = \begin{cases} + & W^{(n)}, Z^{(n)}, \gamma^{(n)}, gluon^{(n)}, q^{(n)}, \ell^{(n)}, \dots \\[2em] - & H^{(n)}, W'^{(n)}, Z'^{(n)}, q'^{(n)}, \ell'^{(n)}, \dots \end{cases}$$
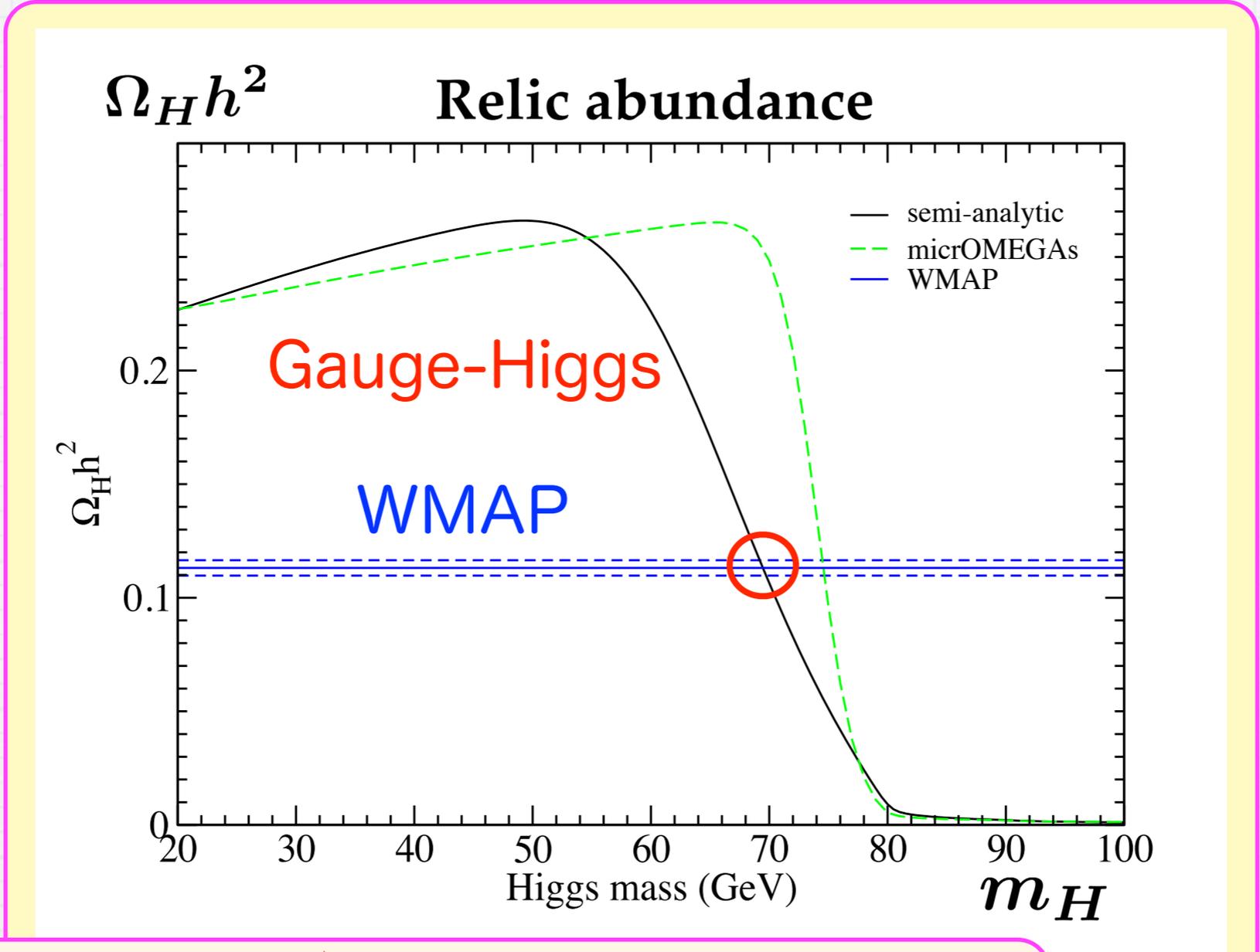
Higgs field :   the lightest P_H-odd field.

WWH, ZZH, Yukawa = 0

Stable

Stable Higgs = Dark Matter

Relic abundance

$\Omega_H h^2$

Gauge-Higgs

WMAP

- semi-analytic
- micrOMEGAs
- WMAP

m_H

WMAP data $\Rightarrow$ $m_H \sim 70\,\mathrm{GeV}$

$T_f \sim 3\,\mathrm{GeV}$

$HH \to b\bar{b}$ 34%
$\to WW$ 61%

z_L	10^5	10^{10}	10^{15}
m_H	$72\,\mathrm{GeV}$	108	135

How to see the Higgs bosons at LHC/ILC

Production:
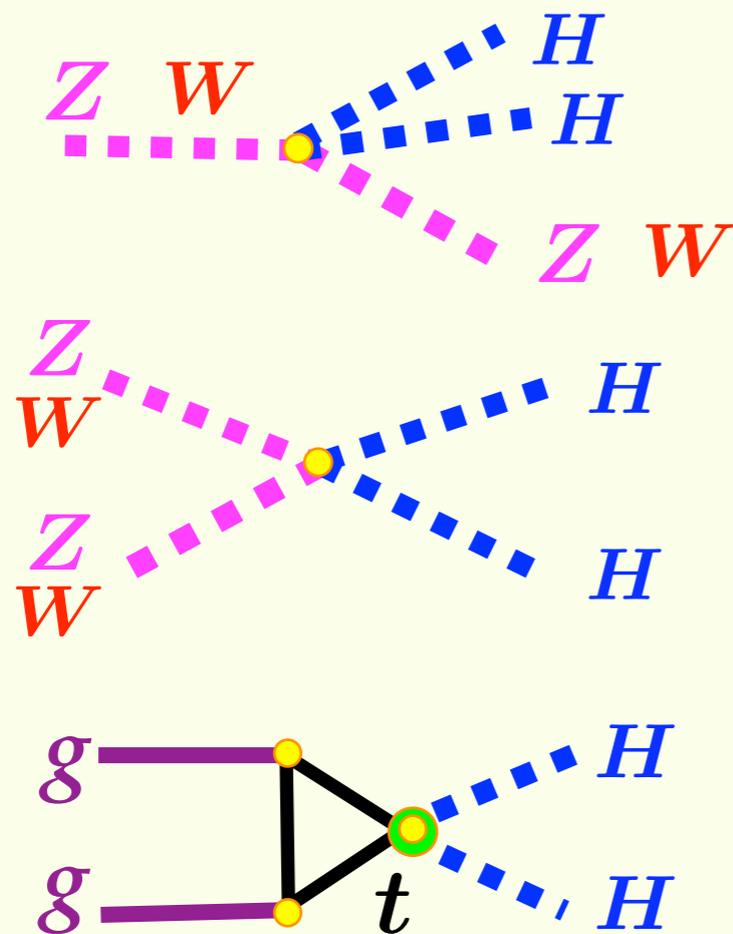
Stable Higgs boson

=

missing energy,

missing momentum

Cheung, Song, 1004.2783

Alves, 1008.0016

$\nu, \bar{\nu}$ **background**

hard at LHC, possible at ILC

Gauge couplings precision measurements

EW universality is slightly broken in 4D.

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

Z-decay widths (branching ratios)

	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	10.8335	6.3044	6.4345	7.1251
$\chi^2(Z \, decay)$	8	13.6264	16.5153	37.6908	184.468

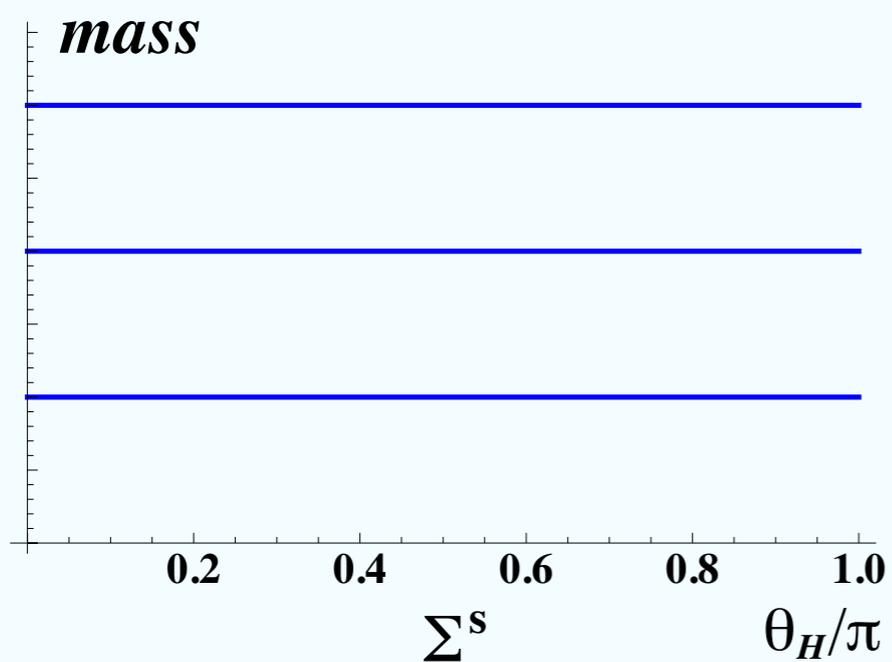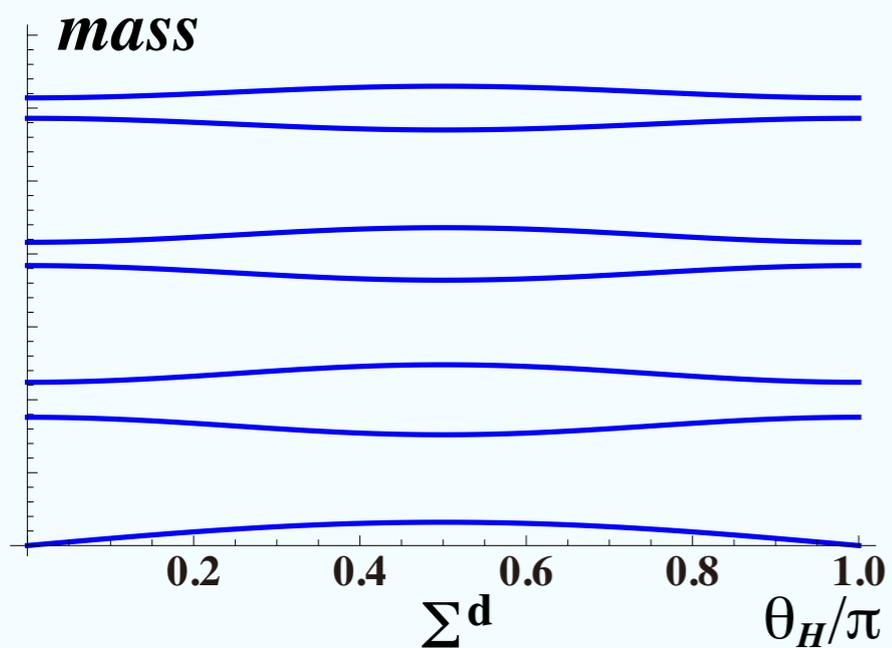$$z_L \geq 10^{15}$$

KK modes

spectrum and production

YH, Tanaka, Uekusa, in preparation

1st KK modes

	$z_L : 10^{15}$	$z_L : 10^5$
m_{KK}	1466	836
$Z^{(1)}$	1130	659
$gluon^{(1)}$	1144	678
$u^{(1)}$	1361	1037
$t^{(1)}$	1121	634

in GeV

couplings/g_w $z_L = 10^{15}$	Z	$Z^{(1)}$
u_L	0.3485	−0.0400
t_L	0.3219	−0.2058
d_L	−0.4260	0.0488
b_L	−0.4265	−0.5581
u_R	−0.1562	−1.6557
t_R	−0.1835	−1.4668
d_R	0.0781	0.8279
b_R	0.0781	0.7227
e_L	−0.2710	0.0311
μ_L	−0.2710	0.0310
e_R	0.2344	2.5161
μ_R	0.2343	2.4201

Stronger for right-handed

KK $Z^{(1)}$

z_L	10^{15}	10^5
m	1130	653
Γ	385	94

in GeV

at Tevatron

$$p\,\bar{p} \to Z' \to e^+ e^-$$

signal

2 pb   for $z_L = 10^5$

0.3 pb 10^{10}

0.08 pb 10^{15}

Consistent for $z_L \geq 10^{15}$

KK $gluon^{(1)}$

Strong couplings for right-handed quarks

Couplings/g_s

u_R	6.32
c_R	6.04
t_R	5.60

In naive perturbation theory $\Gamma \sim 13\, m$

Decays into
light and heavy, right-handed quarks.

Summary

$SO(5) \times U(1)$ *gauge-Higgs unification*

Higgs naturally becomes stable.

Dark Matter＝Higgs $\Rightarrow m_H \sim 70\,\text{GeV} \Rightarrow z_L \sim 10^5$
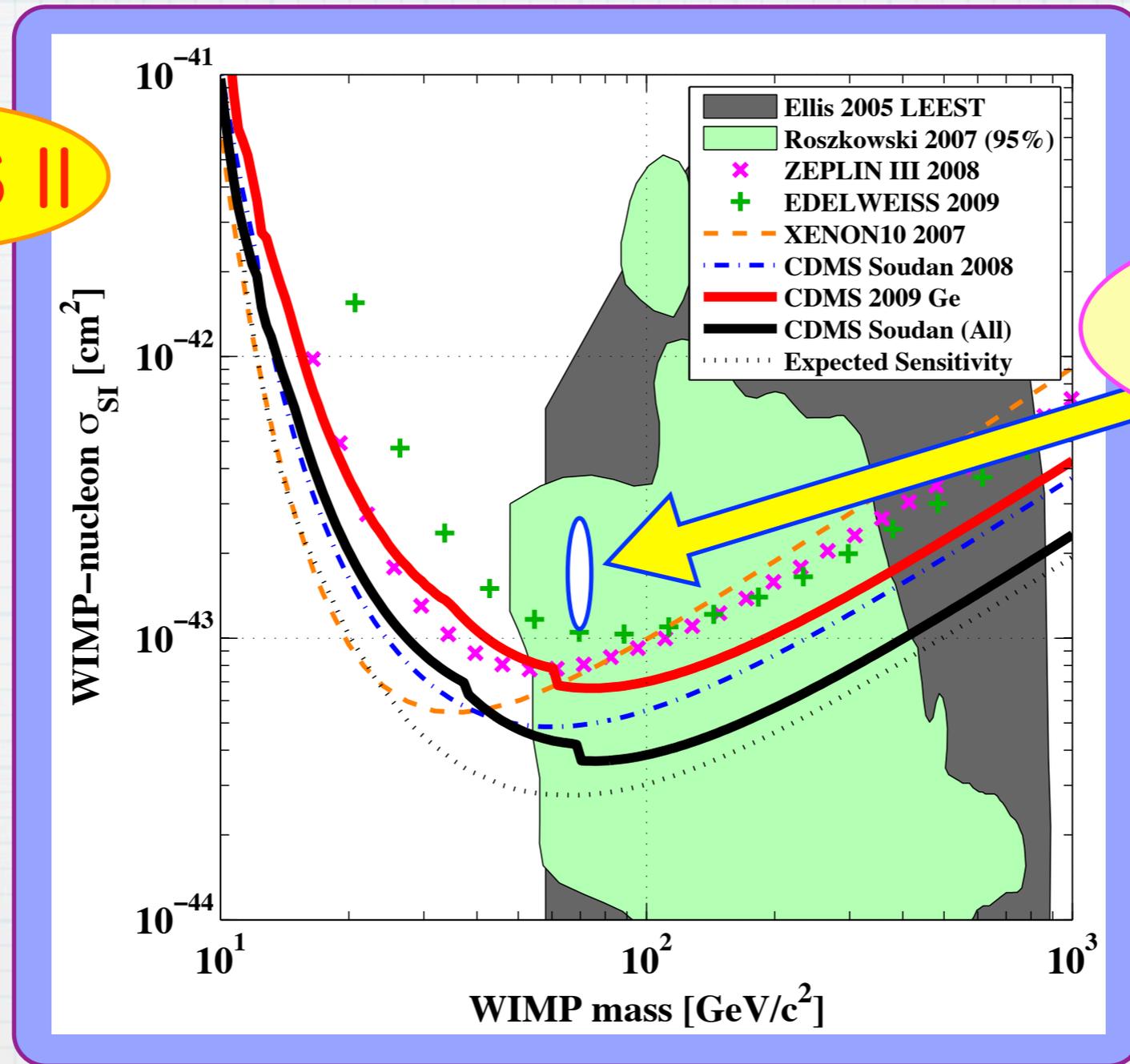
EW precision data (gauge couplings)
$$\Rightarrow z_L \geq 10^{15}$$

KK modes at Tevatron/LHC
$$\Rightarrow z_L \geq 10^{15}$$

Direct detection rate

CDMS II

GHU
stable Higgs

many uncertainties

Legend (left plot):
- Ellis 2005 LEEST
- Roszkowski 2007 (95%)
- ZEPLIN III 2008
- EDELWEISS 2009
- XENON10 2007
- CDMS Soudan 2008
- CDMS 2009 Ge
- CDMS Soudan (All)
- Expected Sensitivity

Axes (left plot): WIMP-nucleon σ_{SI} [cm^2] vs WIMP mass [GeV/c^2]

Legend (right plot):
- DAMA/LIBRA
- CDMS excluded
- XENON10 excl

Axis (right plot): WIMP-mass split

arXiv:0912.3592 [astro-ph.CO]   18 Dec 2009