Extra Dimensions

Clues at LHC

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Introduction : Extra dimensions

The idea is old.

Kaluza (1921), Klein (1926)

Unification in 1980s
EW -> GUT -> ....

11-dim SUGRA
Superstrings

No realistic model in 80'

Explains data.
Gives predictions which can be tested.

Provides deeper understanding.

Clarifies & simplifies the laws of nature.

Success in 1980-2010

Unified theory
Large symmetry

↓

Spontaneous
symmetry breaking

↓

Our world
Small symmetry

Dark matter

Higgs

LHC …

Extra dimensions

Models of extra dimensions

$M^4 \times S^1$

$$\phi(x,y) = \sum \phi_n(x)\ e^{i(n+\alpha)y/R}$$

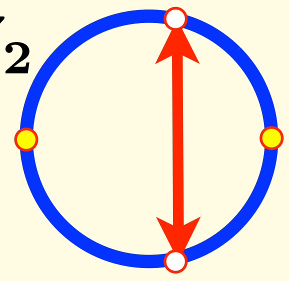
$$m_n^2 = \frac{(n+\alpha)^2}{R^2}$$

KK towers

Chiral fermions

- Topology in $M^4 \times K$
- Monopole on $M^4 \times S^2$

S^1/Z_2



- Orbifolds $M^4 \times (S^1/Z_2)$, RS warped space

$$\phi^a(x,-y) = P_0^{ab}\phi^b(x,y) \quad , \quad P_0^2 = 1$$

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

Symmetry breaking

by 5D Higgs

UED: the same as SM at low energies

by boundary conditions

Higgsless -- soft breaking

by dynamics

gauge-Higgs unification

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

Higgs boson as an AB phase in extra dim

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

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

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

EW sym breaking

H parity & stable Higgs

Dark matter

precision measurements

Higgs production

KK Z production

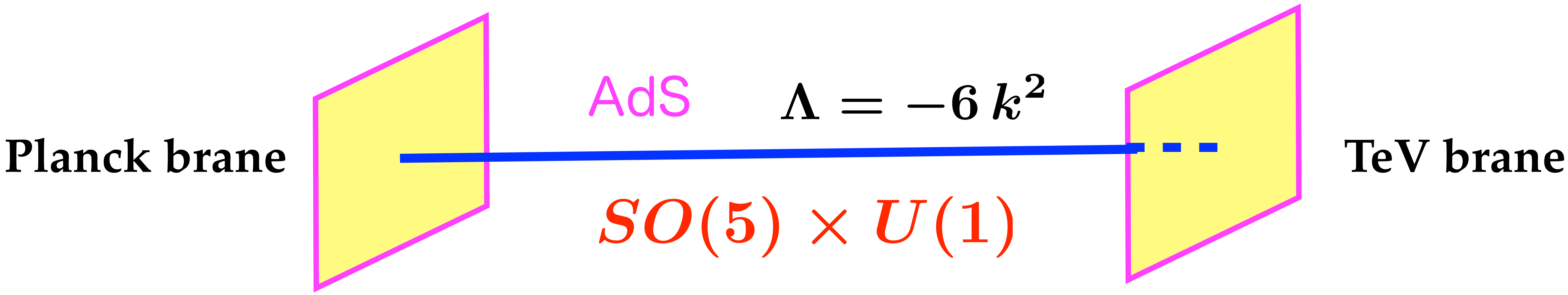
KK gluon ...

$SO(5) \times U(1)$ 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
Hosotani, Sakamura 2006
Medina, Shah, Wagner 2007



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

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

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

W Z γ

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

Higgs

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

4D Higgs doublet

Matter content

YH, Noda, Uekusa 2009

(YH, Oda, Ohnuma, Sakamura 2008)

Planck brane

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

TeV brane

Quarks

$\begin{pmatrix} \hat{T}_R \\ \hat{B}_R \end{pmatrix}$ $\begin{pmatrix} \hat{U}_R \\ \hat{D}_R \end{pmatrix}$ $\begin{pmatrix} \hat{X}_R \\ \hat{Y}_R \end{pmatrix}$

$\begin{pmatrix} T_L \\ B_L \\ t_L \\ b_L \\ t'_R \end{pmatrix}_{\frac{2}{3}}$ $\begin{pmatrix} U_L \\ D_L \\ X_L \\ Y_L \\ b'_R \end{pmatrix}_{-\frac{1}{3}}$

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

Brane scalar

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

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

vector rep

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

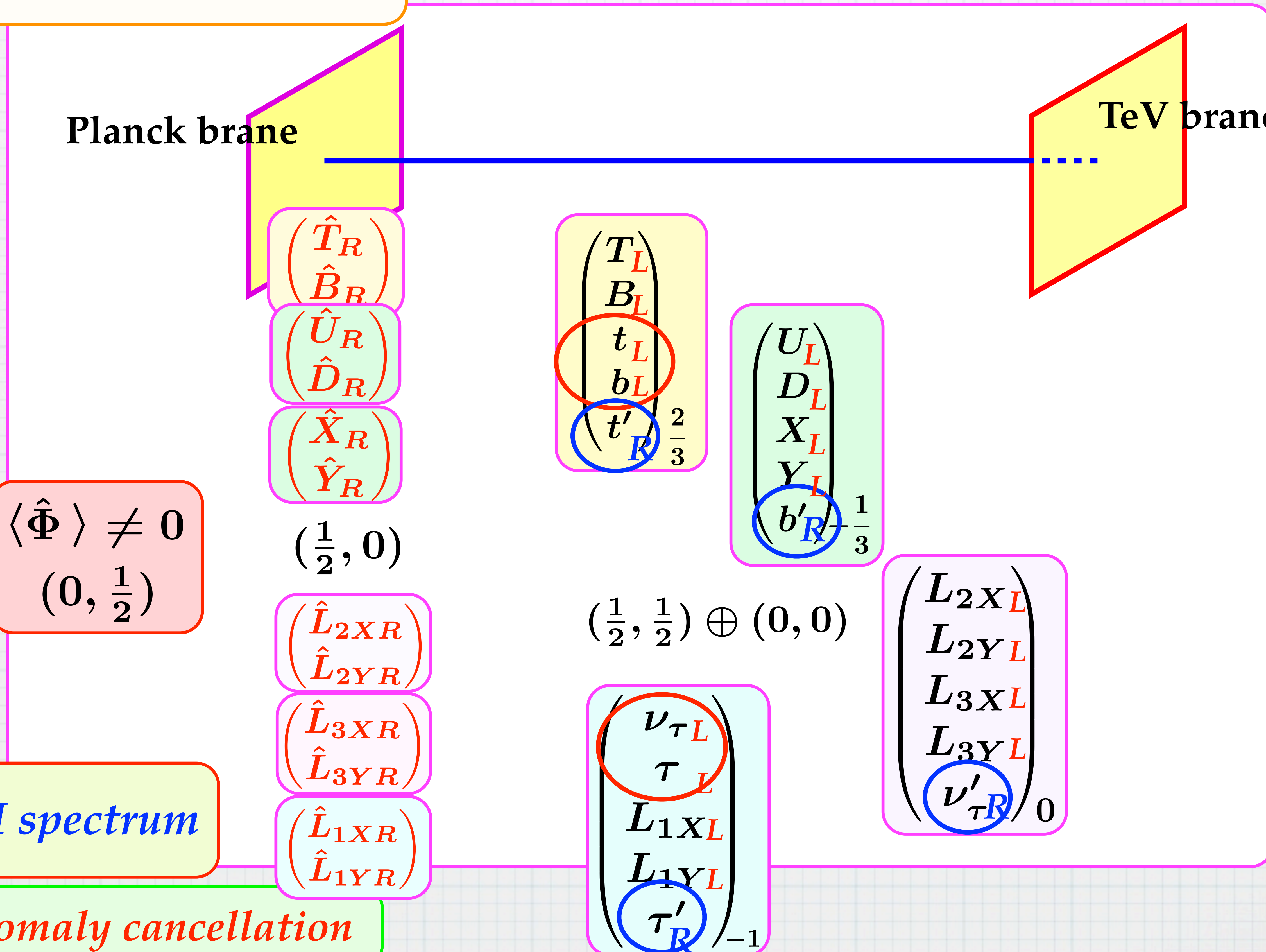
Leptons

$\begin{pmatrix} \hat{L}_{2XR} \\ \hat{L}_{2YR} \end{pmatrix}$ $\begin{pmatrix} \hat{L}_{3XR} \\ \hat{L}_{3YR} \end{pmatrix}$ $\begin{pmatrix} \hat{L}_{1XR} \\ \hat{L}_{1YR} \end{pmatrix}$

$\begin{pmatrix} \nu_{\tau L} \\ \tau_L \\ L_{1XL} \\ L_{1YL} \\ \tau'_R \end{pmatrix}_{-1}$ $\begin{pmatrix} L_{2XL} \\ L_{2YL} \\ L_{3XL} \\ L_{3YL} \\ \nu'_{\tau R} \end{pmatrix}_0$

Matter content

YH, Noda, Uekusa 2009



SM spectrum

Anomaly cancellation

Effective interactions

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

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

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**
$m_W(\hat\theta_H) \sim \frac{1}{2} g \underline{\underline{f_H \sin\hat\theta_H}}$	$\frac{1}{2} g \underline{\underline{(v+H)}}$
$m_Z(\hat\theta_H) \sim \frac{1}{2\cos\theta_W} g \underline{\underline{f_H \sin\hat\theta_H}}$	$\frac{1}{2\cos\theta_W} g \underline{\underline{(v+H)}}$

periodic
nonlinear

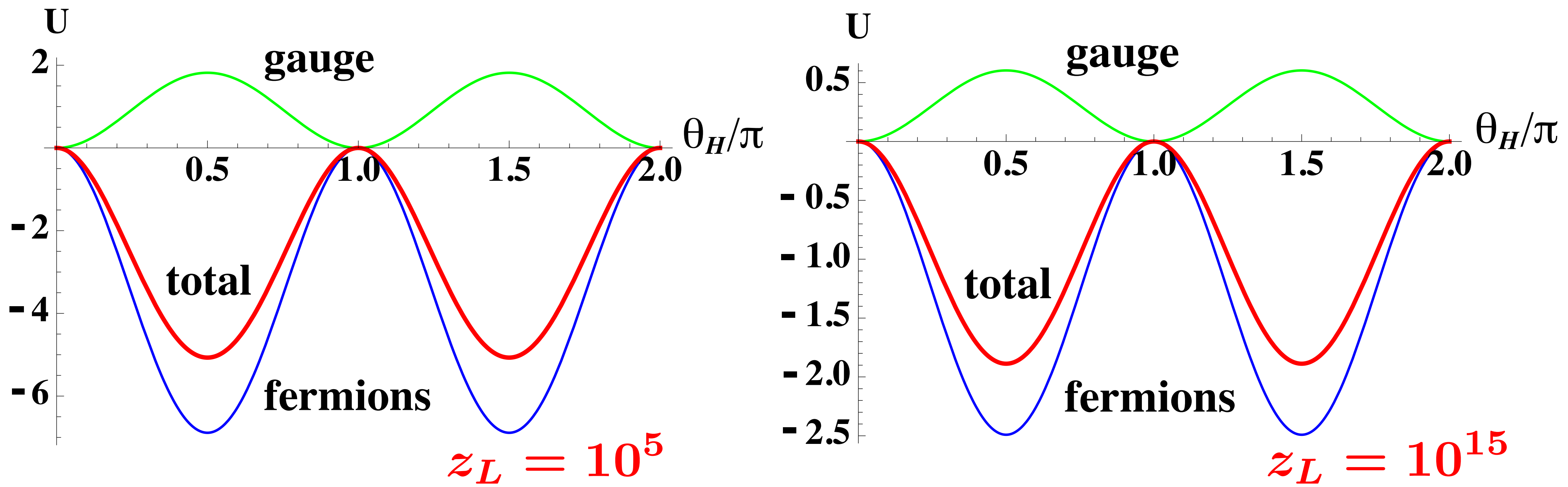
$m_f(\hat\theta_H) \sim y_f \underline{\underline{f_H \sin\hat\theta_H}}$	$y_f \underline{\underline{(v+H)}}$

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

WWH
ZZH
Yukawa
= *SM* × $\cos\theta_H$

WWHH
ZZHH
= *SM* × $\cos 2\theta_H$

Energy density/$m_{\rm KK}^4$



⇨ EW symmetry breaking by Hosotani mechanism

$\theta_H = \frac{\pi}{2}$ ⇨

m_H : 70 GeV $\sim$ 135 GeV

WWH, ZZH, Yukawa = 0

LEP2 bound is evaded.

H parity

Proof (2)

YH, Tanaka, Uekusa, 1010.6135

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

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

Algebra is invariant under

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

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

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

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

T parameter $\quad Zb\bar{b}$

$$\mathbf{At}\ \boldsymbol{\theta_H = \frac{\pi}{2}}$$

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

⇨ P_H -inv

brane interactions P_H odd fields do not couple.

⇨ Theory is H parity invariant.

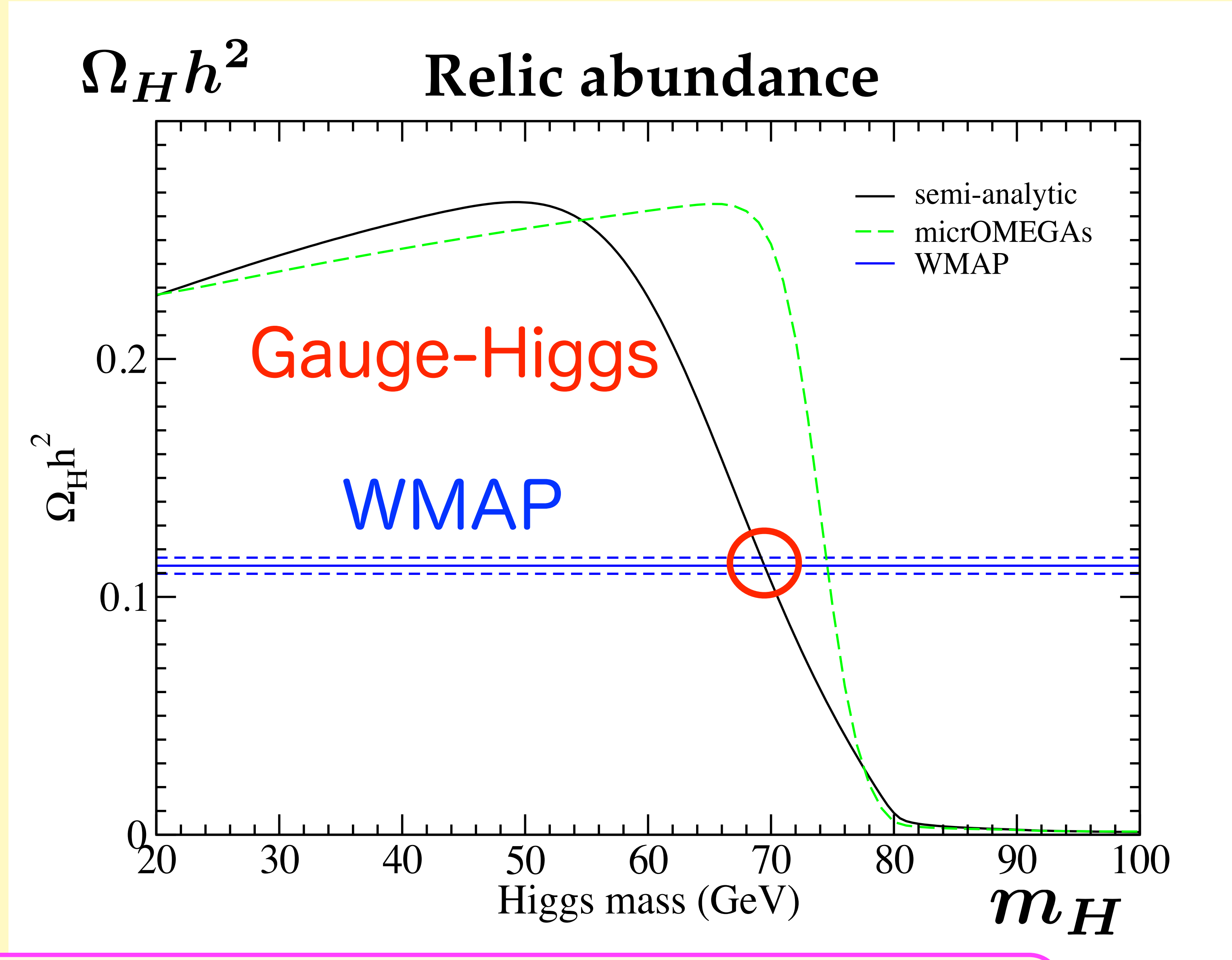
$$P_H = \begin{cases} + & W^{(n)}, Z^{(n)}, \gamma^{(n)}, gluon^{(n)}, q^{(n)}, \ell^{(n)}, \cdots \\ \\ - & H^{(n)}, W'^{(n)}, Z'^{(n)}, q'^{(n)}, \ell'^{(n)}, \cdots \end{cases}$$

Higgs field : the lightest P_H -odd field.

WWH, ZZH, Yukawa = 0

Stable

Stable Higgs → Dark Matter



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

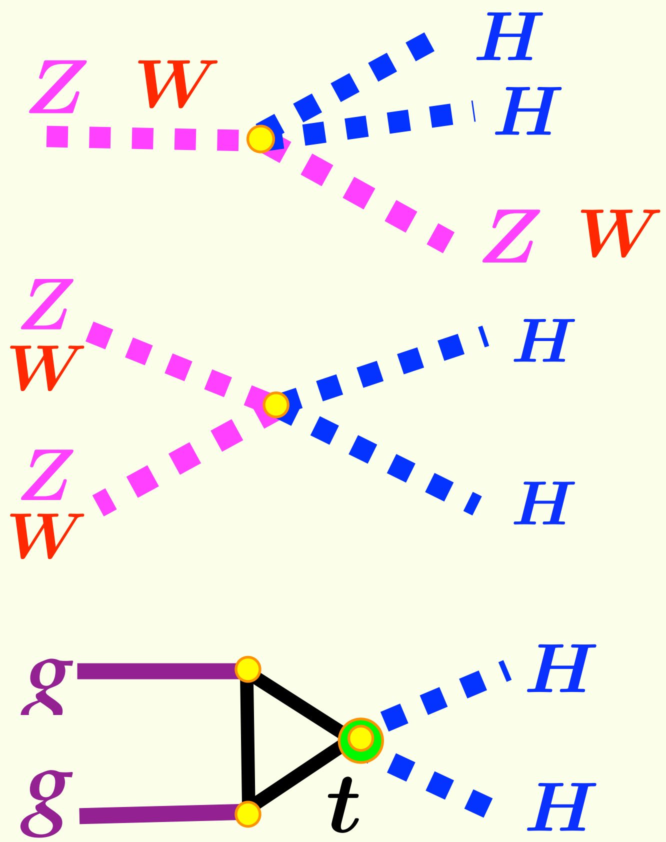
$T_f \sim 3\,\mathrm{GeV}$

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

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

How to see the Higgs bosons at LHC/ILC

Production:



Stable Higgs boson

=

missing energy,

missing momentum

Cheung, Song, 1004.2783

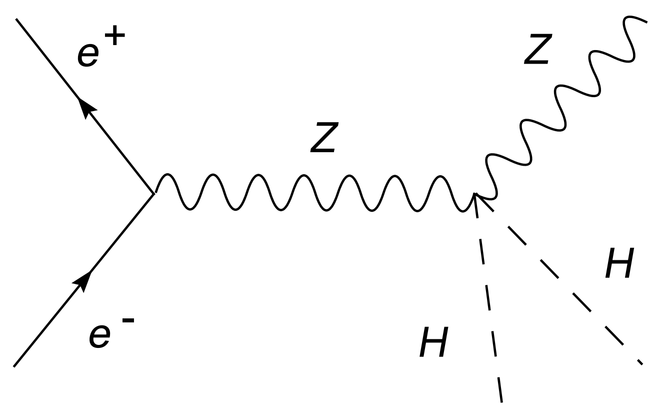
Alves, 1008.0016

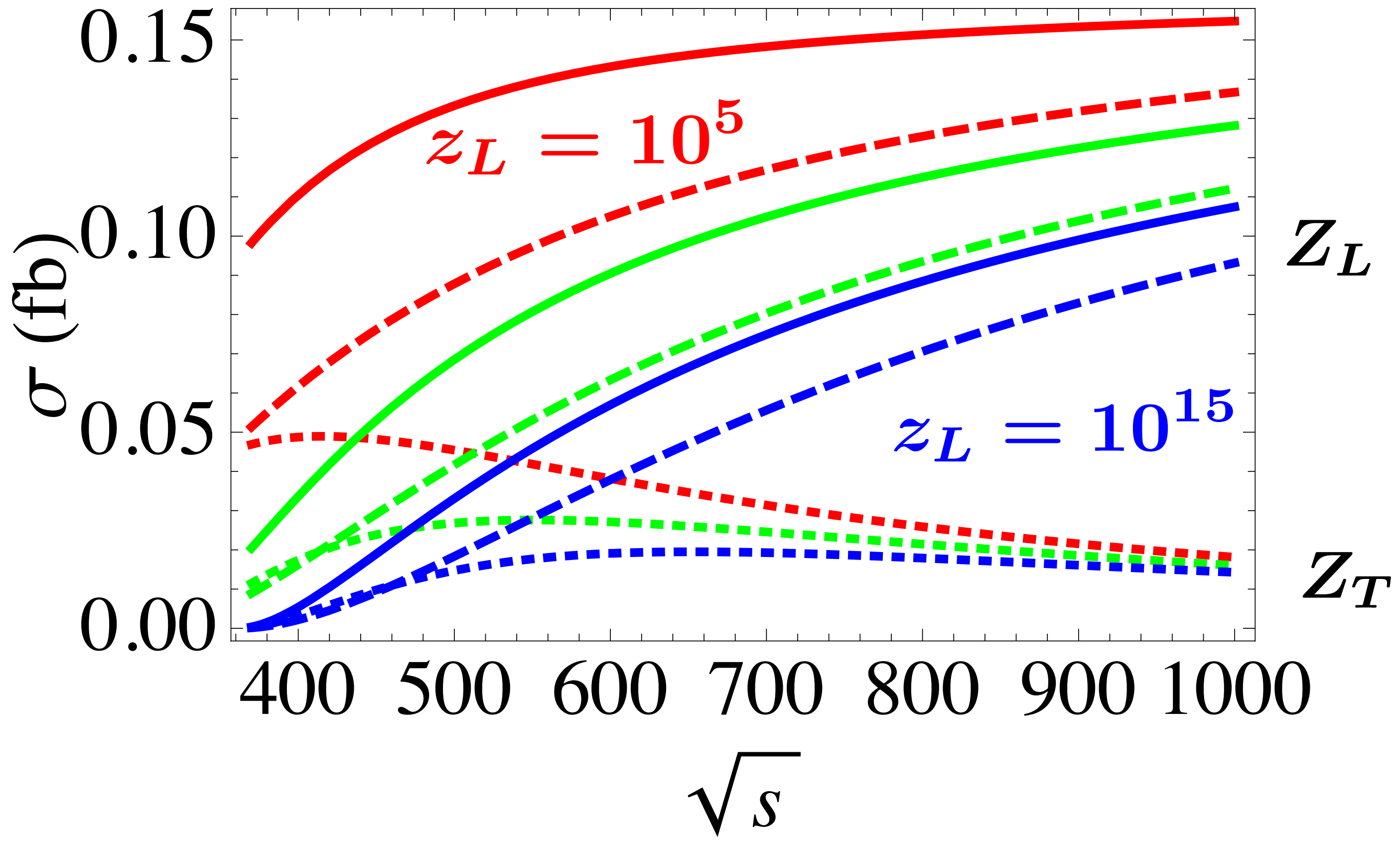
$\nu, \bar{\nu}$ **background**

hard at LHC, possible at ILC

YH, Tanaka, Uekusa, in preparation

$$e^+e^- \to ZHH$$





major background $e^+e^- \to Z\nu\bar{\nu}$

Polarized $e^\pm$

$$\sqrt{s} = 750\,\mathrm{GeV}\ , z_L = 10^{15}, M_{\mathrm{mis}} > 250\,\mathrm{GeV},\ |\cos\theta| < 0.6$$

$$L > 2.0\,\mathrm{ab}^{-1} \quad \text{for } 5\sigma$$

Gauge couplings precision measurements

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

Z-decay widths (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

⇨ $z_L \geq 10^{15}$

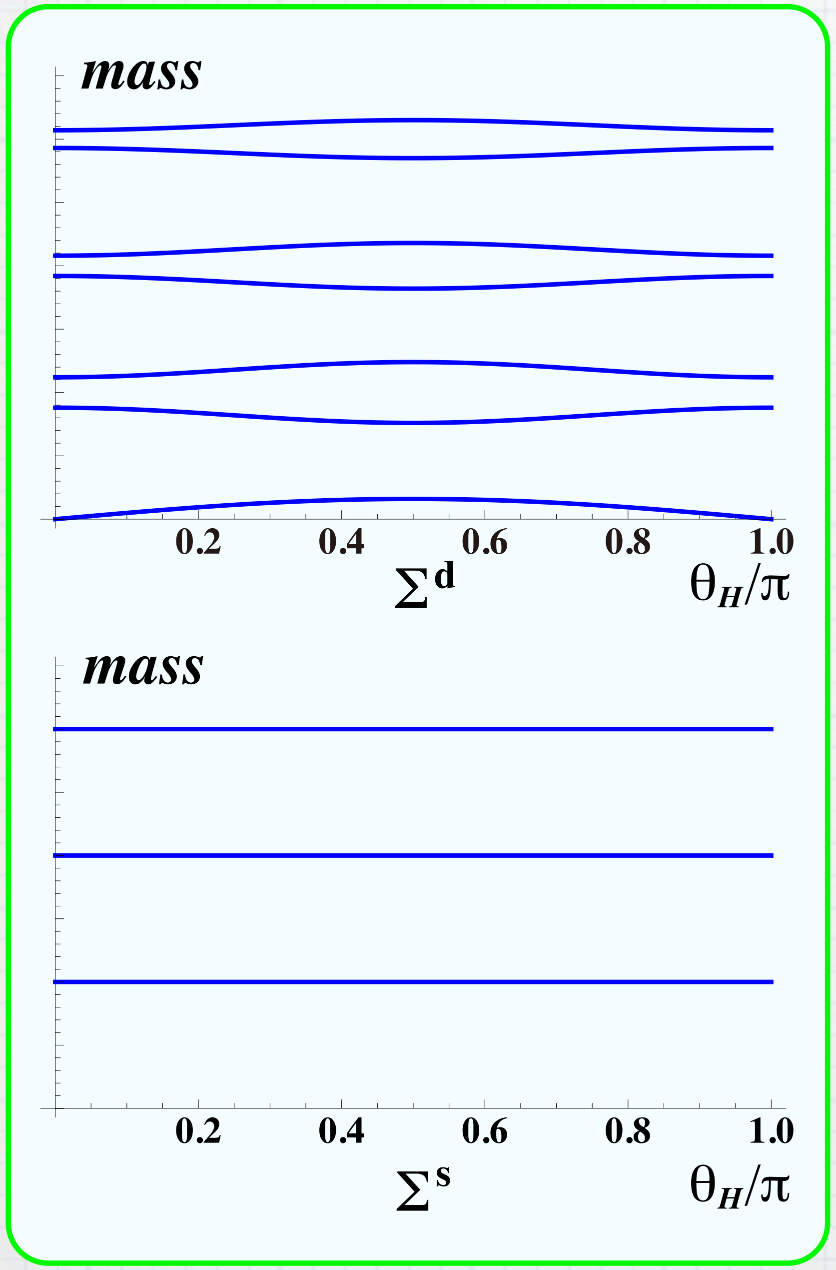
Observe extra dimension

↓

KK modes

YH, Tanaka, Uekusa, in preparation

1st KK modes



	$z_L : 10^{15}$	$z_L : 10^5$
$m_{\rm KK}$	1466	836
$Z^{(1)}$	1130	653
$gluon^{(1)}$	1144	678
$u^{(1)}$	1361	1037
$t^{(1)}$	1121	634

in GeV

KK $Z^{(1)}$

z_L	10^5	10^{15}
m	653	1130
Γ	101	415

in GeV

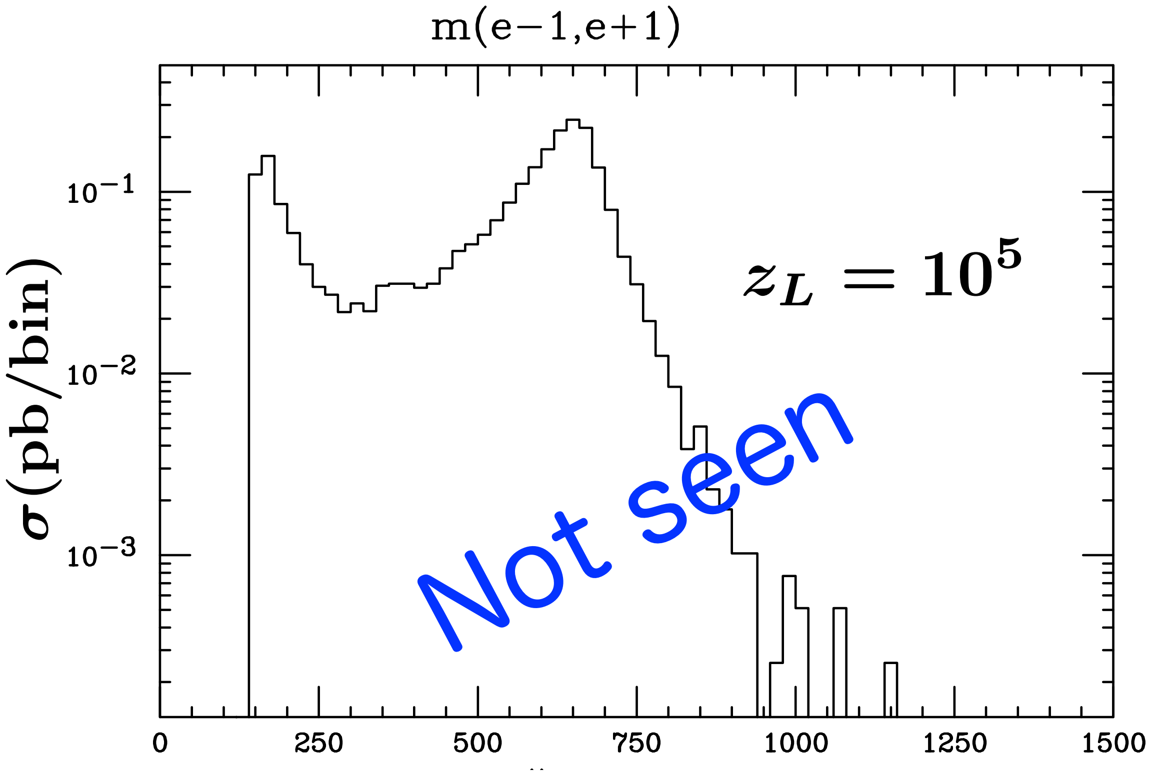
Large couplings for right-handed quarks and lepton

$\sim \quad \times 10$

Large width

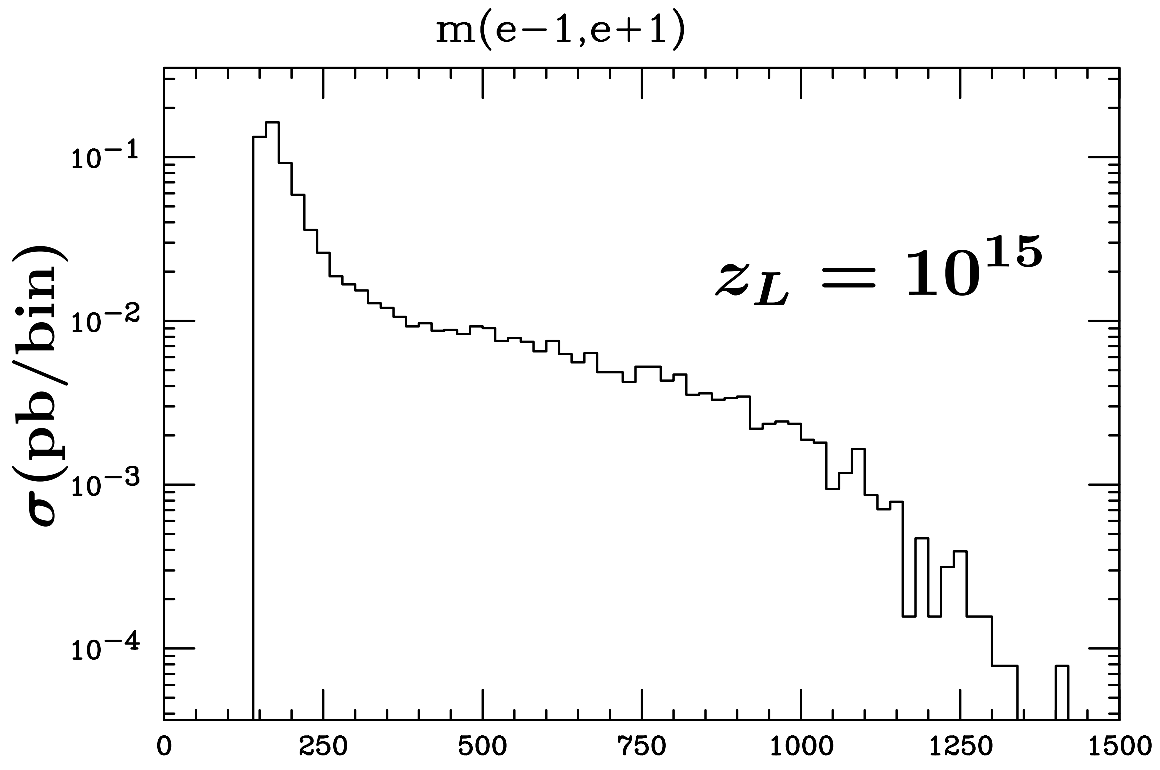
Z' Search at Tevatron

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



$$m = 653\,\mathrm{GeV},\ \ \Gamma = 101\,\mathrm{GeV}$$

signal $\sigma = 1.8\,\mathrm{pb}$



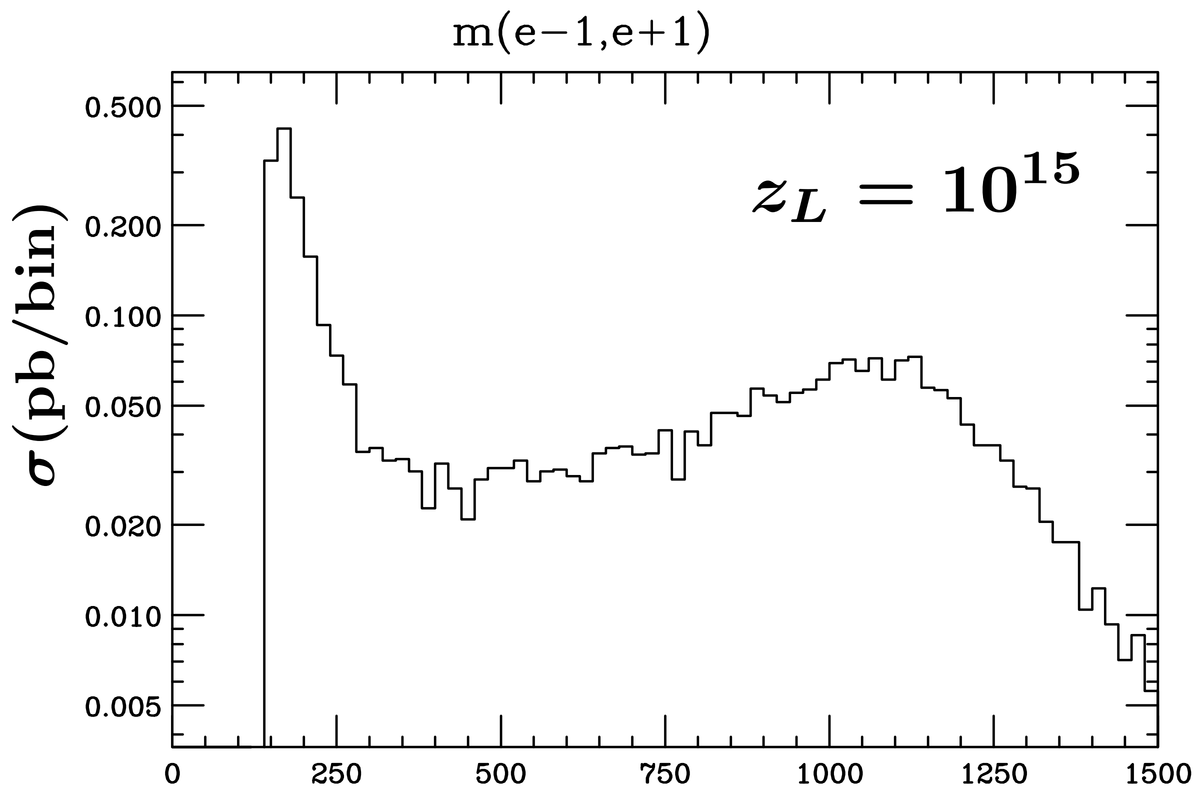
$$m = 1130\,\mathrm{GeV},\ \ \Gamma = 415\,\mathrm{GeV}$$

$$\sigma = 0.06\,\mathrm{pb}$$

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

KK Z at LHC (3.5 + 3.5 TeV)

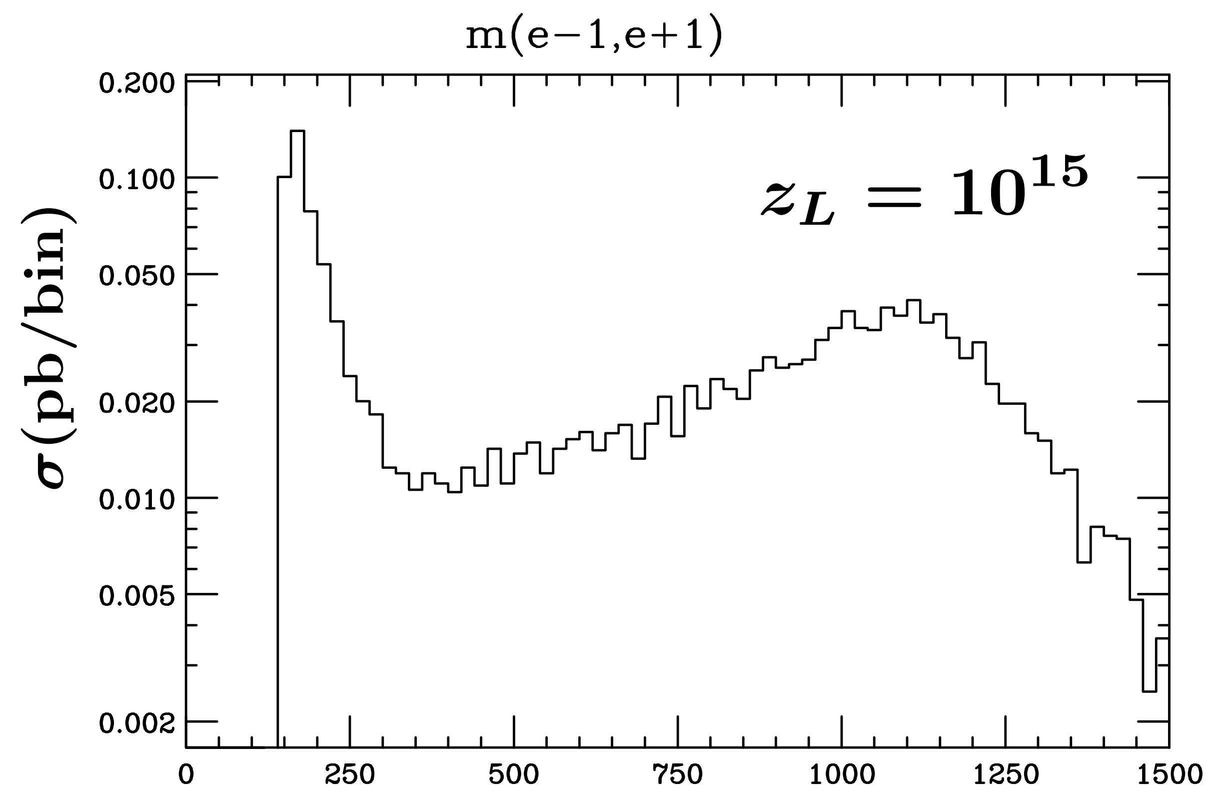
$$q\bar{q} \to Z^{(1)} \to e^+ e^-$$



$$m = 1130\,\mathrm{GeV},\ \Gamma = 415\,\mathrm{GeV}$$

$$\sigma = 1.9\,\mathrm{pb}$$

$$qg \to qZ^{(1)} \to jet + e^+ e^-$$



$$m = 1130\,\mathrm{GeV},\ \Gamma = 415\,\mathrm{GeV}$$

$$\sigma = 1.0\,\mathrm{pb}$$

$\mathbf{KK}\ gluon^{(1)}$

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

Gauge-Higgs unification can be tested.

Higgs naturally becomes stable.

EW precision data (gauge couplings)

Z' search (Tevatron) $\Rightarrow z_L \geq 10^{15}$

Find $Z^{(1)}$ at LHC.

$m \sim 1130\,\mathrm{GeV}, \ \Gamma \sim 415\,\mathrm{GeV}$

Dark Matter=Higgs $\Rightarrow m_H \sim 70\,\mathrm{GeV} \Rightarrow z_L \sim 10^5$