余剰次元における
ゲージ・ヒッグス統合と
ＬＨＣでのシグナル

Yutaka Hosotani,　Osaka University

ICEPP (Univ of Tokyo),　14 April 2011

Hosotani, Tanaka, Uekusa, 1103.6076

力の統一

Unified theory
Large symmetry

Spontaneous
symmetry breaking

Our world
Small symmetry

Higgs

Extra dimensions

ゲージ・ヒッグス統合理論

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

5次元ゲージ場 A_M

KK励起粒子

4次元成分 A_μ

余剰次元成分 A_y

$\cup$

$\cup$

4次元ゲージ場

γ, W, Z, g

4次元ヒッグス場

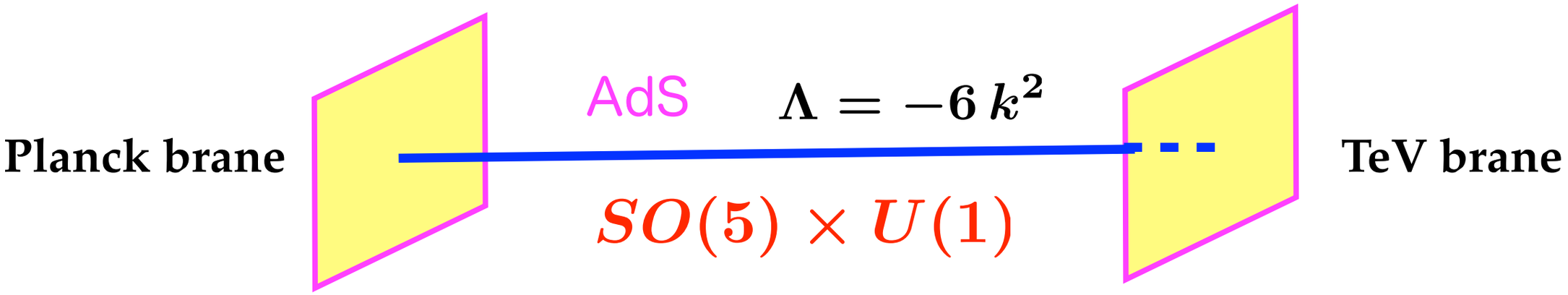
対称性の自発的破れ

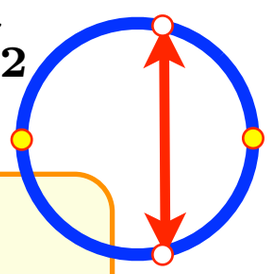
LHCでどのように見るか

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

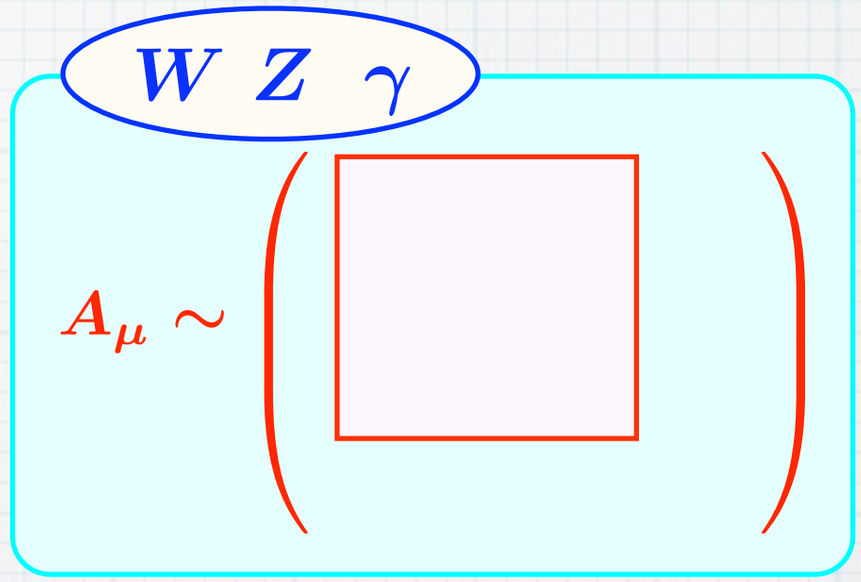
$$\begin{pmatrix} A_\mu \\ A_y \end{pmatrix}(x,-y) = P_0 \begin{pmatrix} A_\mu \\ -A_y \end{pmatrix}(x,y) P_0^\dagger$$

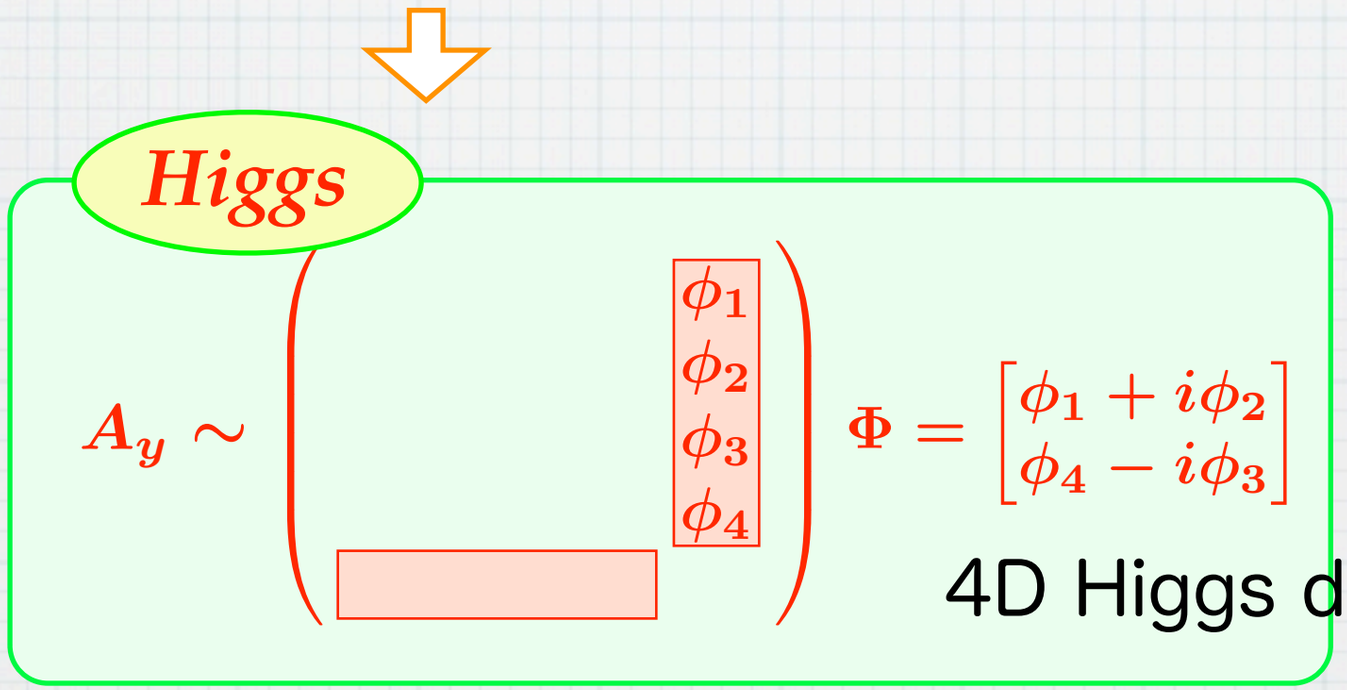
$$\begin{pmatrix} A_\mu \\ A_y \end{pmatrix}(x,\pi R - y) = P_1 \begin{pmatrix} A_\mu \\ -A_y \end{pmatrix}(x,\pi R + y) P_1^\dagger$$

4D gauge bosons and Higgs

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

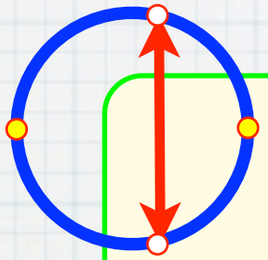
$$SO(5) \to SO(4) \simeq SU(2)_L \times SU(2)_R$$





Matter content

Chiral fermions on orbifolds



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

$$\Psi(x,\pi R - y) = \gamma^5 P_1 \Psi(x,\pi R + y)$$

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

zero (light) modes

Matter content

YH, Noda, Uekusa 2009

(YH, Oda, Ohnuma, Sakamura 2008)

Planck brane

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

TeV brane

Quarks

$\begin{pmatrix} \hat{T}_R \\ \hat{B}_R \end{pmatrix}$ $\begin{pmatrix} \hat{U}_R \\ \hat{D}_R \end{pmatrix}$ $\begin{pmatrix} \hat{X}_R \\ \hat{Y}_R \end{pmatrix}$ $(\frac{1}{2}, 0)$

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

vector rep

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

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

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

Brane scalar

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

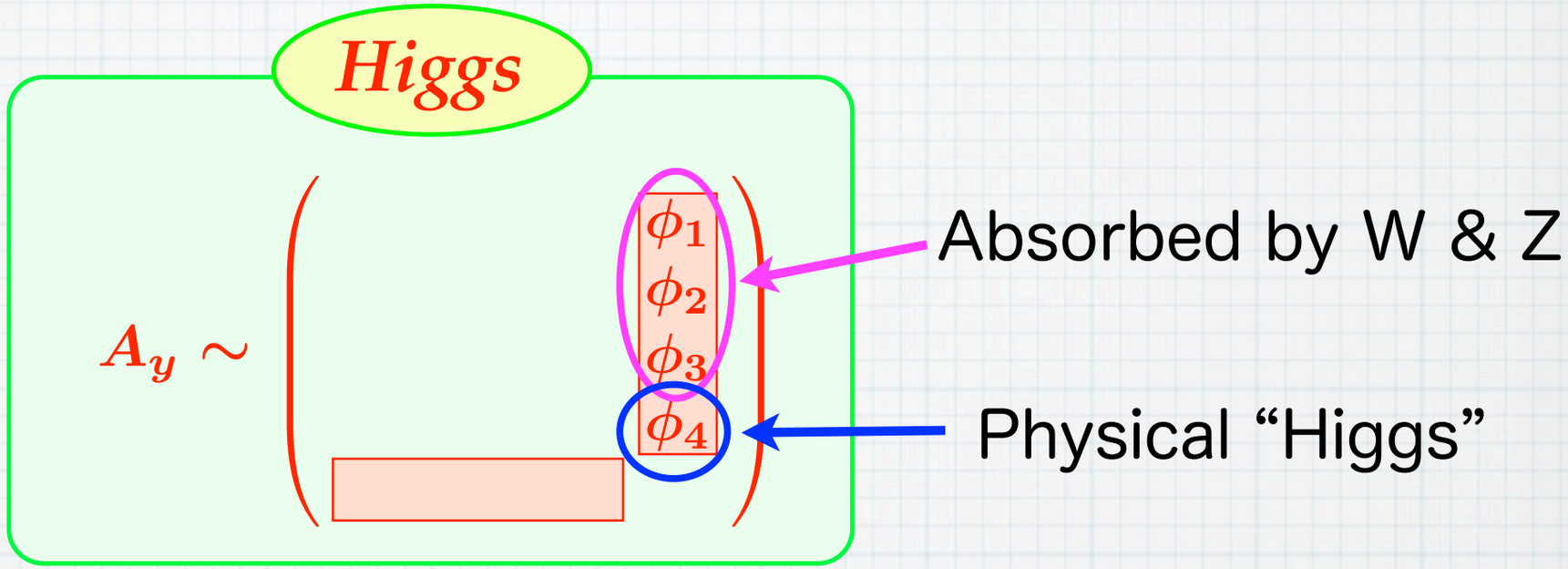
$\langle \hat{\Phi} \rangle \neq 0$

Leptons

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

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

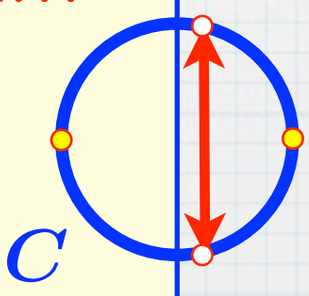
$\begin{pmatrix} L_{2XL} \\ L_{2YL} \\ L_{3XL} \\ L_{3YL} \\ \nu'_{\tau R} \end{pmatrix}_0$



Higgs boson as an AB phase in extra dim

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

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



Effective interactions

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

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

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**

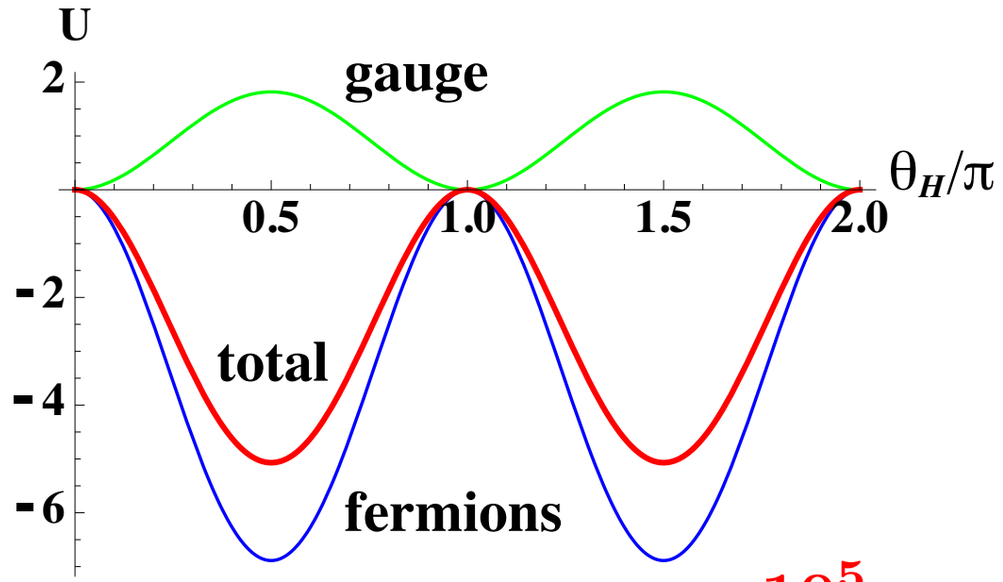
$$\theta_H \sim \theta_H + 2\pi$$

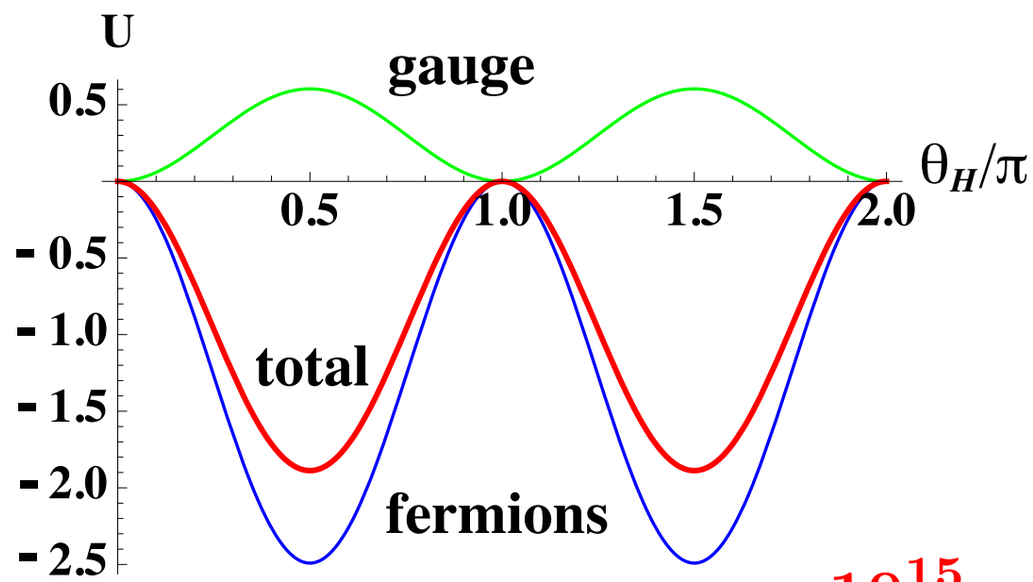
	Gauge-Higgs	SM
$m_W(\hat{\theta}_H)$	$\sim \frac{1}{2} g f_H \sin\hat{\theta}_H$	$\frac{1}{2} g (v+H)$
$m_Z(\hat{\theta}_H)$	$\sim \frac{1}{2\cos\theta_W} g f_H \sin\hat{\theta}_H$	$\frac{1}{2\cos\theta_W} g (v+H)$
	periodic nonlinear	
$m_f(\hat{\theta}_H)$	$\sim y_f f_H \sin\hat{\theta}_H$	$y_f (v+H)$

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

WWH ZZH Yukawa	$= SM \times \cos\theta_H$
WWHH ZZHH	$= SM \times \cos 2\theta_H$

Energy density $/ m_{KK}^4$





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

EW symmetry breaking by Hosotani mechanism

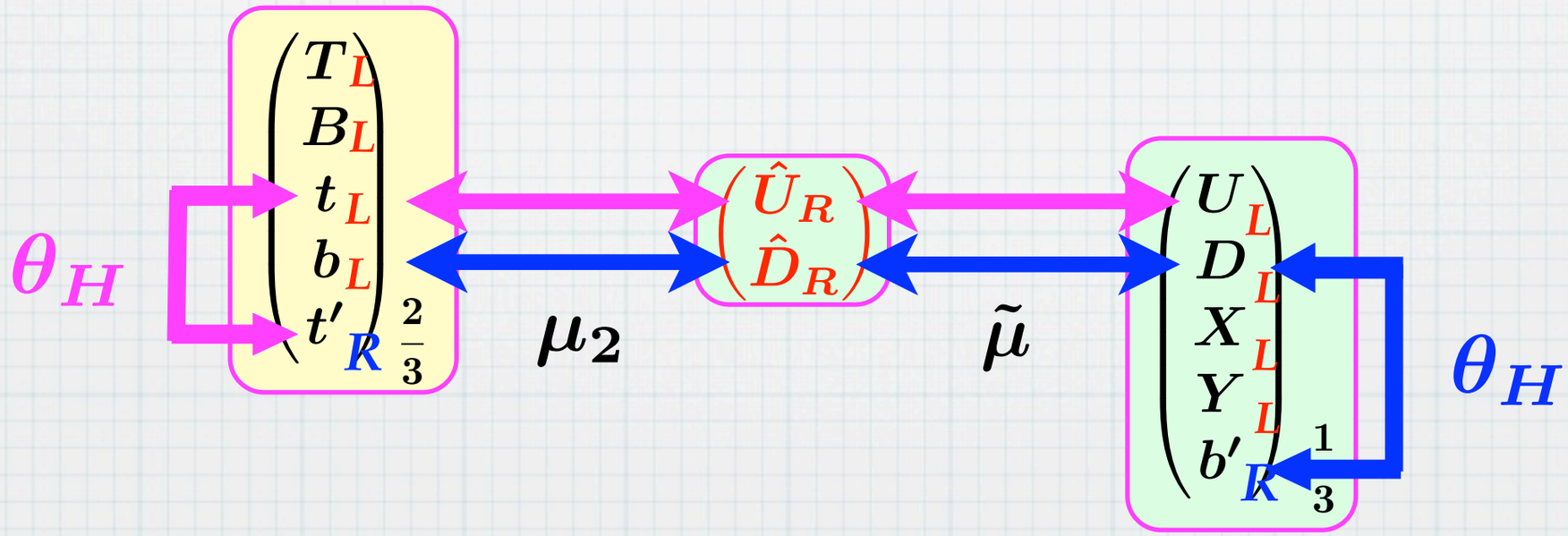
WWH, ZZH, Yukawa = 0

Masses & Yukawa couplings

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

$$g_A \overline{\Psi} A_y \gamma^5 \Psi$$

Ψ_L, Ψ_R couple by gauge int.



$$m(\hat{\theta}_H)\bar{\psi}\psi$$

$$= m(\theta_H)\bar{\psi}\psi + m^{(1)}(\theta_H)\frac{H}{f_H}\bar{\psi}\psi + \frac{1}{2}m^{(2)}(\theta_H)\frac{H^2}{f_H^2}\bar{\psi}\psi + \cdots$$

Yukawa

$$\sim \quad m_f\bar{\psi}\psi \quad + \quad 0 \quad - \quad \frac{m_f}{2f_H^2}H^2\bar{\psi}\psi + \cdots$$

H parity $H \to -H$

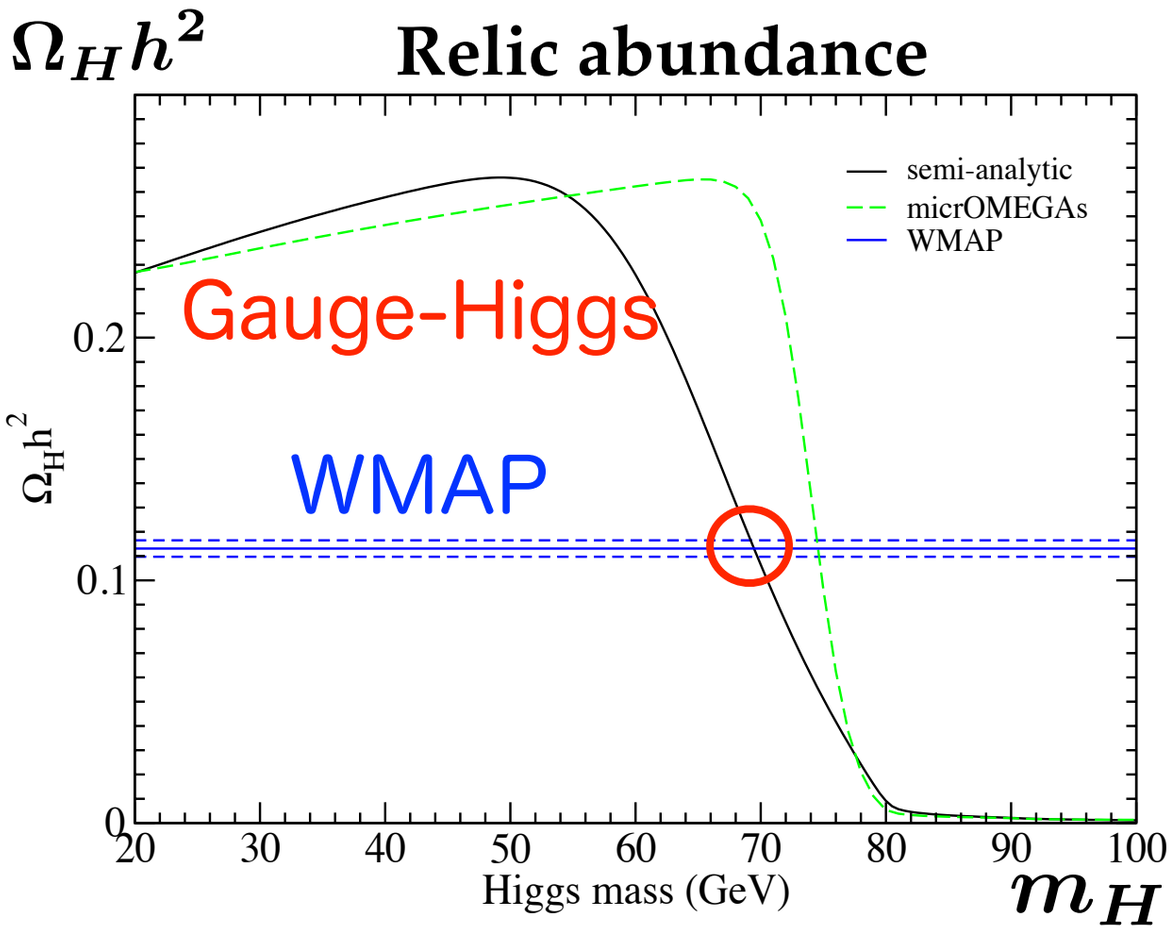
$$P_H = \begin{cases} + & W^{(n)}, Z^{(n)}, \gamma^{(n)}, gluon^{(n)}, q^{(n)}, \ell^{(n)}, \cdots \\ - & H^{(n)}, W'^{(n)}, Z'^{(n)}, q'^{(n)}, \ell'^{(n)}, \cdots \end{cases}$$

Higgs field : the lightest P_H-odd field.

WWH, ZZH, Yukawa = 0

Stable

Stable Higgs → Dark Matter



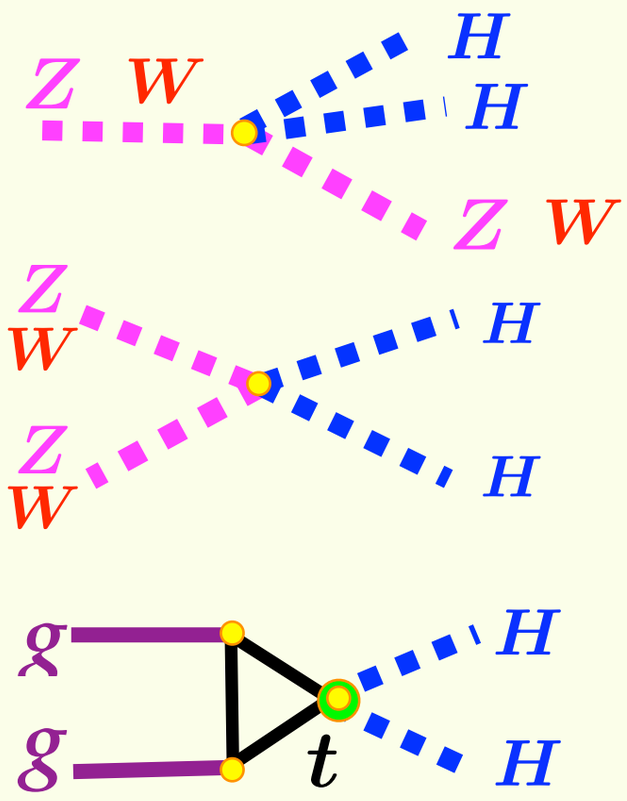
WMAP data → $m_H \sim 70\,\mathrm{GeV}$

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

(Y. Hosotani, ICEPP, U. of Tokyo, 14 April 2011, - 15)

How to see the Higgs bosons at LHC/ILC

Production:



Stable Higgs boson

=

missing energy,

missing momentum

Cheung, Song, 1004.2783

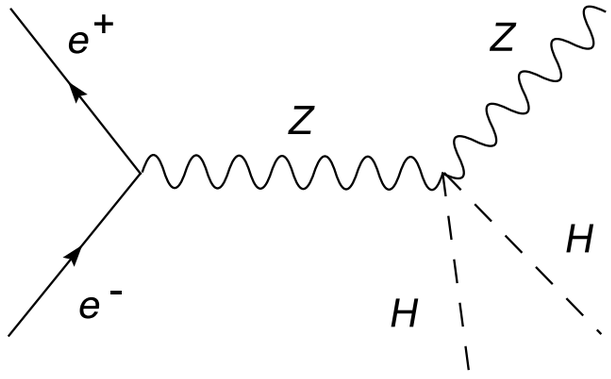
Alves, 1008.0016

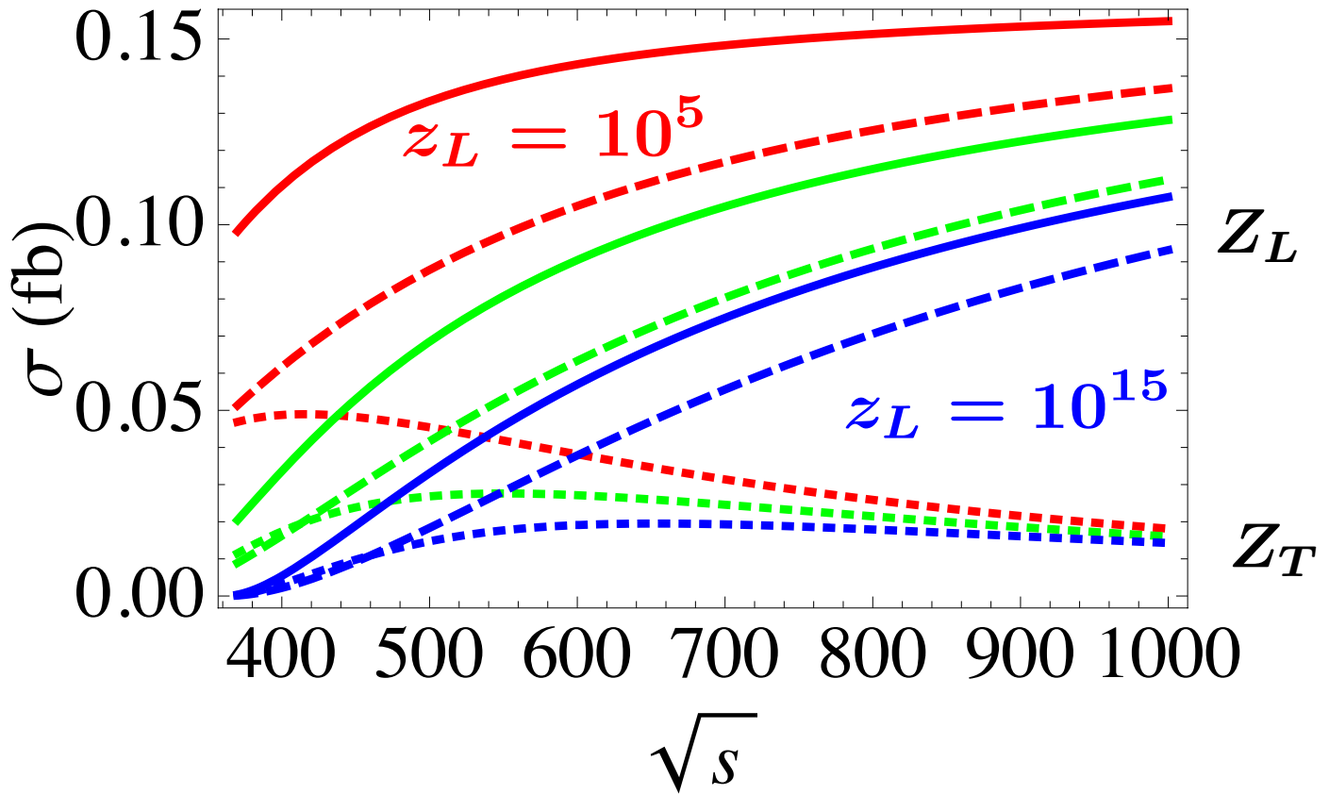
$\nu, \bar{\nu}$ **background**

hard at LHC, possible at ILC

YH, Tanaka, Uekusa, 1103.6076

$e^+e^- \to ZHH$





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

Polarized $e^{\pm}$

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

$L > 2.0\,\mathrm{ab}^{-1}$ for 5σ

Gauge couplings precision measurements

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

Z-decay widths (branching fractions)

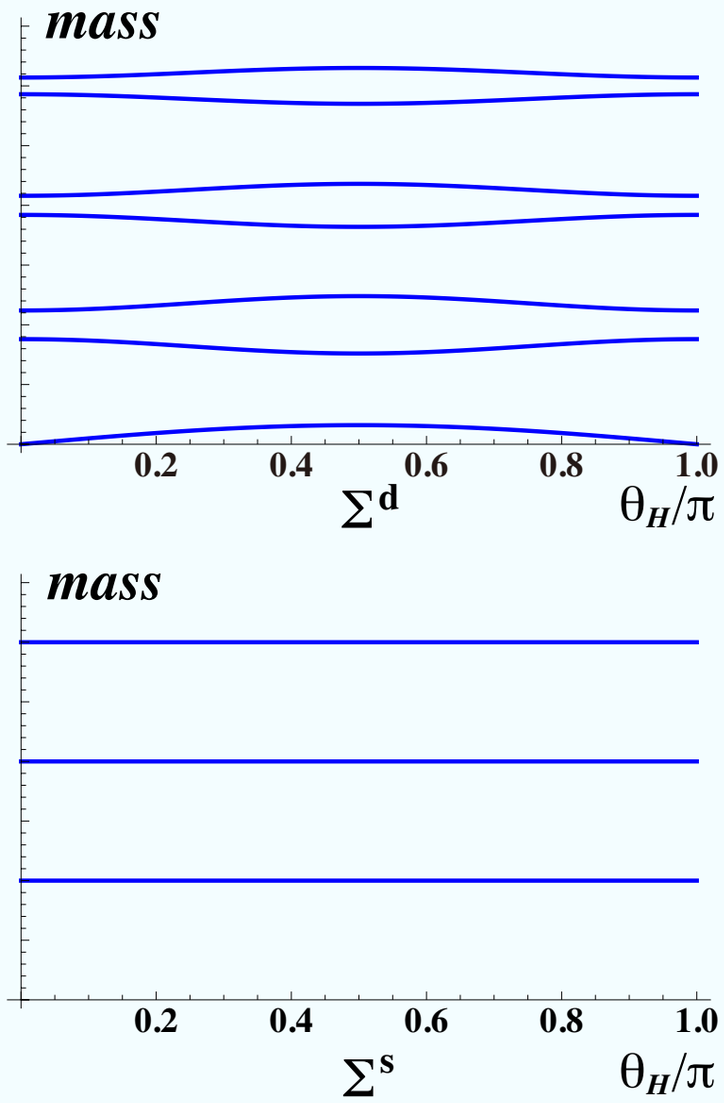
	No. data	SM	$z_L : 10^{15}$	$z_L : 10^{10}$	$z_L : 10^{5}$
$\sin^2\theta_W$		0.2312	0.2309	0.2303	0.2284
$\chi^2(AFB)$	6	10.8	6.3	6.4	7.1
$\chi^2(Z\ decay)$	8	13.6	16.5	37.7	184.5

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

Observe extra dimension

KK modes

1st KK modes



	$z_L : 10^{15}$	$z_L : 10^5$
m_{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

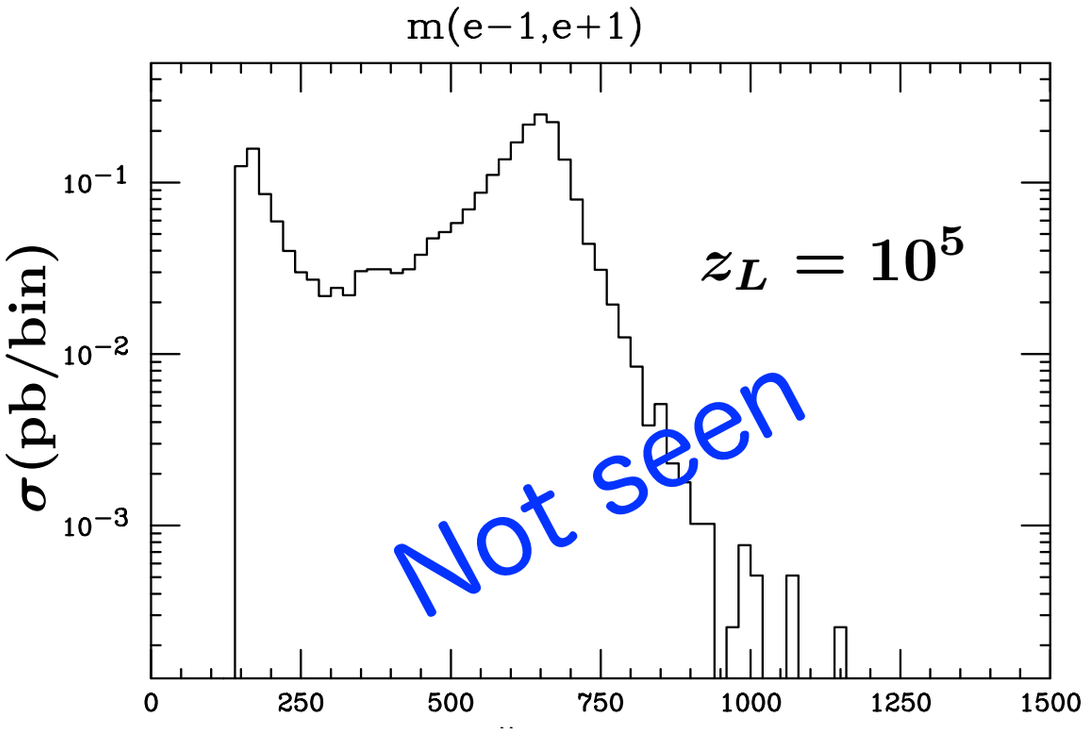
Large couplings for right-handed quarks and lepton

$\sim \quad \times 10$

Large width

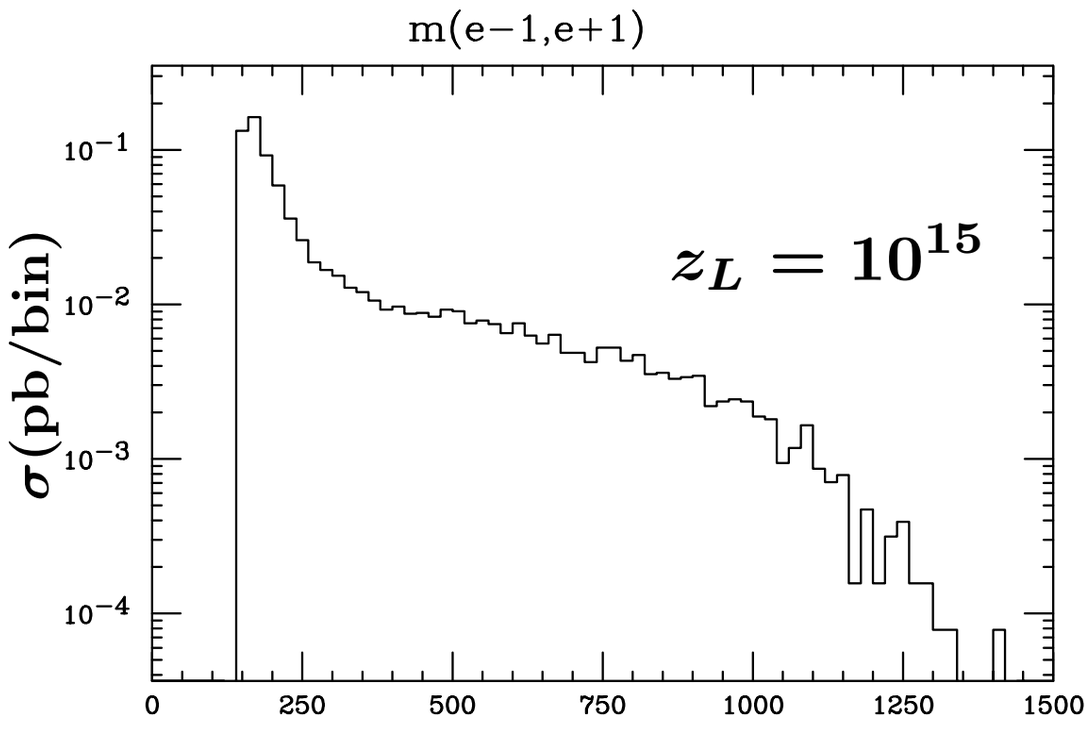
Z' Search at Tevatron

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



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

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

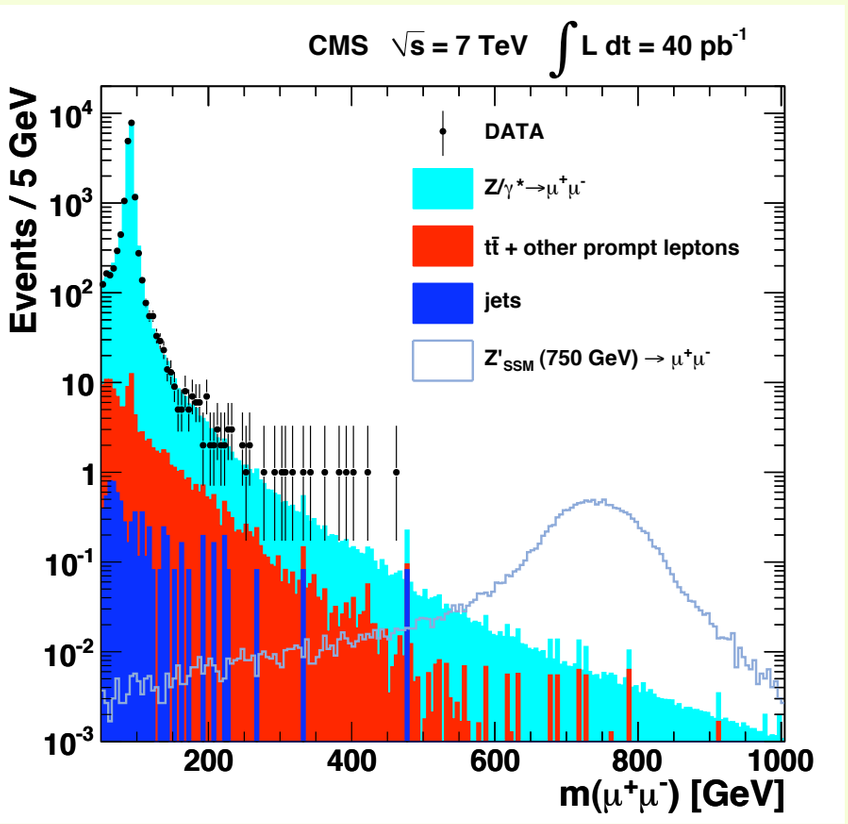


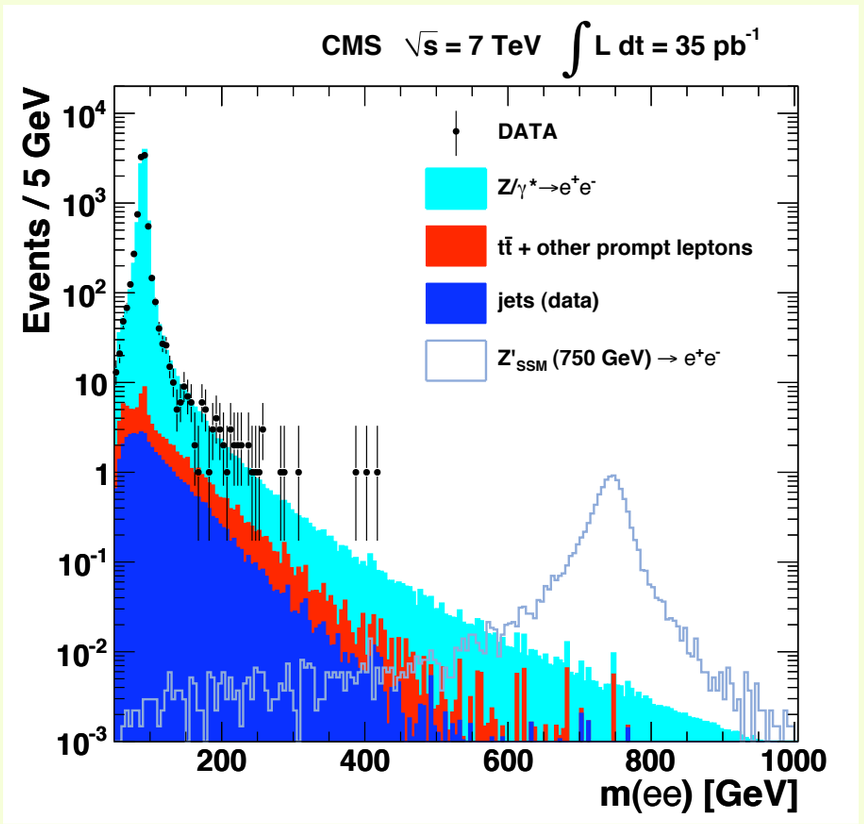
$m = 1130\,\mathrm{GeV},\ \Gamma = 415\,\mathrm{GeV}$

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

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

Z' Search : CMS 1103.0981



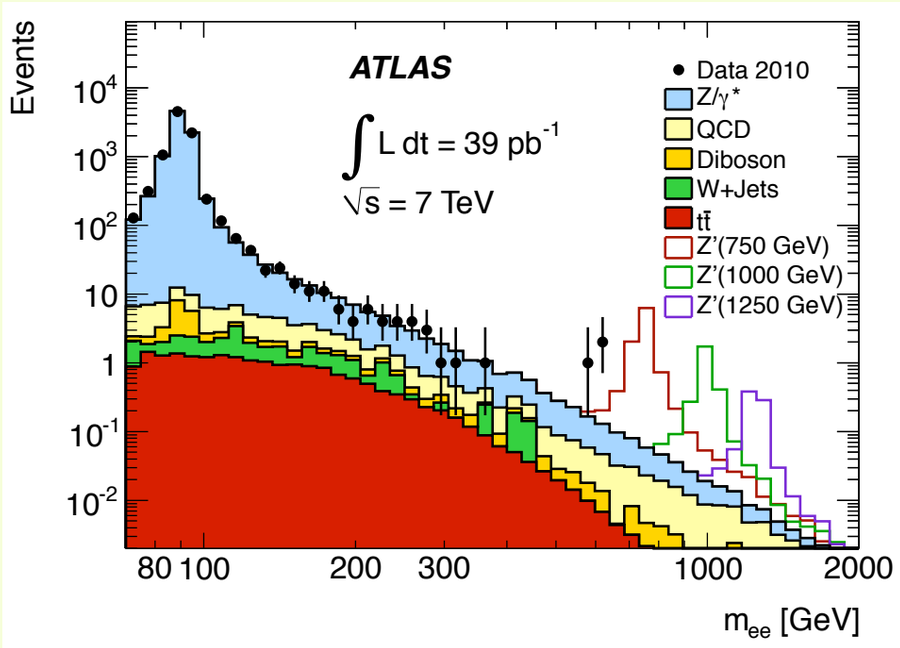


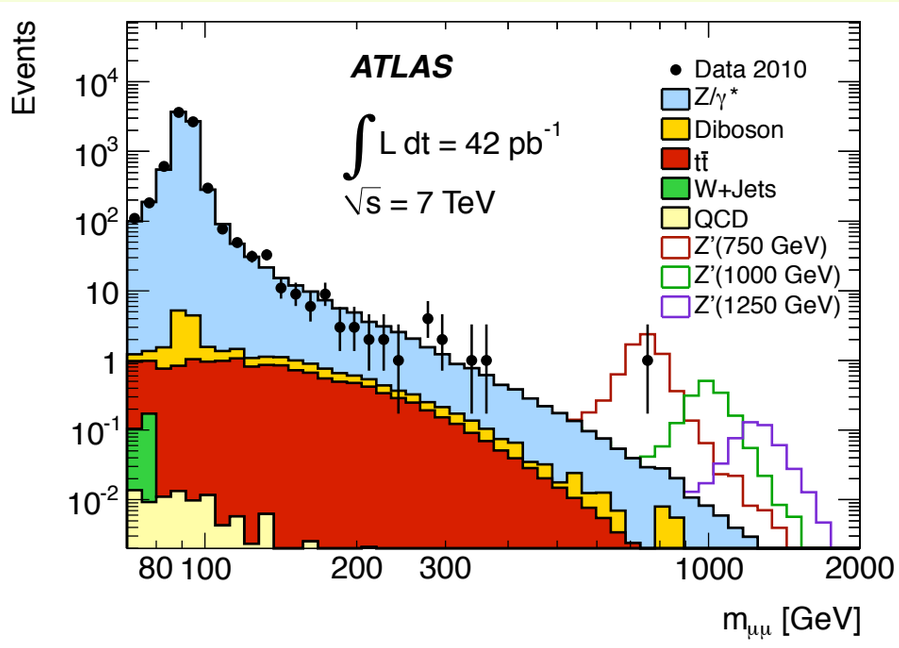
LHC

$$Z'_{\rm SSM}: \frac{\Gamma}{M} = 0.03$$

$$M > 1140\,{\rm GeV}$$

Z' Search : ATLAS 1103.6218

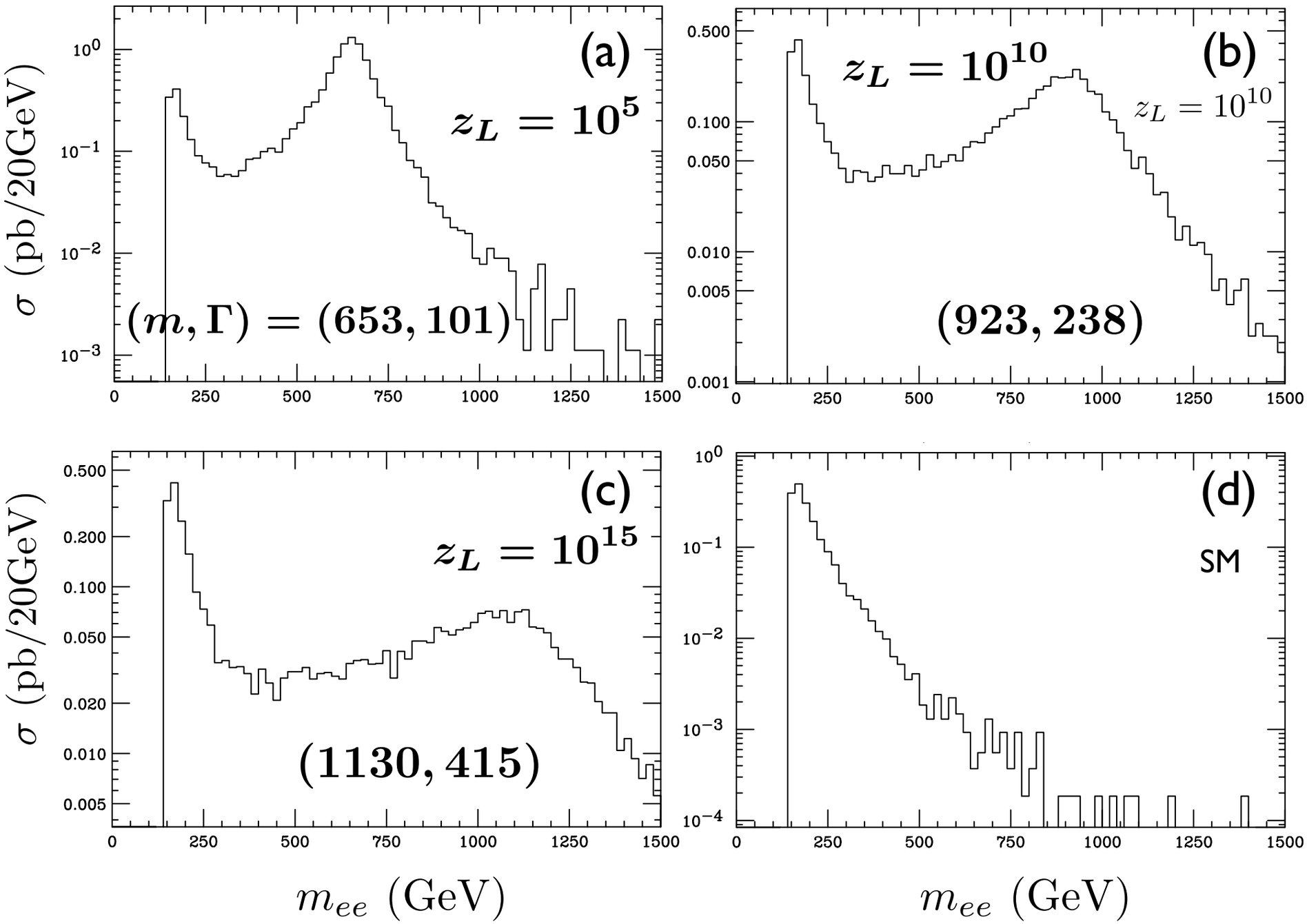




$$M > 1048\,{\rm GeV}$$

KK Z at LHC (3.5 + 3.5 TeV)

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



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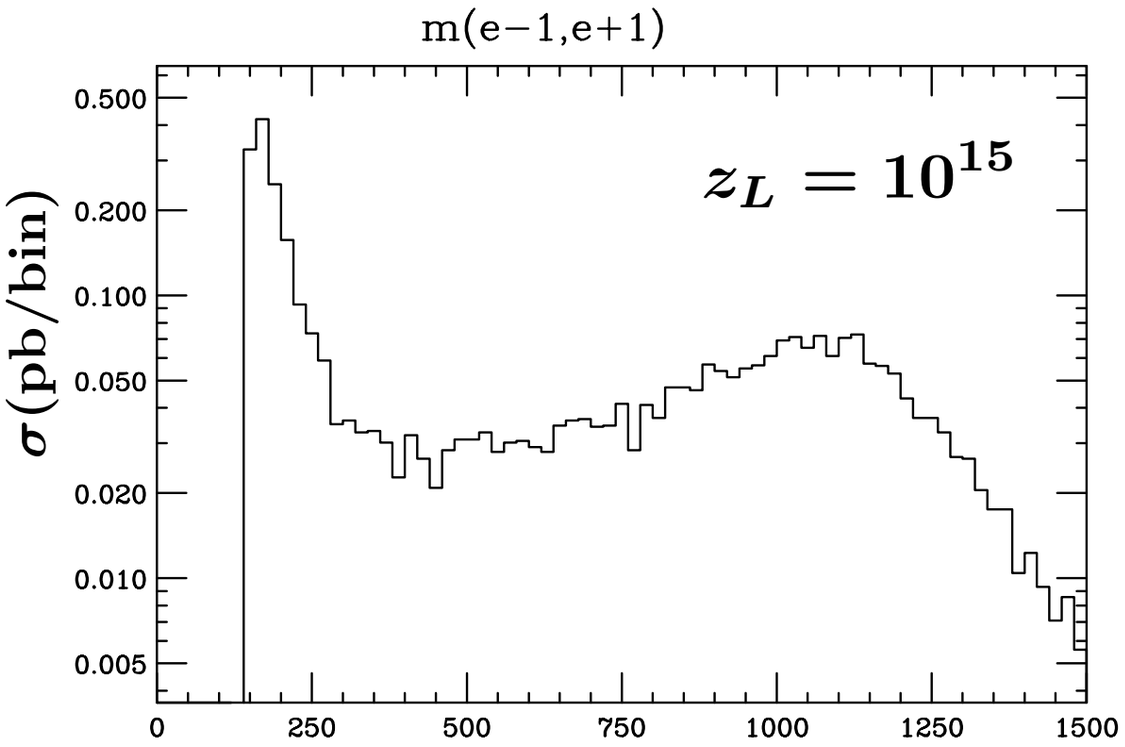
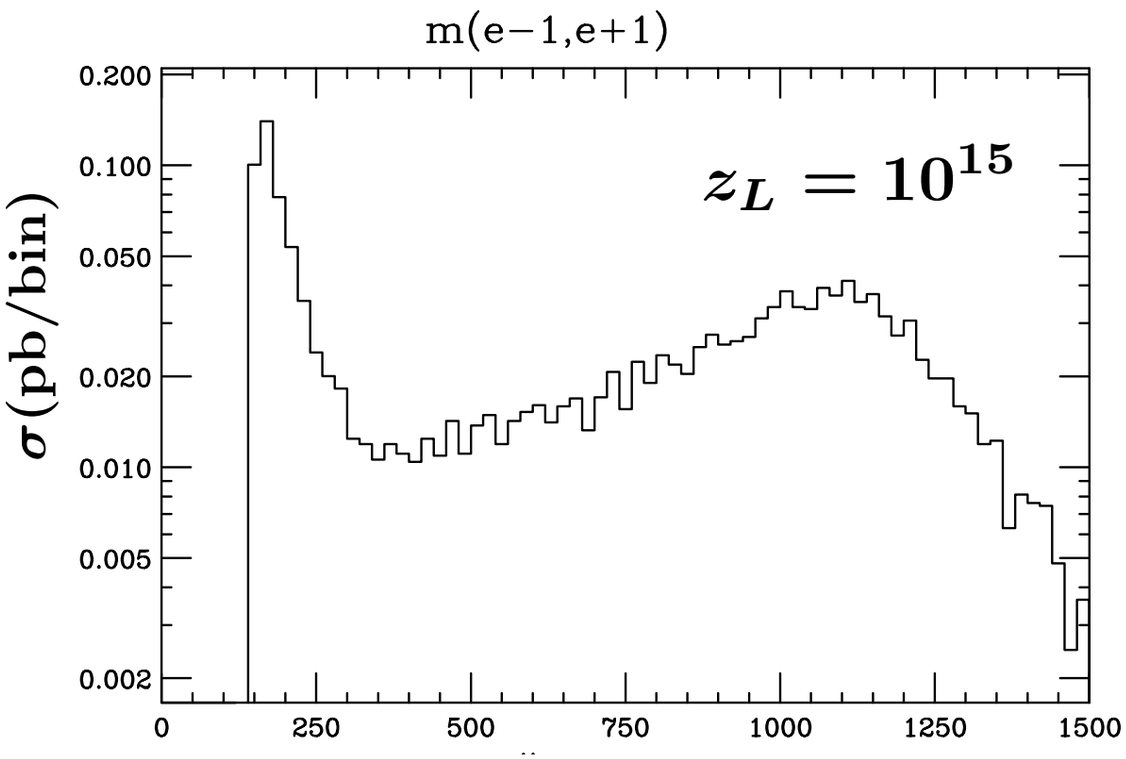


$$m = 1130\,\mathrm{GeV},\ \Gamma = 415\,\mathrm{GeV}$$

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

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



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

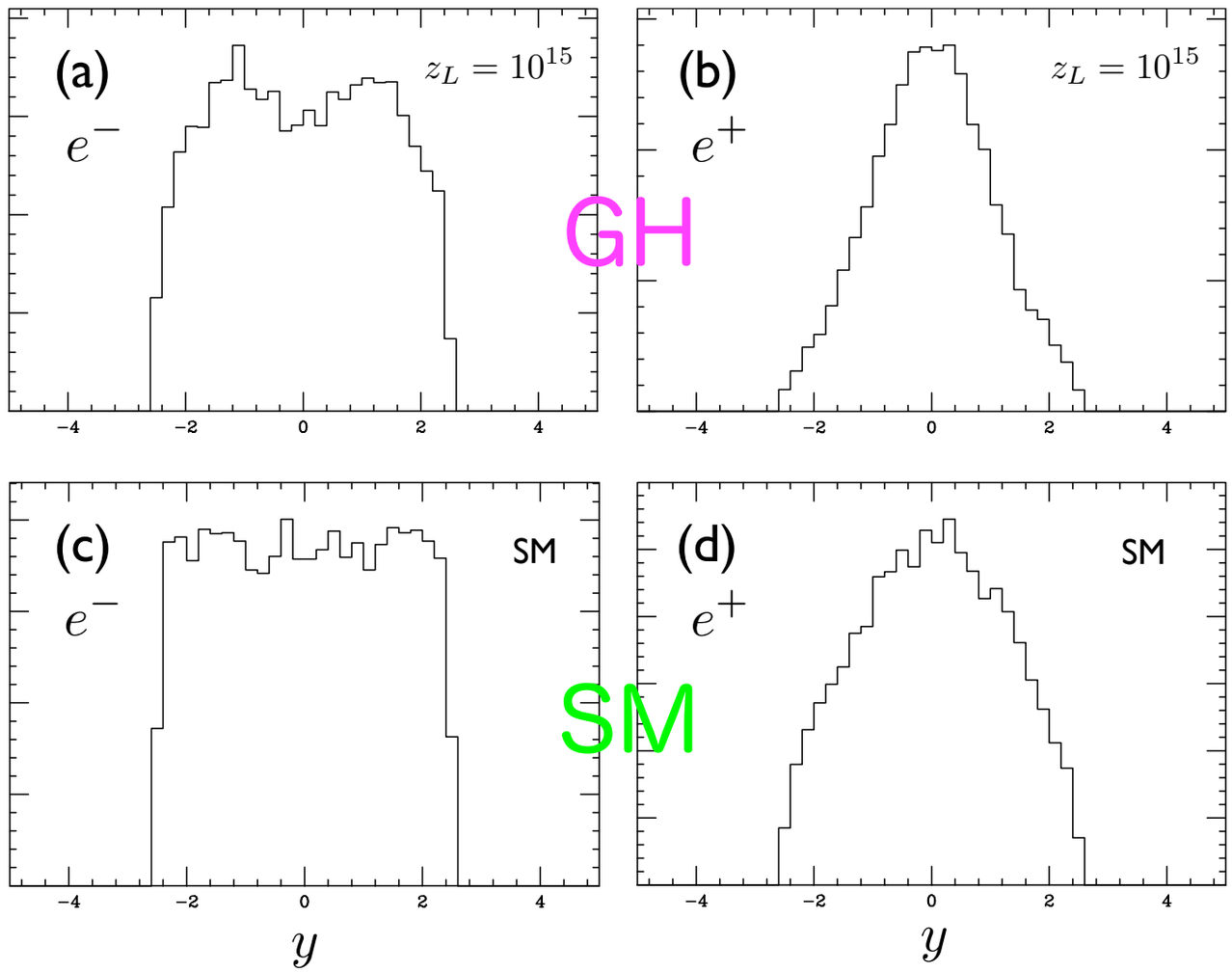
$$\sigma = 1.0\,\mathrm{pb}$$

KK $Z^{(1)}$

Large couplings for right-handed quarks and lepton

Rapidity distribution

e^- wider than e^+ (in pp collider)



KK $gluon^{(1)}$

Strong couplings for right-handed quarks

Couplings/g_s

u_R	6.32
c_R	6.04
t_R	5.60

$\Gamma \sim 13\, m$

Perturbation theory breaks down.

No peak.

Similar for KK photons.

Summary

Gauge-Higgs unification can be tested at LHC.

Higgs naturally becomes stable.

EW precision data A_{FB}, Z decay

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

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

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

Asymmetry in e^+e^- distribution