Gauge-Higgs Unification from EW to GUT

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CTPU, IBS, Korea, 16 September 2015

In search of a Principle

for the 125 GeV Higgs scalar boson

which

regulates Higgs couplings,

explains EW sym breaking,

solves the gauge-hierarchy prob.

Gauge-Higgs unification

Gauge-Higgs EW unification

gauge theory A_M *in 5 dim.*

4-dim. components A_μ

∪

4D gauge fields

γ , W , Z

extra-dim. component A_y

∪

4D Higgs fields

H

Aharonov-Bohm phase

θ_H

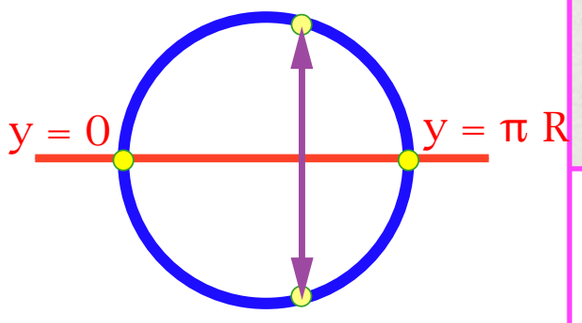
Hosotani mechanism

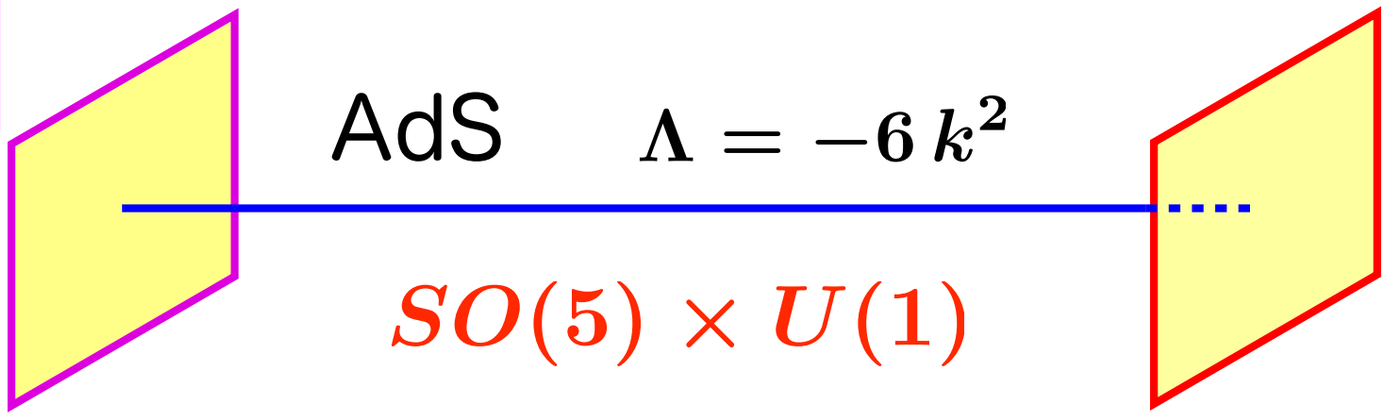
EW symmetry breaking

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

Agashe, Contino, Pomarol 2005
YH, Sakamura 2006

YH, Oda, Ohnuma, Sakamura 2008
YH, Noda, Uekusa 2009
Funatsu, Hatanaka, YH, Orikasa, Shimotani 2013, 2014





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

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

Orbifold BC : P_0 , P_1

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4D gauge bosons and Higgs

Orbifold BC : P_0 , P_1

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

W Z γ

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

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

Higgs

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

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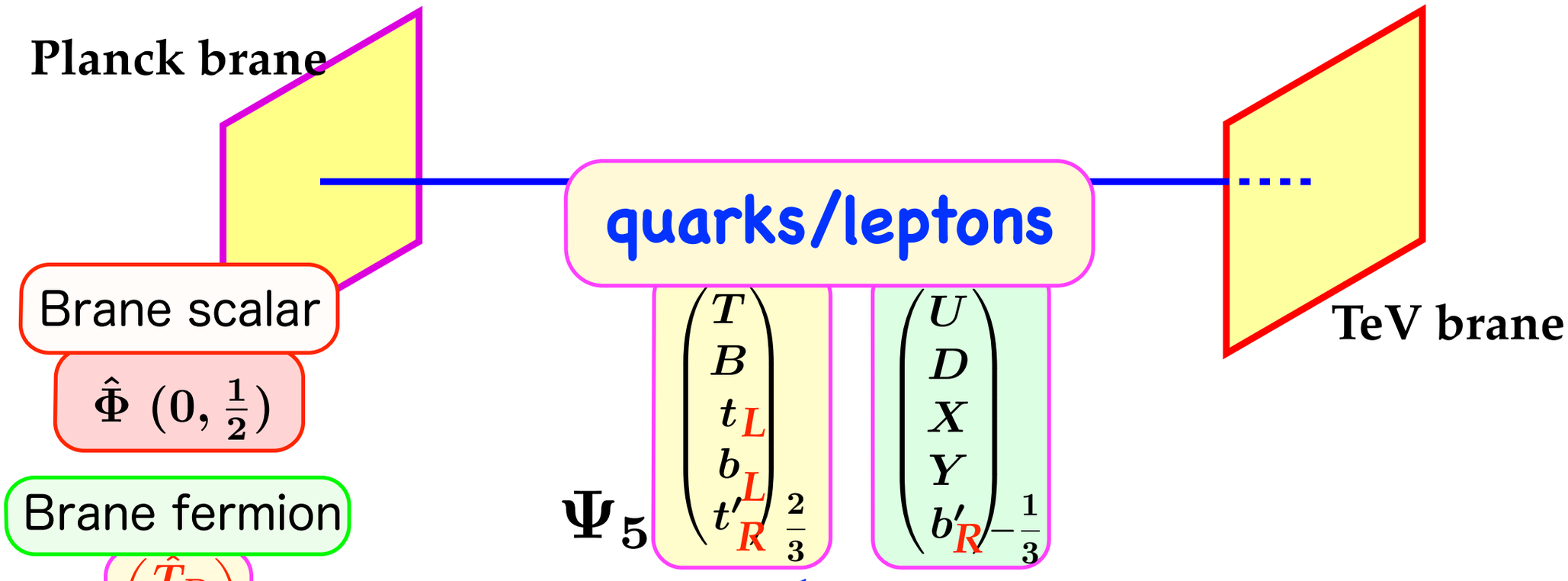
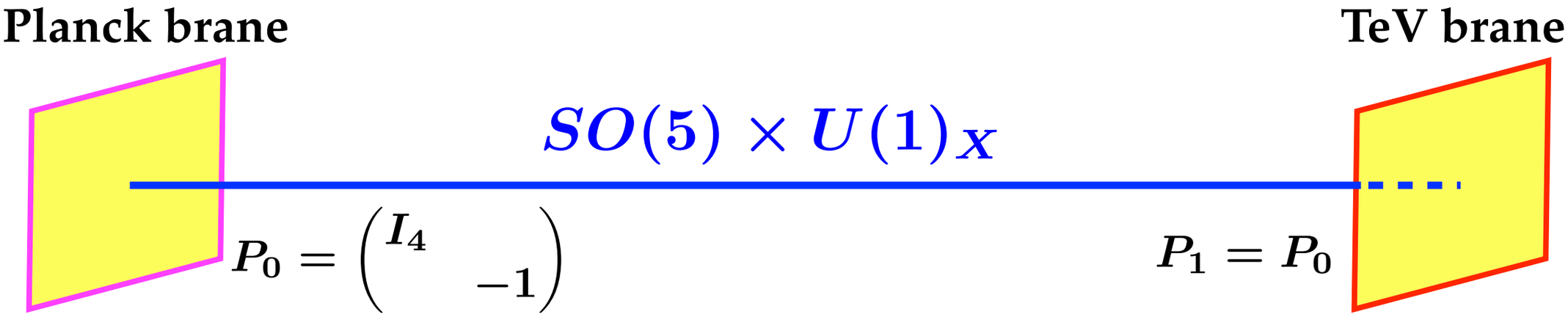
SO(5)xU(1) EW


Planck brane
TeV brane
quarks/leptons
Brane scalar
$\hat{\Phi}\ (0, \frac{1}{2})$
Brane fermion
$\begin{pmatrix} \hat{T}_R \\ \hat{B}_R \end{pmatrix}$
$\begin{pmatrix} \hat{U}_R \\ \hat{D}_R \end{pmatrix}$
$\begin{pmatrix} \hat{X}_R \\ \hat{Y}_R \end{pmatrix}$
$(\frac{1}{2}, 0)$
Ψ_5
$\begin{pmatrix} T \\ B \\ t_L \\ b_L \\ t'_R \end{pmatrix}_{\frac{2}{3}}$
$\begin{pmatrix} U \\ D \\ X \\ Y \\ b'_R \end{pmatrix}_{-\frac{1}{3}}$
vector rep
dark fermions
Ψ_4 spinor rep



$\Rightarrow$ $SO(4) \times U(1)_X$ *B.C.*

$\Rightarrow$ $SU(2)_L \times U(1)_Y$ $\langle \hat{\Phi} \rangle$

Higgs boson : AB phase $\hat{\theta}_H(x) = \theta_H + \dfrac{H(x)}{f_H}$

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

Hosotani mechanism $\Rightarrow$ $U(1)_{EM}$

Why GH ?

"**Gauge principle**" for Higgs

m_H : finite **gauge hierarchy prob : solved**

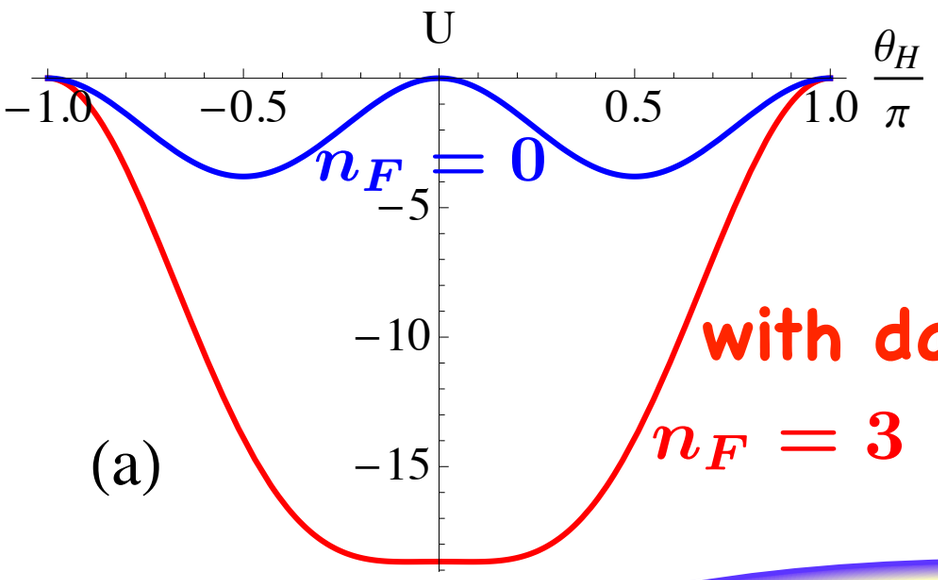
No vacuum instability problem

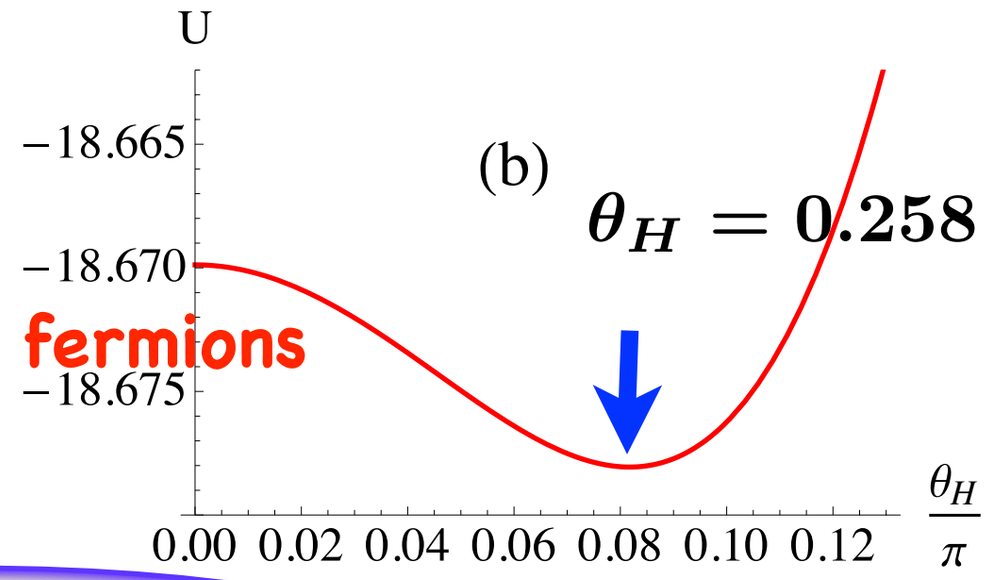
Consistent at low energies, 8TeV LHC

$$\theta_H < 0.1 \ , \ H \to \gamma\gamma \ , \ \cdots$$

and gives predictions

$$V_{\rm eff}(\theta_H) = \left(\frac{m_{\rm KK}}{2\pi}\right)^4 U \qquad z_L = 10^7\,, \quad n_F = 3$$





Hosotani mechanism

Dynamical EW symmetry breaking

Finite Higgs boson mass generated.

Gauge hierarchy prob : solved

No Higgs boson instability prob.

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Funatsu, Hatanaka, YH, Orikasa, Shimotani, 2014

Predictions

We discover

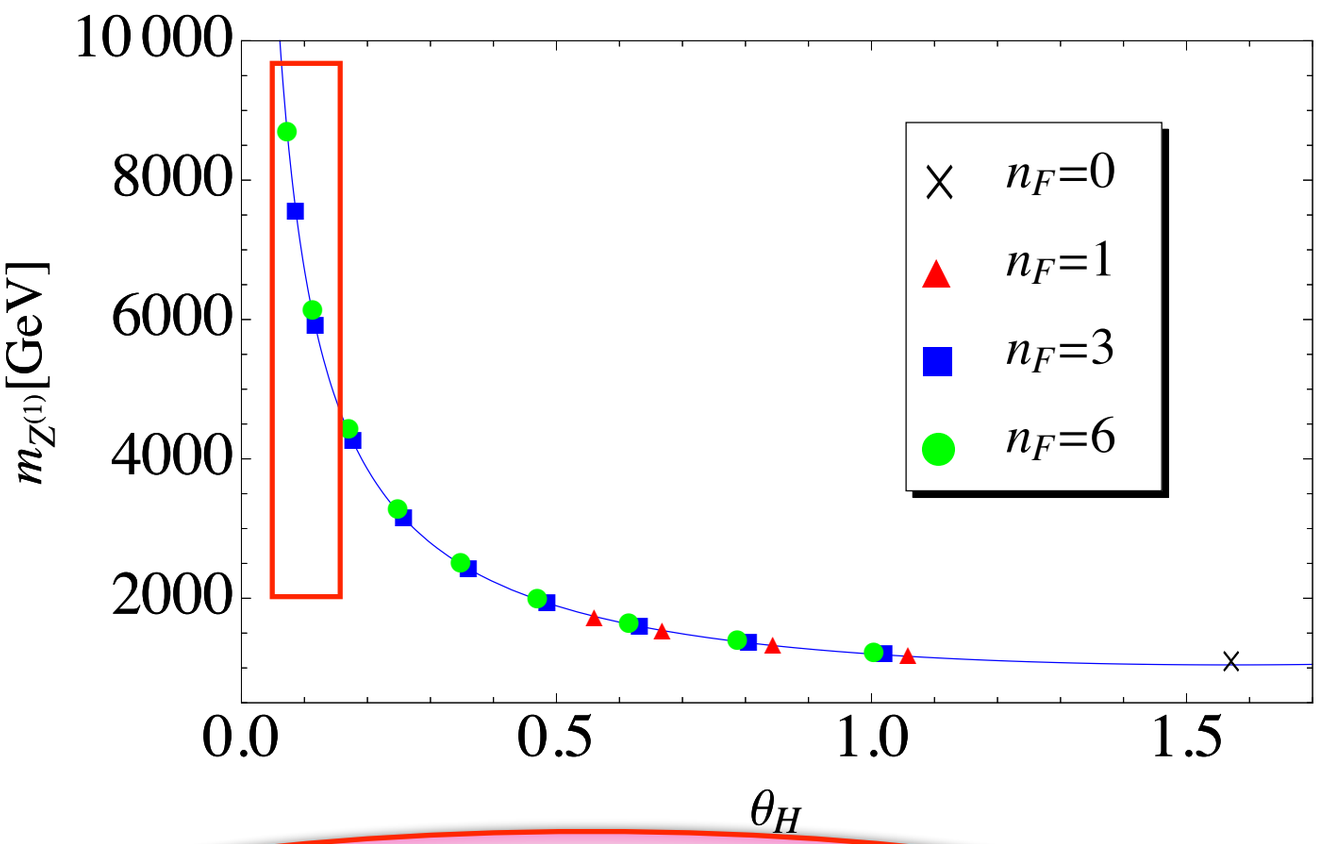
$$m_{\rm KK} \sim \frac{1352\,{\rm GeV}}{(\sin\theta_H)^{0.786}}$$

$$m_{Z_R^{(1)}} \sim \frac{1038\,{\rm GeV}}{(\sin\theta_H)^{0.784}}$$

$$m_{Z^{(1)}} \sim \frac{1044\,{\rm GeV}}{(\sin\theta_H)^{0.808}}$$

$$m_{\gamma^{(1)}} \sim \frac{1056\,{\rm GeV}}{(\sin\theta_H)^{0.804}}$$

independent of "dark fermions" n_F



Universality in θ_H

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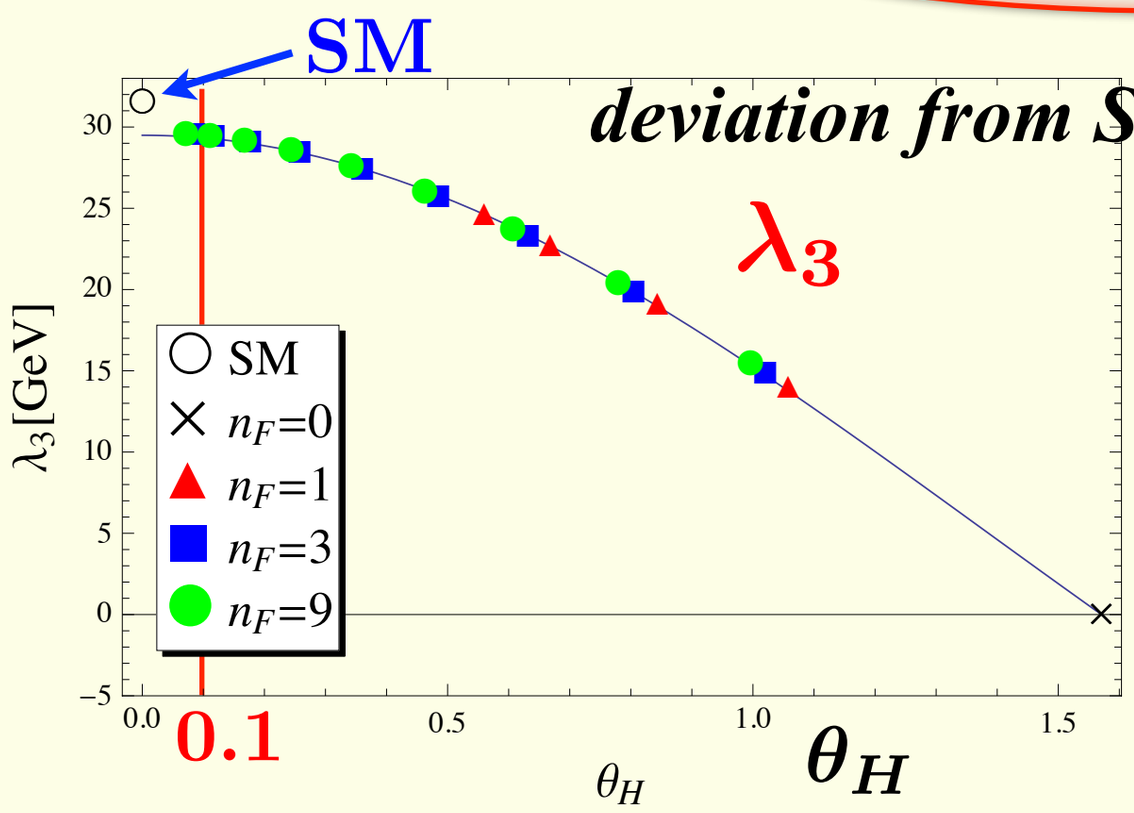
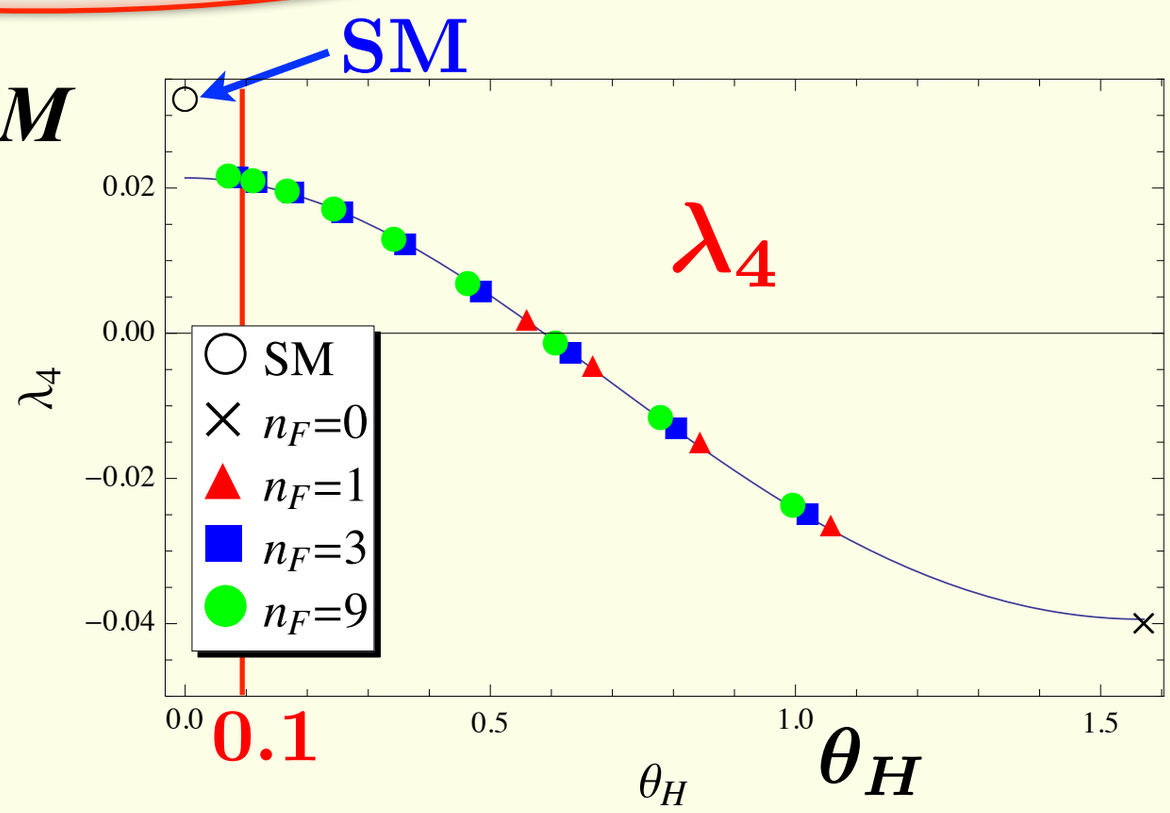
gauge couplings of SM particles : close to SM

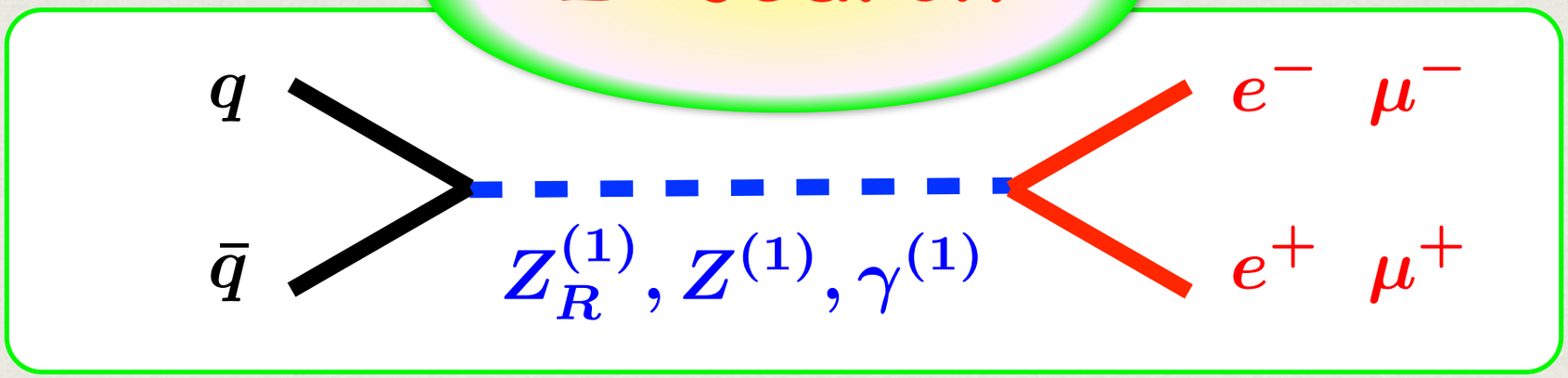
Higgs-WW, -ZZ, -qq, -ll : SM x $\cos\theta_H$

Higgs self-couplings





Z′ search



$\theta_H = 0.114$

Z'	$m\,(\mathrm{TeV})$	$\Gamma\,(\mathrm{GeV})$
$Z_R^{(1)}$	5.73	482
$Z^{(1)}$	6.07	342
$\gamma^{(1)}$	6.08	886

$\theta_H = 0.073$

Z'	$m\,(\mathrm{TeV})$	$\Gamma\,(\mathrm{GeV})$
$Z_R^{(1)}$	8.00	553
$Z^{(1)}$	8.61	494
$\gamma^{(1)}$	8.61	1040

Large widths

large couplings for right handed quarks/leptons

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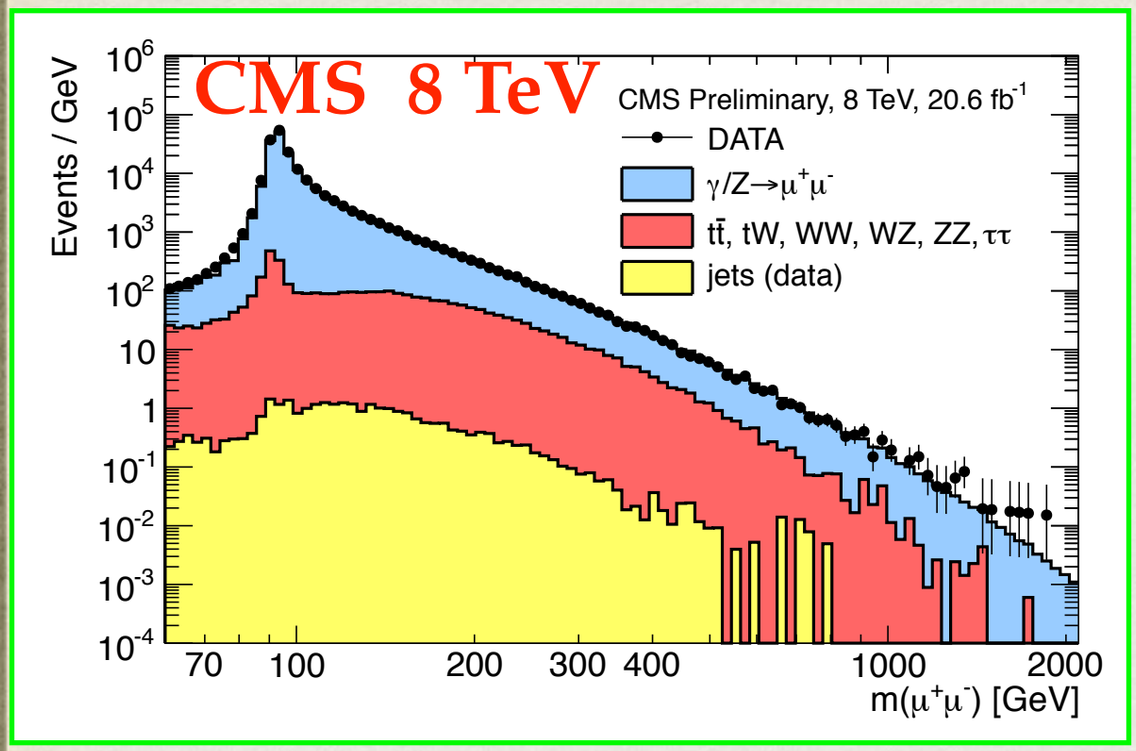
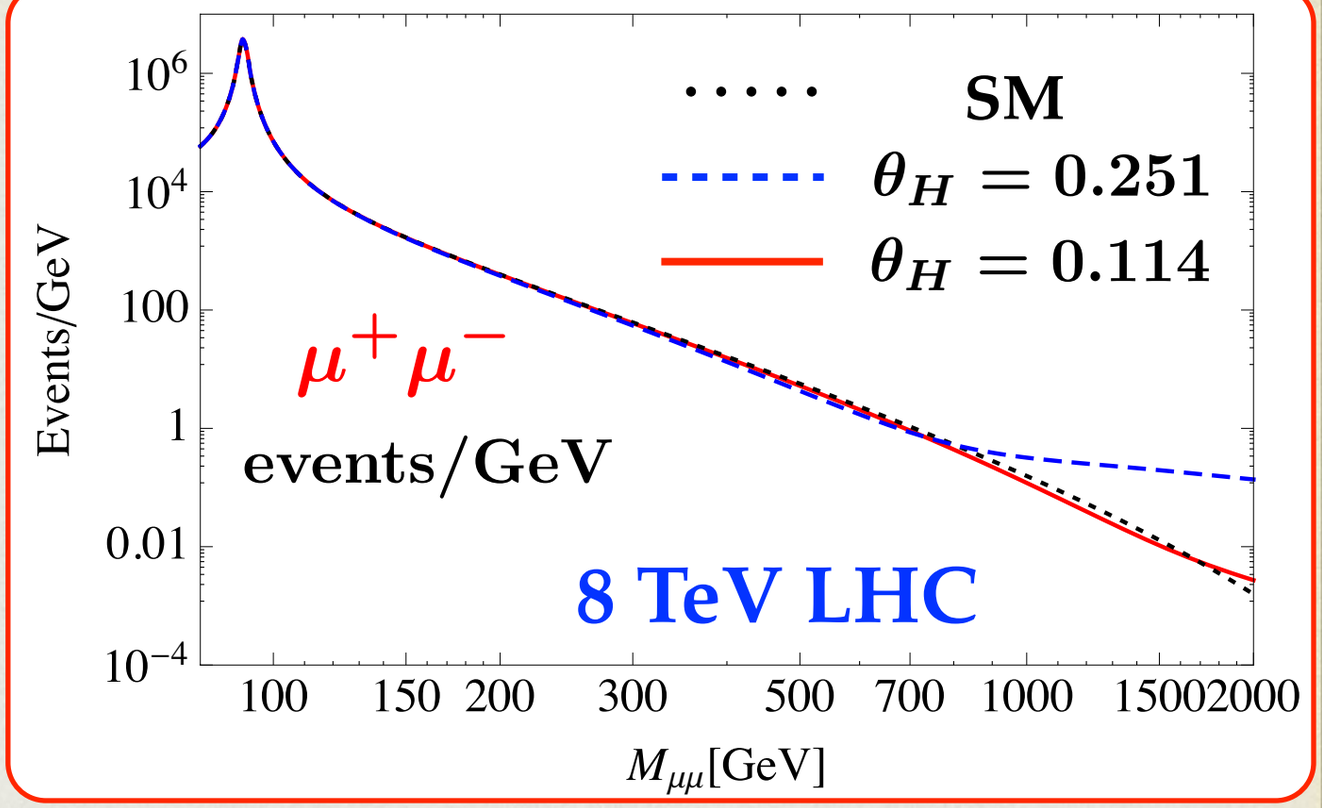
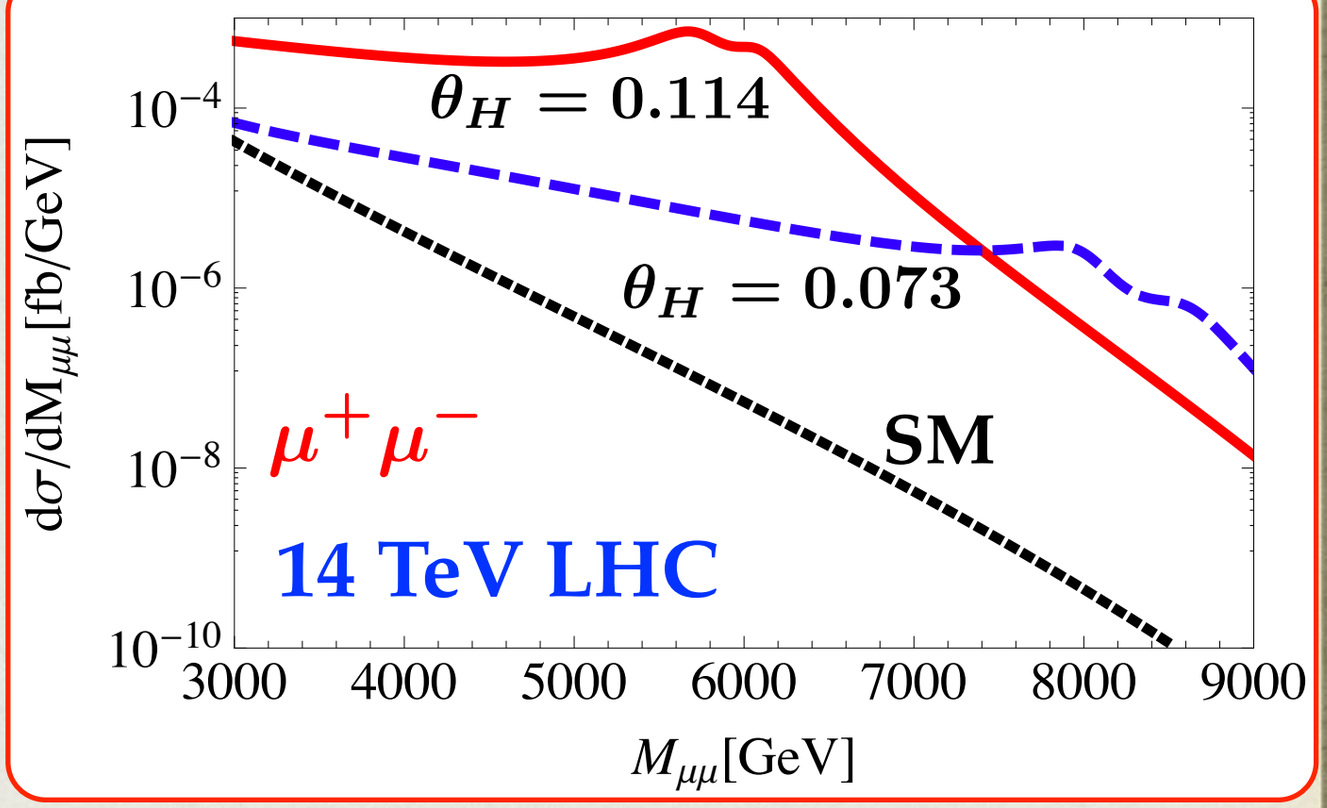




Z′ search

clear signals

CMS 2.9 TeV event ?



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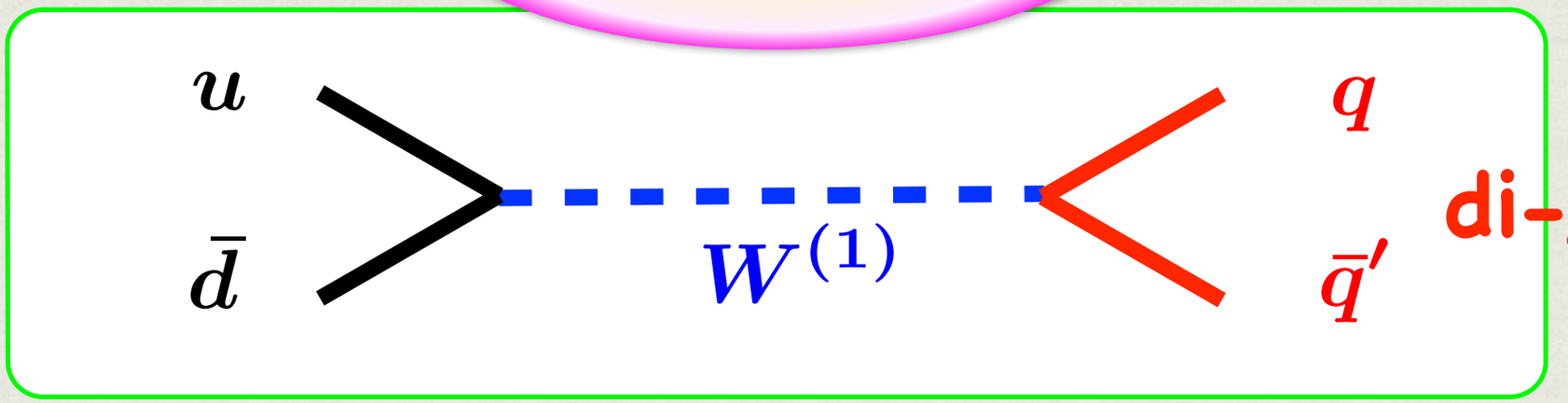
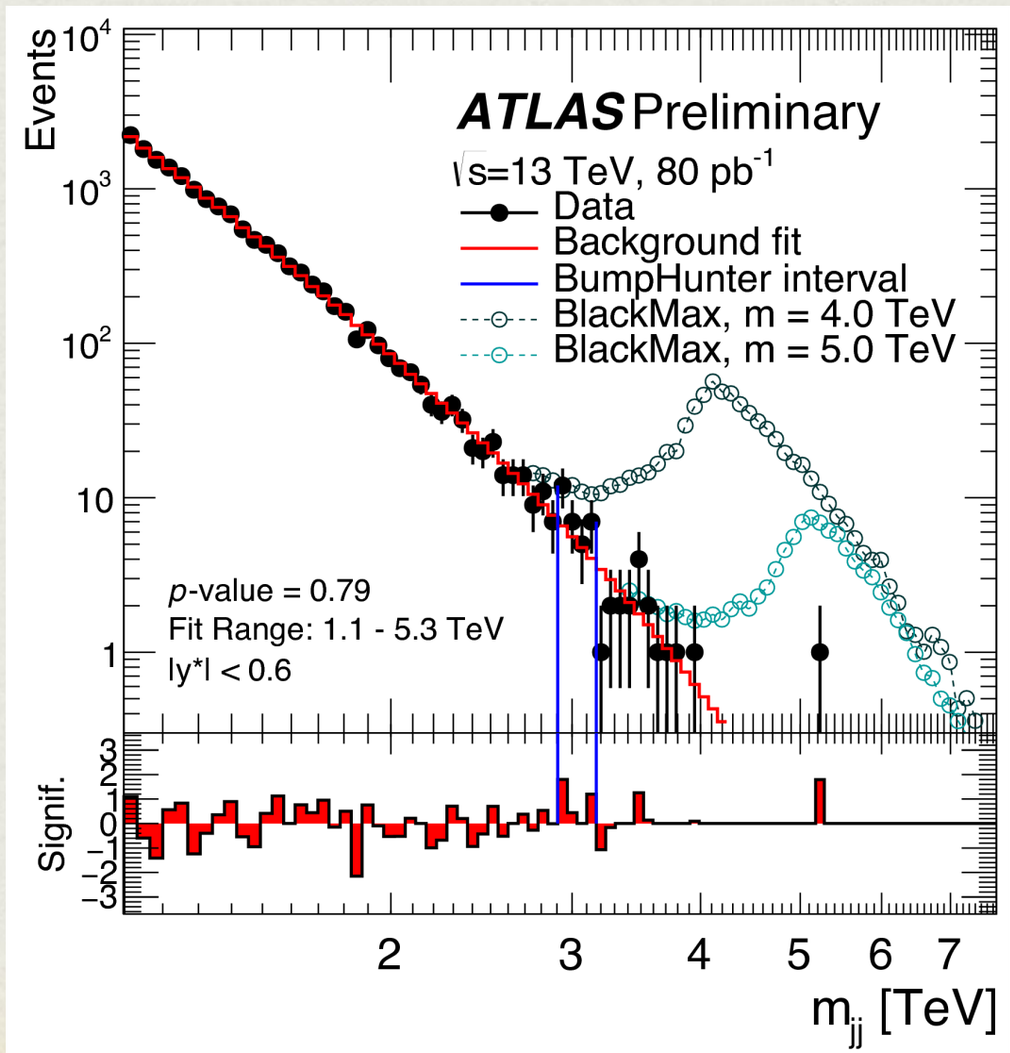
W′ search

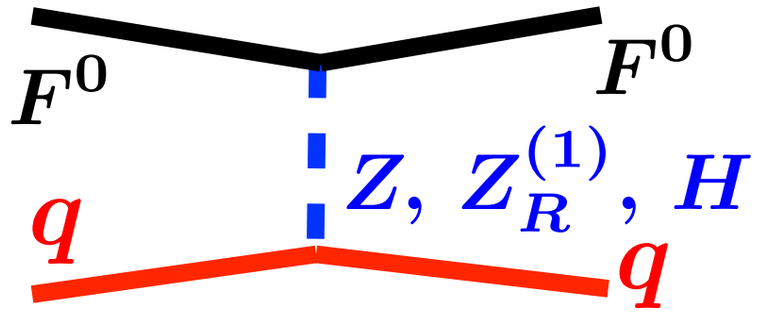

u
$\bar{d}$
$W^{(1)}$
q
$\bar{q}'$
di-jet

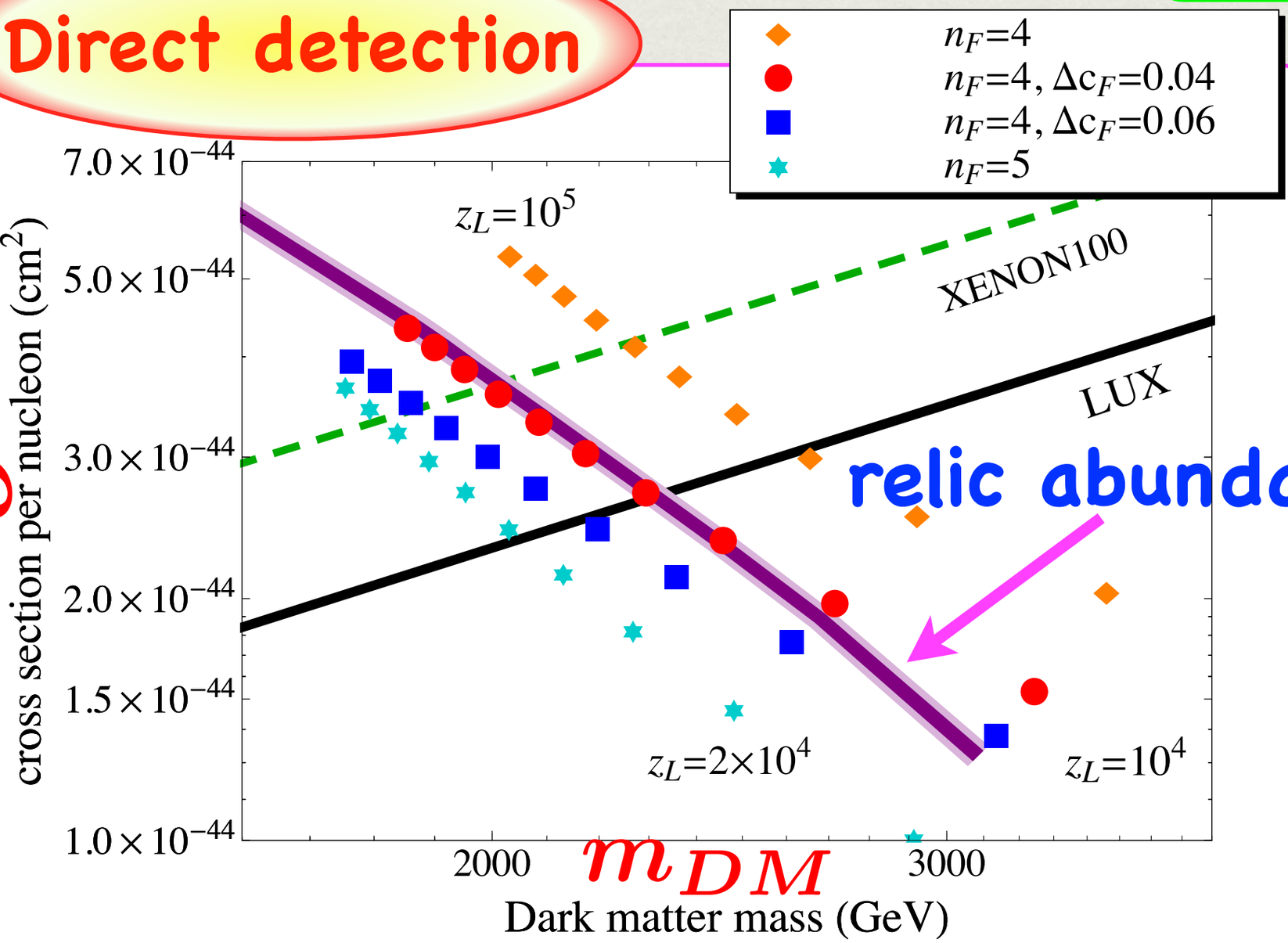

Events
ATLAS Preliminary
√s=13 TeV, 80 pb-1
Data
Background fit
BumpHunter interval
BlackMax, m = 4.0 TeV
BlackMax, m = 5.0 TeV
p-value = 0.79
Fit Range: 1.1 - 5.3 TeV
|y*| < 0.6
Signif.
mjj [TeV]

Dark Matter

Direct detection

Dominant scattering





relic abundance : OK

$$(n_F^{\text{light}}, n_F^{\text{heavy}}) = (1, 3)$$

What's next ?

Gauge-Higgs Grand Unification

EM + Weak + Strong

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

?

Burdman, Nomura, NPB656 (2003)

Haba, Hosotani, Kawamura, Yamashita, PRD70 (2004)

Lim, Maru, PLB653 (2007)

Kojima, Takenaga, Yamashita, PRD84 (2011)

Frigerio, Serra, Varagnolo, JHEP 1106 (2011)

Hosotani, Yamatsu, arXiv: 1504.03817

Scales

Size of 5th dim $\dfrac{\pi}{L} \sim m_{\rm GUT}$ **GUT scale**

$\sim$?

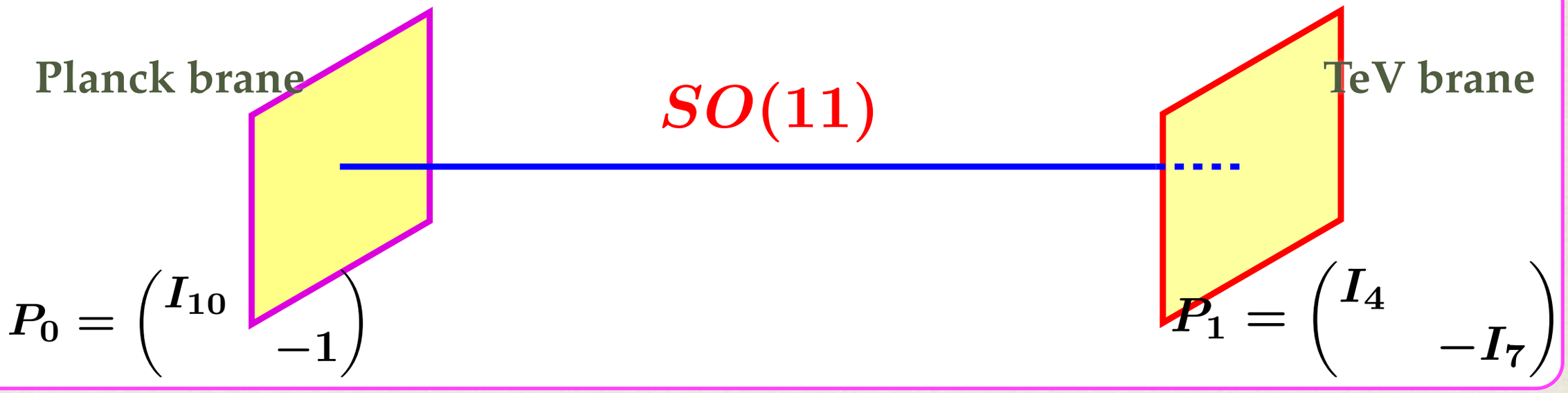
coupling unification

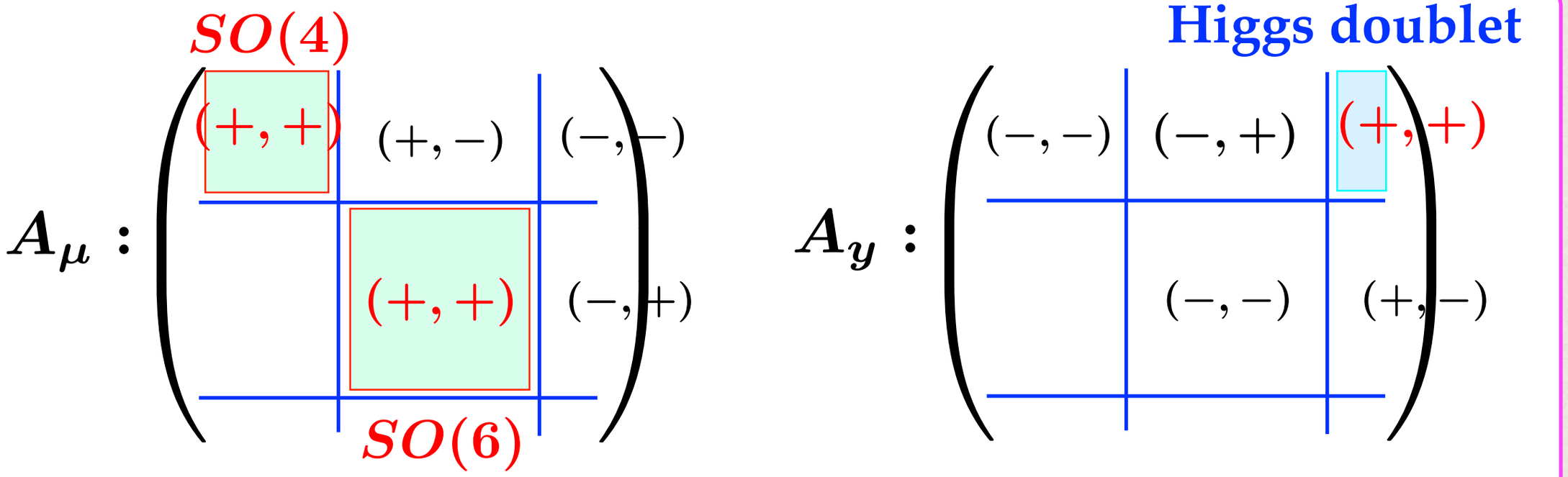
KK scale $m_{\rm KK} = \pi k e^{-kL} \sim \dfrac{\sqrt{kL}}{\sin\theta_H} m_W > 4\,{\rm TeV}$

Weak scale $100\,{\rm GeV}$

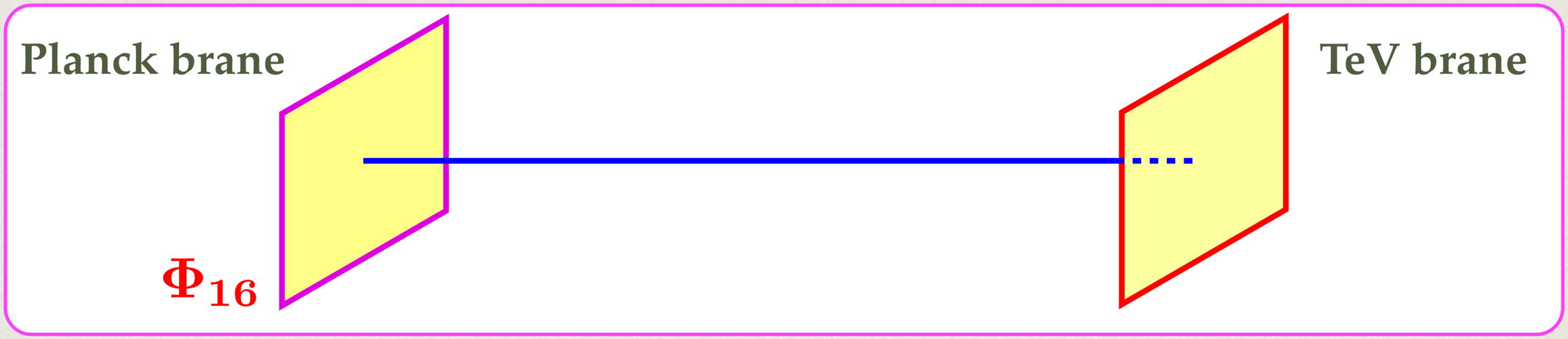
Low energies

SO(11) gauge-Higgs grand unification in RS





$$SO(4) \times SO(6) \to SU(2)_L \times SU(3)_C \times U(1)_Y$$



$$(D_\mu \Phi_{16})^\dagger D^\mu \Phi_{16}\, \delta(y) \to g^2 \langle \Phi_{16}^\dagger \rangle A^\mu A_\mu \langle \Phi_{16} \rangle \, \delta(y)$$

$$Q_Y = \tfrac{1}{2}(T_{12} - T_{34}) - \tfrac{1}{3}(T_{56} + T_{78} + T_{9,10})$$
$$Q_{EM} = T_{12} - \tfrac{1}{3}(T_{56} + T_{78} + T_{9,10})$$

$$\Rightarrow \quad g'_Y = \sqrt{\frac{3}{5}}\, g_w \ , \ e = \sqrt{\frac{3}{8}}\, g_w \quad \Rightarrow \quad \sin^2 \theta_W = \frac{3}{8}$$

Quarks & Leptons

Planck brane

TeV brane

$$P_0^{sp} = I_{16} \otimes \sigma^3$$

$$\Psi_{32}$$

$$P_1^{sp} = I_2 \otimes \sigma^3 \otimes I_8$$

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

$$\Psi_{16} = \begin{pmatrix} \nu \\ e \\ \tilde{d}_1 \\ \tilde{u}_1 \\ u_3 \\ d_3 \\ \tilde{d}_2 \\ \tilde{u}_2 \\ u_1 \\ d_1 \\ \tilde{e} \\ \tilde{\nu} \\ u_2 \\ d_2 \\ \tilde{d}_3 \\ \tilde{u}_3 \end{pmatrix} \begin{matrix} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \\ \\ \text{zero modes} \\ \\ \begin{pmatrix} u_{3L} \\ d_{3L} \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} u_{1L} \\ d_{1L} \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} u_{2L} \\ d_{2L} \end{pmatrix} \\ \\ \end{matrix}$$

$$\Psi_{\overline{16}} = \begin{pmatrix} \tilde{d}'_3 \\ \tilde{u}'_3 \\ u'_2 \\ d'_2 \\ \tilde{e}' \\ \tilde{\nu}' \\ u'_1 \\ d'_1 \\ \tilde{d}'_2 \\ \tilde{u}'_2 \\ u'_3 \\ d'_3 \\ \tilde{d}'_1 \\ \tilde{u}'_1 \\ \nu' \\ e' \end{pmatrix} \begin{matrix} \text{zero modes} \\ \\ \begin{pmatrix} u_{2R} \\ d_{2R} \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} u_{1R} \\ d_{1R} \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} u_{3R} \\ d_{3R} \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} \nu_R \\ e_R \end{pmatrix} \end{matrix}$$

Fits well.

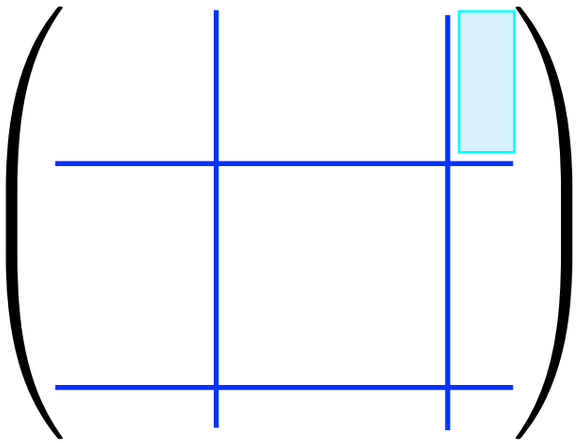
4D Higgs field

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

$$A_y^{4,11}(x,y) = \Big\{\theta_H f_H + H(x)\Big\}u_H(y) + \cdots$$

$$\theta_H \sim \theta_H + 2\pi \qquad f_H = \frac{2}{g}\sqrt{\frac{k}{z_L^2 - 1}}$$

A_y :



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

Higgs field is massless at the tree level.

$$V_{\rm eff}(\theta_H)^{1\,\rm loop} \neq 0$$

$$\rightarrow \theta_H^{\rm min}$$

Higgs field acquires a finite mass at 1-loop.

KK Spectrum

W tower

$$S(1;\lambda)C'(1;\lambda) + \tfrac{1}{2}\lambda \sin^2\theta_H = 0$$

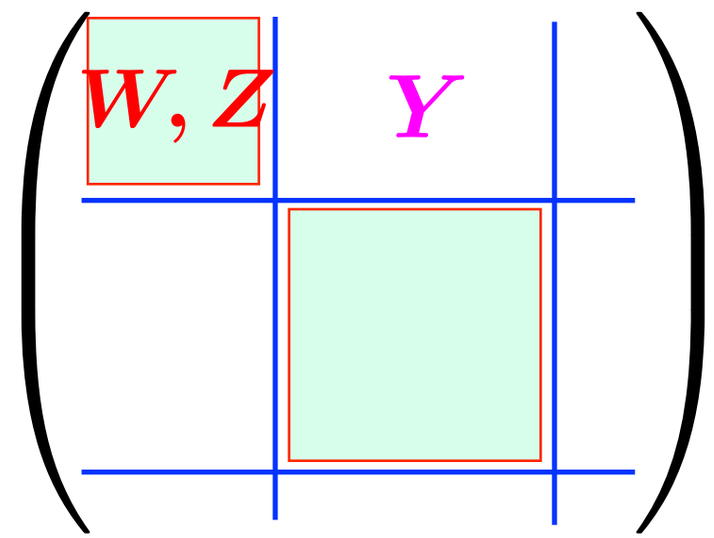
Z tower

$$SC' + \frac{4}{5}\lambda \sin^2\theta_H = 0$$

Y boson towers

$$SC' + \tfrac{1}{2}\lambda(1 + \cos^2\theta_H) = 0$$

A_μ :



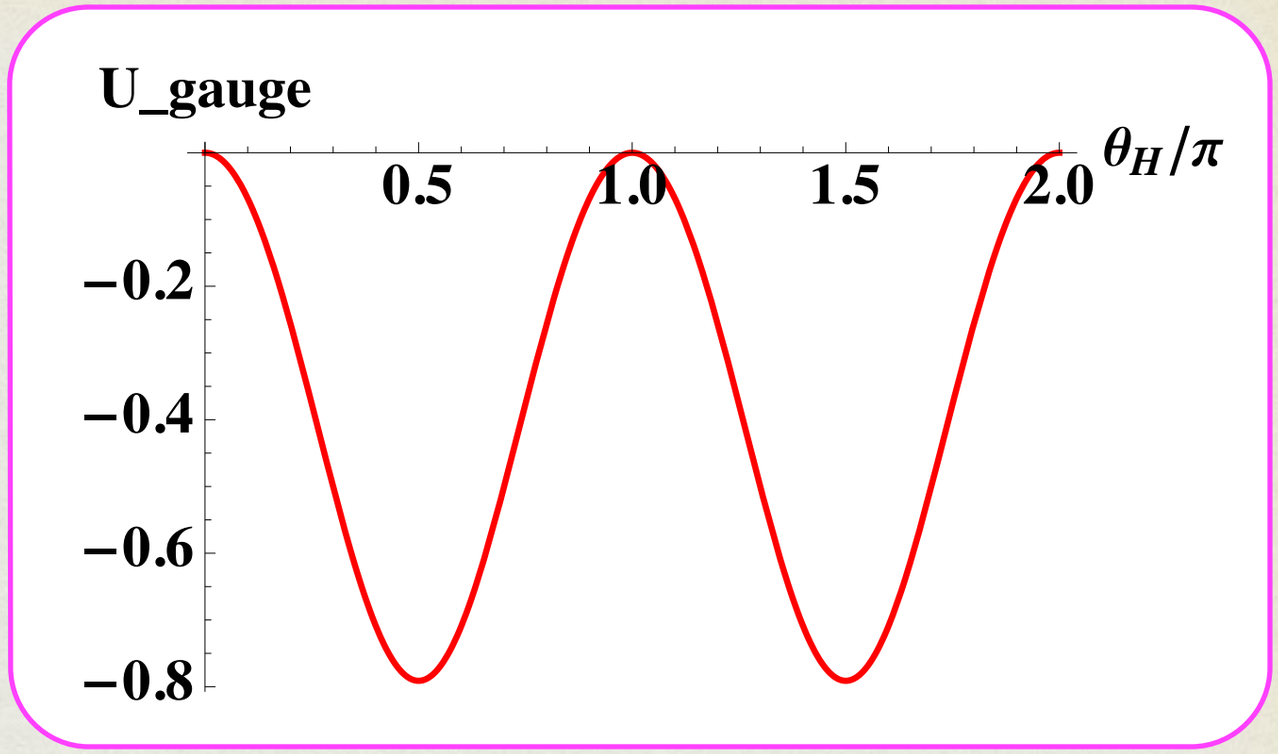
$$m_W \sim \frac{\sin\theta_H}{\pi\sqrt{kL}}\, m_{\rm KK} \quad , \quad m_Z = \frac{m_W}{\cos\theta_W} \quad , \quad \sin^2\theta_W = \frac{3}{8}$$

$$\Psi_{32} \qquad S_L S_R(1;\lambda,c_{32}) + \begin{pmatrix} \sin^2 \frac{1}{2}\theta_H \\ \cos^2 \frac{1}{2}\theta_H \end{pmatrix} = 0$$

$$\Psi_{11} \qquad S_L S_R(1;\lambda,c_{11}) + \begin{pmatrix} \sin^2 \theta_H \\ \cos^2 \theta_H \end{pmatrix} = 0$$

	period
A_M , Ψ_{11}	π
Ψ_{32}	2π

$V_{\rm eff}(\theta_H)$



Gauge fields only

$\rightarrow \theta_H = \frac{1}{2}\pi$ EW symmetry breaking !

but, Higgs boson becomes stable.

Needs

Fermions $\Psi_{32}, \Psi_{11}, \Psi'_{11}$

Brane int. $\overline{\Psi}_{16}\Psi_1\Phi_{16},\ \overline{\Psi}_{\overline{16}}\Psi_{10}\Phi_{16},\ \overline{\Psi}_{16}\Psi_{10}\Phi^*_{16},\ \cdots$

Proton decay

$$m_{\rm KK} \ll m_{\rm GUT}$$

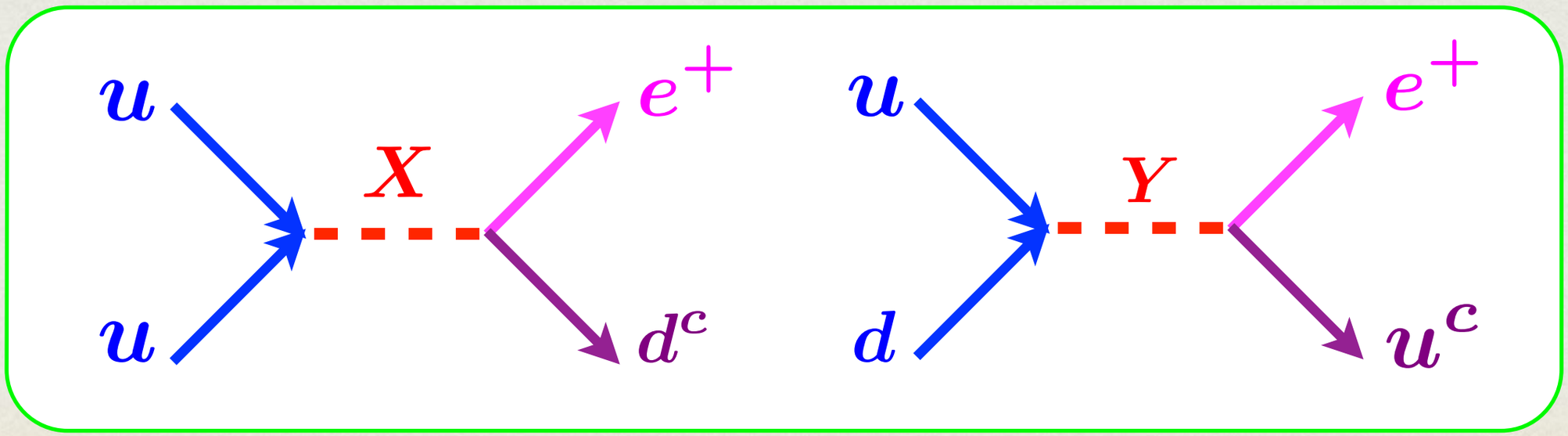
4D SU(5) GUT

$$\overline{5} \quad \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \quad d_L^c$$

$$10 \quad \begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad u_L^c \quad e_L^c$$

4D SO(10) GUT

$$16 = 1 + \overline{5} + 10$$

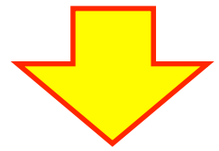


Proton decay - suppressed

$$\Psi_{16} = \begin{pmatrix} \nu \\ e \\ \tilde{d}_1 \\ \tilde{u}_1 \\ u_3 \\ d_3 \\ \tilde{d}_2 \\ \tilde{u}_2 \\ u_1 \\ d_1 \\ \tilde{e} \\ \tilde{\nu} \\ u_2 \\ d_2 \\ \tilde{d}_3 \\ \tilde{u}_3 \end{pmatrix} \begin{matrix} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} u_{3L} \\ d_{3L} \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} u_{1L} \\ d_{1L} \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} u_{2L} \\ d_{2L} \end{pmatrix} \\ \\ \\ \end{matrix} \qquad \Psi_{\overline{16}} = \begin{pmatrix} \tilde{d}'_3 \\ \tilde{u}'_3 \\ u'_2 \\ d'_2 \\ \tilde{e}' \\ \tilde{\nu}' \\ u'_1 \\ d'_1 \\ \tilde{d}'_2 \\ \tilde{u}'_2 \\ u'_3 \\ d'_3 \\ \tilde{d}'_1 \\ \tilde{u}'_1 \\ \nu' \\ e' \end{pmatrix} \begin{matrix} \\ \\ \begin{pmatrix} u_{2R} \\ d_{2R} \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} u_{1R} \\ d_{1R} \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} u_{3R} \\ d_{3R} \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} \nu_R \\ e_R \end{pmatrix} \end{matrix}$$

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

N_Ψ conservation



no proton decay

SO(11) gauge-Higgs

$$\Psi_{32}\quad \Psi_{16}=\begin{pmatrix}\nu\\ e\\ \tilde{d}_1\\ \tilde{u}_1\\ u_3\\ d_3\\ \tilde{d}_2\\ \tilde{u}_2\\ u_1\\ d_1\\ \tilde{e}\\ \tilde{\nu}\\ u_2\\ d_2\\ \tilde{d}_3\\ \tilde{u}_3\end{pmatrix}\begin{matrix}\\ \begin{pmatrix}\nu_L\\ e_L\end{pmatrix}\\ \\ \\ \\ \begin{pmatrix}u_{3L}\\ d_{3L}\end{pmatrix}\\ \\ \\ \\ \begin{pmatrix}u_{1L}\\ d_{1L}\end{pmatrix}\\ \\ \\ \\ \begin{pmatrix}u_{2L}\\ d_{2L}\end{pmatrix}\\ \\ \end{matrix}\qquad \Psi_{\overline{16}}=\begin{pmatrix}\tilde{d}'_3\\ \tilde{u}'_3\\ u'_2\\ d'_2\\ \tilde{e}'\\ \tilde{\nu}'\\ u'_1\\ d'_1\\ \tilde{d}'_2\\ \tilde{u}'_2\\ u'_3\\ d'_3\\ \tilde{d}'_1\\ \tilde{u}'_1\\ \nu'\\ e'\end{pmatrix}\begin{matrix}\\ \\ \\ \begin{pmatrix}u_{2R}\\ d_{2R}\end{pmatrix}\\ \\ \\ \begin{pmatrix}u_{1R}\\ d_{1R}\end{pmatrix}\\ \\ \\ \begin{pmatrix}u_{3R}\\ d_{3R}\end{pmatrix}\\ \\ \\ \begin{pmatrix}\nu_R\\ e_R\end{pmatrix}\end{matrix}$$

4D SO(10) GUT

$$\Psi_{16}=\begin{pmatrix}\nu_L\\ e_L\\ d^c_{1L}\\ u^c_{1L}\\ u_{3L}\\ d_{3L}\\ d^c_{2L}\\ u^c_{2L}\\ u_{1L}\\ d_{1L}\\ e^c_L\\ \nu^c_L\\ u_{2L}\\ d_{2L}\\ d^c_{3L}\\ u^c_{3L}\end{pmatrix}$$

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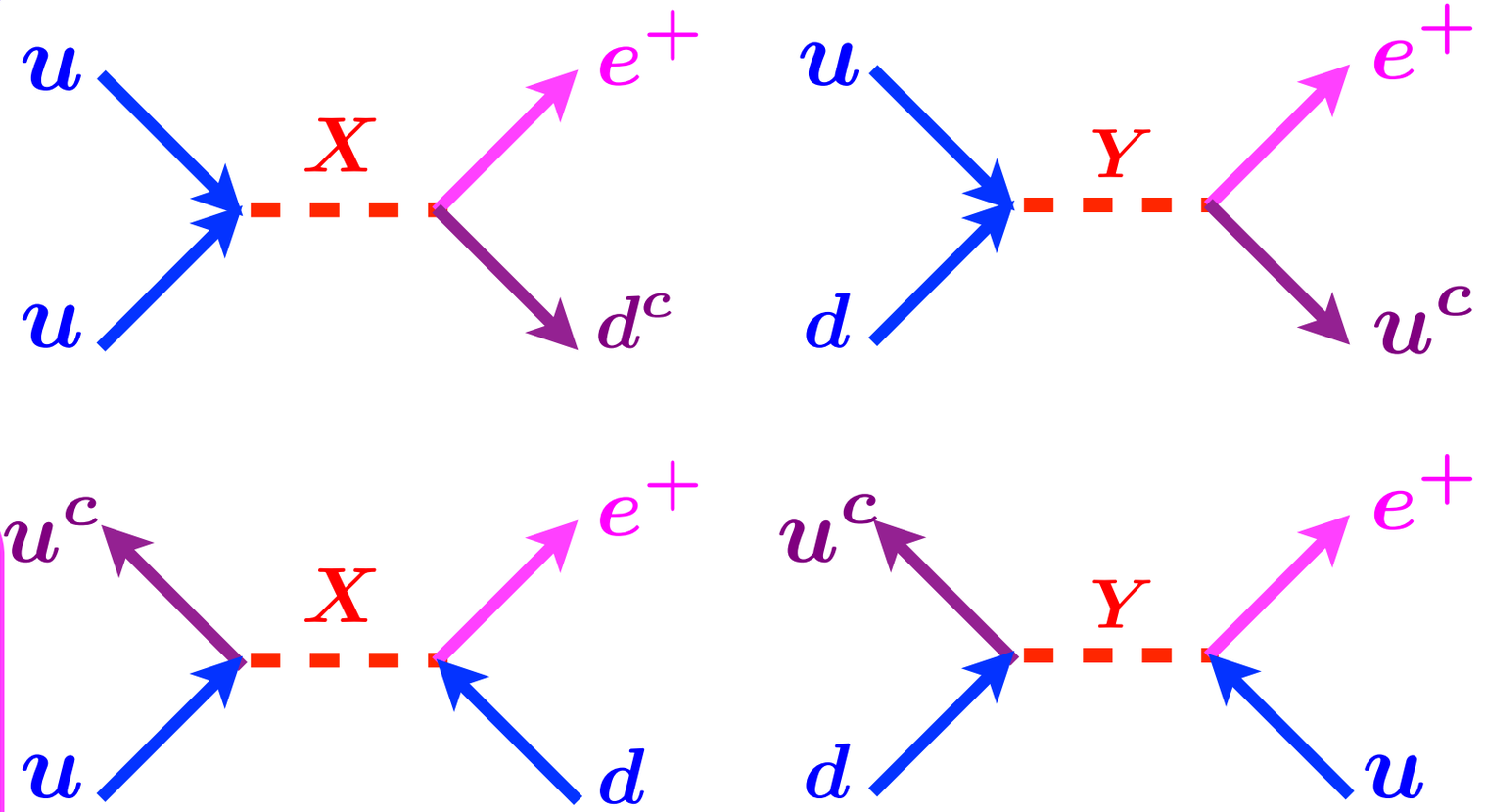
Proton decay

4D SU(5) GUT



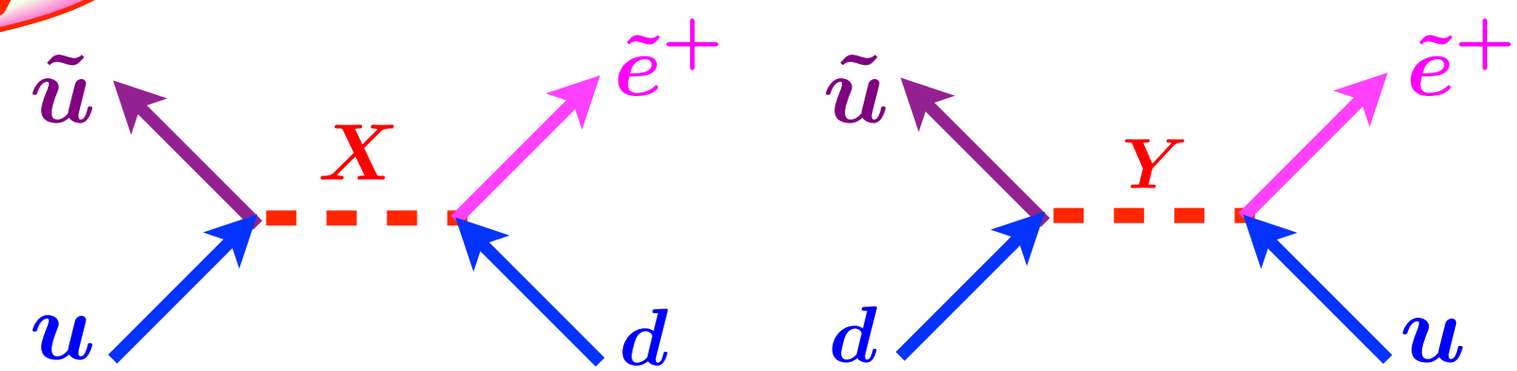
$$p \not\to \pi^0\ e^+$$

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

No proton decay

SO(11)

gauge-Higgs



Summary

SO(5)xU(1) Gauge-Higgs EW Unification

Dynamical EW sym breaking

Consistent at low energies

Predictions for 14 TeV LHC

SO(11) Gauge-Higgs Grand Unification

SO(11) structure above $m_{\rm KK} \ll \pi L^{-1}$

Coupling unification at $m_{\rm GUT} \sim \pi L^{-1}$ **?**

Proton decay suppressed

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