The Most Wanted Higgs Particle

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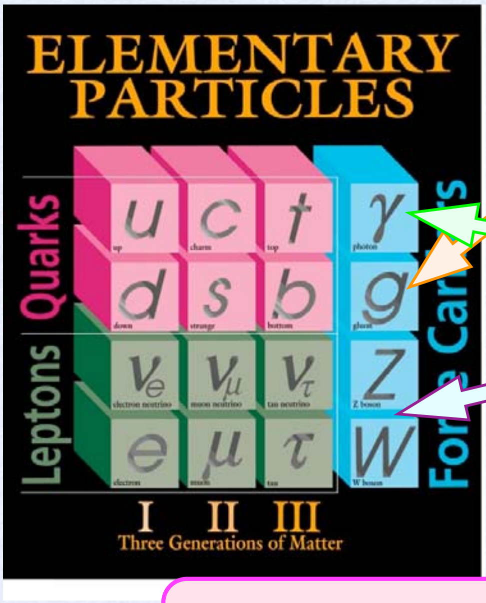
Successful Standard Model of Particle Physics



Strong interactions

$SU(3)$ gauge theory

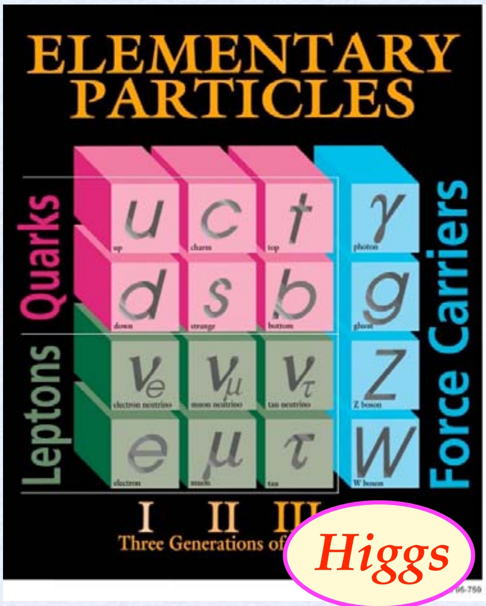
Electromagnetic interactions

Weak interactions

$SU(2) \times U(1)$ gauge theory

Gauge principle rules the standard model.

However,



Higgs

missing !

- ***Higgs field is responsible for***
  - ***EW sym. breaking***

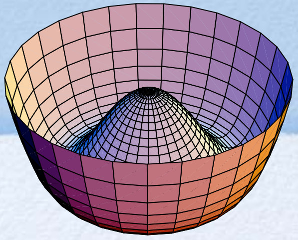
    $SU(2)_L \times U(1)_Y \to U(1)_{EM}$
  - ***masses of quarks and leptons***

    Yukawa couplings

There must be ***Higgs force.***

Hunt for the Higgs particle at LHC !

How is the symmetry broken?



With a potential by hand?

Masses of quarks and leptons

Yukawa couplings

"many arbitrary parameters"

Look for

Hidden principle

New physics

- ***SUSY***
- ***Little Higgs***
- ***Higgsless***
- ***Gauge-Higgs unification***

Old Gauge-Higgs Unification

$A_M = (A_\mu , A_{y_j})$

γ, W, Z Higgs

Fairlie 1979
Forgacs & Manton 1980
Manton 1979

$\mu^2 = -\frac{1}{R^2} < 0$

on $M^4 \times S^2$

$G \longrightarrow SU(2)_L \times U(1)_Y \longrightarrow U(1)_{EM}$

Ansatz: spherical sym. + flux

???

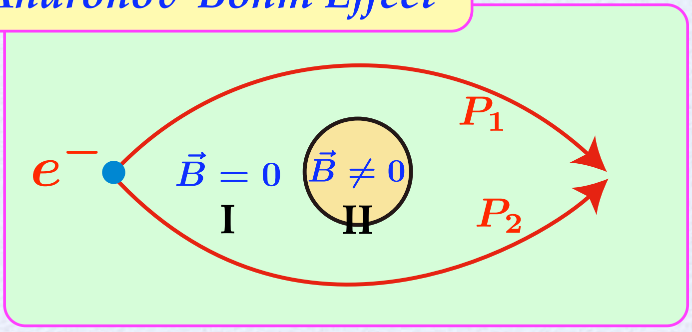
G	$\sin^2\theta_W$	M_W	M_Z	M_H
$SU(3)$	$3/4$	44 GeV	88	88
$O(5)$	$1/2$	54	76	76
G_2	$1/4$	76	88	88

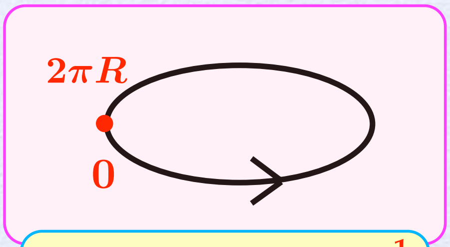
AB effect in extra-dimensions

$A_M = (A_\mu, A_y)$ on $M^4 \times S^1$

$A_y =$ constant ⇒ $F_{MN} = 0$ *but nontrivial !*

Aharonov-Bohm Effect





Extra dimension S^1

$\theta_{AB} = g\int_0^{2\pi R} dy\, A_y$ *is physical, and* = *Higgs*

Yang-Mills AB phases

$$P \exp\left\{ ig \int_0^{2\pi R} dy\, A_y \right\} \sim \begin{pmatrix} e^{i\theta_1} & & \\ & \ddots & \\ & & e^{i\theta_N} \end{pmatrix} \qquad \Big(\sum_j \theta_j = 0 \Big)$$

In U(1),
AB phase does not break gauge symmetry.

In non-Abelian theory,
Yang-Mills AB phases can break gauge symmetry.

New Gauge-Higgs Unification

Higgs = Yang-Mills AB phases θ_H

Massless at the tree level --- flat direction

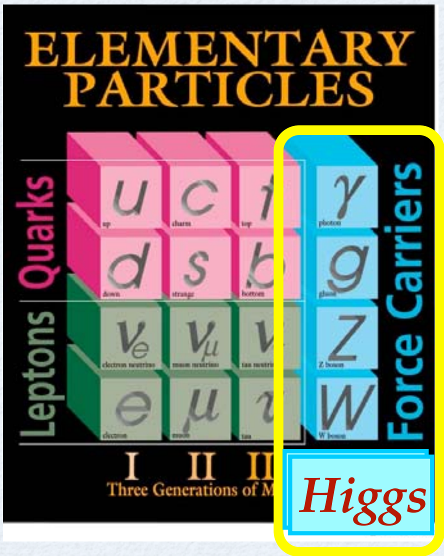
$V_{\rm eff}(\theta_H)$ *--- non-trivial at the quantum level.*
--- finite; independent of a cutoff Λ

Finite Higgs mass : m_H

Dynamical gauge symmetry breaking is induced.

Hosotani mechanism 1983

in EW interactions



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

Chiral fermions

Masses of quarks and leptons
CKM & MNS mixing

Constraints:
$m_H > 114$ GeV
$M_{KK} >$ a few TeV

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① *Gauge group to start with*

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

Higgs doublet $\subset$ gauge fields -- adjoint rep.

⇒ larger group

$SU(3)$

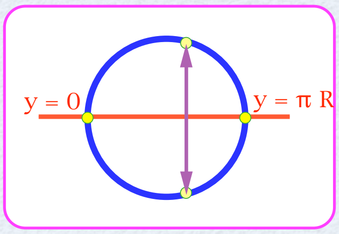
$SU(3) \times U(1) \times U(1)$

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

② *Extra-dimensions: Orbifold*

$M^4 \times (S^1/Z_2)$ *RS spacetime*

$$(x^\mu, +y) \sim (x^\mu, -y)$$
$$(x^\mu, \pi R + y) \sim (x^\mu, \pi R - y)$$



Physics is single-valued.

$$\begin{pmatrix} A_\mu \\ A_y \end{pmatrix} (x, -y) = P_0 \begin{pmatrix} A_\mu \\ -A_y \end{pmatrix} (x, y) P_0^\dagger$$
$$\begin{pmatrix} A_\mu \\ A_y \end{pmatrix} (x, \pi R - y) = P_1 \begin{pmatrix} A_\mu \\ -A_y \end{pmatrix} (x, \pi R + y) P_1^\dagger$$

Orbifold BC : P_0 , P_1 *Parity / Twist*

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③ *Where is a Higgs doublet ?*

$SU(3)$ model

$$P_0 = P_1 = \begin{pmatrix} -1 & & \\ & -1 & \\ & & +1 \end{pmatrix} \Rightarrow A_y = \begin{pmatrix} & \boxed{\Phi} \\ \boxed{} & \end{pmatrix}$$

$\Phi(x)$
(Higgs)

$SO(5) \times U(1)_{B-L}$ model

$$P_0 = P_1 = \begin{pmatrix} -1 & & & & \\ & -1 & & & \\ & & -1 & & \\ & & & -1 & \\ & & & & +1 \end{pmatrix} \Rightarrow A_y \sim \begin{pmatrix} & \boxed{\begin{matrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \end{matrix}} \\ \boxed{} & \end{pmatrix} \quad \Phi = \begin{bmatrix} \phi_1 + i\phi_2 \\ \phi_4 - i\phi_3 \end{bmatrix}$$

Agashe, Contino, Pomarol (2005)

4 Chiral fermions

On $M^4 \times S^1$ theory is vectorlike.

On $M^4 \times (S^1/Z_2)$ theory naturally becomes chiral.

$SU(3)$
$$\boxed{\begin{pmatrix} \nu_L & \tilde\nu_R \\ e_L & \tilde e_R \\ \tilde e_L & e_R \end{pmatrix} \quad (\, \tilde\nu_L \quad \nu_R \,)}$$

$SO(5) \times U(1)$
$$\boxed{\begin{pmatrix} u_L & \tilde u_R \\ d_L & \tilde d_R \\ \tilde u_L & u_R \\ \tilde d_L & d_R \end{pmatrix}}$$

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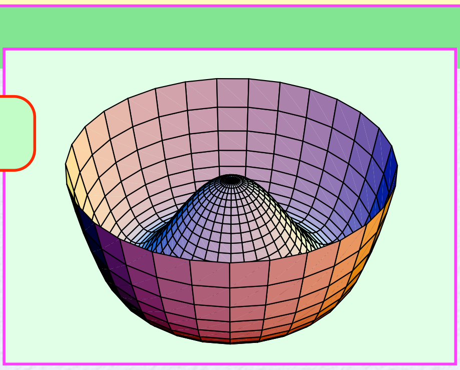
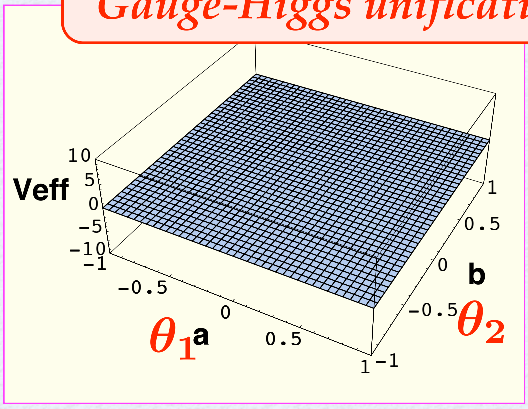
5 Dynamically generated Higgs potential

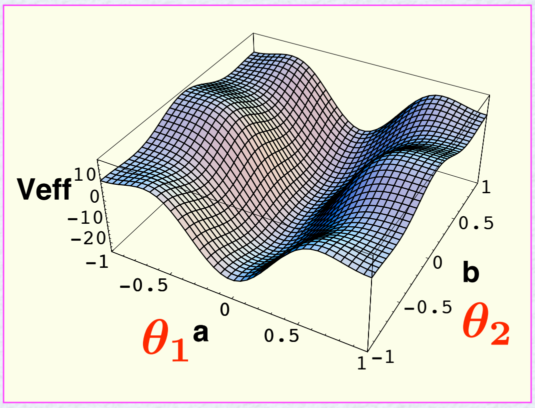
Standard model



Gauge-Higgs unification



quantum effect



Unification on $M^4 \times S^1/Z_2$, T^2/Z_2 , $\cdots$

W

$$m_W \sim \frac{\theta_H}{2\pi} \times \frac{1}{R}$$

too small $M_{KK} = \frac{1}{R} \sim 10\, m_W$

Difficulties in flat space

Higgs

$$m_H \sim \sqrt{\alpha_W}\, \frac{2\pi}{\theta_H}\, m_W$$

too small $m_H \sim 10$ GeV

We need small θ_H *or* *Warped space*

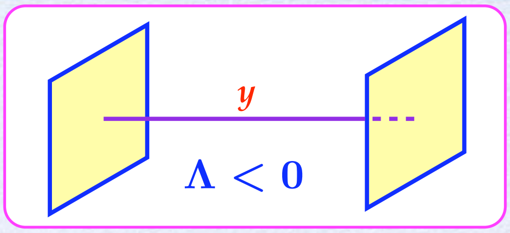
Takenaga's talk in the 4th COE symposium

Electroweak unification in warped space

Randall-Sundrum (1999)

AdS $\Lambda = -k^2$

S^1/Z_2



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

4D Minkowski spacetime

Natural hierarchy

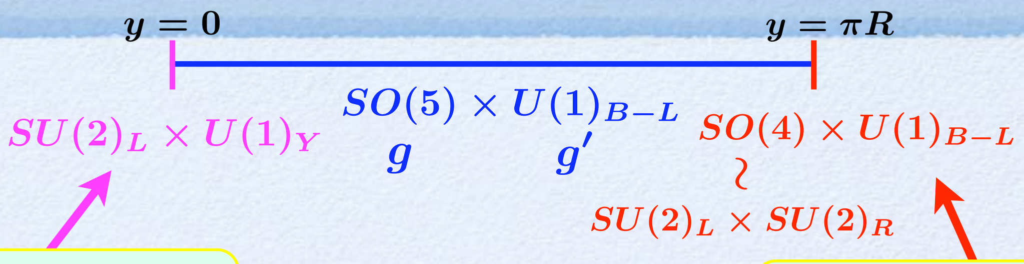
$$k = M_{Pl} \ , \ kR = 12 \ \Rightarrow \ M_{weak} \sim M_{Pl} e^{-\pi kR}$$

More freedom than in $M^4 \times S^1/Z_2$

Suppose :
Gauge fields, quarks, leptons, ... --- in the bulk

$SO(5) \times U(1)_{B-L}$ model

Agashe, Contino, Pomarol (2005)



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

+ additional brane dynamics

$\theta_H \neq 0$

$U(1)_{EM}$

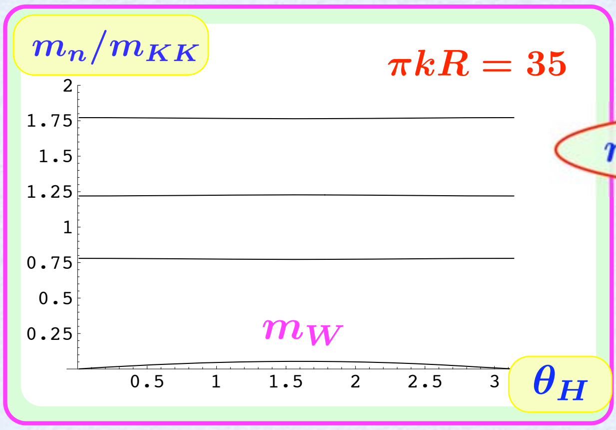
$$P_1 = \begin{pmatrix} -1 &&&& \\ & -1 &&& \\ && -1 && \\ &&& -1 & \\ &&&& +1 \end{pmatrix}$$

$$m_W \sim \sqrt{\frac{k}{\pi R}}\, e^{-\pi k R} \;\sin \theta_H$$

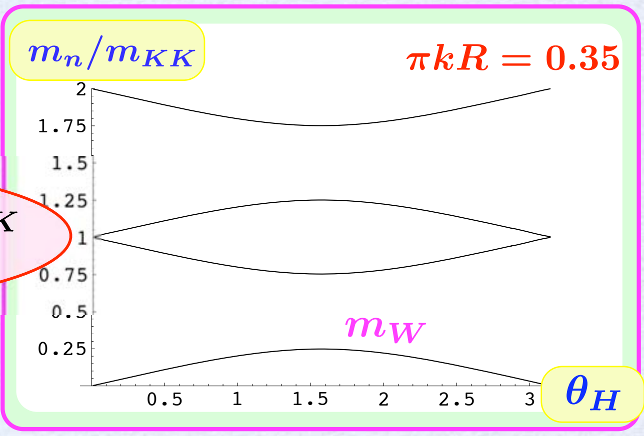
$$m_Z = \frac{m_W}{\cos \theta_W} \qquad \sin^2 \theta_W = \frac{g_Y^2}{g^2 + g_Y^2} = \frac{g'^2}{g^2 + 2g'^2}$$

Mass spectrum
KK tower of W-boson

$SO(5) \times U(1)_{B-L}$ model



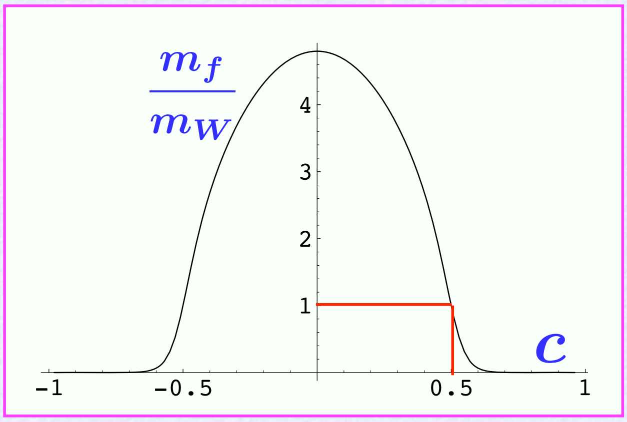
$m_W \ll m_{KK}$ in RS

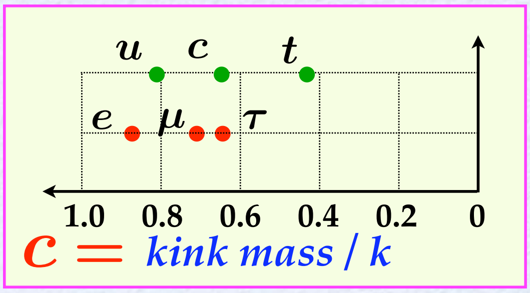


$m_W \sim (0.1 \sim 0.2)\, m_{KK}$
in flat space

Fermion masses

Gauge interactions $g\,\overline{\psi}\,\Gamma^5 e_5{}^z\langle A_z\rangle\,\psi$

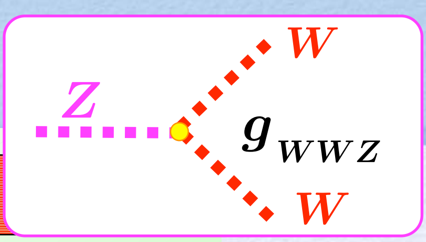




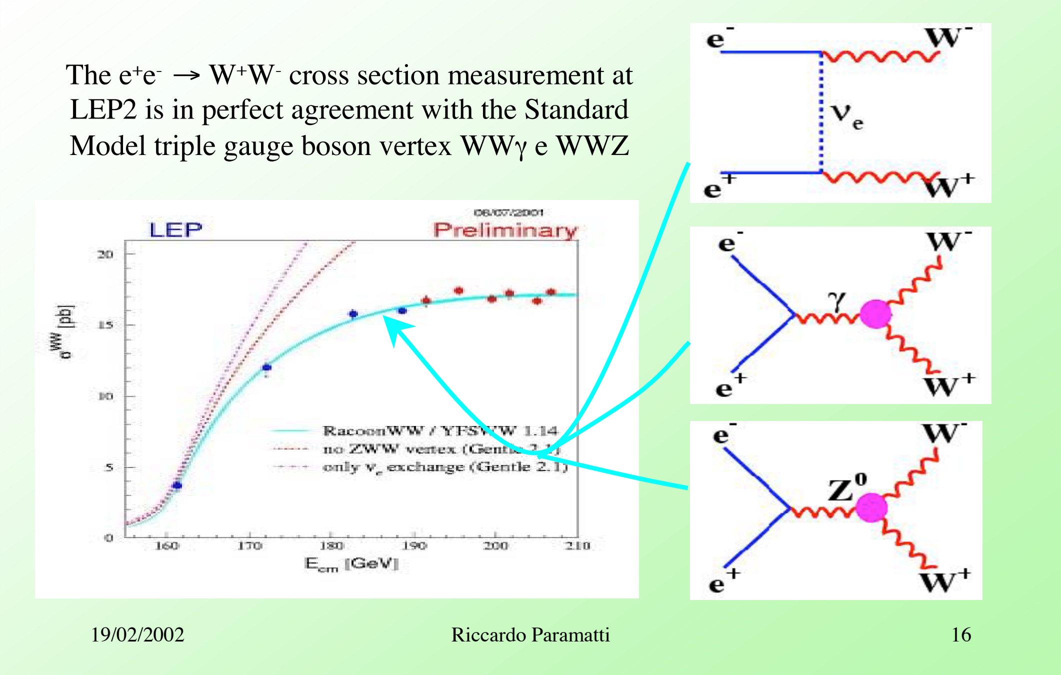
c = *kink mass / k*

The hierarchy is explained.

WWZ coupling



Triple gauge boson vertex

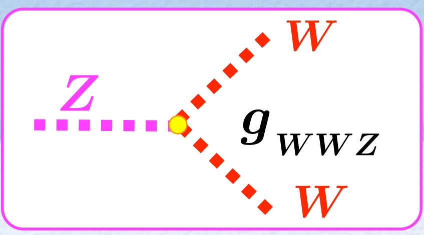


The e+e- → W+W- cross section measurement at LEP2 is in perfect agreement with the Standard Model triple gauge boson vertex WWγ e WWZ

19/02/2002 Riccardo Paramatti 16

from R. Paramatti, 2002

WWZ coupling



$$g_{WWZ} = g_5 \int \frac{dz}{kz} \Big[\tilde{h}_0^{3_L} \Big\{ \big(\tilde{h}_0^{+_L}\big)^2 + \tfrac{1}{2} \big(\tilde{h}_0^{\hat{+}}\big)^2 \Big\} + \tilde{h}_0^{3_R} \Big\{ \big(\tilde{h}_0^{+_R}\big)^2 + \tfrac{1}{2} \big(\tilde{h}_0^{\hat{+}}\big)^2 \Big\} + \tilde{h}_0^{\hat{3}} \tilde{h}_0^{\hat{+}} \Big(\tilde{h}_0^{+_L} + \tilde{h}_0^{+_R} \Big) \Big]$$

$$g_{WWZ} \simeq g \cos\theta_W$$

θ_H	$\pi/10$	$\pi/4$	$\pi/2$
$k\pi R$ =35	0.9999987	0.999964	0.99985
0.35	0.9994990	0.979458	0.83378

Almost universal in RS

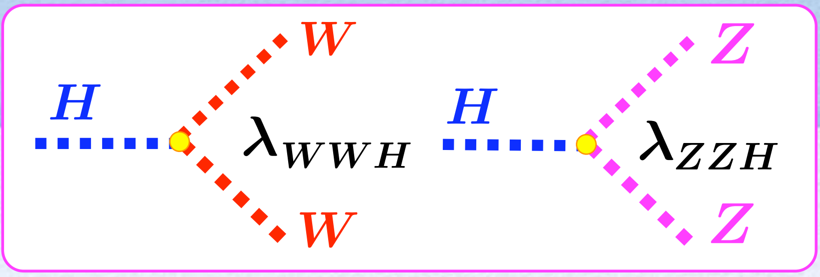
Deviation in flat space

Flat v.s. Warped

for typical θ_H

	S^1/Z_2	*RS*
m_H	$\sim$ 10 GeV	140 $\sim$ 280 GeV
$\sin^2\theta_W$	*X*	*OK*
m_F	*fine tuning*	*natural hierarchy*
WWZ	*X*	*OK*

WWH & ZZH coupling



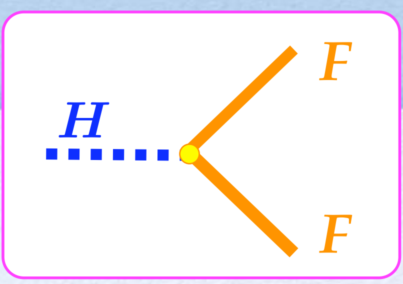
$$\lambda_{WWH} = g_5 k \int \frac{dz}{z}\, \tilde{f}_0^{\hat{4}} \Big\{ \tilde{h}_0^{\hat{+}} \partial_z (\tilde{h}_0^{+_R} - \tilde{h}_0^{+_L}) - \partial_z \tilde{h}_0^{\hat{+}} (\tilde{h}_0^{+_R} - \tilde{h}_0^{+_L}) \Big\}$$

$$\lambda_{WWH} \simeq g m_W \cdot \cos\theta_H$$

$$\lambda_{ZZH} \simeq \frac{g m_Z}{\cos\theta_W} \cdot \cos\theta_H$$

suppression

Yukawa couplings



arise from $g_5\, \overline{\psi}\, \Gamma^5 A_y \psi$

$$\frac{y}{y_{SM}} = \frac{y}{g m_F / 2 m_W}$$

$$\sim \quad \cos\theta_H \quad \text{or} \quad \cos\tfrac{1}{2}\theta_H$$

$$\text{for} \quad |c| > \tfrac{1}{2}$$

in naive models.

m_F depends on additional brane interactions etc.

Deviation from SM expected.

Predictions of Gauge-Higgs Unification

Find deviation from the Standard Model

m_H	$140 \sim 280$ GeV
WWH ZZH	suppressed by $\cos\theta_H$
$WWHH$ $ZZHH$	suppressed by $1 - \frac{2}{3}\sin^2\theta_H$
Yukawa$/m_F$	suppressed by $\cdots$
WWZ $WWWW$	almost universal

Conclusions

Find Higgs.

Determine the Higgs couplings

to establish

Identity of the Higgs
Mechanism of EW symmetry breaking.

We may find

Extra Dimensions
in the Gauge-Higgs Unification.