A 6-D HIGGSLESS STANDARD MODEL

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MODEL

: TWO EXTRA DIM, FLAT
COMPACTIFIED ON A RECTANGLE

: GAUGE GROUP
STANDARD MODEL, $SU(2)_L \times U(1)_Y$

: BULK + BRANE INTERACTIONS,
BRANE DOMINATE

: GAUGE SYM BROKEN TO $U(1)_{EM}$
BY MIXED BOUNDARY CONDITIONS

: MAIN ROLE OF BULK ACTION
$\Rightarrow$ BREAK EW SYMMETRY

BULK MASS PARAMETERS,
M_L, M_Y $\sim$ EW SYM BREAKING SCALE
$\sim$ 100 GeV

$SU(2)_L$ $U(1)_Y$

OUTLINE

A. INTRODUCTION

: Why Higgsless models

: Why extra dimensions

B. BRIEF REVIEW OF 5D MODELS

: FLAT

: WARPED

: PROBLEMS

C. OUR 6D MODEL

: Motivation

: Formalism

: Results — Calculability, Unitarity, EWPT, Mass spectrum

D. CONCLUSIONS AND FUTURE WORK

A. INTRODUCTION

WHY HIGGSLESS MODELS?

Higgs ⇒ A very important ingredient in SM

: Breaks EW sym spontaneously

: Give masses to EW gauge bosons and fermions

: restore unitarity

: NO GARANTEE THAT HIGGS WILL BE FOUND AT LHC

: LEP 2 BOUND > 115 GeV

: What if no Higgs found?

⇒ IMPORTANT TO EXPLORE ALTERNATIVES

: Technicolor

⇒ problems

⇒ EXTRA DIM PROVIDE <u>NEW</u> POSSIBILITY

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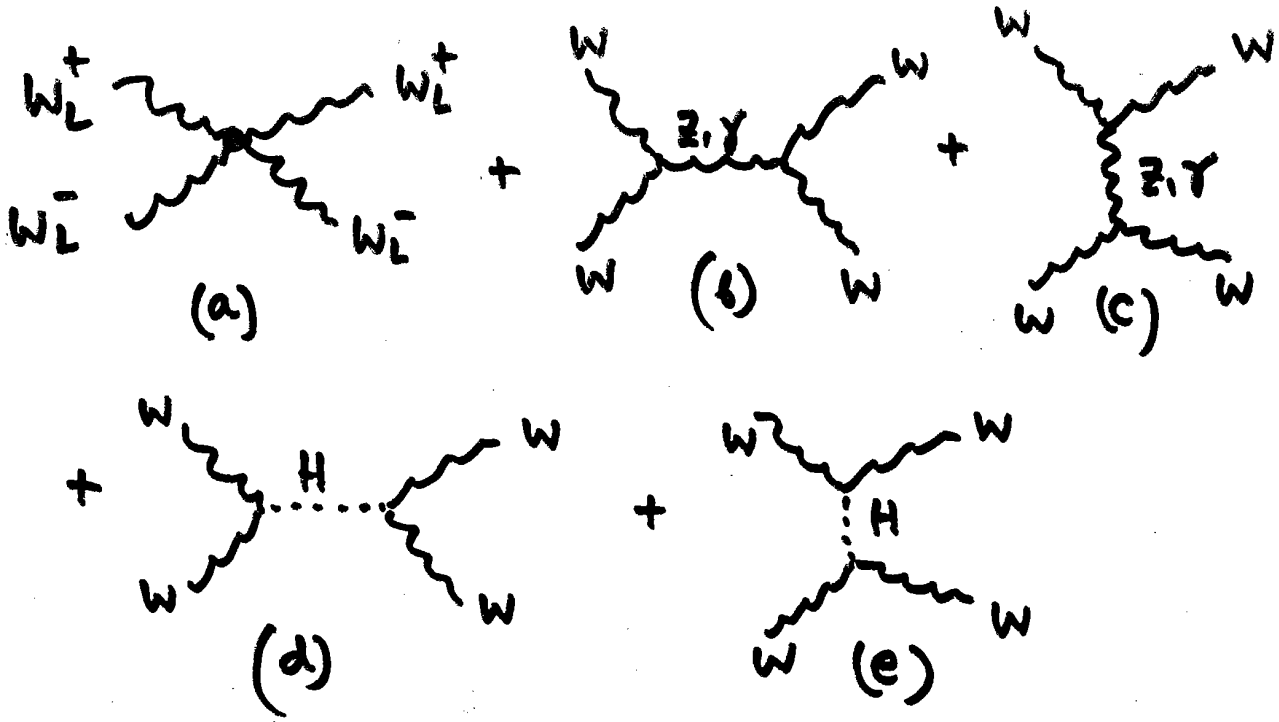
4d, $SU(2)_L \times U(1)_Y$, gauge + Higgs



$$a_\ell(E) \sim A\left(\frac{E^4}{M^4}\right) + B\left(\frac{E^2}{M^2}\right) + C$$

$|a_\ell(E)| \leq 1 \Rightarrow$ Tree unitarity

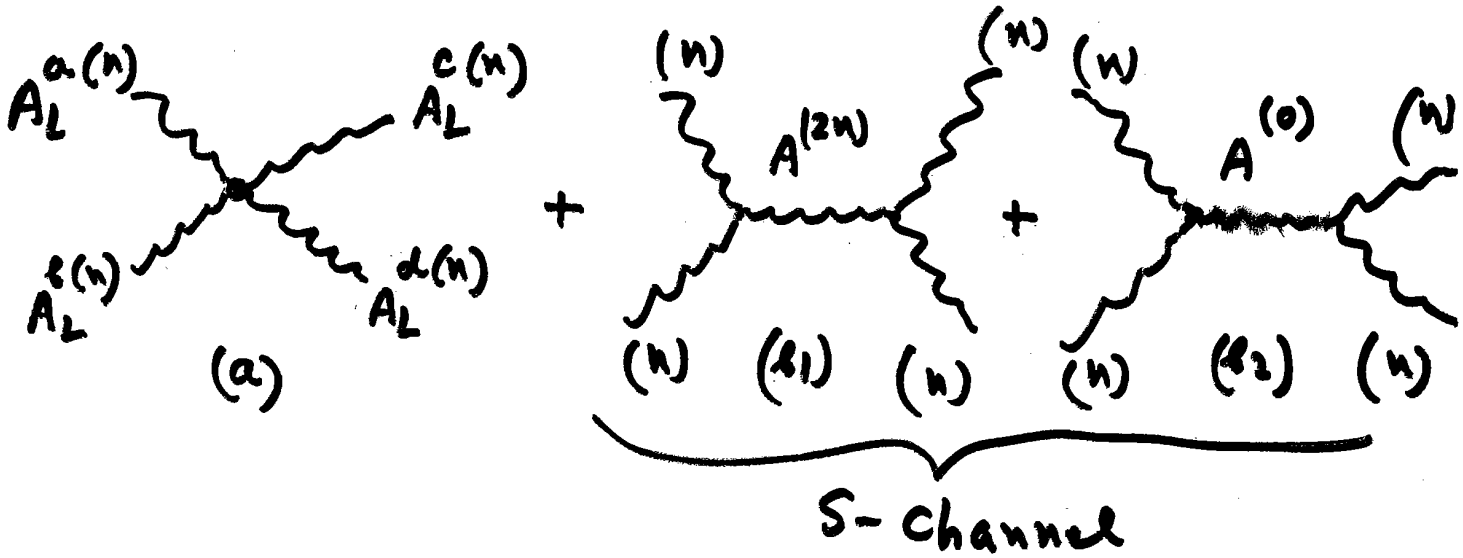
(a) + (b) + (c) $\Rightarrow A = 0, \; B \neq 0$

with Higgs + (d) + (e) $\Rightarrow A = 0, \; B = 0$

$\Rightarrow$ tree unitary

COMPACTIFIED YANG-MILLS THEORY:

$$A_L^{a(n)} \quad A_L^{b(n)} \longrightarrow A_L^{c(n)} \quad A_L^{d(n)}$$



+ t-channel + u-channel

$\Rightarrow$ Energy dependence adds up to zero

(Delicate cancellation involving $A^{(0)}$ and $A^{(2n)}$ mode

$$T\left(A_L^{a(n)}, A_L^{b(n)}, \ldots\right) = T\left(A_5^{a(n)}, A_5^{b(n)}, \ldots\right) + O\left(\frac{m_n}{E}\right)$$

$\therefore$ RHS are scalar fields $\Rightarrow$ tree unitarity obvious

$\Longrightarrow$ "Geometric Higgs Mechanism"

<u>E^0 contribution</u> :

: $|a_{00}(E)| < 1$ $\Rightarrow$ restrict the # of allowed KK modes

longi

5D QCD (compactified) : $N_{KK} \leq 4$

5D EW (compactified) : $N_{KK} \leq 11$

(Chivukula, Dicus, He, Nandi)

EXTRA DIMESIONS

: can break gauge sym via compactification

: can satisfy unitarity without Higgs via cancellation through KK modes "Geometric Higgs mechanism". (Chivukula, Dicus, He, Nandi)

** $\Rightarrow$ (4a), (4b) and (4c)

usual orbifold compactification:

ex. S^1/Z_2

$$A_M(x,-y) = P A_M(x,y) P^{-1}$$

(BC on fields only)

$G \to H$, rank preserved

with mixed BC:

$$A_M(x,y), \quad \partial_{y_i} A_M(x,y)$$

$G \to H$, lower rank

SM: 1st KK excitations $\sim \frac{1}{R}$

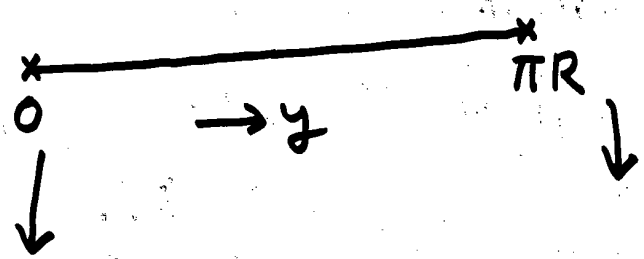
$\Rightarrow$ can be identified with W and Z

Gauge Symmetry Breaking using BC's : no Higgs.

: CONSIDER SU(2) GAUGE SYM,

: one extra dim

$$A_M(x, y)$$



BC: $\partial_y A^a_\mu(x,0) = 0$ $\qquad$ $A^a_\mu(x, \pi R) = 0$

$$\left(A^a_5(x,0) = 0,\ A^a_5(x,\pi R) = 0\right)$$

$SU(2) \longrightarrow$ broken completely

: $M^{(n)} \tan(M^{(n)} \pi R) = 0$

$$M^{(n)} = \left(n + \tfrac{1}{2}\right) \frac{1}{R}$$

: Consider $SU(2)_L \times U(1)_Y$

$\Downarrow$ Break via BC

$U(1)_{EM}$

$$\Rightarrow M_W^{(n)} = M_Z^{(n)} = \left(n + \tfrac{1}{2}\right) \frac{1}{R} \qquad \times$$

BC's :

6a

$y = 0$: $\partial_y A_\mu^{+a} = 0$, $A_\mu^{-a} = 0$, $\partial_y B_\mu = 0$

$A_5^{+a} = 0$, $\partial_y A_5^{-a} = 0$, $B_5 = 0$

$y = \pi R$: $\partial_y A_\mu^{La} = 0$, $A_\mu^{R1,2} = 0$

$g' B_\mu - g A_\mu^{R3} = 0$

$A_5^{La} = 0$, $A_5^{Ra} = 0$, $B_5 = 0$

B. A BRIEF REVIEW OF 5D MODELS

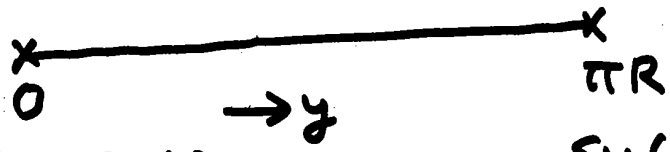
Flat — Warp

: Gauge symmetry : $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

$SU(2)_L \to A_L^a$, $SU(2)_R \to A_R^a$, $U(1)_{B-L} \to B$

: more gauge fields
$\Rightarrow$ more freedom in BC

: <u>ONLY</u> <u>BULK</u> INTERACTION



$SU(2)_L \times SU(2)_R \xrightarrow{\text{broken to}} SU(2)_D$

$SU(2)_R \times U(1)_{B-L} \xrightarrow{\text{broken to}} U(1)_Y$

BC p6a

4D theory $\Rightarrow U(1)_{EM}$

(Csaki, Grojean, Murayama, Pilo + Terning)

SPECTRUM :

$$M_W^{(n)} = (2k-1)\frac{1}{4R}$$

$$M_Z^{(n)} = \left(M_0 + \frac{n-1}{R} \right)$$

$$M_{Z'}^{(n)} = \left(-M_0 + \frac{n}{R} \right)$$

$$M_0 \equiv \frac{1}{\pi R} \tan^{-1}\left(\sqrt{1 + \frac{2g'^2}{g^2}} \right)$$

$$\Rightarrow \rho \simeq 1.10 \qquad \times$$

ALSO : $M_W^{(2)} \simeq 3 M_W \sim 240$ GeV $\times$

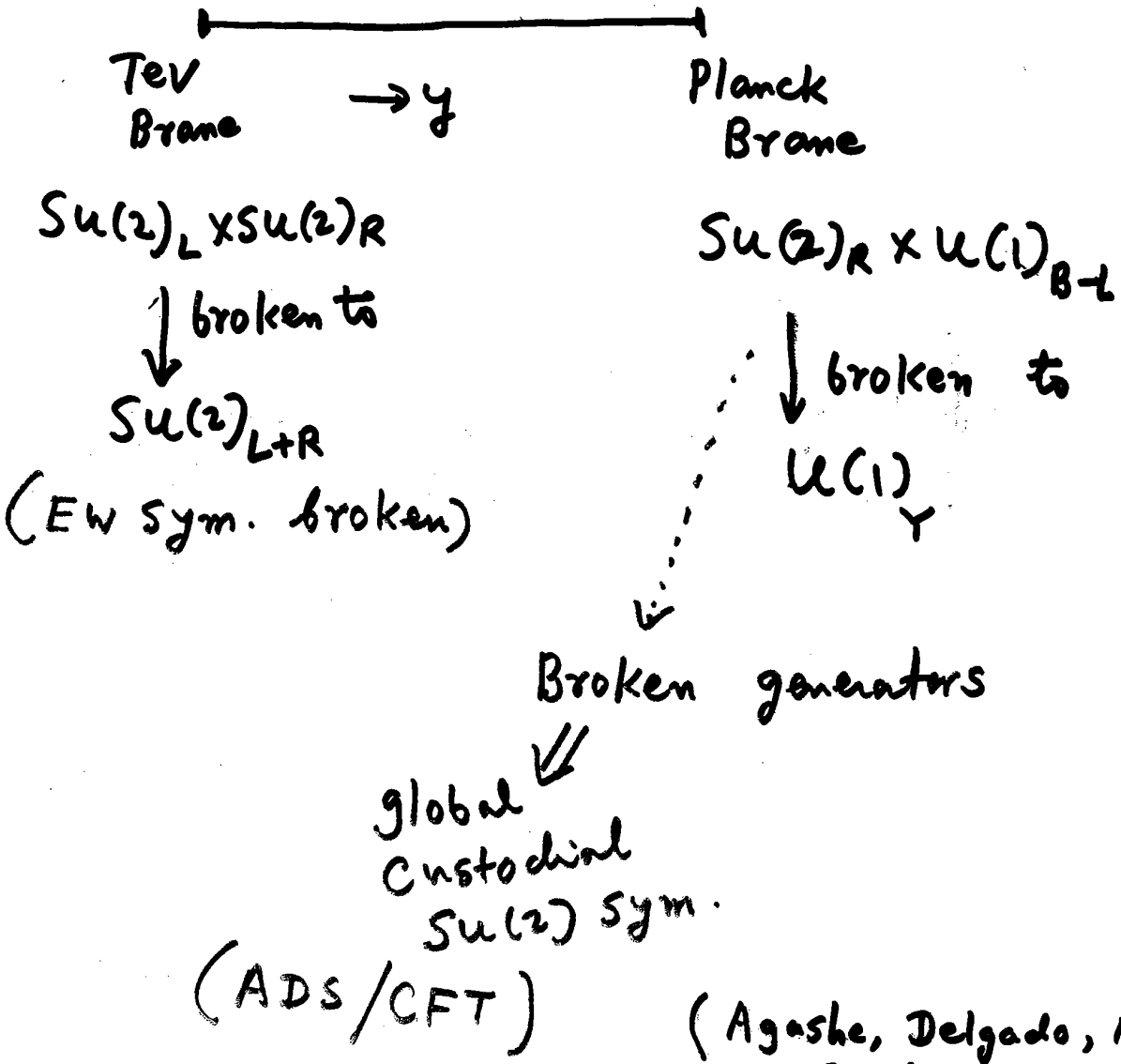
$M_Z^{(2)} \sim 230$ GeV $\times$

5D WARPED MODELS

: Gauge sym. $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

: Warped Space (ADS)

(Csaki, Grojean, Pilo + Terning)
Nomura



Good features:

$\rho = 1$ (custodial sym)

$M_W^{(1)} \sim M_Z^{(1)} \sim 1.2$ TeV

Problem:

ε_3 or S parameter fails EWPT

$\varepsilon_3 \sim 10^{-2}$ compared to $\varepsilon_3\big|_{EXPT} \sim 3 \times 10^{-3}$

: Simple model does <u>not</u> work

Complicated extensions:

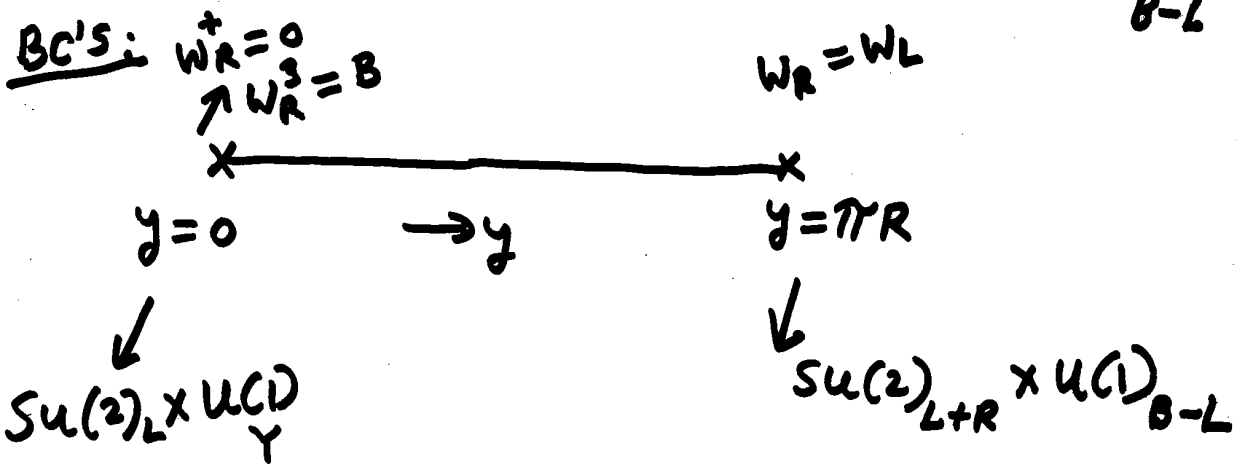
$g_L \neq g_R$, brane interactions, ...

(Davoudiasl, Hewett, Lillie + Rizzo;
Caccciapaglia, Csaki, Grojean + Terning;
Foadi, Gopalakrishna + Schmidt (Decmstruction))

5D FLAT MODEL WITH DOMINANT BRANE INTERACTIONS

(Barbieri, Pomerol + Rattazzi)
" " " + Strumia

: Gauge Sym, $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$



$$L = L_{Bulk} + \delta(y)\, L^0_{Brane} + \delta(y - \pi R)\, L^\pi_{Brane}$$

Bulk mass parameters

$$L_{Bulk} = -\frac{M_L}{4} (F_L)^a_{MN} (F_L)^{MNa} - \frac{M_R}{4} (F_R)^a_{MN} (F_R)^{MNa} - \frac{M_B}{4} B_{MN} B^{MN}$$

$$L^0_{Brane} = -\frac{1}{4g^2} F^a_{\mu\nu} F^{\mu\nu a} - \frac{1}{4g'^2} B_{\mu\nu} B^{\mu\nu}$$

$$L^\pi_{Brane} = -\frac{Z_W}{4} F^a_{\mu\nu} F^{\mu\nu a} - \frac{Z_B}{4} B_{\mu\nu} B^{\mu\nu}$$

$$L_{eff} = \int_0^{\pi R} dy \left[L_{Bulk} + L_{\pi} \right]$$

$$= \left[M_L \, \bar{A}_L^a \, \partial_y A_L^a + \bar{B} \left(M_R \partial_y A_R^3 + M_B \partial_y B \right) \right]_{y=0}$$

$$= \bar{A}^a \Sigma_L(p^2) \bar{A}^a + \bar{A}^3 \Sigma_{3B}(p^2) \bar{B} + \bar{B} \Sigma_{BB}(p^2) \bar{B}$$

where $\bar{A}^a = A(x, y=0)$, $\bar{B} = B(x, y=0)$

RESULTS

SPECTRUM : lowest order :

$$M_W^{(n)} = \underbrace{(n+\tfrac{1}{2})}_{0,1,2,\ldots} \frac{1}{R} \quad , \quad M_W'^{(n)} = \frac{n}{R} \quad , \quad n > 0$$

$$m_0^2 \equiv m_W^2 = 2 \, \frac{g^2 M_L M_R}{(M_L + M_R)} \left(\frac{1}{\pi R} \right)$$

$$m_Z^2 = 2 \, (g^2 + g'^2) \frac{M_L M_R}{(M_L + M_R)} \left(\frac{1}{\pi R} \right)$$

Good features :

$\Rightarrow \rho = 1$ (Custodial sym)

$m_W^{(n)}, m_Z^{(n)} \sim \frac{n}{R}$: decouple from W and Z masses

Problems:

: Bulk parameter, M_L breaks gauge sym.

Cut off, $\Lambda \sim 10$ TeV

$$\sim 24\pi^3 M_L$$

$\Rightarrow M_L \sim$ [illegible] GeV, not EW scale!!

$\Downarrow$

where does this new scale come from?

: $$\varepsilon_3 = \frac{g^2}{18\pi^2}(\Lambda R) \sim 5.7 \times 10^{-3}$$

$$\varepsilon_3\Big|_{EXPT} = (3.7 \pm 0.9) \times 10^{-3}$$

$\Rightarrow$ Border line, at best

C. OUR 6D MODEL

: Two extra dim, y_1, y_2

: flat

: Gauge sym., $SU(2)_L \times U(1)$

MOTIVATION:

: 5D does not work (flat or warped)

how 6D can help?

: In 5D : $M_W^{(n)} = M_Z^{(n)} = (n+\frac{1}{2})\frac{1}{R}$

: In 6D : $M_W^{(n)} \sim (n+\frac{1}{2})\frac{1}{R_1}$

$M_Z^{(n)} \sim (n+\frac{1}{2})\frac{1}{R_2}$

$\Rightarrow$ can fit ρ

: Still problem with $M_W^{(n)}, M_Z^{(n)}$ for $n>1$

: Can be solved by dominant brane interactions.

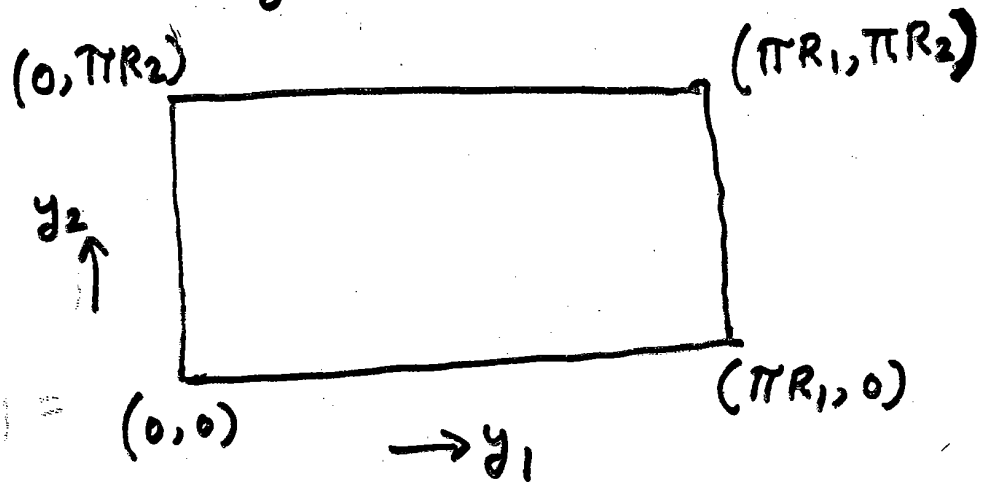
Key features of our model

PLUS
- : Bulk dim parameter, M_L = EW sym breaking scale ~ 100 GeV
- : EWPT, $\varepsilon_1, \varepsilon_2, \varepsilon_3 / S, T, U$ ~ in agreement with experiment

Minus
- : Give up custodial sym (but ρ <u>can</u> be chosen to be 1)

FORMALISM

: TWO extra dim compactified on a rectangle



$$S = \int d^4x \int_0^{\pi R_1} dy_1 \int_0^{\pi R_2} dy_2 \left[\underbrace{\mathcal{L}_6}_{\text{Bulk}} + \delta(y_1)\,\delta(y_2)\,\underbrace{\mathcal{L}_0}_{\text{Brane}} \right]$$

$$\mathcal{L}_6 = -\frac{M_L^2}{4} F^a_{MN} F^{MNa} - \frac{M_Y^2}{4} B_{MN} B^{MN}$$

$$\mathcal{L}_0 = -\frac{1}{4g^2} F^a_{\mu\nu} F^{\mu\nu a} - \frac{1}{4g_1^2} B_{\mu\nu} B^{\mu\nu}$$

: Assume brane interactions dominate

$$\Rightarrow \frac{1}{g^2}, \frac{1}{g_1^2} \gg M_L^2 (\pi^2 R_1 R_2), M_Y^2 (\pi^2 R_1 R_2)$$

($\mathcal{L}_0$ can be produced by quantum loop effects) (Georgi, Grant + Hailu) (Mirabelli + Peskin)

KEY FEATURES:

: $\mathcal{L}_0$ gives dominant interactions in 4D

$\Rightarrow$ all gauge couplings close to their SM values

: Main function of $\mathcal{L}_{bulk}$ is to break EW gauge sym via mixed BC

$\Rightarrow$ EW sym breaking scale,

$M_L, M_Y \sim 100$ GeV

$$\delta S = \int d^4x \int_0^{\pi R_1} dy_1 \int_0^{\pi R_2} dy_2 \Big[M_L^2 \left(\partial_M F^{aM\mu} - f^{abc} F^{bM\mu} A^c_M \right) \delta A^a_\mu + M_Y^2 \partial_M B^{M\mu} \delta B_\mu \Big]$$

BC

$$+ \int d^4x \int_0^{\pi R_2} dy_2 \Big[M_L^2 F^a_{5\mu} \delta A^{a\mu} + M_Y^2 B_{5\mu} \delta B^\mu \Big]_{y=0}^{\pi R_1}$$

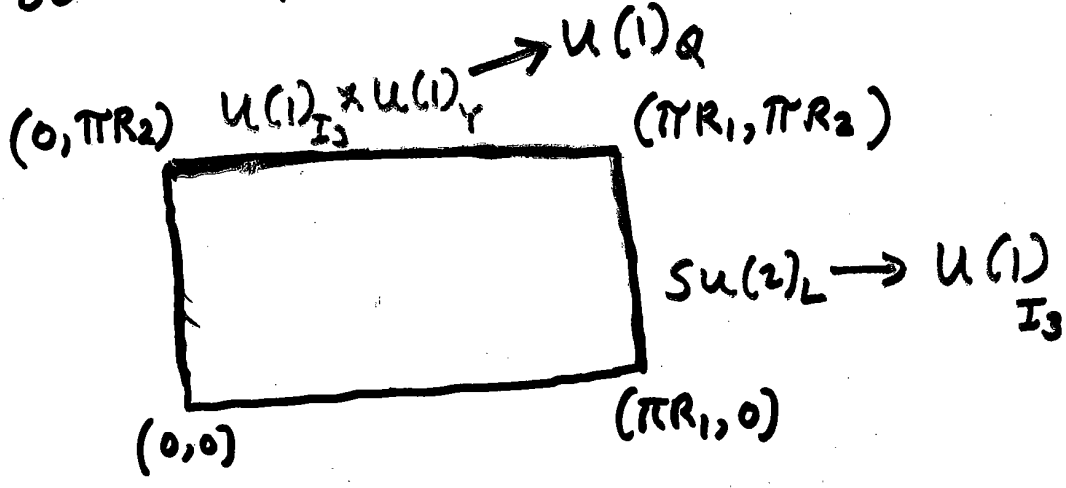
$$+ \int d^4x \int_0^{\pi R_1} dy_1 \Big[M_L^2 F^a_{6\mu} \delta A^{a\mu} + M_Y^2 B_{6\mu} \delta B^\mu \Big]_{y_2=0}^{\pi R_2}$$

$$+ \int d^4x \Big[\frac{1}{g^2} \left(\partial_\mu F^{a\mu\nu} - f^{abc} F^{b\mu\nu} A^c_\mu \right) \delta A^a_\mu + \frac{1}{g'^2} \partial_\mu B^{\mu\nu} \delta B_\nu \Big]_{(y_1, y_2) = (0,0)}$$

$$= 0$$

Choose $A^a_{5,6}$ $(a = 1,2,3) = 0$, $B_{5,6} = 0$

BOUNDARY CONDITIONS :



At $y_1 = \pi R_1$: $A_\mu^{1,2} = 0$

At $y_2 = \pi R_2$: $\partial_{y_2}(M_L^2 A_\mu^3 + M_Y^2 B_\mu) = 0$

$$A_\mu^3 - B_\mu = 0$$

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

At $y_1 = 0$: $A_\mu^{1,2}(x, y_1, y_2) = \bar{A}_\mu^{1,2}(x)$ *

At $y_2 = 0$: $A_\mu^3(x, y_1, y_2) = \bar{A}_\mu^3(x)$ **

$B_\mu(x, y_1, y_2) = \bar{B}_\mu(x)$ **

$\Rightarrow$ * $A_\mu^{1,2}(x, y_1)$, $A_\mu^3(x, y_2)$, $B_\mu(x, y_2)$

(Note: Locally at $y_1 = y_2 = 0$, $SU(2)_L \times U(1)$ is unbroken)

Total 4D Lagrangian

$$L_{TOTAL} = \underset{\text{brane}}{L_0} + \underset{\text{Bulk}}{L_{eff}}$$

$$L_{eff} = \int_0^{\pi R_1} dy_1 \int_0^{\pi R_2} dy_2 \, \mathcal{L}_6$$

$$= -M_L^2 \pi R_2 \left[\bar{A}^1_\mu \partial_{y_1} A^{1\mu} + \bar{A}^2_\mu \partial_{y_1} A^{2\mu} \right]_{y_1=0}$$

$$- \pi R_1 \left[M_L^2 \bar{A}^3_\mu \partial_{y_2} A^{3\mu} + M_Y^2 \bar{B}_\mu \partial_{y_2} B^\mu \right]_{y_2=0}$$

Solutions for bulk eqs. of motion:

$$A^{1,2}_\mu (x, y_1) = \bar{A}^{1,2}_\mu (x) \cos(p y_1) + b^{1,2}_\mu (x) \sin(p y_1)$$

$$A^3_\mu (x, y_2) = \bar{A}^3_\mu (x) \cos(p y_2) + b^3_\mu (x) \sin(p y_2)$$

$$B_\mu (x, y_2) = \bar{B}_\mu (x) \cos(p y_2) + b^Y_\mu (x) \sin(p y_2)$$

$$\Rightarrow L_{eff} = \bar{A}^a_\mu \Sigma_{aa}(p^2) \bar{A}^{a\mu} + \bar{A}^\mu_3 \Sigma_{3B}(p^2) \bar{B}^\mu + \bar{B}_\mu \Sigma_{BB}(p^2) \bar{B}^\mu$$

$$\Sigma_{11}(p^2) = \Sigma_{22}(p^2) = \pi R_2 M_L^2 \, p \cot(\pi p R_2)$$

$$\Sigma_{33}(p^2) = \frac{-\pi R_1 M_L^2}{(M_L^2 + M_Y^2)} p \left[M_L^2 \tan(\pi p R_2) - M_Y^2 \cot(\pi p R_2) \right]$$

manifestly break custodial sym

$$\Sigma_{3B}(p^2) = -2\pi R_1 \frac{M_L^2 M_Y^2 p}{(M_L^2 + M_Y^2)} \left[\tan(\pi p R_2) + \cot(\pi p R_2) \right]$$

$$\Sigma_{BB}(p^2) = -\pi R_1 \frac{M_Y^2 \, p}{(M_L^2 + M_Y^2)} \left[M_Y^2 \tan(\pi p R_2) - M_L^2 \cot(\pi p R_2) \right]$$

RESULTS

MASS SPECTRUM :

: Assume brane interactions dominate

$$\frac{1}{g^2}, \frac{1}{g'^2} \gg (M_L^2, M_Y^2)\, \pi^2 R_1 R_2$$

To Lowest order :

$$m_0^2 = 2g^2 M_L^2 \left(\frac{R_2}{R_1}\right) \equiv M_W^2$$

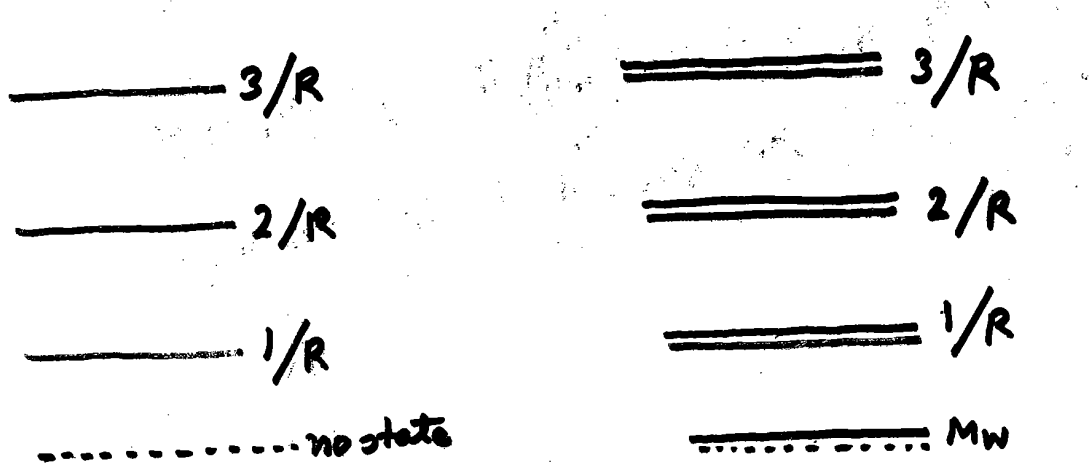
$$m_W^{(n)} = \frac{n}{R_1}, \quad n = 1, 2, 3, \cdots$$

$$m_\gamma^2 = 0,$$

$$M_Z^2 = 2(g^2 + g'^2)\, \frac{M_L^2 M_Y^2}{(M_L^2 + M_Y^2)} \left(\frac{R_1}{R_2}\right)$$

: Plus higher KK modes of γ and $Z \sim \frac{n}{R_1}, \frac{n}{R_2}$

NOTE: M_W, M_Z : decouples from $\frac{1}{R_1}, \frac{1}{R_2}$



No Brane

Dominant brane

ELECTROWEAK PRECISION TEST (EWPT)

OBLIQUE CORRECTIONS :

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = \frac{g^2}{(g^2+g'^2)\cos^2\theta_W}\left[\frac{M_L^2+M_Y^2}{M_Y^2}\left(\frac{R_2}{R_1}\right)^2\right]$$

$$= 1$$

$$\Rightarrow \frac{M_L^2+M_Y^2}{M_Y^2}\left(\frac{R_2}{R_1}\right)^2 = 1 \Leftarrow \text{tunning}$$

[Note: in the limit of $p^2=0$,
$\Sigma_{11} = \Sigma_{22} = \Sigma_{33}$: restore custodial sym]

$$\Sigma_{AB}^{\mu\nu}(p^2) \equiv \Pi_{AB}^{\mu\nu}(p^2) = g_A g_B \left[\Pi_{AB}^{(0)} + p^2 \Pi_{AB}^{(1)}\right] g^{\mu\nu}$$
$$+ p^\mu p^\nu \text{ terms}$$

oblique corrections :

$(\varepsilon_1, \varepsilon_2, \varepsilon_2)$ or (S, T, U)

$$\varepsilon_1 = \alpha T, \quad \varepsilon_2 = -\frac{\alpha}{4} U, \quad \varepsilon_3 = \frac{\alpha}{4\sin^2\theta_W} S$$

EXPT : $\varepsilon_2 \lesssim -10^{-2}$

$\varepsilon_1, \varepsilon_2 \lesssim 3\times10^{-3}$

$\varepsilon_1 = +(3.6 \pm 1.0)\times10^{-3}$

$\varepsilon_2 = -(9.9 \pm 1.2)\times10^{-3}$

$\varepsilon_3 = +(3.7 \pm 0.9)\times10^{-3}$

In our model:

$$\varepsilon_1 \equiv \frac{g^2}{M_W^2}\left[\Pi_{11}^{(0)} - \Pi_{33}^{(0)}\right]$$

$$= -g^2 \frac{M_L^2}{M_W^2}\left(\frac{R_1}{R_2}\right)\underbrace{\left[\frac{M_Y^2}{M_L^2+M_Y^2} - \left(\frac{R_2}{R_1}\right)^2\right]}_{\text{set to zero}}$$

$$\varepsilon_2 \equiv g^2\left[\Pi_{33}^{(1)} - \Pi_{11}^{(1)}\right]$$

$$= -g^2\left(\frac{4\pi^2}{3}\right)\frac{M_L^4}{M_L^2+M_Y^2}(R_1R_2)$$

$$\varepsilon_3 \equiv -g^2\Pi_{3B}^{(1)} = g^2\left(\frac{4\pi^2}{3}\right)\frac{M_L^2M_Y^2}{M_L^2+M_Y^2}(R_1R_2)$$

$\varepsilon_1 = 0$ (by choice)

$|\varepsilon_2|, |\varepsilon_3| \Rightarrow$ bounded below

Estimate of ε_2, ε_2:

: use dim analysis

For D-dim gauge theory

Cut off scale, $\Lambda^{D-4} \sim (4\pi)^{D/2}\,\Gamma(D/2)\,/\,g_D^2$

bulk coupling

For $D = 6$, $\Lambda \sim \sqrt{2}\,(4\pi)^{3/2}\,M_{L,Y}$

Bulk mass parameters

using $M_L \sim 100$ GeV

$\Rightarrow \boxed{\Lambda \sim 6 \text{ TeV}}$

using $M_L \sim M_Y$, we obtain $|\varepsilon_2| \sim |\varepsilon_3|$

$$\varepsilon_3 \simeq \frac{g^2}{96\sqrt{2}\,\pi}\,(\Lambda R_2)^2 \simeq 2.3\times10^{-3} \times (g\,\Lambda R_2)^2$$

$$\varepsilon_3\big|_{EXPT} \lesssim 3\times10^{-3}$$

$\frac{1}{\Lambda R_2} \sim$ loop expansion parameter

	5D		6D
Λ :	10 TeV	$\longrightarrow$	6 TeV

ε_3 : decreases by ~ 2.5

$g \sim 0.5$, $\Lambda R_2 \sim 2 \Rightarrow$ few KK modes

constraint on unitarity and calculability

CONCLUSIONS

: 6D, flat Higgless model

: Gauge sym : $SU(2)_L \times U(1)_Y$

: Bulk + Brane interactions,
Brane dominate

: Main role of bulk
$\Rightarrow$ Break EW symmetry to $U(1)_{EM}$

Bulk parameters, $M_L, M_Y \sim 100$ GeV
$\sim$ EW sym. breaking scale

: Model passes EW Precision Test

: Lowest KK states of γ, W, Z
in the few TeV scale.