Precision Electroweak Physics and Higgsless Models in Warped Space

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Higgsless Model in AdS

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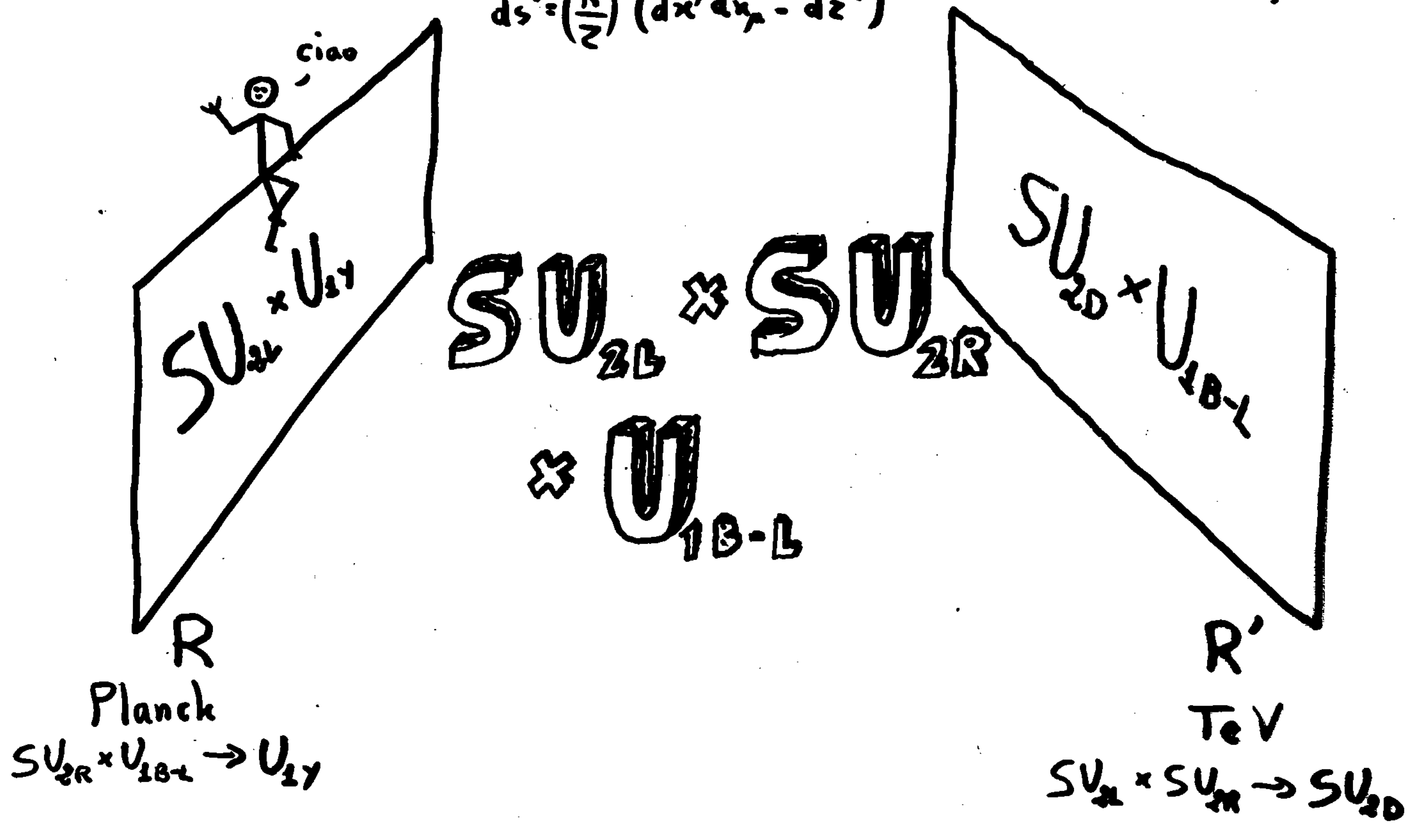
$$ds^2 = \left(\frac{R}{z}\right)^2 \left(dx^\mu dx_\mu - dz^2\right)$$



- ★ $SU_{2L} \times U_{1Y}$ is broken, the $W^\pm$ and Z get masses proportional to the extra dimension size:

$$M_W^2 \sim \frac{1}{R'^2 \log R'/R} \qquad (R')^{-1} = 500 \text{ GeV}$$

- ★ Custodial symmetry in AdS ensures the correct Z mass at leading order — Agashe, Delgado, May, Sundrum

- ★ Unitarity of GB scattering recovered by the contribution of KK modes, starting at 1.2 TeV. — Csaki, Grojean, Pilo, Murayama, Terning

- ★ No "light" scalar in the theory!

Warp factor

$$\mathcal{L}_{gauge} = \int_R^{R'} dz \, \frac{R}{z} \left(-\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} - \frac{1}{2} \left(\partial_z A^a_\mu \right)^2 \right)$$

$$A_\mu = \begin{cases} A^L_\mu & SU(2)_L & g_{5L} \\ A^R_\mu & SU(2)_R & g_{5R} \\ B_\mu & U(1)_{B-L} & \tilde{g}_5 \end{cases}$$

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g_5 f^{abc} A^b_\mu A^c_\nu$$

in the unitary gauge, where the (massive) A_5's have been eaten up by the KK modes.

At $z = R'$

$SU(2)_L \times SU(2)_R \to SU(2)_D$

$$\begin{cases} g_{5L} A^L_\mu - g_{5R} A^R_\mu = 0 \\ \partial_z \left(g_{5R} A^L_\mu + g_{5L} A^R_\mu \right) \equiv \partial_z A^D_\mu = 0 \\ \partial_z B_\mu = 0 \end{cases}$$

TeV

At $z = R$

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

$$\begin{cases} \partial_z A^L_\mu = 0 \\ A^{R(1,2)}_\mu = 0 \\ \partial_z \left(g_{5R} B_\mu + \tilde{g}_5 A^{R3}_\mu \right) \equiv \partial_z B^Y_\mu = 0 \\ \tilde{g}_5 B_\mu - g_{5R} A^{R3}_\mu = 0 \end{cases}$$

plank

K-K expansion:

neutral

$$B_\mu = \frac{1}{\tilde{g}_5} a_0 \gamma_\mu + \sum_{k=1}^{\infty} \psi_k^{(B)}(z)\, Z_\mu^k$$

$$A_\mu^{L3} = \frac{1}{g_{5L}} a_0 \gamma_\mu + \sum_{k=1}^{\infty} \psi_k^{(L3)}(z)\, Z_\mu^k$$

$$A_\mu^{R3} = \frac{1}{g_{5R}} a_0 \gamma_\mu + \sum_{k=1}^{\infty} \psi_k^{(R3)}(z)\, Z_\mu^k$$

charged

$$A_\mu^{L\pm} = \sum_{k=1}^{\infty} \psi_k^{(L\pm)}(z)\, W_\mu^{k(\pm)}$$

$$A_\mu^{R\pm} = \sum_{k=1}^{\infty} \psi_k^{(R\pm)}(z)\, W_\mu^{k(\pm)}$$

The BC's fix the wave functions $\psi_k^{(B)} - \psi_k^{(L3)} - \psi_k^{(R3)}$ and $\psi_k^{(L\pm)} - \psi_k^{(R\pm)}$, up to an overall normalization.

- We expand the wave functions in $\log R'/R \sim 30$ keeping only the leading terms.

$$M_W^2 \simeq \frac{1}{R'^2 \log}$$

$$\left(\partial_z^2 - \frac{1}{z}\partial_z + m^2\right)\psi = 0 \qquad \psi(z) = z\left(a\, J_1(mz) + b\, Y_1(mz)\right)$$

Fermion masses

★ necessarily bulk fields: they have to feel the EWSB on both branes.

★ In the minimal setting:

$$[2_L, 1_R] = \begin{array}{cc} \begin{pmatrix} \chi^L_{ul} \\ \bar{\psi}^L_{ur} \\ \chi^L_{dl} \\ \bar{\psi}^L_{dr} \end{pmatrix} & \begin{array}{c} ++ \\ -- \\ ++ \\ -- \end{array} \end{array} \qquad [1_L, 2_R] = \begin{array}{cc} \begin{pmatrix} \chi^R_{ul} \\ \bar{\psi}^R_{ur} \\ \chi^R_{dl} \\ \bar{\psi}^R_{dr} \end{pmatrix} & \begin{array}{c} -- \\ ++ \\ -- \\ ++ \end{array} \end{array}$$

★ Bulk mass: $\frac{c_L}{R}\left(\psi^L \chi^L + \bar{\psi}^L \bar{\chi}^L\right) + \frac{c_R}{R}\left(\psi^R \chi^R + \bar{\chi}^R \bar{\psi}^R\right)$

zero modes localized on the Planck brane for $c_L > 1/2$ ($c_R < -1/2$) and TeV brane for $c_L < 1/2$ ($c_R > -1/2$).

★ TeV Dirac mass $M_D R' \left(\psi_R \chi_L + \bar{\chi}_L \bar{\psi}_R\right) \delta(z - R')$

gives a $SU(2)_D$ sym. mass (vectorlike).

★ Planck brane localized fermion mixing

$$f\left(\eta \xi + \bar{\xi} \bar{\eta}\right) + M\sqrt{R}\left(\psi^R_{dr} \xi + \bar{\xi} \bar{\psi}^R_{dr}\right)$$

lowers the mass of the lightest guy.

→ Easy to localize the first two (light) generations on the Planck brane.

For $c_L > 1/2 \quad c_R < -1/2$

$$\begin{cases} m_d \sim M_D \left(\frac{R}{R'}\right)^{c_L - c_R - 1} \\ m_u \sim \frac{f}{M}\, m_d \end{cases}$$

→ The 3^{rd} quark generation may be composite, i.e. localized towards the TeV brane.

Indeed, for large M_D it appears a light mode

$$\sim \frac{2}{R'} \left(\frac{R'}{R}\right)^{-(c_L - 1/2)}$$

Higgsless models
vs
Experiments

1. Oblique corrections, at tree level from the non trivial GB wave functions in the bulk. Generically, same problems as in technicolor theories are expected:

   $S \sim 1$
   $T \sim 0$ → thanks to cust. $SU(2)$ in AdS_5
   $U \sim$ small

2. Non-oblique corr.: in particular the couplings of the 3rd generation with gauge bosons.
   $Zb\bar{b}$ vertex,

3. Possible light resonances: LEPII and TEVATRON constraints on Z'.

4. Is partial wave Unitarity always ensured by the resonances?
   Or: does the theory remain perturbative?

Formalism of Oblique Corrections

Peskin,
Takeuchi

$$\mathcal{L}_{eff} = -\frac{1}{2} Z_W \, W^+_{\mu\nu} W^{-\mu\nu} - \frac{1}{4} Z_Z \, Z_{\mu\nu}^2 - \frac{1}{4} Z_\gamma \, F_{\mu\nu}^2$$

$$+ \frac{1}{2} \Pi'_{\gamma Z} \, F_{\mu\nu} Z^{\mu\nu} + \Pi_{WW} \, W^+_\mu W^{-\mu} + \frac{1}{2} \Pi_{ZZ} \, Z_\mu^2$$

$$\Pi'_{11} = \frac{1}{g^2}(1 - Z_W) \qquad \Pi'_{33} = \frac{1}{g^2 + g'^2}(1 - Z_Z) \qquad \Pi'_{QQ} = \frac{1}{e^2}(1 - Z_\gamma)$$

$$\Pi'_{Q3} = \frac{c}{eg} \Pi'_{\gamma Z} \qquad \Pi_{11} = \frac{1}{g^2} \Pi_{WW} \qquad \Pi_{33} = \frac{1}{g^2 + g'^2} \Pi_{ZZ}$$

$$S \simeq 16\pi \left(\Pi'_{33} - \Pi'_{3Q} \right)$$

$$U \simeq 16\pi \left(\Pi'_{11} - \Pi'_{33} \right)$$

$$T \simeq \frac{4\pi}{s^2 c^2 M_Z^2} \left(\Pi_{11} - \Pi_{33} \right)$$

$$\rho = \frac{M_W^2}{M_Z^2 c^2} \sim 1 + \alpha T$$

- Π's are defined at 0 momentum!

$$Z_W = \int_R^{R'} \frac{R}{z} \left(\left|\psi_1^{L+}\right|^2 + \left|\psi_1^{R+}\right|^2 \right) dz$$

$$Z_Z = \int_R^{R'} \frac{R}{z} \left(\left|\psi_1^{L3}\right|^2 + \left|\psi_1^{R3}\right|^2 + \left|\psi_1^{B}\right|^2 \right) dz$$

$$Z_\gamma = \int \frac{R}{z} \left(\left|\frac{a_0}{g_{5L}}\right|^2 + \left|\frac{a_0}{g_{5R}}\right|^2 + \left|\frac{a_0}{\tilde{g}_5}\right|^2 \right) dz$$

$$\Pi_{WW} = \int_R^{R'} \frac{R}{z} \left(\left|\partial_z \psi_1^{L+}\right|^2 + \left|\partial_z \psi_1^{R+}\right|^2 \right) dz$$

$$\Pi_{ZZ} = \int_R^{R'} \frac{R}{z} \left(\left|\partial_z \psi_1^{L3}\right|^2 + \left|\partial_z \psi_1^{R3}\right|^2 + \left|\partial_z \psi_1^{B}\right|^2 \right)$$

$$\Pi'_{Z\gamma} = 0$$

Oblique or not oblique: definition of the 4D gauge couplings!

For fermions localized on the Planck brane:

$$\bar{f}_L \left(g_{5L}\, T_{3L} \not{A}^{L3} + g_{5L}\, T_{\pm L} \not{A}^{L\mp} + \tilde{g}_5 \frac{Y}{2} \not{B} \right) f_L\, \delta(z-R) =$$

$$= \bar{f}_L \left(a_0\, Q \not{\gamma} + g_{5L}\, \psi_1^{L\pm}(R)\, T_\pm \not{W}^\mp + g_{5L}\, \psi_1^{L3}(R) \left(T_3 + \frac{\tilde{g}_5\, \psi_1^{B}(R)}{g_{5L}\, \psi_1^{L3}(R)} \frac{Y}{2} \right) \not{Z} \right) f_L$$

$$\frac{Y}{2} = T_{3R} + Q_{B-L} \qquad T = T_L \qquad Q = \frac{Y}{2} + T_3$$

SM: $$\bar{f}_L \left(e\, Q \not{\gamma} + g\, T_\pm \not{W}^\mp + g c \left(T_3 - \frac{s^2}{c^2} \frac{Y}{2} \right) \not{Z} \right) f_L$$

★ Unbroken $U(1)_{em}$: $e = a_0$

$$Z_\gamma = \left[\left(\frac{a_0}{\tilde{g}_5}\right)^2 + \left(\frac{a_0}{g_{5L}}\right)^2 + \left(\frac{a_0}{g_{5R}}\right)^2 \right] V = 1$$ $V = R \log$

★ Independent on the overall normalizations:

$$\frac{g'^2}{g^2} = - \frac{\tilde{g}_5\, \psi_1^{B}(R)}{g_{5L}\, \psi_1^{L3}(R)}$$

→ Now the recipe is complete: let's go computing!

Basic model

At leading order in $\frac{1}{\log R'/R} \sim \frac{1}{30}$:

$$\frac{1}{g^2} = \frac{V}{g_{5L}^2}$$

$$\frac{1}{g'^2} = V\left(\frac{1}{g_{5L}^2} + \frac{1}{\tilde{g}_5^2}\right)$$

$V = R \log R'/R$

$$\begin{cases} S \sim \frac{6\pi}{g^2 \log} \sim 1.15 \\ T = 0 \\ U \sim 0 \end{cases}$$

Experimentally:

$S = -0.03 \pm 0.11$

But:

- the fit assumes a SM Higgs @ 115 GeV. We should replace the Higgs contribution in the SM loops with the full KK Tower of Z and W's...

- the theory has additional parameters:

  * brane induced kinetic terms on the Planck and TeV brane

  * $g_{5L} \neq g_{5R}$

$$\mathcal{L}_{PL} = -\left(\frac{r}{4} W^{L\,2}_{\mu\nu} + \frac{r'}{4} B^{Y\,2}_{\mu\nu}\right) \delta(z-R)$$

$$\mathcal{L}_{TeV} = -\frac{R'}{R}\left(\frac{\tau}{4} W^{D\,2}_{\mu\nu} + \frac{\tau'}{4} B^{2}_{\mu\nu}\right) \delta(z-R')$$

→ new BC's, affect spectrum, wave functions and couplings:

$$R' \quad \begin{cases} \partial_z A^D_\mu - \tau\, m_n^2 \frac{R'}{R} A^D_\mu = 0 \\ \partial_z B_\mu - \tau'\, m_n^2 \frac{R'}{R} B_\mu = 0 \end{cases}$$

$$R \quad \begin{cases} \partial_z A^L_\mu + r\, m_n^2 A^L_\mu = 0 \\ \partial_z B^Y_\mu + r'\, m_n^2 B^Y_\mu = 0 \end{cases}$$

→ Note that τ is a direct contribution to S, i.e. to the mixing $W^3_L - B^Y$

Analitical results:

$g_{5R} \neq g_{5L}$ & Planck

- $$\frac{1}{g^2} = \frac{V+r}{g_{5L}^2} \qquad \frac{1}{g'^2} = (V+r')\left(\frac{1}{g_{5R}^2} + \frac{1}{\tilde{g}_5^2}\right)$$

$V = R \log$

$\kappa = g_{5R}/g_{5L}$

- $$S \simeq \frac{6\pi}{g^2 \log} \frac{2}{1+\kappa^2} \frac{1}{1+\frac{r}{V}} + \cdots$$

$$T = 0 \qquad U \simeq 0 + \cdots$$

- $$M_W^2 = \frac{1}{R'^2 \log} \frac{2}{1+\kappa^2} \frac{1}{1+\frac{r}{V}}$$

A large κ or $\frac{r}{V}$ can lower S but it also:

- decreases R' $\Rightarrow$ lift the res. masses

For example, $S \sim 0.1 \Longrightarrow$ res. @ ~ 4 TeV

Analitical results:

TeV

For $\tau, \tau' << V = R \log$:

- $\frac{1}{g^2} \simeq \frac{V + r + \tau}{g_{5L}^2}$ $\qquad \frac{1}{g'^2} \simeq \frac{V + r' + \tau}{g_{5R}^2} + \frac{V + r' + \tau'}{\tilde{g}_5^2}$

- $S \simeq S_0 \left(1 + \frac{4}{3}\frac{\tau}{R}\right)$

  $T \sim U \sim 0$

- $M_W^2 = M_{W0}^2 \left(1 - \frac{\kappa^2}{1+\kappa^2}\frac{\tau}{V + r} + \ldots\right)$

For $\tau < 0$ a tachyon in the spectrum destabilizes the theory. So, generically:

- S increases
- resonances are slightly lifted
- as it "repels" the wave function from the TeV brane, almost degenerate W' and Z' (light) appear, mostly coupling as $SU(2)_L$.

$$\partial_z A^0 - \tau \frac{R'}{R} m^2 A^0 = 0$$

Analitical results:

B-L kin. term

$$S \sim S_0 \left(1 - \frac{4}{3}\left[1-\left(\frac{g'}{g^*}\right)^2\right]\left(\frac{\tau'}{V}\right)^2 \log + \dots\right)$$

$$T \sim -\frac{2\pi}{g^2}\left[1-\left(\frac{g'}{g}\right)^4\right]\left(\frac{\tau'}{V}\right)^2$$

$$U \sim 0$$

For example, if
$S = 0$
$\Rightarrow \begin{cases} T \sim -0.4 \\ m_{Z'} \sim 300 \text{ GeV} \end{cases}$

At quadratic order:

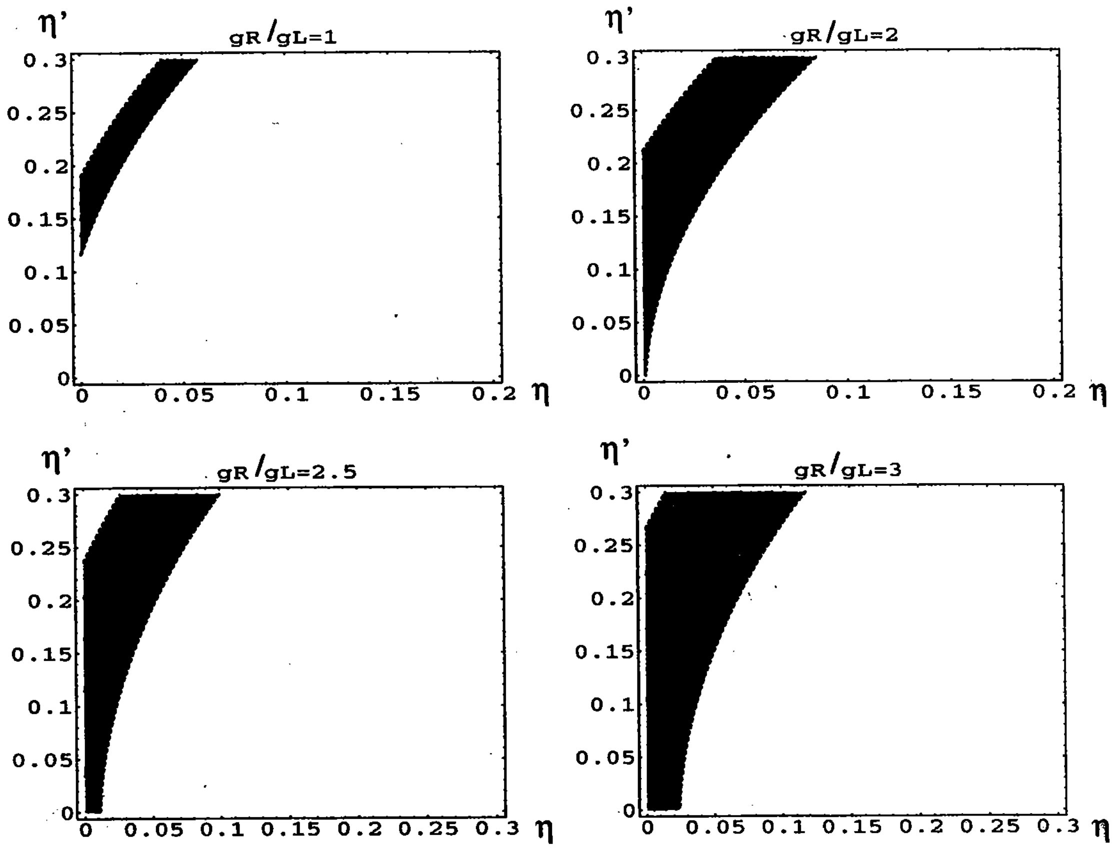
- <u>neg.</u> contrib. to S
- a "light" Z', coupling like $U(1)_Y$

Numerical parameter scan:

- neglect the Planck kin. terms.
- fixed $\kappa = g_R/g_L$
- scan in the $\tau - \tau'$ space.

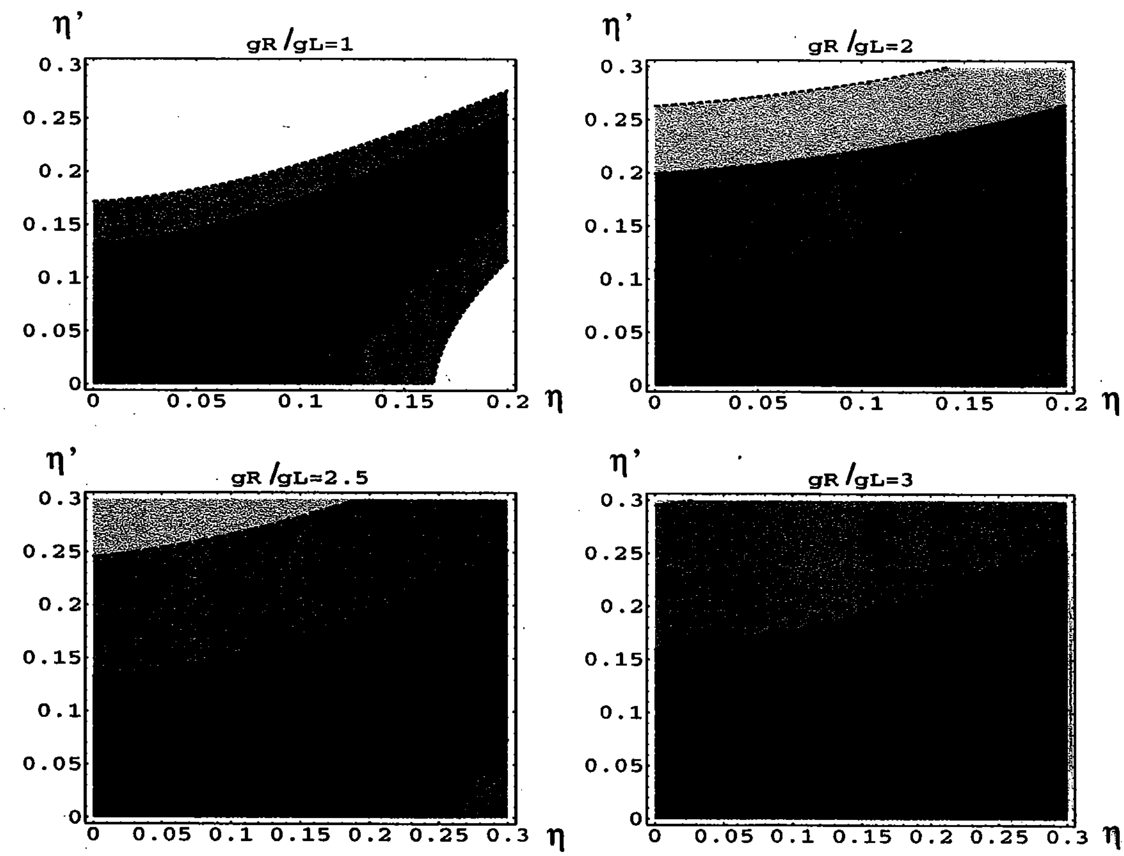
Note: r is mostly equivalent to κ.

5



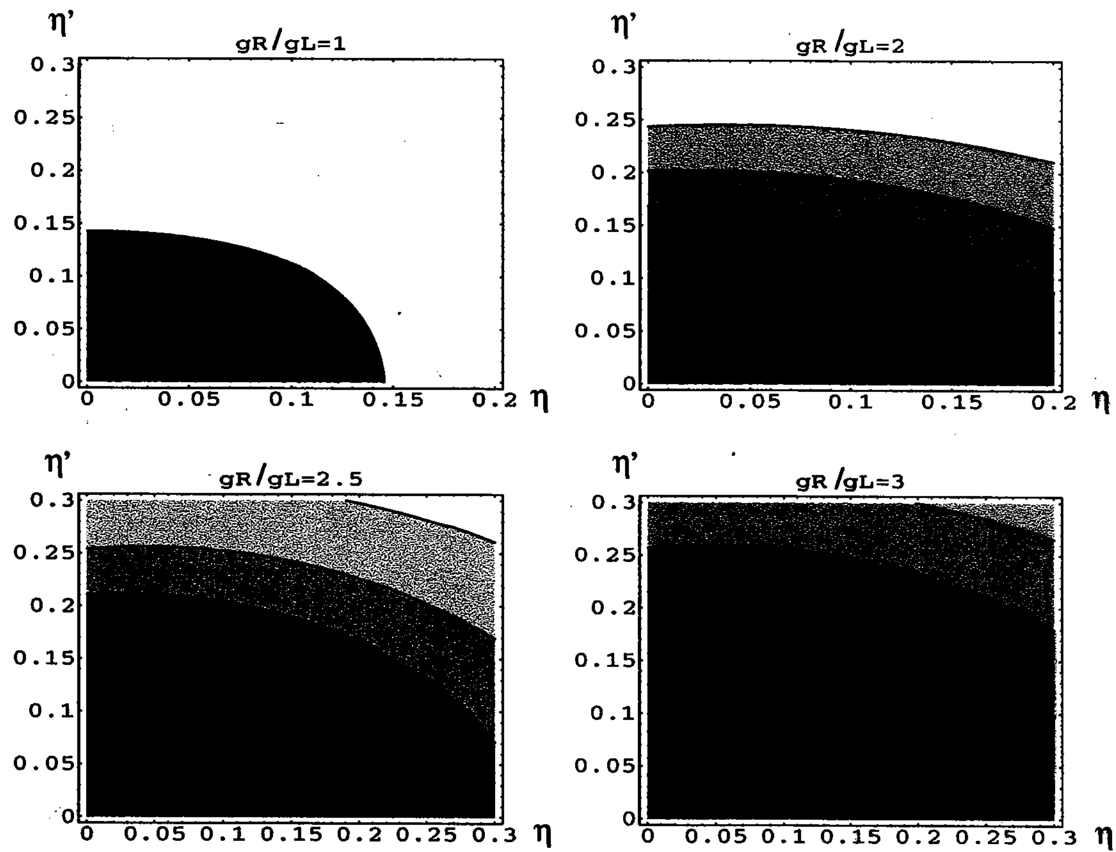
Contours at 0.1 0.3 0.5

T



Contours @ 0.1 0.3 0.5

LEP II

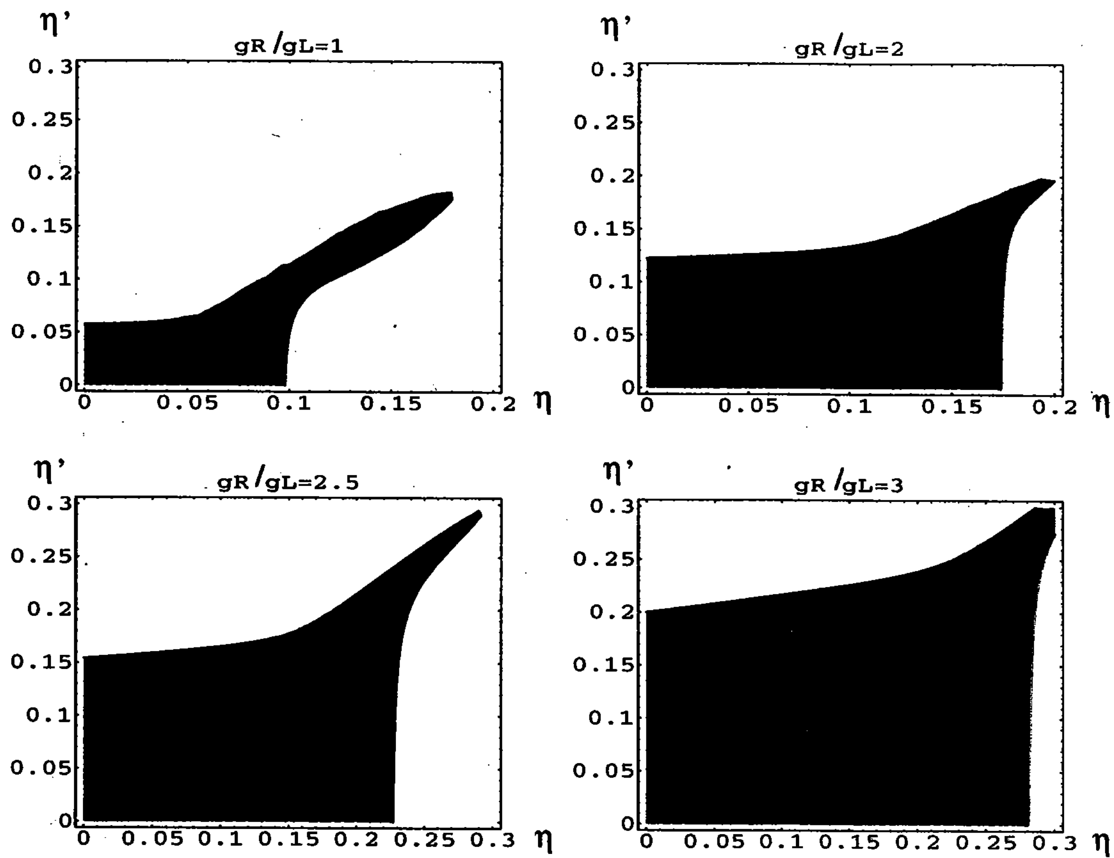


Deviation from the SM cross section

6 5% 7% 10%

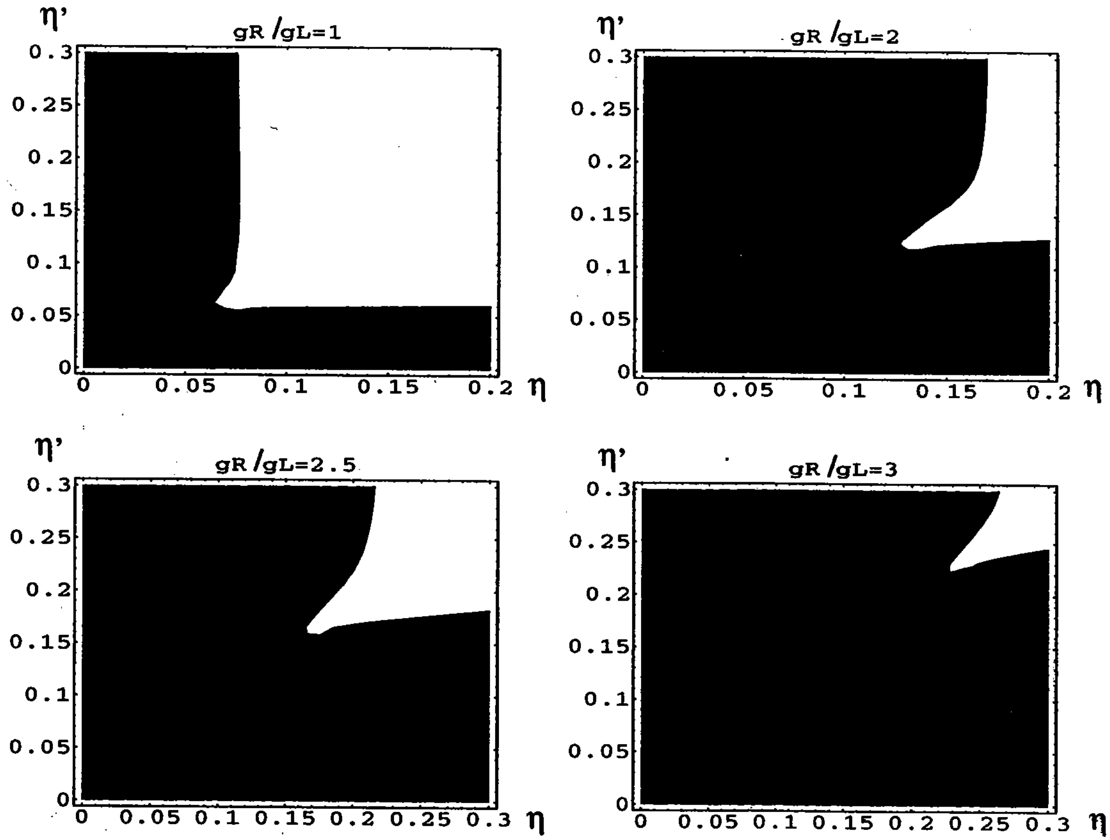
including both Z' and Z".

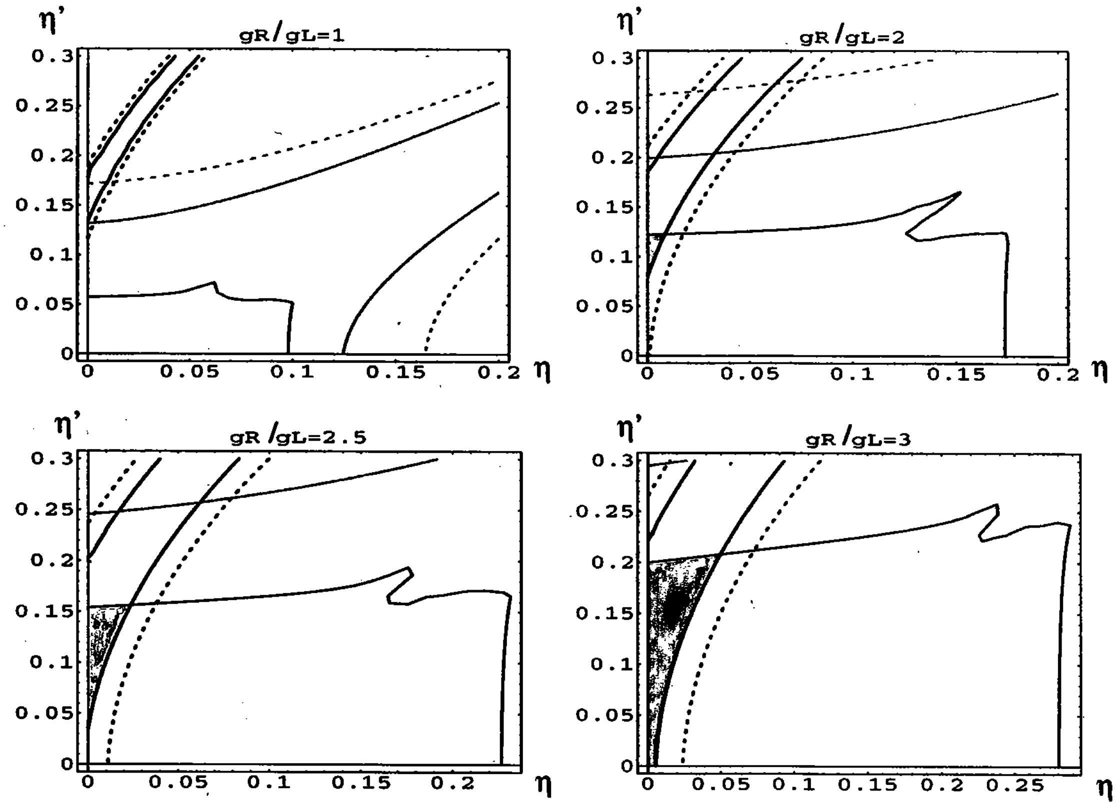
TEVATRON: Z'



η'
gR /gL=1
0.3
0.25
0.2
0.15
0.1
0.05
0
0 0.05 0.1 0.15 0.2 η
η'
gR /gL=2
0.3
0.25
0.2
0.15
0.1
0.05
0
0 0.05 0.1 0.15 0.2 η
η'
gR /gL=2.5
0.3
0.25
0.2
0.15
0.1
0.05
0
0 0.05 0.1 0.15 0.2 0.25 0.3 η
η'
gR /gL=3
0.3
0.25
0.2
0.15
0.1
0.05
0
0 0.05 0.1 0.15 0.2 0.25 0.3 η

TEVATRON: Z''





— SG 0.3 (0.5)

— TG 0.3 (0.5)

— LEP + TEVATRON

$Zb\bar{b}$ vertex

In a simple scenario for 3rd gen. masses:

$$\begin{pmatrix} \chi_2^L \\ \bar\psi_r^L \end{pmatrix}\begin{matrix} ++ \\ -- \end{matrix} \quad \begin{pmatrix} \chi_2^R \\ \bar\psi_r^R \end{pmatrix}\begin{matrix} -- \\ ++ \end{matrix} \quad + \begin{cases} \text{Dirac mass } M_D \text{ on TeV} \\ \bar\psi_{b_r}^R \text{ mixed with Planck bd. f} \end{cases}$$

• If $c_L > 1/2$, increasing M_D the lightest mode saturates to:

$$m \sim \frac{2}{R'}\sqrt{\frac{c_L - 1/2}{c_L + 1/2}}\left(\frac{R}{R'}\right)^{c_L - 1/2}$$

$$\begin{cases} \psi_L = -M_D R' \psi_R \\ \chi_R = M_D R' \chi_L \end{cases} \xrightarrow{M_D \to \infty} \begin{cases} \psi_R = 0 \\ \chi_L = 0 \end{cases}$$

$$\begin{pmatrix} \chi_L \\ \psi_L \end{pmatrix}\begin{matrix} ++ \\ -- \end{matrix} \longrightarrow \begin{matrix} +- \\ -+ \end{matrix}$$

light mode!

For $c_L = 1/2^+$

$$m_{light} \sim \frac{2}{R'^2 \log R'/R}$$

Top mass with $c_L > 1/2$ (i.e. t_L, b_L on the Planck b.) only if $1/R' \gtrsim 1\,\text{TeV}$

- Fix M_D to fit the top mass.
- Fix f/M to fit the bottom mass.
- Scan in $c_L - c_R$.

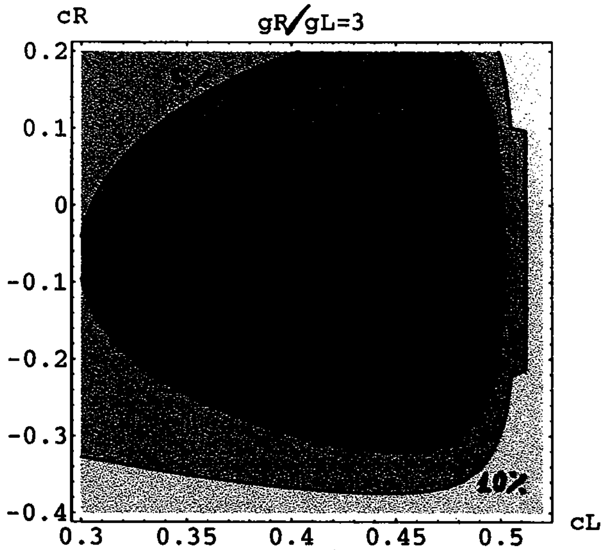
Generically:

- b_R mostly lives in the localized ind. fermion.

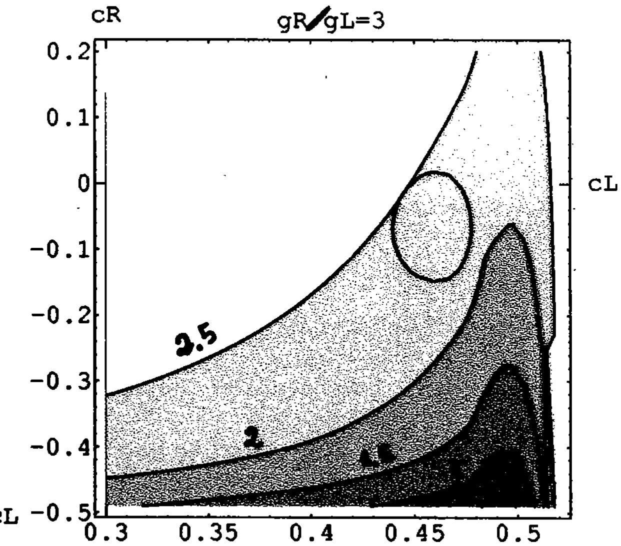
  $Z b_R \bar{b}_R$ agrees with the SM value at 2%

- For $c_L > 1/2$, b_L has a large component in χ^R
- For $c_L < 1/2$, χ^L is localized on the TeV brane. Usually, corrections of order 20-30% to $Z b_L \bar{b}_L$. But...

$\frac{\delta g_L}{g_L}$



Top' mass



$\frac{\tau}{V} = 0.043 \qquad \frac{\tau'}{V} = 0.20$

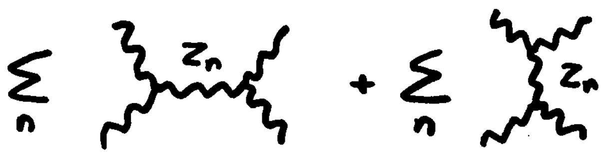
Partial Wave Unitarity

$$A = A^{(4)}\left(\frac{E}{M_W}\right)^4 + A^{(2)}\left(\frac{E}{M_W}\right)^2 + A^{(0)} + \ldots$$

In the SM, $A^{(4)} = 0$ due to gauge invariance.

$A^{(2)}$ is cancelled by the Higgs contribution.

In Higgsless Models, including all the Z resonances:



$$A^{(4)} \sim g_4 - e^2 - \sum_{k=1}^{\infty} g_{3k}^2 = 0$$

Due to 5d gauge inv.!

$$A^{(2)} \sim g_4 - \frac{3}{4}\sum_{k=1}^{\infty} g_{3k}^2 \left(\frac{M_k}{M_W}\right)^2 = 0$$

These sum rules are well satisfied even including few resonances. Is it enough to ensure PWU?

$$a_0 = \left|\frac{1}{32\pi}\int_{-1}^{1} A \, d\cos\theta\right| < \frac{1}{2}$$

Typically, $a_0 > 1/2$ @ 2-3 TeV. in Higgsless models.

However, the PWU violation is due to a Log term coming from the integration of the T-channel amplitude in the forward region:

$$a_0 \sim \sum_k \frac{g_{3k}^2}{32\pi}\left(2-\left(\frac{M_{zk}}{M_W}\right)^2\right)^2 \mathrm{Log}\frac{4E^2}{M_{zk}^2} + \dots$$

$$\int A^t_{zk}\, d\cos\theta \sim \int \frac{E^2}{\underbrace{-2E^2(1-\cos\theta)}_{t} - M_{zk}^2}\, d\cos\theta \sim \mathrm{Log}\frac{E^2}{M_{zk}^2}$$

→ This is there in the SM too:

$$g_{zzw}^2\left(2-\left(\frac{M_z}{M_W}\right)^2\right)^2 \sim \frac{(g^2-g'^2)^2}{g^2+g'^2} \sim \mathcal{O}(g^2)$$

$$a_0 \sim 1/2 \quad \Rightarrow \quad E \sim M_W\, e^{8\pi/g^2}$$

→ In the Higgsless models, it is enhanced by the ratio $\left(\frac{M_{zk}}{M_W}\right)^4$.

→ Does it mean that the theory becomes strongly coupled at 2 TeV?

Or, perturbation theory breaks down in the forward region, like in QED?

Conclusions

☆ Higgsless models in warped space provide a new intriguing mechanism for EWSB through BC's.

☆ Oblique corrections and direct bounds on light Gauge bosons strongly constraint such models.

- $g_{5R}/g_{5L} < 2$ is excluded
- " > 2 has still room with
  $|S| < 0.3 \qquad |T| < 0.1$

☆ It is possible to fit the top mass and small corrections to the $Zb\bar{b}$ vertex.

For $g_{5R}/g_{5L} = 3$: $\qquad \left.\frac{\delta g}{g}\right|_{b_L} \lesssim 3\% \qquad \left.\frac{\delta g}{g}\right|_{R} \lesssim 2\%$

☆ Partial wave amplitude unitarity violation is due to a Log term, coming from the forward scattering region.

4D example

SU(2) , complex higgs in the $(2j+1)$-rep.

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} (v, 0 \dots 0)$$

$$M_{W^\pm}^2 = 2j \; \frac{g^2 v^2}{4}$$

$$M_{W_3}^2 = (2j)^2 \; \frac{g^2 v^2}{4}$$

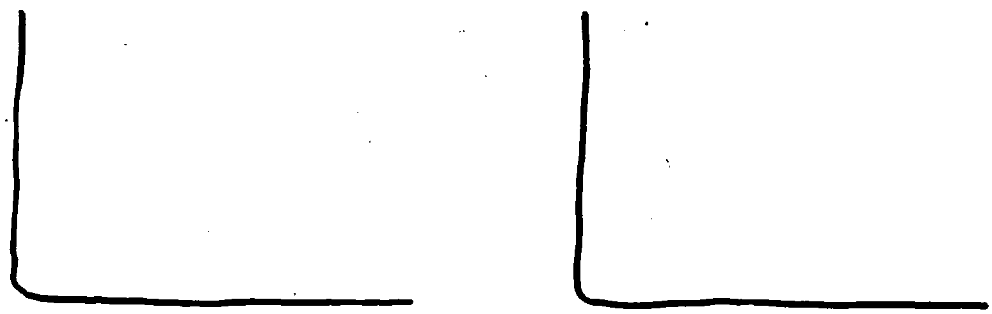
→ $A^{(1)}$ and $A^{(2)}$ still cancelled by gauge inv. and the Higgs contribution.

→ Log term: $\sim \frac{g^2}{32\pi} \, 4 (j-1)^2 \log \frac{4E^2}{M_{W_3}^2}$

$$E \sim \frac{1}{2} M_W \sqrt{2j} \; e^{\frac{2\pi}{g^2} \frac{1}{(j-1)^2}}$$

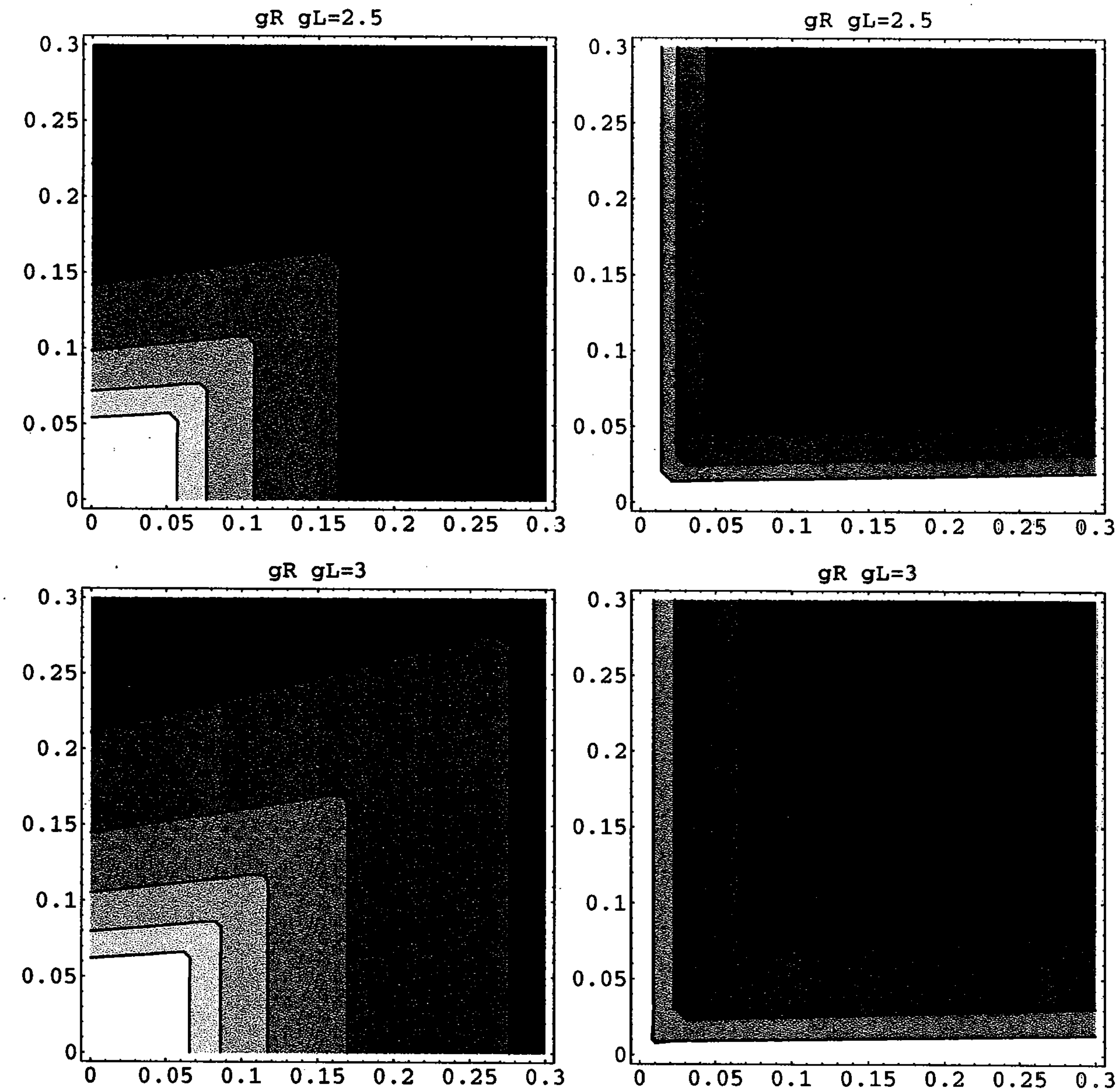
For $j = \frac{5}{2}$, $M_{W_3} = 180$ GeV and $E \sim 4$ TeV.

But the theory is asymptotically free!



$M_{Z''} \lesssim 1.5$ TeV

Z'   Z''



500
600
700
800
900

$$\mathcal{L}_{Pl} = -\left(\frac{r_L}{4} W_{\mu\nu}^{L\,2} + \frac{r_Y}{4} B_{\mu\nu}^{Y\,2} \right) \delta(z-R)$$

$$B_\mu^Y = \frac{1}{\sqrt{g_{5R}^2 + \tilde{g}_5^2}} \left(g_{5R} B_\mu + \tilde{g}_5 A_\mu^{R3} \right)$$

$$\mathcal{L}_{TeV} = -\frac{R'}{R} \left(\frac{\tau_B}{4} B_{\mu\nu}^2 + \frac{\tau_D}{4} W_{\mu\nu}^{D\,2} \right) \delta(z-R)$$

$$A_\mu^D = \frac{1}{\sqrt{g_{5L}^2 + g_{5R}^2}} \left(g_{5R} A_\mu^L + g_{5L} A_\mu^R \right)$$

$\to$ New BC's

$\to$ 5 new parameters

Experimental data:

$S = -0.03 \pm 0.11$

$T = -0.02 \pm 0.13$

$U = 0.24 \pm 0.13$

$S \sim 1.15$!

Are we already dead ?

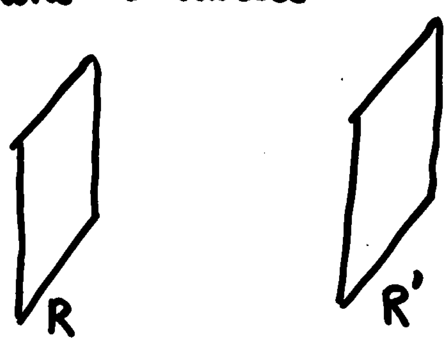
No :

- STU from experiment assuming a SM Higgs @ 115 GeV.

We should replace the Higgs contributions with the full KK tower of Z and W's...

- The theory has additional parameters :
  - brane induced kinetic terms

See also Nomura



$SU_{2L} \times U_{1Y}$ $\qquad$ $SU_{2D} \times U_{1B-L}$

- $g_{5L} \neq g_{5R}$

Basic Model

$$g_{5L} = g_{5R} = g_5$$

- $$\frac{1}{g^2} = \frac{V}{g_5^2} \qquad \frac{1}{g'^2} = V\left(\frac{1}{g_5^2} + \frac{1}{\tilde{g}_5^2}\right)$$

- At leading order in $1/\log$:

$$\Pi'_{11} = \Pi'_{33} = \frac{3}{8}\frac{1}{g^2 \log} \qquad \Pi'_{3Q} = 0$$

no γ-Z mixing at tree level

$$\Pi_{11} = \Pi_{33} = \frac{1}{g^2 R'^2 \log}$$

- Check: $$M_W^2 = g^2 \Pi_{11}\left(1 + g^2 \Pi'_{11}\right) = \frac{1}{R'^2 \log}\left(1 + \frac{3}{8}\frac{1}{\log} + \dots\right)$$

OK!

- Results:

$$\begin{cases} S = \dfrac{6\pi}{g^2 \log} \sim 1.15 \\ T \sim U \sim 0 \end{cases}$$

$T \sim 0$: thanks to custodial symmetry

$S \sim 1$: as expected... Barbieri, Pomarol, Rattazzi

RESULTS

1) Planck k.t. + g_{SR}/g_{SL}

$$S = 1.15 \Big(\underbrace{\frac{1}{1+\frac{r_L}{V}} \frac{2}{1+\left(g_{SR}/g_{SL}\right)^2}}_{\xi^{-1}} \Big)$$

OK. if $\xi \sim 10$, but $R' \sim \left(500\,\mathrm{GeV}\cdot\sqrt{\xi}\right)^{-1}$ ...

Resonances are lifted $\longrightarrow$ UNITARITY ?

2) TeV: $SU(2)_D$

τ_D is a direct contribution to S. Linearizing:

$$S = 1.15 \left(1 + \frac{4}{3}\frac{\tau_D}{R}\right)$$

If $\tau_D < 0$, the theory is destabilized by a (light) Tachyon!

Generically τ_D increases S!

3) TeV: $U(1)_{B-L}$

τ_B only contribute at quadratic order to S:

$$S = 1.15\left(1 - 35.5\left(\frac{\tau_B}{V}\right)^2 + \dots\right)$$

but also to $\quad T \sim -14\left(\frac{\tau_B}{V}\right)^2 + \dots$

If $\tau_B \sim 0.15\,V$:

$$S \sim 0 \qquad T \sim -0.4 \qquad U \sim 0.02$$

But, a light Z' also appear at 300-400 GeV, that couples like a sequential hypercharge boson.

$\rightarrow$ Excluded by LEP + Tevatron!

★ It is possible to break the EWS via BC's and give "correct" masses to gauge bosons and fermions, without any (light) Higgs field.

★ Precision EW Tests:

→ generically $S \sim 1$ (like in Technicolor)

→ brane kinetic Terms can in principle lower S, but we have to cope with:

- PerTurbative Unitarity (heavy resonances)
- Light GB (LEP + Tevatron exclusions)

→ a general scanning of the full parameter space is in progress.

→ detailed study of the Unitarity issue.

Planck brane kinetik terms

$$\mathcal{L}_{UV} = -\left(\frac{r}{4}\, W^{L\,2}_{\mu\nu} + \frac{r'}{4}\, B^{Y\,2}_{\mu\nu}\right)\delta(z-R)$$

$$B^Y_\mu = \frac{1}{\sqrt{g_{5R}^2+\tilde{g}_5^2}}\left(g_{5R}\, B_\mu + \tilde{g}_5\, A^{R3}_\mu\right)$$

New BC's at $z=R$:

$$\partial_z A^L_\mu + r\, m^2 A^L_\mu = 0$$
$$\partial_z B^Y_\mu + r' m^2 B^Y_\mu = 0$$

$$\frac{1}{g^2} = (V+r)\,\frac{1}{g_{5L}^2} \qquad\qquad \frac{1}{g'^2} = (V+r')\left(\frac{1}{g_{5R}^2} + \frac{1}{\tilde{g}_5^2}\right)$$

▶ Results:

$$\begin{cases} S = \dfrac{6\pi}{g^2 \log}\overbrace{\left(\dfrac{2}{1+(g_{5R}/g_{5L})^2}\cdot\dfrac{1}{1+r/V}\right)}^{\xi^{-1}} \sim 1.15\ \xi^{-1} \\[2em] T \sim U \sim 0 \end{cases}$$

☺K if $\xi \sim 10$! But...

... the spectrum of the gauge bosons is also modified:

$$M_W^2 = \xi^{-1} \cdot \frac{1}{R'^2 \log}$$

$$\Rightarrow \quad R' \sim \left(500\ \text{GeV} \cdot \sqrt{\xi}\right)^{-1}$$

Roughly, all the KK spectrum is lifted by a factor $\sqrt{\xi}$. In particular, the first resonance:

$$M_W' \sim \sqrt{\xi}\ 1200\ \text{GeV}$$

We have numerically checked:

$$\xi = 10 : \qquad M_W' \sim 3.8\ \text{TeV}$$

Unitarity is lost!

TeV brane kinetic terms

$$\mathcal{L}_{TeV} = -\frac{R'}{R}\left(\frac{\tau'}{4}\, B_{\mu\nu}^{2} + \frac{\tau}{4}\, W_{\mu\nu}^{D\,2}\right)\delta(z-R')$$

$$A_\mu^D = \frac{1}{\sqrt{g_{5L}^2 + g_{5R}^2}}\left(g_{5R}\, A_\mu^L + g_{5L}\, A_\mu^R\right)$$

- τ is a direct contribution to S, as it introduces a mixing between A_μ^{L3} and B^Y.

- Linearize in $\frac{\tau}{V}$ and $\frac{\tau'}{V}$:

$$\frac{1}{g^2} = \frac{V+r+\tau}{g_{5L}^2} \qquad \frac{1}{g'^2} = \frac{V+r'+\tau}{g_{5R}^2} + \frac{V+r'+\tau'}{\tilde{g}_5^2}$$

$$S = 1.15\ \xi^{-1}\left(1 + \frac{4}{3}\frac{\tau}{R}\right)$$

- S could vanish if $\tau < 0$!

But, for negative τ a Tachyon appears in the W spectrum, destabilizing the theory.

For $\tau = -\left(\frac{4}{3}\right)^{-1} R$: $\quad m_T^2 \sim -(800\ \text{GeV})^2$

Effect of B-L kin. term

τ' does not appear at linear level, but quartic.

For the sake of simplicity:

$$g_{5L} = g_{5R} = g_5 \qquad r = r' = \tau = 0$$

- $$S = 1.15 \left(1 - \frac{4}{3}\left(1 - t_g^{\,2}\right)\left(\frac{\tau'}{V}\right)^2 \log\right)$$

$$T \sim -\frac{2\pi}{g^2}\left(1 - t_g^{\,4}\right)\left(\frac{\tau'}{V}\right)^2 \qquad U \sim 0$$

- it is possible to cancel S with a positive value of τ'!

- We numerically checked that $S = 0$ for:

$$\frac{\tau'}{V} \sim 0.15 \quad (\ll 1)$$

$$\Rightarrow \quad \left[\begin{array}{l} S \sim 0 \\ U \sim 0.02 \\ T \sim -0.4 \end{array}\right.$$

Are we happy?

1. $T \sim -0.4$: it seems too large, but

   – we expect other positive contributions...

   – this is actually defined at the Z-pole!

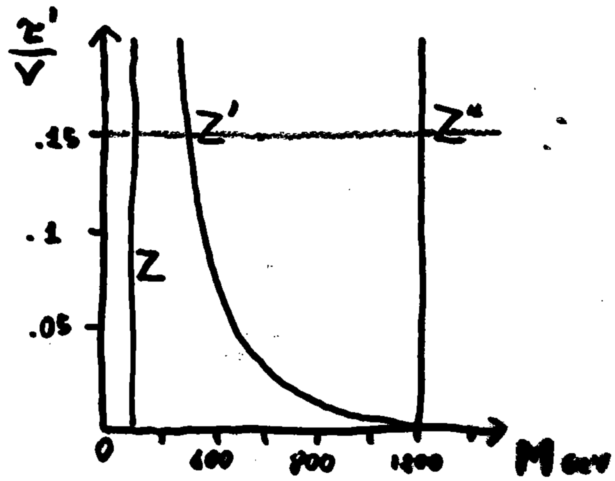
We have indeed neglected 4-fermion operators from the exchange of the Z resonances.

Barbieri, Pomarol, Rattazzi

$$T_{Z\text{-pole}} \sim -0.4 \qquad T_{p^2=0} \sim 0$$

2. spectrum

$M_{Z'} \sim 300\text{–}400$ GeV



$$\bar{f}_L \left(g_{5L}\, \psi^{L3}_{Z'}(R)\, T_3 + \tilde{g}_5\, \psi^{3}_{Z'}(R)\, \frac{Y}{2} \right) Z' f_L$$

Numerically:

$$\frac{\psi^{L3}_{Z'}}{\psi^{L3}_{Z}} \sim 0.03 \qquad \frac{\psi^{3}_{Z'}}{\psi^{B}_{Z}} \sim 0.8$$

$$\sim 0.2\, e\, \bar{f}_L \frac{Y}{2} Z' f_L$$

It's a sequential hypercharge Z'.

Not yet excluded in the literature(?)

Bounds may vary 150–800 GeV...

★ It is possible to break the EWS via BC's and give the "correct" masses to the GBs.

★ Fermion masses through BCs ?

Yes! Light generations on the Planck brane (almost), 3rd gen. in the bulk... Csaki, Grojean, Hubisz, Shirman, Terning

★ Precision Electroweak Tests:

→ oblique corrections: S, T, U

→ non-oblique corr.: $Zb\bar{b}$ vertex ... (in progress)

Conclusions

- Generically, we find $S \sim 1$, $U \sim T \sim 0$, as in techicolor theories.

  see also Barbieri, Pomarol, Rattazzi

- Planck brane induced kinetic terms and $g_{5L} \neq g_{5R}$ can lower S, but at the price of loosing tree-level Unitarity.

- SU_{2D} kin. term on the TeV brane generically increases S.

- U_{1B-L} kin. term on the TeV gives a negative contribution to S. We can achieve:

$$S \sim 0, \qquad U \sim 0, \qquad T \sim -0.4$$

However, an hypercharge-like Z' will appear at

$$M_{Z'} \sim 300\text{-}400 \text{ GeV}$$