HIGGSLESS MODELS OF EWSB

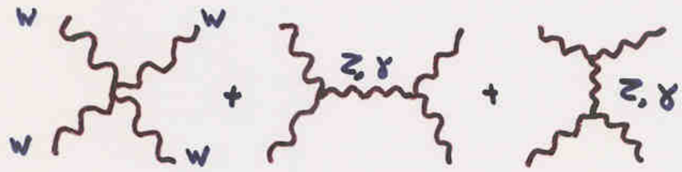
. Electroweak symmetry breaking sector in the SM has never been directly tested.

→ LHC will do it (we believe), we need to analise possible alternatives to the Higgs mechanism.

LES HOUCHES WORKSHOP
May 17 - 2005

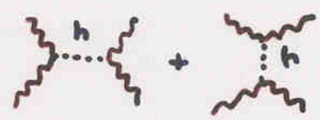
Partial wave Unitarity

$$W^+W^- \to W^+W^- \quad (WZ \to WZ)$$



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

- $A^{(4)} \sim g_{WWWW} - e^2 - g^2_{WWZ} = 0$ (gauge invariance)
- In the SM, $A^{(2)}$ is cancelled by the contrib. of the higgs:



- Without higgs, unitarity breaks down @ 1.8 TeV
  $\to$ strong dynamics @ TeV? (technicolor)

- Can we maintain perturbative unitarity in the W scattering amplitude without scalars?

→ Let's add a massive Z' (and W')

$$A^{(4)} \sim g_{WWWW} - e^2 - g^2_{WWZ} - g^2_{WWZ'} = 0$$

$$A^{(2)} \sim g_{WWWW} - \frac{3}{4} g^2_{WWZ} \frac{M_Z^2}{M_W^2} - \frac{3}{4} g^2_{WWZ'} \frac{M_{Z'}^2}{M_W^2}$$

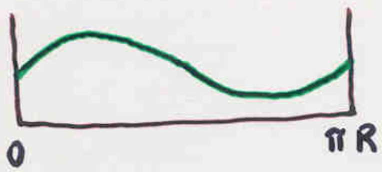
☆ Tune $M_{Z'}$ so that $A^{(2)} = 0$

But, $W'W' \to W'W'$ $(W'Z' \to W'Z')$ will violate P.U. (at a larger scale).

- We can further unitarize this scattering with another set of gauge bosons W'' Z''... and so on!

→ need to add an infinite "tower" of massive gauge bosons → X-dimensions ←

Extra dimensions



$$\Phi(\vec{x}, y) = \sum_n f_n(y) \cdot \varphi_{(n)}(\vec{x})$$

Boundary conditions determine the spectrum of the field ϕ. We can choose the BC's so that no massless mode is allowed.

→ New mechanism to break symmetries and give mass to vector bosons

→ WW scattering:

$+ \sum_n$ 

$+ \sum_n$ 

$$A^{(4)} \sim g_{WWWW} - e^2 - \sum_n g^2_{WWZ_n} = 0$$

Due to 5D gauge invariance

$$A^{(2)} \sim g_{WWWW} - \frac{3}{4} \sum_n g^2_{WWZ_n} \frac{M_n^2}{M_W^2} = 0$$

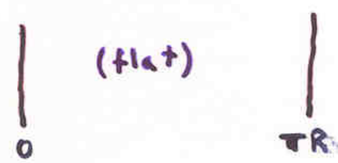
→ sum rules ensure the cancellation of terms growing with the energy

→ PU breakdown delayed by the pert. contrib. of KK mode

→ 5D theories are non-renormalizable: perturbativity will eventually break down at a scale $\gg 1.8$ TeV

(Higgs decoupling limit)

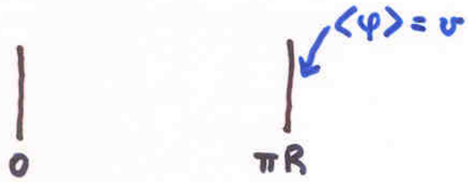
This model can be thought of as the limit of a theory with (localized) higgs:



$$\begin{cases} \partial_5^2 W_\mu + m^2 W_\mu = 0 \\ \partial_5 W(0) = \partial_5 W(\pi R) = 0 \end{cases}$$ → Flat zero mode!

→ W_5 is gauged away

If we add a higgs on one of the boundaries:



$$\begin{cases} \partial_5 W(0) = 0 \\ \partial_5 W(\pi R) + g_5^2 v^2 W(\pi R) = 0 \end{cases}$$

→ no zero mode

→ sym. is spontaneously broken

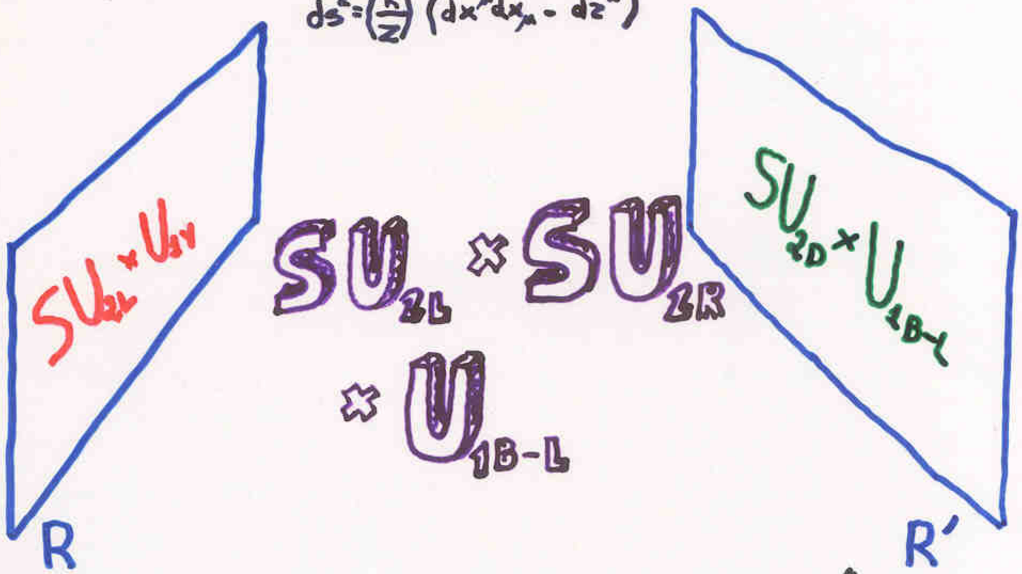
- small v: $M_W^2 \sim g_5^2 v^2$
- large v: $M_W^2 \sim 1/R^2$ → $W(\pi R) = 0$

$m_h^2 \sim \lambda v^2 \to \infty$

In the $v \to \infty$ limit, the higgs decouples, however the W mass stays finite.

Higgsless Model in AdS_5

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



"Planck"
$SU_2(R) \times U_{1B-L} \to U_{1Y}$

"TeV"
$SU_{2L} \times SU_{2R} \to SU_{2D}$

☆ $SU_{2L} \times U_{1Y}$ is broken to U_{1em}, the $W^\pm$ and Z get mass:

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

☆ Custodial symmetry built in AdS ensures the correct Z mass at leading order.

☆ KK modes are heavy $\quad M_K^2 \sim \frac{\mu_K^2}{R'^2} \quad \mu_K = 2.4, \ldots$ zeros of Bessel f.

☆ KK modes delay PU breakdown

☆ no "light" scalar (Higgs) in the spectrum

Can we write down a realistic theory?

We need to check:

→ Is the PU breakdown scale (cut-off) large enough? Are the gauge KK modes avoiding LEP bounds on massive g.b.?

→ Tree level corrections to EWP observables: (universal) oblique parameters: S

→ (Light) fermion masses and flavour universality violation.

→ Third generation: m_t v.s. $Zb_L\bar{b}_L$

(this is the challenge)

Unitarity

NDA estimate of the 5D cut-off:

$$\Lambda_{NDA} \sim \eta \frac{24\pi^3}{g_5^2} \frac{R}{R'} \sim \eta \frac{24\pi^3}{g^2} \, 2.4 \, \frac{M_W^2}{M_{Z'}}$$

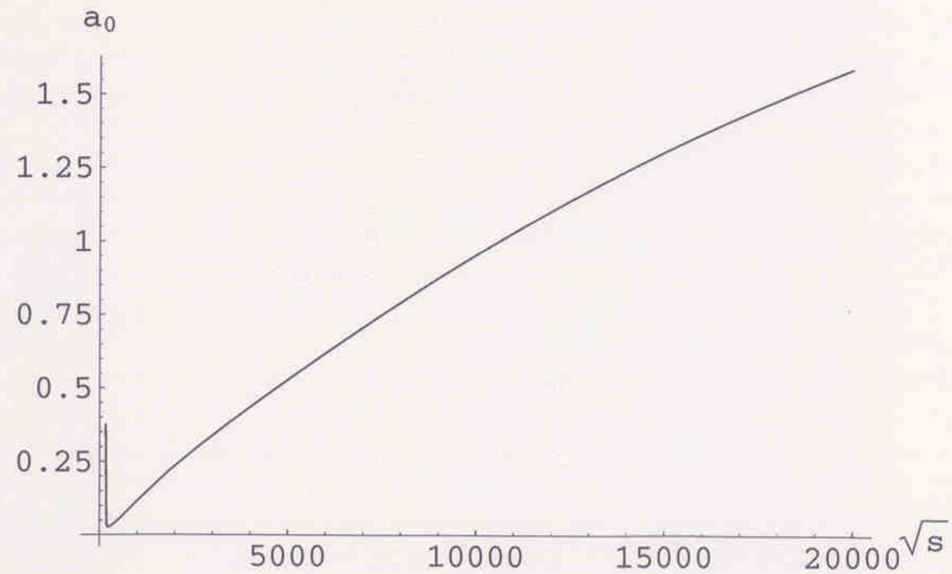
$\eta \sim \frac{1}{4}$ (explicit calculation of WW inelastic scattering

→ the lighter the Z', the higher the cutoff!

i.e. $M_{Z'} \sim 600$ GeV ⇒ $\Lambda \sim 10$ TeV

(Note: the scale $M_{Z'}$ fixes R')

Question: is it too light for LEP?


a_0
1.5
1.25
1
0.75
0.5
0.25
5000
10000
15000
20000
$\sqrt{s}$

Oblique corrections: the S problem

- tree level corr. originating from distorsions of the GB wave functions
- Universal $\Longrightarrow$ can be parametrized as Oblique :

For example, $SU(2)_L$ doublet on the Planck brane:

$$\underbrace{g_{5L}\,\psi_1^{L3}(R)}_{g\cos\theta_W \text{ overall norm.}}\;\bar{f}_\ell\left(T_3+\underbrace{\frac{\tilde{g}_5\,\psi_1^B(R)}{g_{5L}\,\psi_1^{L3}(R)}}_{-\,tg\,\theta_W^2}\frac{Y}{2}\right)Z_\mu\gamma^\mu f_\ell$$

4D-5D matching

$$S\sim\frac{6\pi}{g^2}\frac{1}{\log\frac{R'}{R}}\sim 1.15$$

$\longrightarrow$ turn on other parameters, like $\frac{g_{5R}}{g_{5L}}\neq 1$ and brane kinetic terms, however we either find a light resonance (excluded by LEP) or heavy resonances (violating Pert. Unitarity).

$\longrightarrow$ the model with Planck brane localized fermions is disfavoured

see also Barbieri, Pomarol, Rattazzi, Strumia

Delocalized fermions

Consider bulk fermions with a bulk mass

$$M = \frac{c}{R}$$

c controls the localization of the wave functions:

	Planck b.	flat	TeV b.
l.h.	$c > 1/2$	$c = 1/2$	$c < 1/2$
r.h.	$c < -1/2$	$c = -1/2$	$c > -1/2$

Zero mode $\quad \chi_L(z) = A\left(\frac{z}{R}\right)^{2c-1}$

The couplings of light fermions are modified by their w.f.s (universally)

$\Rightarrow$ effective shift of S

$$S = \frac{2\pi}{g^2}\frac{1}{\log}\left(1 + (2c-1)\log + \dots\right) \qquad \text{for } c \sim \frac{1}{2}$$

$$S \sim 0 \quad \text{if} \quad c \sim \frac{1}{2}\left(1 - \frac{1}{\log}\right)$$

Tuning c we can always cancel S !

Another beneficial effect: gauge KK modes decouple from the light fermions and can evade LEP bounds.

→ W and Z wave functions are almost flat.

Orthogonality implies $\int dz \, \frac{R}{z} \psi_n(z) \cong 0$

→ if fermion wave functions are flat too, the couplings are proportional to:

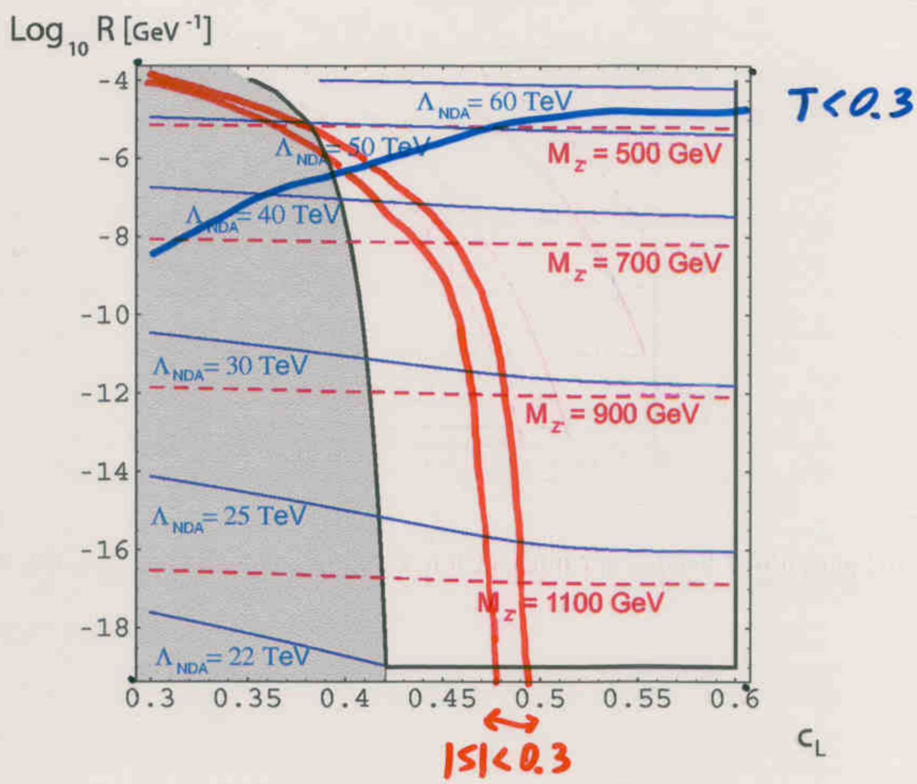
$$\int dz \, \frac{R}{z} \psi_f^2(z) \, \psi_n(z) \sim 0$$

Parameters of the theory:

R, R' → fixed by M_W and $M_{Z'}$ (cutoff)

$g_5, \tilde{g}_5$ → fixed by e and M_Z

c_L → constrained by S



Log10 R [GeV -1]
-4
-6
-8
-10
-12
-14
-16
-18
0.3
0.35
0.4
0.45
0.5
0.55
0.6
cL
ΛNDA = 60 TeV
ΛNDA = 50 TeV
ΛNDA = 40 TeV
ΛNDA = 30 TeV
ΛNDA = 25 TeV
ΛNDA = 22 TeV
MZ' = 500 GeV
MZ' = 700 GeV
MZ' = 900 GeV
MZ' = 1100 GeV
T<0.3
|S|<0.3

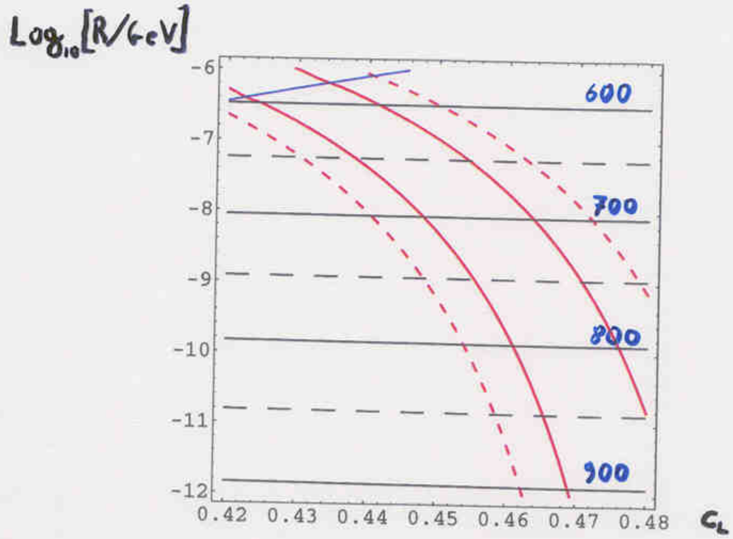


Figure 1: Mass of the first resonance (Z'). S @ 0.25 and 0.5 in red and T @ 0.25 in blue.

Tests and predictions

→ @ colliders: detection of relatively light Z' and W'

(see Maxim's talk)

→ check of the sum rules: g_{WWZ_k} , M_{Z_k}

$$
\begin{cases}
g_{WWWW} = e^2 + g_{WWZ}^2 + g_{WWk}^2 \\
g_{WWWW} = \frac{3}{4} g_{WWZ}^2 \frac{M_Z^2}{M_W^2} + \frac{3}{4} g_{WWk}^2 \frac{M_{Zk}^2}{M_W^2}
\end{cases}
$$

→ deviations in the WWWW and WWZ couplings

- emerging from distorsions in the wave functions
- necessary for the sum rules

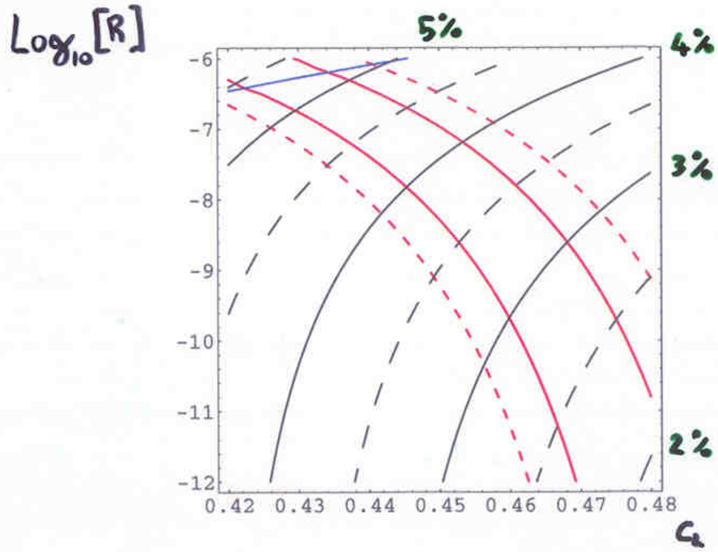


Figure 1: % deviation in the $WWWW$ coupling w.r.t. the SM value. S @ 0.25 and 0.5 in red and T @ 0.25 in blue.

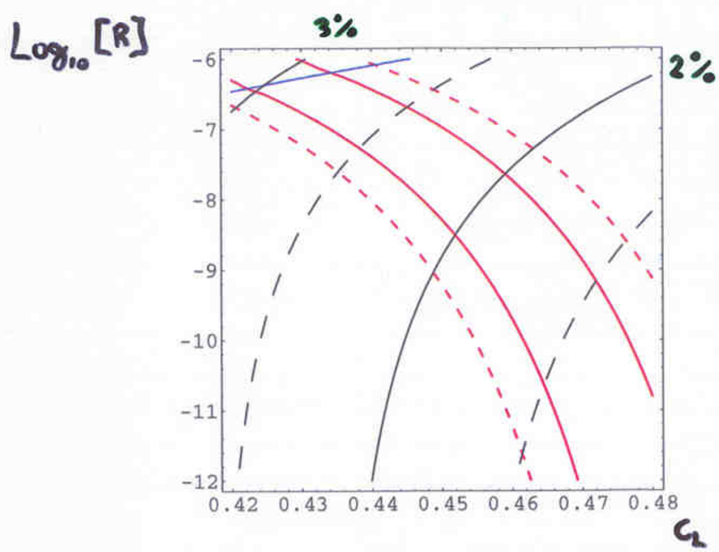


Figure 2: % deviation in the WWZ coupling w.r.t. the SM value. S @ 0.25 and 0.5 in red and T @ 0.25 in blue.

Fermion masses

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

* In the minimal setting:

$$[2_L, 1_R] = \begin{pmatrix} \chi^L_{u_\ell} \\ \bar\psi^L_{u_r} \\ \chi^L_{d_\ell} \\ \bar\psi^L_{d_r} \end{pmatrix} \begin{array}{c} ++ \\ -- \\ ++ \\ -- \end{array} \qquad [1_L, 2_R] = \begin{pmatrix} \chi^R_{u_\ell} \\ \bar\psi^R_{u_r} \\ \chi^R_{d_\ell} \\ \bar\psi^R_{d_r} \end{pmatrix} \begin{array}{c} -- \\ ++ \\ -- \\ ++ \end{array}$$

* 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

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

lowers the mass of the lightest guy.

Third generation

m_t v.s. $Zb_L\bar{b}_L$

In this simple model it is impossible to fit at the same time m_t and the $Zb_L\bar{b}_L$ coupling.

☆ $c_L > 1/2$: the top is too light.

Increasing M_D, the Top mass saturates :

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

$$\xrightarrow[c_L \to 1/2]{} \frac{\sqrt{2}}{R'\sqrt{\log}} \sim \sqrt{2}\, M_W$$

BC's on the TeV brane :

$$\begin{aligned} \psi_L &= -M_D R' \psi_R \\ \chi_R &= M_D R' \chi_L \end{aligned} \longrightarrow \begin{aligned} \psi_R &= 0 \\ \chi_L &= 0 \end{aligned}$$

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

☆ $c_L \lesssim 1/2$: m_t can be achieved with a sizeable $M_D R' \sim \mathcal{O}(1)$

However, the same BC's apply to the bottom:

$$\underbrace{\chi_{bR} = M_D R' \cancel{\chi}_{bL}}_{b_\ell}$$

A sizable component of the l.h. b lives in χ_R ($SU(2)_R$ doublet) $\Rightarrow$ large corr. to $Z b_\ell \bar{b}_\ell$

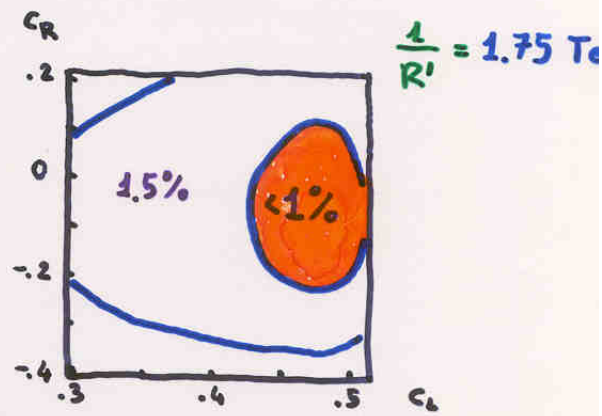
[above 1%]

☆ $c_L \ll 1/2$: small M_D needed to get the Top mass

But the Z w.f. is modified near the TeV-brane

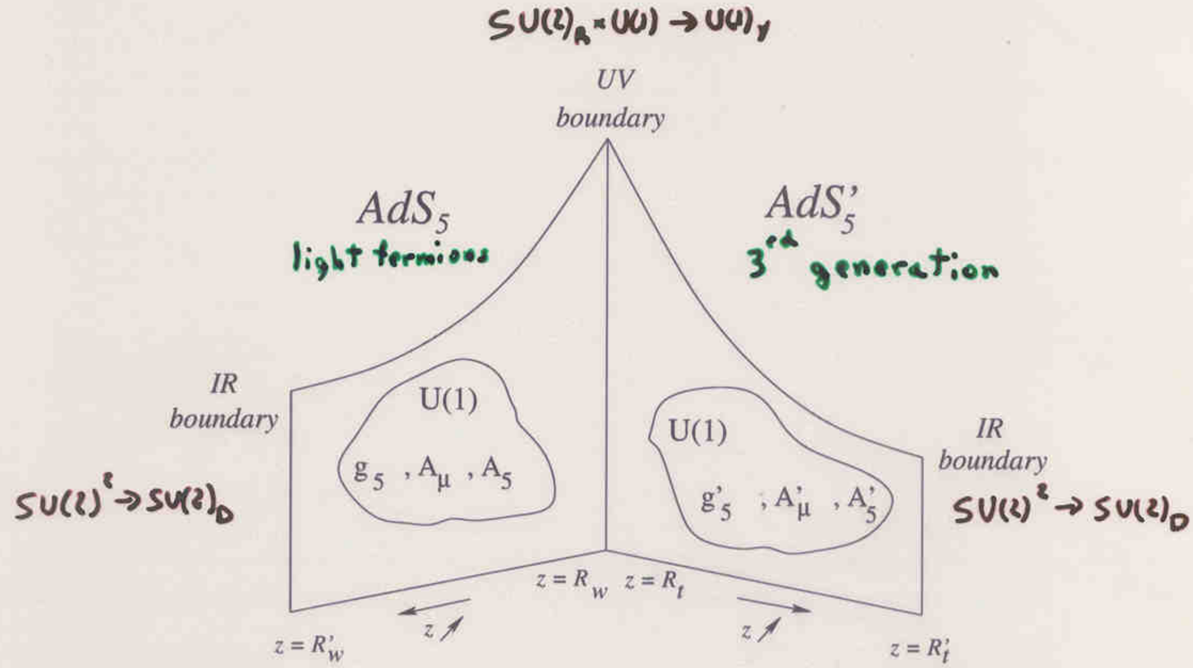
$\rightarrow$ large $\delta Z b_\ell \bar{b}_\ell$

Possible solution: increase $1/R'$, so that $M_D R'$ (i.e. $m_t R'$) small.



Top & bottom: a brane on their own?

hep-ph/0505001



Schematic view of the double AdS space that we consider.

- AdS_5 provides EWSB (as described before)
- AdS'_5 gives a small contrib. to EWSB + large contribution to m_t $\left(1/R'_t \gg 1/R'_w\right)$

  → issues: strong coupling (Topcolor), ...

  → generic prediction: a light pseudoscalar strongly coupled to top and bottom (Top-pion)

Conclusions

- Symmetry breaking via boundary conditions can provide an intriguing alternative to the Higgs mechanism.

- It is possible to write down a reliable theory of EWSB that:
  - → is perturbative up to 10 TeV
  - → does not run into troubles with EWPT

- The remaining challenge is the 3rd generation

- LHC is on the way! Can we:
  - → test the idea?
  - → make predictions? signatures? Theoretically constrained!
  - → distinguish it from the SM, Susy, ... ?