

# Electroweak Symmetry Breaking from a Holographic Fourth Generation

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# Outline

- Motivation
- Setup: RS Bulk with a highly localized fourth generation.
- Fourth Generation Condensation: EWSB and Fermion masses.
- Electroweak Precision Constraints
- Phenomenology
- Conclusions/Outlook

# Motivation I

Top-condensation models (Nambu'89; Bardeen, Hill, Lindner '90):

- Top quark is too light:  $m_t \sim 600$  GeV if  $\Lambda \sim O(1)$  TeV.  
Or  $\Lambda \sim 10^{15}$  GeV if  $m_t \sim 200$  GeV.
- $\Rightarrow$  Heavy fourth generation  $M_4 \sim 600$  GeV.
- Problems:
  - All of 4th Gen must condense, but  
What's the underlying interaction ?
  - Fermion masses ?
- Fourth generation in  $AdS_5$ :
  - Only one fermion condensation necessary.
  - Fermion localization given by bulk masses
  - KK gauge bosons mediate the 4-fermion interactions

# Motivation II

- In RS Bulk models, since Higgs must be localized around TeV brane

Fermion localization  $\Rightarrow$   $\left\{ \begin{array}{l} \text{light fermions are Planck brane localized} \\ \text{heavier fermions localized toward TeV brane} \end{array} \right.$

- One dynamical mechanism for localizing the Higgs close to the TeV brane:

$$A_5 \rightarrow H$$

(Nomura, Contino, Pomarol '03; Agashe, Contino, Pomarol '04)

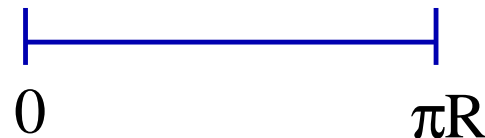
- Fourth generation condensation provides one more alternative.

# The Hierarchy Problem in $AdS_5$

- Randall-Sundrum: Exponential Separation of energy scales induced by bulk metric.
- Warped 5D metric in RS

$$ds^2 = e^{-2\kappa|y|} \eta^{\mu\nu} dx_\mu dx_\nu + dy^2$$

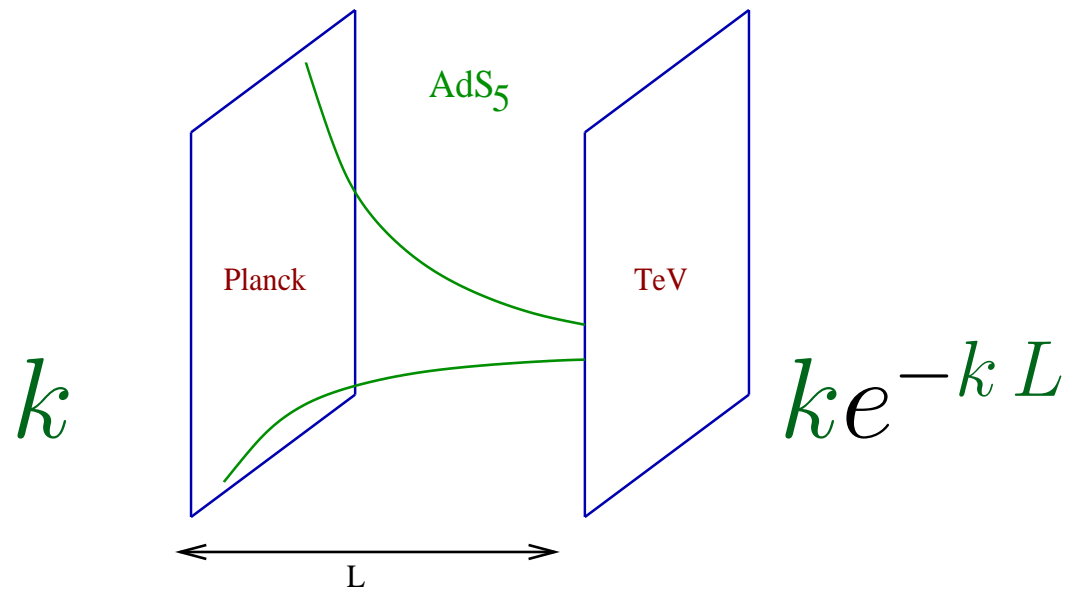
- Compactified on  $S_1/Z_2$  with  $L = \pi R$



and  $k \lesssim M_P$ ,  $AdS_5$  curvature.

# The Hierarchy Problem in $AdS_5$

- One compact extra dimension. Non-trivial metric induces small energy scale from Planck scale.



- For  $kR \simeq (11 - 12) \Rightarrow$

$$\Lambda_{\text{TeV}} \sim M_{\text{Planck}} e^{-kL}$$

with  $k$  the curvature

# 4Gen Model Setup

- Gauge group in the bulk is  $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X$   
(Agashe, Delgado, May, Sundrum '04)  
 $\Rightarrow$  greatly reduces isospin violation in the bulk.
- Perhaps enlarged by  $P_{LR}$  to protect  $Z \rightarrow b\bar{b}$   
(Agashe, Contino, Da Rold, Pomarol '06)
- Four generations of SM fermions:
  - First two, localized towards the Planck brane
  - Third, localized closer to the TeV brane
  - Fourth, localized very close to the TeV brane
  - Choices for fermion representation, localization
- No Higgs (yet).

# Fermions in the Bulk

- Fermion Fields in the bulk: 5D fermion field KK decomposition

$$\Psi_{L,R}(x, y) = \frac{1}{\sqrt{2\pi R}} \sum_{n=0} \psi_n^{L,R}(x) e^{2\kappa|y|} f_n^{L,R}(y)$$

- 5D fermion bulk mass term  $\longrightarrow$  localization of fermion fields:

$$S_f = \int d^4x dy \sqrt{-g} \{ \dots - c \kappa \bar{\Psi}(x, y) \Psi(x, y) \} ,$$

with  $c \simeq O(1)$ .

- $\Rightarrow$  Fermion zero-modes can be localized by choosing  $c$  :

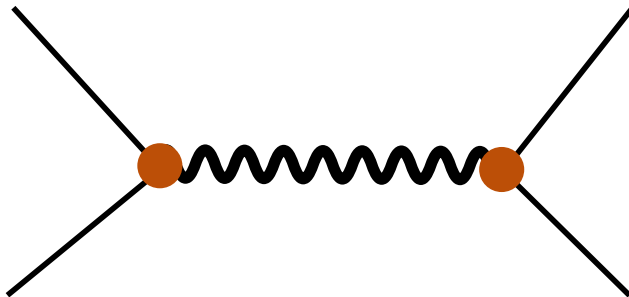
$$f_0^{R,L}(y) = \sqrt{\frac{k\pi R (1 \pm 2c)}{e^{k\pi R(1 \pm 2c)} - 1}} e^{\pm c k y}$$

# Couplings to KK Gauge Bosons

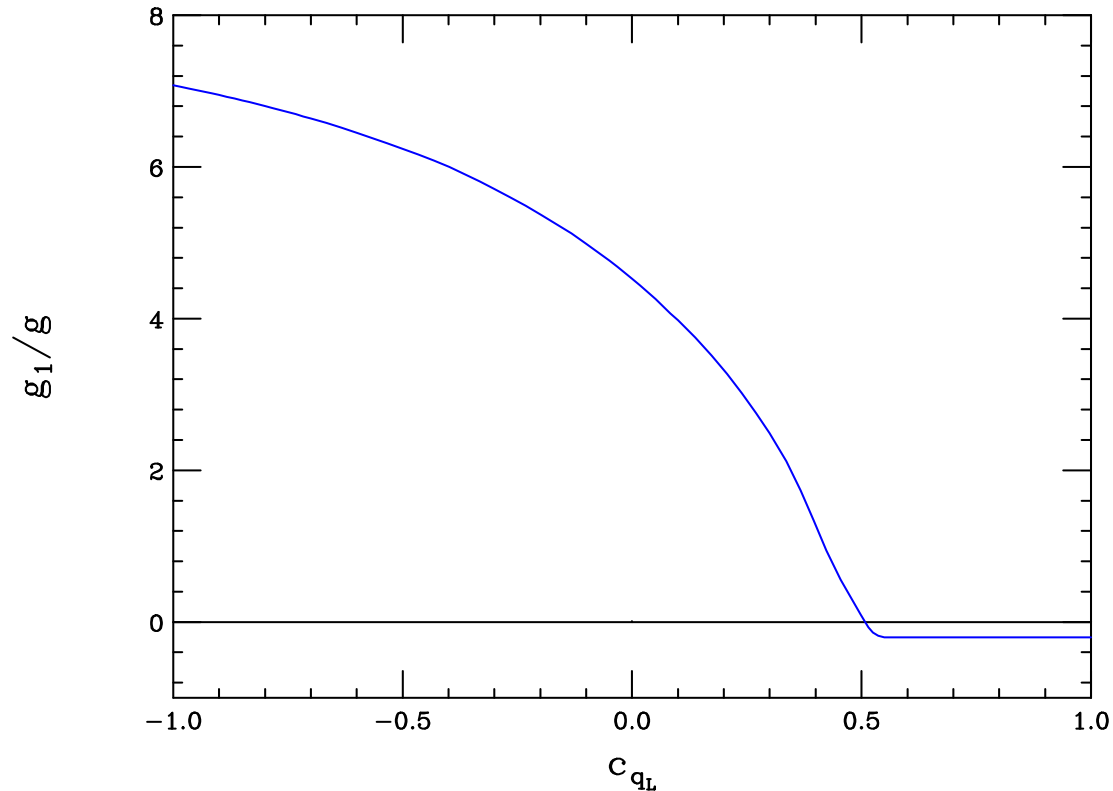
From the 5D couplings (Gherghetta, Pomarol '00)

$$\int d^4x dy \sqrt{-g} g_5 \bar{\Psi}(x, y) i\gamma_\mu A_\mu(x, y) \Psi(x, y)$$

- Couplings of zero-mode fermions to 1st KK gauge bosons are strong if fermion localized near TeV brane ( $c_L, -c_R < 0.5$ ).
- E.g.: Fourth generation quarks are strongly coupled to KK gluon.



# Couplings to KK Gauge Bosons



⇒ Strong four-fermion interactions among TeV localized fermions.

# Zero-mode Four-fermion Operators

Integrating out KK gauge boson

$$-\frac{g_{01}^L g_{01}^R}{M_{KK}^2} (\bar{U}_L \gamma_\mu T^A U_L) (\bar{U}_R \gamma_\mu T^A U_R)$$

leading to

$$\frac{g_U^2}{M_{KK}^2} \{ \bar{U}_L^a U_R^a \bar{U}_R^b U_L^b + \dots \}$$

with

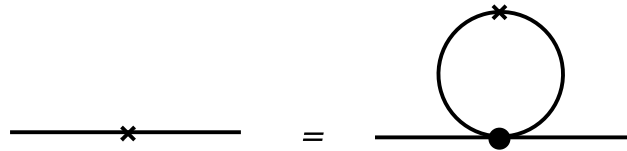
$$g_U^2 \equiv g_{01}^L g_{01}^R .$$

⇒ attractive four-fermion color-singlet interaction.

# EWSB

$$\text{If } g_U > g_U^{\text{crit.}}, \Rightarrow \langle \bar{U}_L U_R \rangle \neq 0$$

$\Rightarrow$  Solution to the gap equation:


$$\text{---} \times \text{---} = \text{---} \text{---} \text{---}$$

This implies

- Electroweak Symmetry Breaking
- Dynamical  $m_U$

We can also write an effective theory at low energy for the Higgs.

# Effective Higgs Theory

At the cutoff  $M_{KK}$

$$\mathcal{L} = \bar{U}_L i \not{D} U_L + \bar{U}_R i \not{D} U_R + \frac{g_U^2}{M_{KK}^2} (\bar{U}_L U_R \bar{U}_R U_L)$$

which we can rewrite as

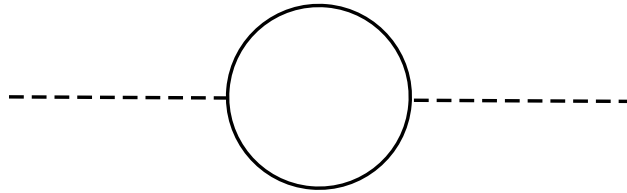
$$\mathcal{L} = \bar{U}_L i \not{D} U_L + \bar{U}_R i \not{D} U_R + g_U \bar{Q}_L H U_R - M_{KK}^2 H^\dagger H + \text{h.c.} ,$$

At  $\mu < M_{KK}$

$$\begin{aligned} \mathcal{L}(\mu) = & \dots + Z_{g_U} g_U \bar{Q}_L H U_R + \text{h.c.} \\ & + Z_H (D_\mu H)^\dagger D^\mu H - m_H^2 H^\dagger H - \frac{\lambda}{2} (H^\dagger H)^2 \end{aligned}$$

# Effective Higgs Theory

From



we have

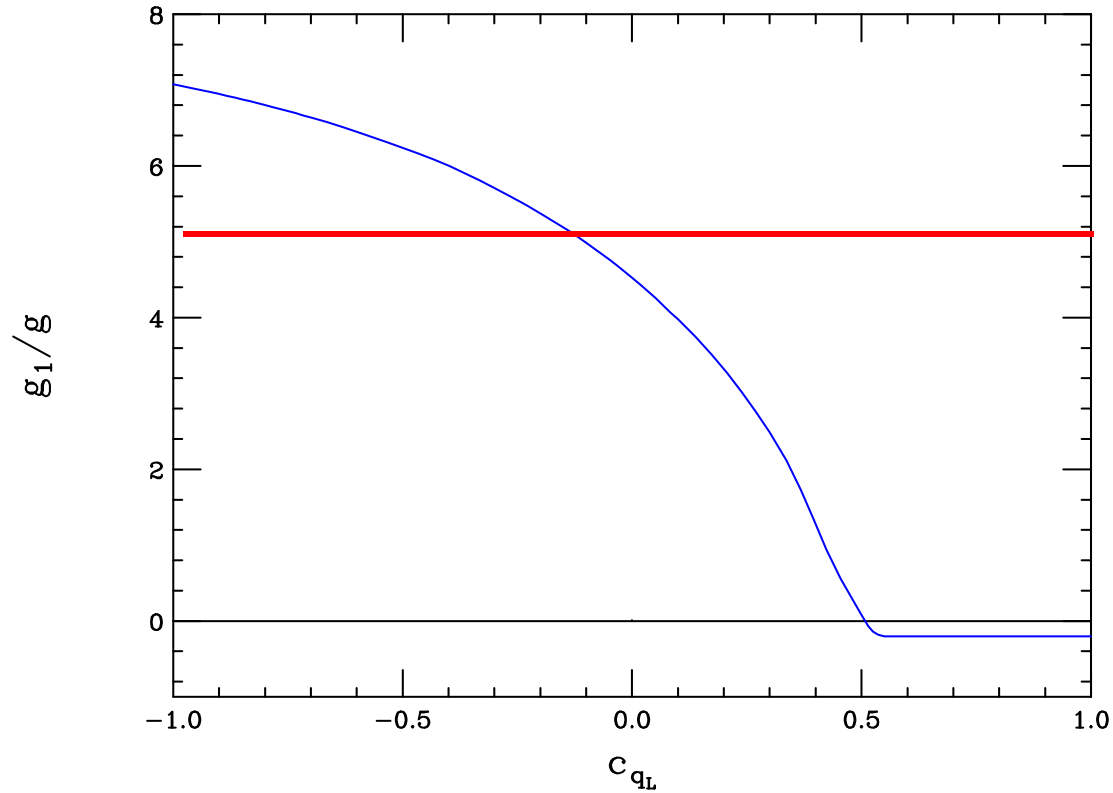
$$m_H^2 = M_{KK}^2 \left( 1 - \frac{g_U^2 N_c}{8\pi^2} \right) + \dots$$

⇒ Criticality condition is

$$g_U^2 > \frac{8\pi^2}{N_c}$$

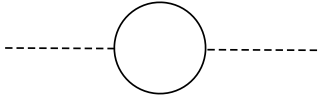
Tells us how localized the fourth-generation should be to get EWSB.

# Super-critical Localization

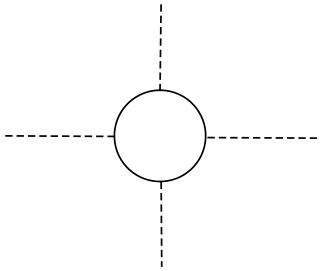


$\Rightarrow$  Need  $c_L^4 < -0.12$  and  $c_R^4 > 0.12$ .

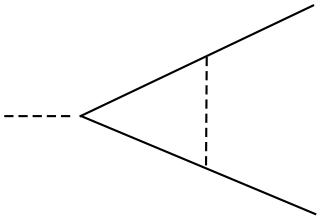
# Effective Higgs Theory



$$Z_H = \frac{g_U^2 N_c}{16\pi^2} \ln \left( \frac{M_{KK}^2}{\mu^2} \right)$$



$$\lambda = \frac{g_U^4 N_c}{8\pi^2} \ln \left( \frac{M_{KK}^2}{\mu^2} \right)$$



$$\Rightarrow \bar{g}_U \equiv \frac{g_U}{Z_H^{1/2}}$$

# EWSB

- Criticality condition equivalent to

$$\langle H \rangle = \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix}$$

- In this approximation:

$$m_U = \bar{g}_U \frac{v}{\sqrt{2}}$$

implies

$$v^2 = m_U^2 \frac{N_c}{8\pi^2} \ln \left( \frac{M_{KK}^2}{m_U^2} \right)$$

# Predictions for $m_U, m_H$

- For  $M_{KK} = 3$  TeV,
  - $\Rightarrow m_U \simeq 750$  GeV
  - and (naively)  $m_h = 2m_U$
- Running the RGEs for  $\bar{g}_U$  and the renormalized self-coupling

$$\bar{\lambda} = \lambda/Z_H^2$$

we get

$$\begin{aligned} m_U &\simeq 600 \text{ GeV} \\ m_h &\simeq 900 \text{ GeV} \end{aligned}$$

- Higgs naturally TeV-brane localized

# Zero-mode Fermion Condensation

Can the top-quark condense in RS models ?

- Cutoff of the NJL is  $M_{KK} \simeq O(1)$  TeV,  $\Rightarrow m_t \simeq (600 - 700)$  GeV
- One way to avoid this: if many KK modes condense (Dobrescu '99, Cheng, Dobrescu, Hill '00, Rius, Sanz '01)
- But here we see that KK excitations are not strongly coupled enough.

# Fermion Masses

- Bulk 4-fermion ops. suppressed by  $M_P$  (Gherghetta, Pomarol '00):

$$\int dy \sqrt{-g} \frac{C^{ijkl}}{M_P^3} \bar{\Psi}_L^i(x, y) \Psi_R^j(x, y) \bar{\Psi}_R^k(x, y) \Psi_L^\ell(x, y) ,$$

- Zero-mode fermion masses from zero-mode four-fermion ops. like

$$C^{ij44} N^{ij44} \frac{k}{M_P^3} \frac{e^{k\pi R(4 - c_L^i + c_R^j + c_R^4 - c_L^4)}}{4 - c_L^i + c_R^j + c_R^4 - c_L^4} \bar{\psi}_L^i \psi_R^j \bar{U}_R U_L$$

and  $\langle \bar{U}_R U_L \rangle$

- Light fermions have small overlap with condensate (TeV)  
**3rd** and **4th** generation fermions: more TeV localized.

# Fermion Masses

- Light fermions ( $\sim$  1st and 2nd generations):  $(c_L^i, -c_R^j) > 1/2$ .

$$m_{ij} \simeq C^{ij44} \left( \frac{m_U}{k e^{-k\pi R}} \right)^2 \sqrt{(2c_L^i - 1)(2c_L^4 - 1)} \sqrt{(1 + 2c_R^j)(1 + 2c_R^4)} \\ \times e^{k\pi R(1 - c_L^i + c_R^j)} m_U$$

- Heavy fermions ( $\sim$  1st and 2nd generations):  $(c_L^i, -c_R^j) < 1/2$   
Plus at least one of  $c_L^i$  or  $-c_R^j > -0.12$  to avoid condensation.

$$m_{ij} \simeq C^{ij44} \left( \frac{m_U}{k e^{-k\pi R}} \right)^2 \sqrt{(2c_L^i - 1)(2c_L^4 - 1)} \sqrt{(1 + 2c_R^j)(1 + 2c_R^4)} \\ \times m_U$$

# Electroweak Precision Constraints

- Original model (without the 4th generation) has a tree-level  $S$  (Agashe, Delgado, May, Sundrum '04)

$$S \simeq 12\pi \frac{v^2}{M_{KK}^2}$$
$$\sim (0.25 - 0.35) \quad \text{for } M_{KK} \sim (2.5 - 3) \text{ TeV}$$

- New contributions:
  - 4th generation fermions to  $S$  and  $T$ .
  - Heavy Higgs.

# Higgs Contribution

The heavy Higgs gives (see Graham's talk and 0706.3718):

$$\begin{aligned}\Delta S_h &\sim +0.1 \\ \Delta T_h &\sim -0.2\end{aligned}$$

But

- 4th gen. fermions can give large positive contribution to  $T$ .
- $\Delta S_h$  and  $\Delta T_h$  can be partially cancelled by mass and kinetic mixing effects (in progress).

# Contributions from 4th Gen. Fermions

- The usual contribution to  $S$  from one gen. of chiral fermions

$$\Delta S_f \sim 2/(3\pi) \sim 0.2$$

- $\Delta T_f > 0$  can be easily obtained.
- KK contributions are smaller.

# Phenomenology

- Usual QCD production of Heavy Quarks:  
 $\sigma_{Q\bar{Q}} \sim (1 - 10^{-1}) \text{ pb}$  for  $M_Q \sim (600 - 800) \text{ GeV}$ .
  - Since  $m_U > m_D$ ,  $\Rightarrow U \rightarrow DW$ .
  - $D$  may have large CKM mixing with  $t$   
 $\Rightarrow D \rightarrow tW$
  - In this case, reach  $m_Q \sim 900 \text{ GeV}$ .
- Leptons: Assuming  $N_R$  zero mode giving Dirac  $m_N$ ,  
There can be non-prompt decays such as  
 $N_R \rightarrow 3 \text{ body}$  (if  $m_{E_R} > m_{N_R}$ )  $\Rightarrow$  large missing  $E_T$ .

# Phenomenology

- 4th generation strongly coupled to KK gauge bosons:  
Decays of KK gauge bosons possibly dominated by 4th generation. E.g.

$$\frac{Br(G^{(1)} \rightarrow \bar{U}U)}{Br(G^{(1)} \rightarrow \bar{t}t)} \sim (5 - 10)$$

- Need to disentangle from potentially light KK fermions.

# Conclusions

- RS bulk model allows working 4th generation condensation model
- The electroweak symmetry is fully broken (unlike in top-color).
- Alternative to  $A_5$  for Higgs localization on TeV brane.
- Fermion masses from 4f ops. in bulk  $\leftrightarrow$  Yukawa couplings ok.
- Heavy 4 gen. masses:  $m_4 \sim (600 - 800)$  GeV.
- Heavy “Higgs”:  $m_h \sim 1$  TeV
- Electroweak precision constraints need work:
  - Delocalized LH light fermions (Giacomo’s talk)
  - Other cancellations.
- Phenomenology potentially very different from an SM 4th generation