Electroweak Symmetry Breaking

in

Warped Extra Dimensions

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Rencontres de Moriond Electroweak, La Thuile, March 1-8 2008

Outline

- EWSB and New Strong Dynamics at the TeV
- One extra-dimension in AdS and the hierarchy problem(s)
- AdS models of EWSB and fermion masses
  - Higgsless
  - Gauge-Higgs unification
  - Fourth-generation condensation
- Conclusions/Outlook

EWSB and Strong Dynamics

The hierarchy problem:

- Why is $M_{\mathrm{EW}} \ll M_{\mathrm{Planck}}$?
- What's the (dynamical) origin of EWSB ?
- Suggests new physics at the TeV scale.

A possible solution: New strong dynamics at the TeV scale.

- EWS broken by critically strong new interactions: e.g. *Techni-color*.
- Analogy with QCD: Scale of EWSB is *exponentially* separated from M_{Planck} by running of coupling.
- No Higgs boson, or composite Higgs (e.g. Little Higgs).

Strong Dynamics at the TeV Scale

Problems:

- Flavor: requires many different flavor scales (ETC), walking, Top-Color for m_t
- Electroweak precision bounds: strong dynamics result in a large S parameter

$$S \simeq O(1)\,\frac{N}{\pi}$$

Strong Dynamics from AdS in 5D

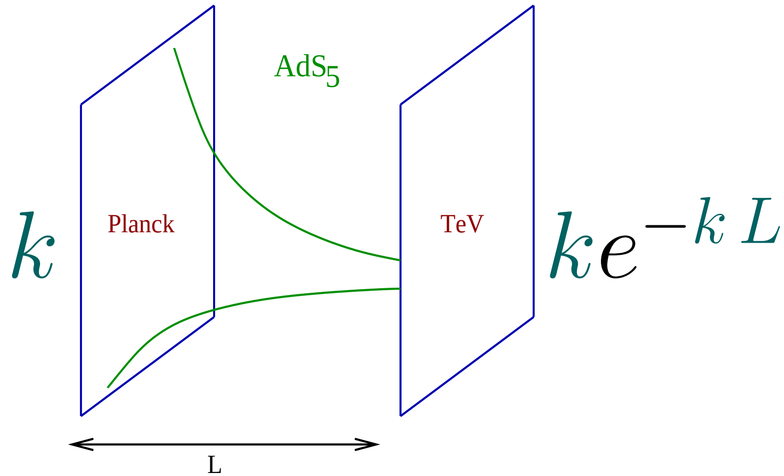
AdS/CFT Correspondence:

- AdS in 5D $\leftrightarrow$ CFT in 4D (Maldacena)
- (Quasi-)Conformal strongly coupled in 4D (large N) dual to weakly coupled in 5D
- Build models of strongly coupled sectors using weakly coupled AdS_5

AdS$_5$ and the Hierarchy Problem

- Non-trivial metric induces small energy scale from Planck scale(L. Randall, R. Sundrum)

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



- Geometry of extra dimension generates hierarchy *exponentially*.

$$\boxed{\Lambda_{\rm TeV} \sim M_{\rm Planck}\, e^{-k\,L}}$$

k the AdS curvature

Natural EWSB

If the Higgs is localized at (or near) the TeV brane ($y = \pi R$)

$$S_H = \int d^4x \int_0^{\pi R} dy \sqrt{-g}\, \delta(y - \pi R) \left[g_{\mu\nu} \partial^\mu H^\dagger \partial^\nu H - \lambda \left(|H|^2 - v_0^2 \right)^2 \right]$$

Even if $v_0 \simeq M_{\text{Planck}}$, the v.e.v. (and mass) of the physical Higgs is

$$v = e^{-k\pi R} v_0$$

To solve the hierarchy problem need Higgs localization.

Bulk WED Model Building

- In original proposal, *only gravity* propagates in 5D bulk.
- Allowing gauge fields and matter to propagate in the bulk
  $\Rightarrow$ models of EWSB, flavor, GUTs, etc.
- Bulk Randall-Sundrum models:
  - Choose the gauge symmetry in the bulk: enlarge the electroweak SM gauge group to avoid large T (Agashe, Delgado, May, Sundrum):
    $$SU(2)_L \times SU(2)_R \times U(1)_X$$
    Plus an extension of the custodial symmetry ($L \leftrightarrow R$) to protect $Z \to b\bar{b}$ (Agashe, Contino, Da Rold, Pomarol)
  - Write theory in the bulk and expand in Kaluza-Klein modes
    KK gauge bosons start at $O(1)$ TeV

Flavor in Warped Extra Dimensions

Fermion mass hierarchy from localization:

- Fermion *bulk mass* $\Rightarrow$ zero-mode localization:

$$M_f = c\,k, \qquad\qquad c \sim O(1)$$

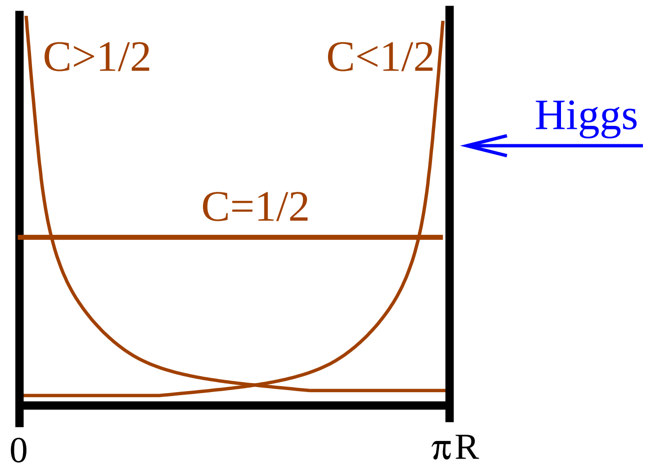
- The zero-mode fermion wave-function is

$$F^L_{\rm ZM}(y) = \frac{1}{\sqrt{2\pi R}}\, f^L_0(0) e^{(\frac{1}{2}-c_L)\,ky}$$

- If $c_L > 1/2 \Rightarrow$ fermion localized near $y = 0$, Planck brane.
  If $c_L < 1/2 \Rightarrow$ fermion localized near $y = \pi R$, TeV brane.

Flavor Models in WED

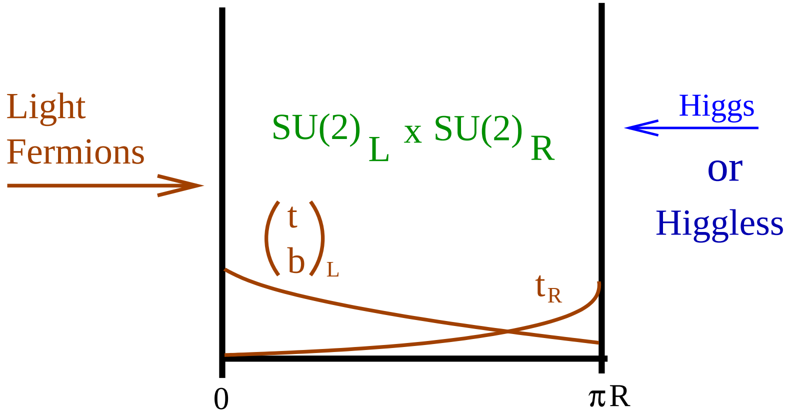
- $O(1)$ flavor breaking in bulk can generate fermion mass hierarchy:



Fermions localized toward the TeV brane can have larger Yukawas, Those localized toward the Planck brane have highly suppressed ones.

Electroweak Symmetry Breaking and WED

Several possibilities for model building:



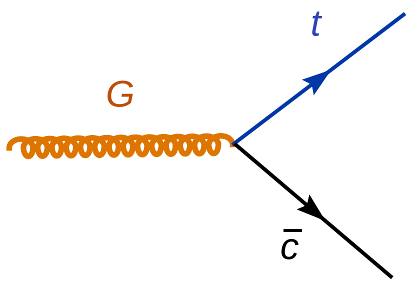
- Higgs or Higgsless (BC breaking)
- We have a theory of flavor: $O(1)$ parameters (the $c_i' s$) are responsible for generating all fermion masses.
- Fermion Localization is responsible for the large separation of scales between light fermion masses (exponentially less overlapped with TeV scale), and heavier fermions (i.e. top) localized around TeV scale.

Warped Extra Dimensions - Signals

- Narrow states $\rightarrow$ KK modes:
  Spin 2 (graviton), plus all other SM fields at the LHC
  - New Gauge bosons
  - New Fermions

  $\Rightarrow$ Evidence for the RS bulk set up

- But, what are the signals for the **Flavor Theory** ?
  Localization of 3rd generation near TeV brane $\Rightarrow$ flavor violation, e.g.:



$\Rightarrow$ Anomalous single top at high invariance mass (Aquino, G.B., Eboli)
Also in low energy flavor physics.

Higgsless EWSB in AdS_5

Break EWS by Boundary Conditions (Csaki,Grojean,Pilo,Terning)

- BCs on branes $\Rightarrow SU(2)_L \times SU(2)_R \times U(1)_X \rightarrow U(1)_{\mathrm{EM}}$
  - TeV brane: $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$:
    Preserves custodial symmetry.
  - Planck brane: $SU(2)_R \times U(1)_X \rightarrow U(1)_Y$:
    Allows fermion mass terms on TeV brane.
- Z and W are KK modes. $\rho \sim 1$
- Fermion masses:
  - vector-like mass terms on TeV brane.
  - Isospin symmetry broken on Planck brane.
  - E.g.: top quark is TeV-brane localized $\Rightarrow$ larger mass (larger overlap with chiral-symmetry breaking).

Higgsless EWSB in AdS$_5$

EWPC:

- S parameter is large
- S can be made small by de-localizing fermions
- $Z \to b_L \bar{b}_L$ requires protective symmetry.
  Still, deviates some from data

Higgsless EWSB in AdS$_5$

Signals:

- Unitarization of $WW, WZ, \ldots$ scattering done by KK resonances
- Couplings of $V^{(n)}$'s to $W^\pm$ and Z must satisfy sum rules (to cancel E^2, E^4 behavior). E.g. for $WW \to WW$:

$$g_{WWWW} = g_{WWZ}^2 + g_{WW\gamma}^2 + \sum_n (g_{WWV^{(n)}})^2$$

$$= \frac{3}{4M_W^2}\left[{g_{WWZ}}^2 M_Z^2 + \sum_n (g_{WWV^{(n)}})^2 M_n^2 \right]$$

- KK gauge bosons $\Rightarrow$ narrow resonances, lighter ($M_{V^{(1)}} \lesssim 1$ TeV) than in Techni-color or other strongly coupled models.

Gauge-Higgs Unification in AdS_5

If there is a Higgs: what is its dynamical origin ?
Or why is it localized towards the TeV brane ?

- Gauge field in 5D has scalar A_5
- To extract H from A_5 need to enlarge SM gauge symmetry.

  E.g. $SU(3) \to SU(2) \times U(1)$ by boundary conditions:

$$A_\mu : \left(\begin{array}{cc|c} (+,+) & (+,+) & (-,-) \\ (+,+) & (+,+) & (-,-) \\ \hline (-,-) & (-,-) & (+,+) \end{array}\right)$$

$$A_5 : \left(\begin{array}{cc|c} (-,-) & (-,-) & (+,+) \\ (-,-) & (-,-) & (+,+) \\ \hline (+,+) & (+,+) & (-,-) \end{array}\right)$$

$\Rightarrow$ Higgs doublet from $A_5 = A_5^a t^a$

Gauge-Higgs Unification in AdS$_5$

To build realistic models of EWSB from AdS$_5$:

- Isospin symmetry: need $SO(4) \times U(1)_X$ in bulk
  $\Rightarrow$ $SO(5) \times U(1)_X \to SO(4) \times U(1)_X$ by BCs
  (Agashe, Contino, Pomarol)
- Higgs is $\mathbf{4}$ of $SO(4)$: 4 d.o.f. $\leftrightarrow$ complex $SU(2)_L$ doublet
- Gauge bosons and fermions in complete $SO(5)$ multiplets
- Implementing additional symmetry to protect $Z \to b\bar{b}$
  $\Rightarrow$ spectrum of KK fermions, lighter than KK gauge bosons.
  (Contino, Da Rold, Pomarol)

Gauge-Higgs Unification in AdS$_5$

- E.g.: Fermions can be

$$\mathbf{5_{2/3}} = (\mathbf{2},\mathbf{2})_{2/3} \oplus (\mathbf{1},\mathbf{1})_{2/3}$$

or

$$\mathbf{10_{2/3}} = (\mathbf{2},\mathbf{2})_{2/3} \oplus (\mathbf{1},\mathbf{3})_{2/3} \oplus (\mathbf{3},\mathbf{1})_{2/3}$$

  to satisfy custodial + $L \leftrightarrow R$ symmetry.

- BCs $\Rightarrow$ masses of KK fermions tend to be light (because top is heavy)

Gauge-Higgs Unification in AdS$_5$

Signals:

- Rich gauge boson spectrum, at few TeV
- Light KK fermion spectrum: could be as light as 500 GeV
- Very distinctive signals:
  - E.g. b-type KK fermion $\rightarrow tW$
    $\Rightarrow$ 4W's + 2b signals (Dennis, Servant, Unel, Tseng)
  - Enhanced t^1 pair production through KK gluon
    (Carena, Medina, Panes, Shah, Wagner)

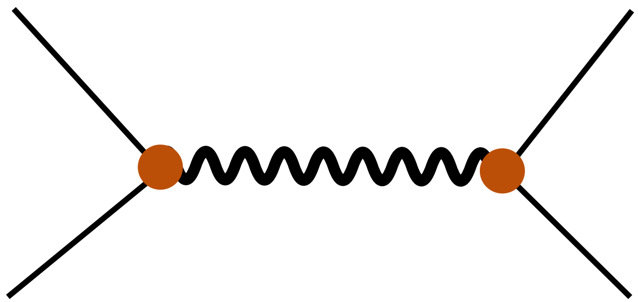
EWSB from Fourth-Generation in AdS$_5$

Top-condensation models (Nambu; Bardeen, Hill, Lindner):
EWS broken by $\langle \bar{t}t \rangle \neq 0$

- 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 ?

EWSB from Fourth-Generation in AdS$_5$

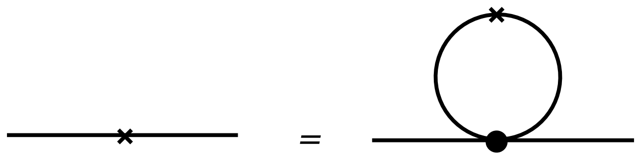
- Need 4th-generation strongly coupled to new interaction
- If 4th-generation propagates in AdS$_5$ bulk and is highly localized on the TeV brane (G.B., Da Rold)
  4th-generation quarks are strongly coupled to KK gluon:



EWSB from Fourth-Generation in AdS$_5$

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

$\Rightarrow$ Solution to the gap equation:



This implies

- Electroweak Symmetry Breaking
- Dynamical m_U

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

Predictions for m_U, m_H

- For $M_{KK} = 3$ TeV, we get

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

- Higgs naturally TeV-brane localized
- Fermion masses (other than m_U):
  From bulk Higher Dimensional Ops.
- Non-condensing 4th-generation fermions could be as light as 300 GeV!

Phenomenology

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

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

- Need to disentangle from potentially light KK fermions.
- KK gluon tends to be very broad: from 30% width on!! Need to extract this signal at high invariant mass, or look for the electroweak KK gauge bosons

Conclusions

- We are building strongly coupled theories of the TeV scale using AdS_5
- RS solves the hierarchy problem.
  RS bulk models also solve the fermion mass hierarchy problem
- Choosing a dynamical model for the Higgs:
  - Higgsless,
  - Gauge-Higgs unification,
  - 4th-generation condensation,

  affects the phenomenology at the LHC.
- If evidence of a strongly coupled TeV sector should appear at the LHC, model building in AdS_5 should be a helpful tool