Physics with Extra Dimensions
Lecture II
Warped Extra Dimensions and Strong Dynamics

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Strong Dynamics and AdS/CFT

AdS/CFT Correspondence (Maldacena):

- Originally:

  AdS$_5$ $\times$ S^5 String Theory $\leftrightarrow$ $\mathcal{N} = 4$ 4D SU(N) Theory (CFT)

- In general: Assume 5D theory in AdS$_5$ $\leftrightarrow$ 4D SCFT (Arkani-Hamed, Porrati, Randall)

- Need

$$g^2 N \gg 1$$

  to ignore string corrections.

- $\Rightarrow$ Holographic dual is 4D strongly coupled theory

Strong Dynamics from a Slice of AdS_5

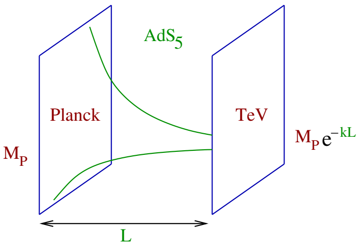
Ingredients to build Strongly Coupled Theories in AdS_5

- UV cutoff in the 4D Theory $\leftrightarrow$ UV ("Planck") boundary
- Break 4D Conformal Invariance in the IR $\leftrightarrow$ IR boundary
- 4D Strongly Coupled Gauge Theory described by 5D Weakly Coupled Theory

Solving the Hierarchy Problem in AdS$_5$

Metric in extra dimension ⇒ small energy scale from M_P (Randall-Sundrum)

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



Corrections to m_h OK
If Higgs close to TeV brane

Need Higgs IR localization

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 $v_0 \simeq M_{\rm Planck}$, 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 AdS$_5$ Models

Allowing Gauge and Matter fields in 5D bulk
(Gherghetta-Pomarol, Grossman-Neubert)

- Avoid effects of Higher Dimensional Operators only suppressed by IR/TeV scale
- Natural Models of Flavor:
  Zero-mode fermion localization $\leftrightarrow$ fermion mass

$$M_f^{(5D)} = ck, \qquad c \simeq O(1)$$

Flavor in Warped Extra Dimensions

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

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

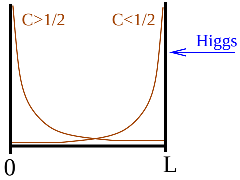
- The zero-mode fermion wave-function is

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

- 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.

Fermion Masses in Bulk RS Models

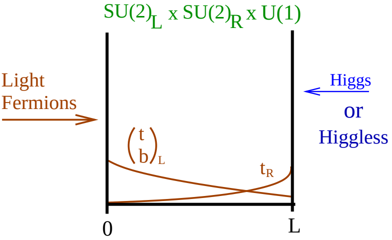
- $O(1)$ flavor breaking in bulk can generate fermion mass hierarchy:



TeV localization → larger Yukawas,
Planck localization → suppressed Yukawas.

- Heavier fermions couple stronger to gauge KK modes:
  - $G^{(1)} \to t\bar{t}$ dominates
  - Tree-level flavor violation

The Bulk RS Picture



Models of
EWSB *and* Flavor

- EWPC: T OK, but $S \simeq N/\pi$ at tree-level

$$M_{KK} \gtrsim (2-3)\ \mathrm{TeV}$$

- $Z \to \bar{b}b$ require discrete symmetry ($L \leftrightarrow R$) (Agashe, Contino, Da Rold, Pomarol)
- Potentially important bounds and/or effects from flavor violation

Dynamical Origin of the Higgs Sector

What localizes the Higgs to/near the IR/TeV brane ?

- Gauge-Higgs Unification
- Zero-mode Fermion Condensation
- Higgsless

Gauge-Higgs Unification in AdS$_5$

- 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 **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 $\to tW$
    $\Rightarrow$ 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

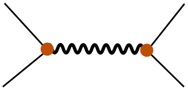
Top-condensation models (Nambu; Bardeen, Hill, Lindner):
EWS broken by $\langle \bar{t} t \rangle \neq 0$

- 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 ?

Fermion Condensation

Fourth-Generation Condensation in AdS$_5$ (G.B. Da Rold)

- Fourth Generation in the AdS$_5$ bulk
- Choose zero-mode fermions IR localized $\Rightarrow$ strongly coupled to KK gauge bosons



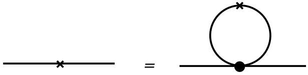
E.g. KK gluon exchange $\longrightarrow \langle \bar{U} U \rangle \neq 0$

- EWSB
- $m_U^{(0)} \sim (600 - 700)$ GeV (ala Bardeen-Hill-Lindner)
- Heavy Higgs: $m_h \simeq (600 - 900)$ GeV

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.

Fermion Condensation (cont.)

- All other fermion masses: Bulk higher dimensional operators

$$\frac{C^{ijk\ell}}{M_P^3}\,\bar{\Psi}_L^i(x,y)\Psi_R^j(x,y)\bar{\Psi}_R^k(x,y)\Psi_L^\ell(x,y)$$

- Phenomenology dominated by 4th generation
  - $V^{(1)} \to \bar{U}U$ (broader KK gauge bosons)
  - Flavor physics: E.g. new sources of CPV in mixing, ...
  - Additional contributions to S, T

Higgsless Models

Higgsless RS Bulk Models (Csaki, Grojean, Murayama, Pilo, Terning)

- Boundary Condition breaking
$$SU(2)_L \times SU(2)_R \times U(1)_X \rightarrow U(1)_{EM}$$
- IR localized mass terms $\Rightarrow$ fermion masses
- Kaluza-Klein modes of gauge fields unitarize amplitudes.
$\Rightarrow$ KK modes "light": $M_{KK} \lesssim 1$ TeV
- Phenomenology in the Gauge boson sector:
    - $V_L V_L$ scattering
    - Sum Rules
- Corresponds to Walking Technicolor Models

Higgsless EWSB in AdS$_5$

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

- BCs on branes $\Rightarrow SU(2)_L \times SU(2)_R \times U(1)_X \to U(1)_{\rm EM}$
  - TeV brane: $SU(2)_L \times SU(2)_R \to SU(2)_V$: Preserves custodial symmetry.
  - Planck brane: $SU(2)_R \times U(1)_X \to U(1)_Y$: 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.

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- If LHC reveals Strongly Coupled TeV scale
  $\Rightarrow$ Model Building in AdS_5 should be a useful tool