Coarse Deconstruction of $\text{AdS}_5$

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Outline

• Introduction/Motivation

• Deconstruction of $\text{AdS}_5$: quiver theories of EWSB and fermion masses

• Phenomenology:
  - Flavor physics and EWPC
  - Bounds on Resonances
  - The (pNGB) Higgs

• Conclusions/Outlook
The Standard Model

The Standard Model is now complete \( m_h \approx 125 \text{ GeV} \)
Separation of Scales

Higgs is light compared to UV cutoff

If Higgs is a composite from an IR strong sector

Why is \( m_h \ll O(1) \text{ TeV} \)?

Higgs should be a pNGB: scale of new physics is separated by \( O(4\pi) \) from \( m_h \)

How do we model strong dynamics separating \( m_h \) from the UV and even from the TeV scale
Separation of Scales in AdS$_5$

• One compact extra dimension. Non-trivial metric induces a small energy scale from a high one. (Randall, Sundrum ’99)

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

• Geometry of extra dimension generates exponential hierarchy

• Higgs must be IR localized to solve HP. E.g. Gauge-Higgs unification \iff Composite Higgs models
Fermion Fields in AdS Bulk

• Massive fermion in curved 5D space

\[ S_f = \int d^4x \; dy \; \sqrt{g} \left\{ \frac{i}{2} \bar{\Psi} \hat{\gamma}^M \left[ \mathcal{D}_M - \mathcal{D}_M^\dagger \right] \Psi - M_f \bar{\Psi} \Psi \right\} \]

• To be natural \( M_f \simeq O(1)k \)

\[ M_f \equiv c_f k \quad \text{with} \quad c_f \simeq O(1) \]

• The parameter \( c_f \) determines the localization of the ZM fermion
Fermion Fields in AdS Bulk

$O(1)$ flavor breaking in bulk can give fermion mass hierarchy

- Fermions localized near TeV brane have $O(1)$ Yukawas
- Those localized near the Planck brane have highly suppressed Yukawas
- Flavor violation at tree level $\Rightarrow$ stringent bounds
Hierarchies of Scales and Fermion Masses

$\text{AdS}_5$ is a representation of a strongly coupled 4D theory

Can we build a 4D representation with the good features of $\text{AdS}_5$?

• Large scale separation
• Fermion hierarchies with small flavor violation
• A light Higgs + heavy new physics
Deconstructing AdS$_5$

Gauge theory in $AdS_5$ (Randall, Shadmi, Weiner and Falkowski, Kim ’02)

\[ S_5 = \int d^4x \int_0^L dy \sqrt{g} \left[ -\frac{1}{2 g_5^2} \text{Tr}[F_{MN}^2] + \cdots \right] \]

Discretize the extra dimension

with $L = aN$
Deconstructing AdS$_5$

$$S_4 = \int d^4 x \left\{ -\sum_{j=0}^{N} \frac{1}{2g_j^2} \text{Tr} \left[ F_{j\mu\nu}^j F^{j\mu\nu} \right] + \sum_{j=1}^{N} \frac{1}{2} \text{Tr} \left[ v_j^2 (A^j_\mu - A^{j-1}_\mu)^2 \right] \right\}$$

Equivalent to (N+1) Gauge theories $F_{\mu\nu}^j$

N bi-fundamental scalar fields $\Phi^j$

Quiver 4D Theory
Gauge Couplings

$S_4$ reproduces continuum limit if

$$g_0(v) = g_1(v_1) = \cdots = g_j(v_j) = g_{j+1}(v_{j+1}) = \cdots \equiv g$$

matches the continuum
mimics (quasi) conformal behavior
Quiver Theories

Link field $\Phi_j$ transforms as $(F, F)$ under $G_{j-1} \times G_j$

Breaks $G_{j-1} \times G_j \rightarrow G_{j-1}^D$

$$\Phi_j = \frac{v_j}{\sqrt{2}} e^{\sqrt{2} \frac{\pi_j}{v_j}}$$

To match discretized 5D theory we need

$$\frac{1}{g^2} \leftrightarrow \frac{a}{g_5^2}$$

$$v_j \leftrightarrow \frac{e^{-ka_j}}{a}$$
Quiver Theories and Large Hierarchies

• 4D theories with N gauge “sites”

\[ S_4 = \int d^4x \left\{ -\sum_{j=0}^{N} \frac{1}{2 g^2} \text{Tr} \left[ F_{\mu\nu}^j F^{j\mu\nu} \right] + \sum_{j=1}^{N} \frac{1}{2} \text{Tr} \left[ v_j^2 \left( A^j_\mu - A^{j-1}_\mu \right)^2 \right] \right\} \]

• N Link fields break (N+1) gauge groups to \( G_0^{D}, \ldots, N \)

\[ \Rightarrow \begin{cases} \text{1 massless zero-mode} \\ \text{N massive gauge bosons} \end{cases} \]

• Mass Eigenstates:

\[ A^{(n)}_\mu = \sum_{j=0}^{N} f_{j,n}^* A^j_\mu \]
Quiver Theories and Large Hierarchies

For instance, if we want $M_P$ at UV and $M_W$ at IR

$$k \ a \ N \sim 35$$

**Continuum Limit**

$$k \ll \frac{1}{a}$$

$\implies$ For $N \gg 35$ we recover AdS$_5$

Build theories in the coarse limit, small $N$
Quiver Theories and Large Hierarchies

• Large hierarchy between UV and IR (0 and N sites):

\[ v_j = e^{-kaj} v \quad \Rightarrow \quad \text{large } k a N \]

• Define

\[ q \equiv e^{-k a} \]

Continuum limit \( a \to 0, \ N \to \infty \)

\[ \Rightarrow \quad q \to 1 \]

• Ordered vacua

\[ v_j = q^j v \]
Fermion Masses in FHQT

(Bai, GB, Hill '09, De Curtis, Redi, Tesi '12)

E.g.: left-handed zero mode

\[
S_f = \int d^4x \sum_{j=0}^{N} \left\{ \bar{\psi}_L^j i \slashed{D}_j \psi_L^j + \bar{\psi}_R^j i \slashed{D}_j \psi_R^j - (\mu_j \bar{\psi}_L^j \psi_R^j + \lambda_j \bar{\psi}_R^{j-1} \Phi_j \psi_L^j + \text{h.c.}) \right\}
\]
Fermion Masses in FHQT

• Diagonalization of fermion masses: 1 zero mode + excited states

\[ \chi^{(n)}_{L,R} = \sum_{j=0}^{N} h_{L,R}^{*j,n} \psi_{L,R}^{j} \]

• Equations of Motion

\[ (\mu_{j}^{2} + \frac{\lambda_{j}^{2} v_{j}^{2}}{2} - m_{n}^{2}) h_{L}^{j,n} - \frac{\lambda_{j} v_{j}}{\sqrt{2}} \mu_{j-1} h_{L}^{j-1,n} - \frac{\lambda_{j+1} v_{j+1}}{\sqrt{2}} \mu_{j} h_{L}^{j+1,n} = 0 \]
\[ (\mu_{j}^{2} + \frac{\lambda_{j+1}^{2} v_{j+1}^{2}}{2} - m_{n}^{2}) h_{R}^{j,n} - \frac{\lambda_{j} v_{j}}{\sqrt{2}} \mu_{j} h_{R}^{j-1,n} - \frac{\lambda_{j+1} v_{j+1}}{\sqrt{2}} \mu_{j+1} h_{R}^{j+1,n} = 0 \]

\[ \Rightarrow \text{ difference eqns. for } h_{j,n} \]
Fermion Zero-Modes

• For $m_n = 0$

\[
\mu_j h^{j,0}_L + \frac{\lambda_{j+1}}{\sqrt{2}} v_{j+1} h^{j+1,0}_L = 0
\]

\[
\mu_j h^{j,0}_R + \frac{\lambda_j}{\sqrt{2}} v_j h^{j-1,0}_R = 0
\]

Freedom in the choice of $\mu_j$‘s and $\lambda_j$‘s

$\Rightarrow$ localize zero-mode fermions in quiver

\[
\sqrt{2} \frac{\mu_j}{v \lambda_{j+1}} \equiv -q^{j+c_L+1/2} \quad \Rightarrow \quad \frac{h^{j+1,0}_L}{h^{j,0}_L} = q^{c_L-1/2}
\]

\[
\sqrt{2} \frac{\mu_j}{v \lambda_j} = -q^{j+c_R+1/2} \quad \Rightarrow \quad \frac{h^{j,0}_R}{h^{j-1,0}_R} = q^{-(c_R+1/2)}
\]
Fermion Zero-Mode

Localization parameters \( c_L, c_R \)

how much of each \( \psi^j_{L,R} \) is the zero mode

It determines \[
\begin{align*}
\text{Couplings to gauge excited states} & \quad A^{(n)}_{\mu} \\
\text{Couplings to Higgs}
\end{align*}
\]
Higgs Sector in Quiver Theories

Need Higgs mostly close to Nth site
Analogy with IR-localized H in $AdS_5$

Dynamical origin of N-site localization:
H is remnant of breaking with “defective” $G_0$ and $G_N$

E.g.: $(SU(2) \times U(1))_0 \times \cdots SU(3)_j \cdots (SU(2) \times U(1))_N$

$\Rightarrow$ H is a pNGB similar to composite H models
Phenomenology of Quiver Theories

• Flavor Violation: can we build models with good FV properties?

• EWPT: Compatibility with $S$ and $T$

• Higgs sector

• Current direct bounds from LHC

• Predictions for the LHC
Flavor Violation

• Tree-level FV from couplings of ZM fermions to excited gauge bosons

• Compute coupling to first excited state of gauge bosons

\[ g^{01}_{L,R} \bar{\chi}^{(0)}_{L,R} \gamma^{\mu} A^{(1)}_{\mu} \chi^{(0)}_{L,R} \]

with

\[ g^{01}_{L,R} = \sum_{j=0}^{N} g_j \left| h^{j,0}_{L,R} \right|^2 f_{j,1} \]
Flavor Violation at Tree Level

Coupling of first
gauge excitation
to zero-mode fermion
Flavor Violation

Tree-level couplings of ZM fermions to 1st excited state

N=4 (5 sites)

Left-handed
Flavor Violation

Tree-level couplings of ZM fermions to 1st excited state

N=4

Right-handed down

$D_R$ sector is nearly universal

$\Rightarrow$ no conflict with $K^0 \bar{K}^0$, $B^0 \bar{B}^0$
Flavor Violation

Tree-level couplings of $ZM$ fermions to 1st excited state

$N=4$

Right-handed up

$\Rightarrow$ largest flavor violation in the up sector
Flavor Violation Bounds

Bounds from $\Delta F = 2$ assuming $SU(3)_c$ propagates in quiver

<table>
<thead>
<tr>
<th>Parameter</th>
<th>95% allowed range (GeV$^{-2}$)</th>
<th>Lower limit on $\Lambda$ (TeV) for arbitrary NP</th>
<th>Bound on Color-octect Mass in FHQT (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Re}C^1_K$</td>
<td>$[-9.6, 9.6] \cdot 10^{-13}$</td>
<td>$1.0 \cdot 10^3$</td>
<td>0.2</td>
</tr>
<tr>
<td>$\text{Re}C^4_K$</td>
<td>$[-3.6, 3.6] \cdot 10^{-15}$</td>
<td>$17 \cdot 10^3$</td>
<td>0.1</td>
</tr>
<tr>
<td>$\text{Re}C^5_K$</td>
<td>$[-1.0, 1.0] \cdot 10^{-14}$</td>
<td>$10 \cdot 10^3$</td>
<td>0.1</td>
</tr>
<tr>
<td>$\text{Im}C^1_K$</td>
<td>$[-2.6, 2.8] \cdot 10^{-15}$</td>
<td>$1.9 \cdot 10^4$</td>
<td>2.6</td>
</tr>
<tr>
<td>$\text{Im}C^4_K$</td>
<td>$[-4.1, 3.6] \cdot 10^{-18}$</td>
<td>$49 \cdot 10^4$</td>
<td>3.0</td>
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<tr>
<td>$\text{Im}C^5_K$</td>
<td>$[-1.2, 1.1] \cdot 10^{-17}$</td>
<td>$29 \cdot 10^4$</td>
<td>1.0</td>
</tr>
<tr>
<td>$</td>
<td>C^1_D</td>
<td>$</td>
<td>$&lt; 7.2 \cdot 10^{-13}$</td>
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<tr>
<td>$</td>
<td>C^4_D</td>
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<tr>
<td>$</td>
<td>C^1_{B_d}</td>
<td>$</td>
<td>$&lt; 2.3 \cdot 10^{-11}$</td>
</tr>
<tr>
<td>$</td>
<td>C^4_{B_d}</td>
<td>$</td>
<td>$&lt; 2.1 \cdot 10^{-13}$</td>
</tr>
<tr>
<td>$</td>
<td>C^5_{B_d}</td>
<td>$</td>
<td>$&lt; 6.0 \cdot 10^{-13}$</td>
</tr>
<tr>
<td>$</td>
<td>C^1_{B_s}</td>
<td>$</td>
<td>$&lt; 1.1 \cdot 10^{-9}$</td>
</tr>
<tr>
<td>$</td>
<td>C^4_{B_s}</td>
<td>$</td>
<td>$&lt; 1.6 \cdot 10^{-11}$</td>
</tr>
<tr>
<td>$</td>
<td>C^5_{B_s}</td>
<td>$</td>
<td>$&lt; 4.5 \cdot 10^{-11}$</td>
</tr>
</tbody>
</table>
Flavor Violation Bounds

All flavor bounds satisfied for $M_1 > 3$ TeV

Bounds weaker if $SU(3)_c$ does not propagate in quiver
Electroweak Precision Bounds

In a generic model w.o. custodial symmetry

E.g.: \([SU(2) \times U(1)]^{N+1}\) i.e. the SM in the quiver

Leading contributions

\(W^a\) exchange

\(W^{a(i)}\)

\(W^a, B\)

universal vertex shift
Electroweak Precision Bounds

Tree-level contributions to $S$ and $T$

E.g.: N=4

\[
S \simeq 0.16 \left( \frac{3 \text{ TeV}}{M_1} \right)^2 \\
T \simeq 0.15 \left( \frac{3 \text{ TeV}}{M_1} \right)^2
\]

\{ OK with fit \}

• Custodial protection not forced by tree-level contributions to $T$

• Might be needed at one loop (fermions)
Higgs as a pseudo NGB
(in progress)

Dynamical origin of N-site localization:
H is remnant of breaking with “defective” $G_0$ and $G_N$

E.g.: $(SU(2) \times U(1))_0 \times \cdots SU(3)_j \cdots (SU(2) \times U(1))_N$

$H$: from excess d.o.f. in link fields $\implies H$ is a pNGB
Higgs as a pseudo NGB

N-localization:

\[ H^a = C \sum_{j=1}^{N} q^{N-j} \pi_j^a \]

Extract Higgs \( h \) from \( H^a \)

Small \( N \) \( \Rightarrow \) \( h \) very localized close to site \( N \)

Compute \( V_{\text{eff}} \) \( \rightarrow \) tuning issues
Phenomenology at the LHC
(with N. Fonseca and G. Lichtenstein)

Gauge excitations as s-channel resonances

\[ \begin{align*}
    \text{with } & N. \text{ Fonseca and } G. \text{ Lichtenstein} \\
    \text{Gauge excitations as } & \text{s-channel resonances} \\
    \begin{array}{c}
        \text{\textbf{q}} \\
        \text{\textbf{\overline{q}}}
    \end{array}
    \rightarrow
    \begin{array}{c}
        \text{\textbf{G}} \\
        \text{\textbf{\overline{G}}}
    \end{array}
    \rightarrow
    \begin{array}{c}
        \text{\textbf{j, b, t}} \\
        \text{\textbf{j, \overline{b}, \overline{t}}}
    \end{array}
    \\
    \begin{array}{c}
        \text{\textbf{q}} \\
        \text{\textbf{\overline{q}}}
    \end{array}
    \rightarrow
    \begin{array}{c}
        \text{\textbf{Z', \gamma'}} \\
        \text{\textbf{\overline{Z'}, \overline{\gamma'}}}
    \end{array}
    \rightarrow
    \begin{array}{c}
        \text{\textbf{j, b, t}} \\
        \text{\textbf{j, \overline{b}, \overline{t}}}
    \end{array}
\end{align*} \]
Couplings to Zero-mode Fermions

\[ \frac{g_{01}}{g} \]

\[ \begin{align*} 
N &= 15 \\
N &= 9 \\
N &= 4 
\end{align*} \]
Couplings to Zero-mode Fermions

\[ \frac{g_{01}^{aR}}{g} \]

\[ N = 15 \]
\[ N = 9 \]
\[ N = 4 \]
Resonances at the LHC

Production of color-octet

\[ \sqrt{s} = 8 \text{ TeV} \]

\[ G \rightarrow jj \]

\[ \sigma \times \text{BR} \] [pb] vs. \[ M_G \] [GeV]
Resonances at the LHC

Production of color-octet $\sqrt{s} = 8$ TeV

$G \rightarrow t\bar{t}$

Graph showing $\sigma \times \text{BR}$ (pb) versus $M_G$(GeV) for $G \rightarrow t\bar{t}$.
Resonances at the LHC

Production of $Z' + \gamma'$ \[\sqrt{s} = 8 \text{ TeV}\]

\[(Z' + \gamma') \rightarrow jj\]
Resonances at the LHC

Production of $Z' + \gamma'$

$\sqrt{s} = 8$ TeV

$Z' \rightarrow t\bar{t}$
Bounds on FHQT Resonances at the LHC

Cross Section $\times A$ (pb)

$\sqrt{s} = 8$ TeV, $L = 19.6$ fb$^{-1}$

Expected 95% CL Upper Limit

Observed 95% CL Upper Limit

Expected Limit ± 1$\sigma$

Expected Limit ± 2$\sigma$

Obs. 95% CL upper limit

Exp. 95% CL upper limit

uncertainty

Exp. 1 $\sigma$ uncertainty

Exp. 2 $\sigma$ uncertainty

Leptophobic $Z'$ (LO x 1.3)

ATLAS Preliminary

<table>
<thead>
<tr>
<th>$N$</th>
<th>Dijet</th>
<th>$t\bar{t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>3.0</td>
<td>2.7</td>
</tr>
<tr>
<td>9</td>
<td>1.6</td>
<td>2.6</td>
</tr>
<tr>
<td>15</td>
<td>–</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Color-octet

$(Z' + \gamma')$

<table>
<thead>
<tr>
<th>$N$</th>
<th>Dijet</th>
<th>$t\bar{t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1.7</td>
<td>2.1</td>
</tr>
<tr>
<td>9</td>
<td>–</td>
<td>2.0</td>
</tr>
<tr>
<td>15</td>
<td>–</td>
<td>1.8</td>
</tr>
</tbody>
</table>
Conclusions and Outlook

• FHQT with small N, complementary to $\text{AdS}_5$ models

• Distinct phenomenology
  
  Improved flavor violation behavior
  
  Passes EWPC even w.o. custodial protection (tree-level)

  At the LHC: different cross sections, BR, etc.

• To explore:
  
  Higgs sector, H as a pNGB (similar to CHM)

  Details of Model building (e.g. lepton sector, …)