Full-Hierarchy Quiver Theories

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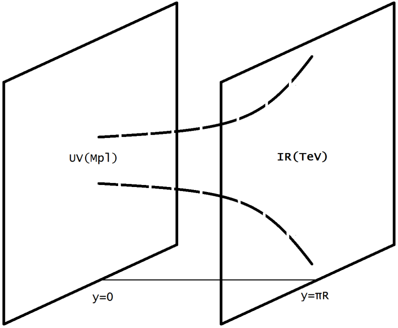
Motivation

- If the Higgs is a composite from strong sector, we need to explain why $m_h \ll \mathcal{O}(1)$ TeV $\rightarrow$ pNGB Higgs.
- How do we model strong dynamics separating m_h from the UV and even from the TeV scale?
- AdS_5 is a representation of a strongly coupled 4D theory
- Can we build a 4D representation with the good features of AdS_5 ?
  - Large scale separation
  - Fermion hierarchies with small flavor violation
  - A light Higgs + heavy new physics

Hierarchy in AdS_5

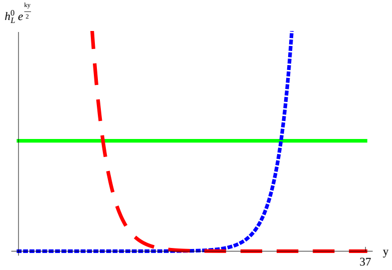
(Randall, Sundrum, '99)



- AdS_5 metric:
  $g_{MN}dx^M dx^N = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$,
  $0 < y < \pi R$
- Scale symmetry:
  $y \to y + \lambda,\ x \to e^{k\lambda}x$
  $\Rightarrow$ *warping*: $p_\mu \to e^{-k\lambda}p_\mu$
- UV cutoff:
  $\Lambda_{UV} \sim M_{Pl} \to \Lambda_{IR} = e^{-k\pi R}M_{Pl}$
- With Higgs IR localized,
  $\Lambda_{IR} \sim \mathcal{O}(\mathrm{TeV}) \ \to\ k\pi R \sim 37$.

Fermions in AdS_5

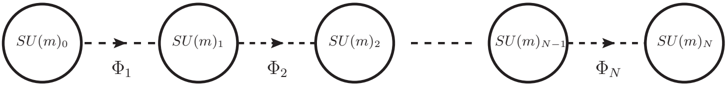
- Fermion bulk mass parameter: $M_\Psi = ck$
- Naturalness $\rightarrow$ $c \sim \mathcal{O}(1)$
- ZM profile: $h^{(0)}_{L(R)}(y) = A(c)e^{(1/2\mp c)ky}$
- Mass hierarchies generated from $\mathcal{O}(1)$ parameters.
- Stringent bounds from flavor violation.



Dimensional Deconstruction

(Arkani-Hamed et al., Hill et al., '01, Randall et al., Falkowski et al., '02)

$$S_A = \int d^4x \left\{ -\frac{1}{2}\sum_{j=0}^{N} \mathrm{Tr}[F_{\mu\nu,j}\, F_j^{\mu\nu}] + \sum_{j=1}^{N} \mathrm{Tr}\left[(\mathcal{D}_\mu \Phi_j)^\dagger (\mathcal{D}^\mu \Phi_j)\right] - V(\Phi) \right\}$$



- $N+1$ gauge groups in 4d: $G = G_0 \times G_1 \times \ldots \times G_{N-1} \times G_N$.
- Bifundamental fields: $\Phi_j \to L_{j-1}\Phi_j R_j^\dagger$.
- $\Phi_j = v_j e^{i\pi_j^a(x) T_j^a / v_j} \to$ vevs break gauge group down to diagonal.

Matching

- In unitary gauge:

$$S_A = \frac{1}{g^2}\int d^4x \sum_{j=0}^{N}\left\{-\frac{1}{2}\mathrm{Tr}\left[F_{\mu\nu,j}\,F_j^{\mu\nu}\right] + v_j^2 g^2 \mathrm{Tr}\left[A_{\mu,j} - A_{\mu,j-1}\right]^2\right\}$$

- Discretized AdS_5:

$$S_5 = \frac{a}{g_5^2}\int d^4x \sum_{j=0}^{N}\left\{-\frac{1}{2}\mathrm{Tr}\left[F_{\mu\nu,j}F_j^{\mu\nu}\right] + e^{-2kaj}\mathrm{Tr}\left[\frac{A_{\mu,j} - A_{\mu,j-1}}{a}\right]^2\right\}$$

- Both agree in continuum limit provided:

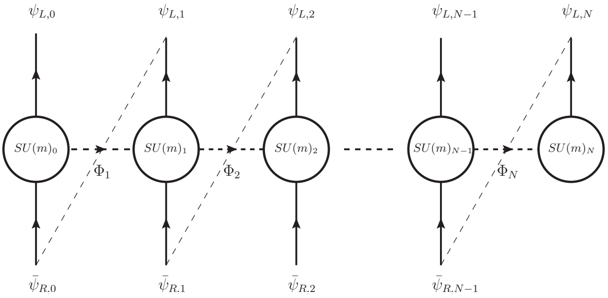
$$v_j \equiv vq^j \quad \leftrightarrow \quad \frac{e^{-kaj}}{ag}$$

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

- Parameter $0 \leq q \leq 1$. Hierarchy $\Rightarrow q^N = e^{-kaN} \sim e^{-36}$.
- Gauge mass matrix is diagonalized by $A_\mu^j = \sum_{j=0}^{N} f_{n,j} A_\mu^{(n)}$

Fermions

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



- Left-handed ZM $\rightarrow \bar{\psi}_{R,N} = 0$ (b.c.).

$$S_f = \int d^4x \left\{ \sum_{j=0}^{N} \bar{\psi}_{L,j} i \not{\partial} \psi_{L,j} + \bar{\psi}_{R,j} i \not{\partial} \psi_{R,j} + \left(\mu_j \bar{\psi}_{L,j} \psi_{R,j} + \lambda_j v_j \bar{\psi}_{R,j-1} \psi_{L,j} + \mathrm{h.c.} \right) \right\}$$

Fermion Zero Modes

- diagonalization: $\psi^{j}_{L,R} = \sum_{n=0}^{N} h^{L,R}_{j,n} \psi^{(n)}_{L,R}$
- ZM equations of motion are

$$\mu_j \, h^L_{j,0} + \lambda_{j+1} v_{j+1} h^L_{j+1,0} = 0$$
$$\mu_j \, h^R_{j,0} + \lambda_j v_j h^R_{j-1,0} = 0$$

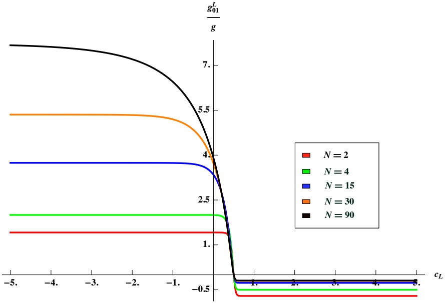
- Matching with AdS_5 implies:

$$\frac{\mu_j}{\lambda_{j+1} v_{j+1}} = q^{c_L - 1/2} \rightarrow h^L_{j,0} = A(c) q^{(c_L - 1/2)j}$$

- Localization in the quiver controlled by $\mathcal{O}(1)$ $c_{L,R}$.
- Higgs as doublet at site $N+1$ gives fermion masses (can be localized dynamically as a pNGB).

Gauge Couplings

- The gauge coupling to the first excited gauge mode is given by $g^L_{01} = \sum_{k=0}^{N} g|h^L_{k,0}|^2 f_{k,1}$.

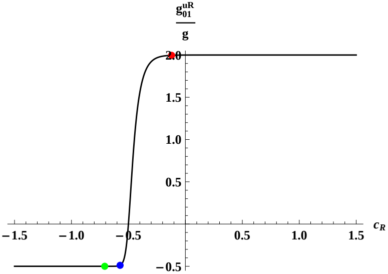


- Rapid coupling saturation in the IR at small N.
- Parametrically smaller flavor violation and EWPO.
- Narrow, weaklier coupled resonances.

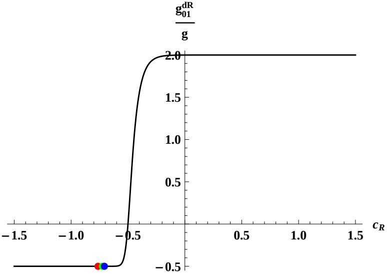
Flavor Bounds

(G.Burdman, N.Fonseca, L.L, arXiv:1210.5568, JHEP 1301(2013) 094)

Tree-level couplings of ZM fermions to 1st excited state ($N = 4$).

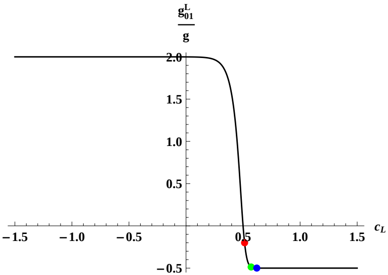


Right-handed up sector.



Right-handed down sector.

Flavor Bounds



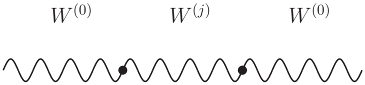
Left-handed sector.

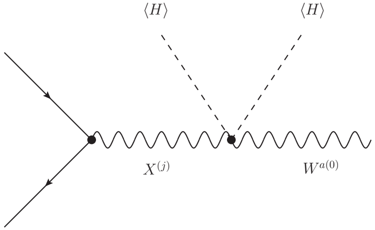
- Largest flavor violation in the up sector, down sector near universal.
- Most stringent bounds from $K_0 \leftrightarrow \bar{K}_0$, $D_0 \leftrightarrow \bar{D}_0$.
- Bounds are derived assuming $SU(3)_c$ in the quiver.

Flavor Bounds

Parameter	95% allowed range (GeV^{-2})	Lower limit on NP scale Λ (TeV)	Bound on color-octet mass M_G (TeV)
ReC_K^1	$[-9.6, 9.6] \cdot 10^{-13}$	$1.0 \cdot 10^3$	0.2
ReC_K^4	$[-3.6, 3.6] \cdot 10^{-15}$	$17 \cdot 10^3$	0.1
ReC_K^5	$[-1.0, 1.0] \cdot 10^{-14}$	$10 \cdot 10^3$	0.1
ImC_K^1	$[-2.6, 2.8] \cdot 10^{-15}$	$1.9 \cdot 10^4$	2.6
ImC_K^4	$[-4.1, 3.6] \cdot 10^{-18}$	$49 \cdot 10^4$	3.0
ImC_K^5	$[-1.2, 1.1] \cdot 10^{-17}$	$29 \cdot 10^4$	1.0
$\lvert C_D^1 \rvert$	$< 7.2 \cdot 10^{-13}$	$1.2 \cdot 10^3$	1.0
$\lvert C_D^4 \rvert$	$< 4.8 \cdot 10^{-14}$	$4.6 \cdot 10^3$	2.9
$\lvert C_D^5 \rvert$	$< 4.8 \cdot 10^{-13}$	$1.4 \cdot 10^3$	0.5
$\lvert C_{B_d}^1 \rvert$	$< 2.3 \cdot 10^{-11}$	$0.21 \cdot 10^3$	0.3
$\lvert C_{B_d}^4 \rvert$	$< 2.1 \cdot 10^{-13}$	$2.2 \cdot 10^3$	0.3
$\lvert C_{B_d}^5 \rvert$	$< 6.0 \cdot 10^{-13}$	$1.3 \cdot 10^3$	0.1
$\lvert C_{B_s}^1 \rvert$	$< 1.1 \cdot 10^{-9}$	30	0.1
$\lvert C_{B_s}^4 \rvert$	$< 1.6 \cdot 10^{-11}$	250	0.1
$\lvert C_{B_s}^5 \rvert$	$< 4.5 \cdot 10^{-11}$	150	0.03

Electroweak Precision Observables



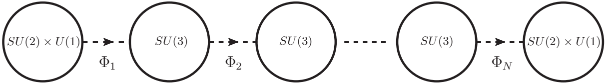


- Electroweak sector $[SU(2) \times U(1)]^{N+1}$.
- Tree level S and T are generated from mixing between gauge zm and resonances due to EWSB.
- Universal part of vertex correction can be shifted to S, T.
- $S \simeq 0.17 \times \left(\frac{3\ \mathrm{TeV}}{M^{(1)}}\right)^2$, $T \simeq 0.16 \times \left(\frac{3\ \mathrm{TeV}}{M^{(1)}}\right)^2$.
- $M^{(1)} \gtrsim 3$ TeV satisfies bounds without custodial protection (might be needed at one loop).

pNGB Higgs

(G.Burdman, N.Fonseca, L.L, in progress)

- Separation between resonance scale and the Higgs mass suggests h is a pNGB.
- Higgs localization in the quiver can be obtained dynamically.
- Minimal choice $[SU(2) \times U(1)] \times SU(3)^{N-1} \times [SU(2) \times U(1)]$ contains four physical NG d.o.f:

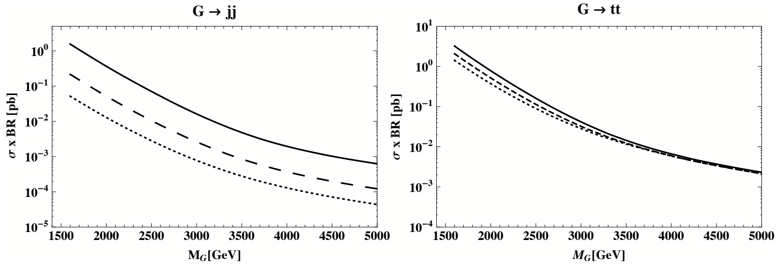


$$H^a = \sum_{j=1}^{N} \frac{q^{N-j}}{\sqrt{\sum_{j=1}^{N} q^{2(j-1)}}} \pi_j^a$$

- The Higgs boson h is contained in the doublet H^a and is N localized ($0 \leq q \leq 1$).
- For three sites or more, the one loop potential is calculable (finite).

Phenomenology of Gauge Resonances

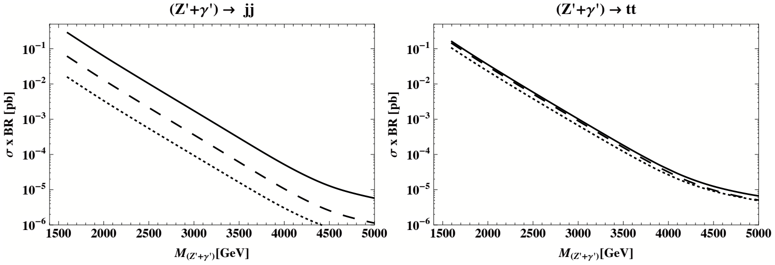
(G.Burdman, N.Fonseca, G. Lichtenstein, arXiv:1308.5988)
Color octet and color singlet ($Z' + \gamma'$) resonances at $\sqrt{s} = 8$ TeV ($q\bar{q} \to X \to jj(t\bar{t})$).



$N = 4$ (solid), $N = 9$ (dashed) and $N = 15$ (dotted).

- Dijet cross section falls with N ($t\bar{t}$ insensitive).
- $\Gamma/M \simeq 0.05$.

Phenomenology of Gauge Resonances



$N = 4$ (solid), $N = 9$ (dashed) and $N = 15$ (dotted).

N	dijet	$t\bar{t}$
4	3.0	2.7
9	1.6	2.6
15	-	2.5

N	dijet	$t\bar{t}$
4	1.7	2.1
9	-	2.0
15	-	1.8

Conclusions/Outlook

- FHQT with small N are complementary to AdS_5 models, with distinct phenomenology.
- Flavor bounds are improved.
- Passes EWPC even w.o. custodial protection (tree-level).
- At the LHC: different cross sections, BR, etc.
- To explore:
  - pNGB Higgs (similar to CHM/Little Higgs)
  - Model building details (e.g. lepton sector)