

# Full-Hierarchy Quiver Theories

**Leonardo de Lima**

**IFT - São Paulo State University (UNESP)**

**arXiv:1210.5568 JHEP 1301 (2013) 094, arXiv:1308.5988,  
arXiv:13XX.XXXX, ...**

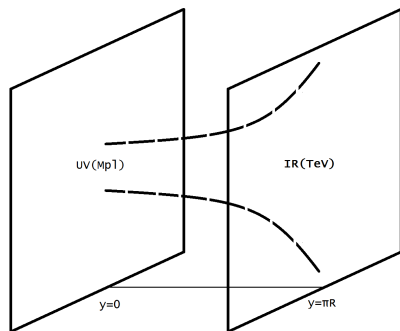
**In collaboration with: G. Burdman, N. Fonseca, G. Lichtenstein, R.  
Matheus and C. Machado.**

# Motivation

- If the Higgs is a composite from strong sector, we need to explain why  $m_h \ll \mathcal{O}(1) \text{ TeV} \rightarrow \text{pNGB Higgs}$ .
- 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:

$$y \rightarrow y + \lambda, \quad x \rightarrow e^{k\lambda} x \\ \Rightarrow \text{warping: } p_\mu \rightarrow e^{-k\lambda} p_\mu$$

- UV cutoff:

$$\Lambda_{UV} \sim M_{Pl} \rightarrow \Lambda_{IR} = e^{-k\pi R} M_{Pl}$$

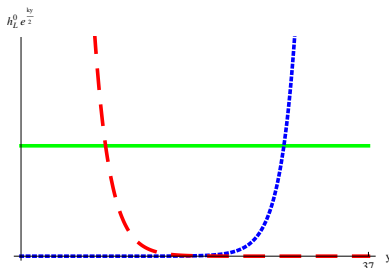
- With Higgs IR localized,

$$\Lambda_{IR} \sim \mathcal{O}(TeV) \rightarrow k\pi R \sim 37.$$

# Fermions in $AdS_5$

- Fermion bulk mass parameter:  $M_\Psi = ck$
- Naturalness  $\rightarrow c \sim \mathcal{O}(1)$
- ZM profile:  

$$h_{L(R)}^{(0)}(y) = A(c)e^{(1/2 \mp c)ky}$$
- 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)

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



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

# Matching

- In unitary gauge:

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

- Discretized  $AdS_5$ :

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

- Both agree in continuum limit provided:

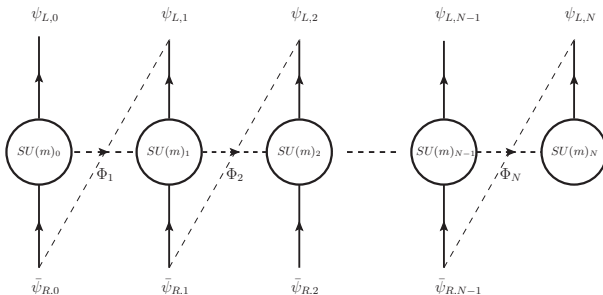
$$v_j \equiv v q^j \quad \leftrightarrow \quad \frac{e^{-kaj}}{ag}$$

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

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

# Fermions

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



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

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

# Fermion Zero Modes

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

$$\mu_j h_{j,0}^L + \lambda_{j+1} v_{j+1} h_{j+1,0}^L = 0$$

$$\mu_j h_{j,0}^R + \lambda_j v_j h_{j-1,0}^R = 0$$

- Matching with AdS<sub>5</sub> implies:

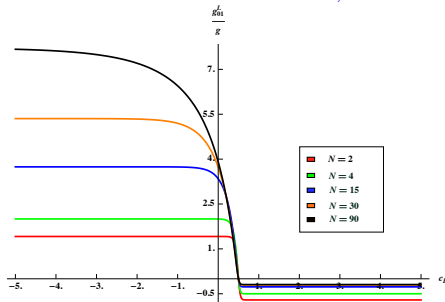
$$\frac{\mu_j}{\lambda_{j+1} v_{j+1}} = q^{c_L - 1/2} \rightarrow h_{j,0}^L = A(c) q^{(c_L - 1/2)j}$$

- **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  $g_{01}^L = \sum_{k=0}^N g |h_{k,0}^L|^2 f_{k,1}$ .

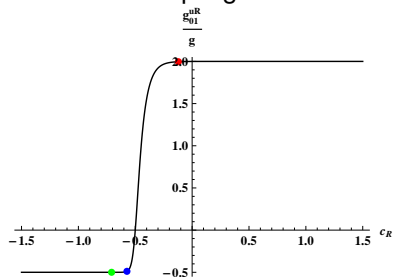


- Rapid coupling **saturation** in the **IR** at **small  $N$** .
- Parametrically smaller** flavor violation and EWPO.
- Narrow, **weaker coupled** resonances.

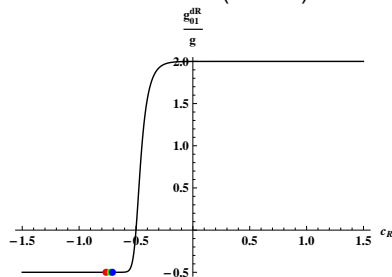
# Flavor Bounds

(G.Burdman, N.Fonseca, L.L, [arXiv:1210.5568](https://arxiv.org/abs/1210.5568), JHEP 1301(2013) 094)

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

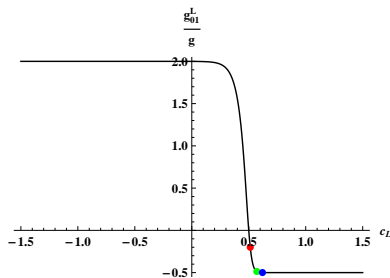


Right-handed up sector.



Right-handed down sector.

# Flavor Bounds



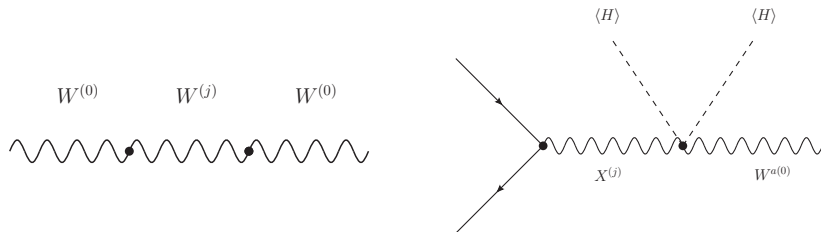
Left-handed sector.

- 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 <sup>-2</sup> )	Lower limit on NP scale $\Lambda$ (TeV)	Bound on color-octet mass $M_G$ (TeV)
$\text{Re}C_K^1$	$[-9.6, 9.6] \cdot 10^{-13}$	$1.0 \cdot 10^3$	0.2
$\text{Re}C_K^4$	$[-3.6, 3.6] \cdot 10^{-15}$	$17 \cdot 10^3$	0.1
$\text{Re}C_K^5$	$[-1.0, 1.0] \cdot 10^{-14}$	$10 \cdot 10^3$	0.1
$\text{Im}C_K^1$	$[-2.6, 2.8] \cdot 10^{-15}$	$1.9 \cdot 10^4$	2.6
$\text{Im}C_K^4$	$[-4.1, 3.6] \cdot 10^{-18}$	$49 \cdot 10^4$	<b>3.0</b>
$\text{Im}C_K^5$	$[-1.2, 1.1] \cdot 10^{-17}$	$29 \cdot 10^4$	1.0
$ C_D^1 $	$< 7.2 \cdot 10^{-13}$	$1.2 \cdot 10^3$	1.0
$ C_D^4 $	$< 4.8 \cdot 10^{-14}$	$4.6 \cdot 10^3$	<b>2.9</b>
$ C_D^5 $	$< 4.8 \cdot 10^{-13}$	$1.4 \cdot 10^3$	0.5
$ C_{B_d}^1 $	$< 2.3 \cdot 10^{-11}$	$0.21 \cdot 10^3$	0.3
$ C_{B_d}^4 $	$< 2.1 \cdot 10^{-13}$	$2.2 \cdot 10^3$	0.3
$ C_{B_d}^5 $	$< 6.0 \cdot 10^{-13}$	$1.3 \cdot 10^3$	0.1
$ C_{B_s}^1 $	$< 1.1 \cdot 10^{-9}$	30	0.1
$ C_{B_s}^4 $	$< 1.6 \cdot 10^{-11}$	250	0.1
$ C_{B_s}^5 $	$< 4.5 \cdot 10^{-11}$	150	<b>0.03</b>

# 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.
- $S \simeq 0.17 \times \left(\frac{3 \text{ TeV}}{M^{(1)}}\right)^2$  ,  $T \simeq 0.16 \times \left(\frac{3 \text{ TeV}}{M^{(1)}}\right)^2$ .
- $M^{(1)} \gtrsim 3 \text{ TeV}$  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**:



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

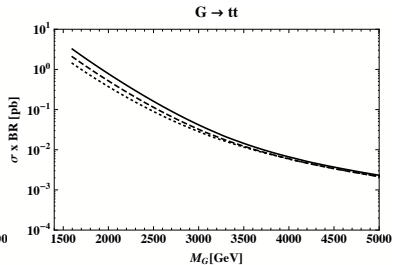
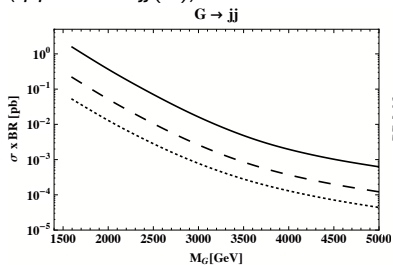
- The Higgs boson  $h$  is contained in the doublet  $H^a$  and is **N localized** ( $0 \leq q \leq 1$ ).
- For **three sites** or more, the one loop **potential** is calculable (finite).

# Phenomenology of Gauge Resonances

(G.Burdman, N.Fonseca, G. Lichtenstein, [arXiv:1308.5988](https://arxiv.org/abs/1308.5988))

Color octet and color singlet ( $Z' + \gamma'$ ) resonances at  $\sqrt{s} = 8$  TeV

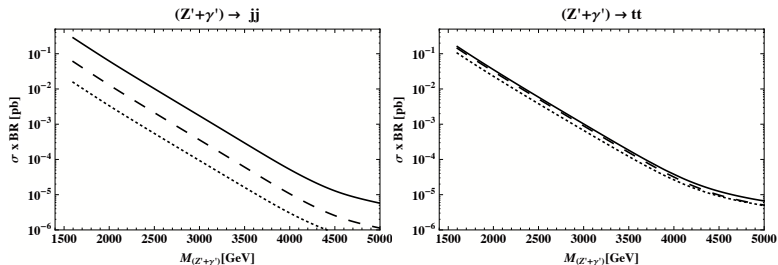
( $q\bar{q} \rightarrow X \rightarrow jj(t\bar{t})$ ).



$N = 4$  (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)