Electroweak Symmetry Breaking from a Strongly Coupled Fourth Generation

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Based on arXiv:0710.0623, arXiv:0812.0368, +...
with *Oscar Eboli, Leandro Da Rold, Ricardo Matheus, Eduardo Lascio and Carlos Haluch*

Outline

The Origin of Electroweak Symmetry Breaking

Dynamical EWSB:

- Technicolor: Asymptotically free, unbroken gauge interaction

$$\Rightarrow \langle \bar{F}_L F_R \rangle \neq 0 \qquad \Rightarrow \text{EWSB}$$

F's are confined fermions, just as quarks in QCD.

- Alternative: gauge interaction spontaneously broken at $\Lambda \sim 1$ TeV
  $\Rightarrow$ F's un-confined heavy fermions with EW quantum #'s

First attempt: Top Condensation – Topcolor

Top Condensation: Nambu '89, Bardeen–Hill–Lindner '90

New interaction at scale Λ

- Strongly coupled to 3rd generation
- Leads to top condensation:

$$\langle \bar{t}t \rangle \neq 0$$

Breaks EW symmetry, gives dynamical mass to top

Top Condensation Problems

But,

$$v^2 \simeq \frac{N_c}{8\pi^2} m_t^2 \left(\log \frac{\Lambda^2}{m_t^2} + k \right)$$

So to get $m_t \sim 170$ GeV need $\Lambda \sim 10^{15}$ GeV !!

Alternatively, if we want to avoid fine-tuning

$$\Lambda \sim 1 \text{ TeV} \Rightarrow m_t \simeq (600 - 800) \text{ GeV}$$

Possible Fixes

- Topcolor-assisted Technicolor (Hill '95):
- Top See-saw (Dobrescu, Hill '97):
- Assume a Chiral Fourth Generation
  - Couples strongly to new interaction
  - 4G condensation $\Rightarrow$ EWSB, $m_4 \sim 600$ GeV

EWSB from Fourth Generation Condensation

Ingredients:

- A Chiral Fourth Generation: $Q_4, U_{4R}, D_{4R}, L_4, E_{4R}, N_{4R}$
- New strong interaction at the $O(1)$ TeV scale:
  - E.g. Broken gauge symmetry $M \sim TeV$
  - Strongly coupled to 4th gen. $\Rightarrow \langle \bar{F}_4 F_4 \rangle \neq 0$
- Fermion masses: higher dimensional operators like

$$\frac{x_{ij}}{\Lambda^2} \; \bar{f}_L^i f_R^j \; \bar{U}_R U_L$$

Fourth Generation Condensation and AdS_5

Models of 4G Condensation in Compact Extra Dimensions
(G.B., Da Rold '07)

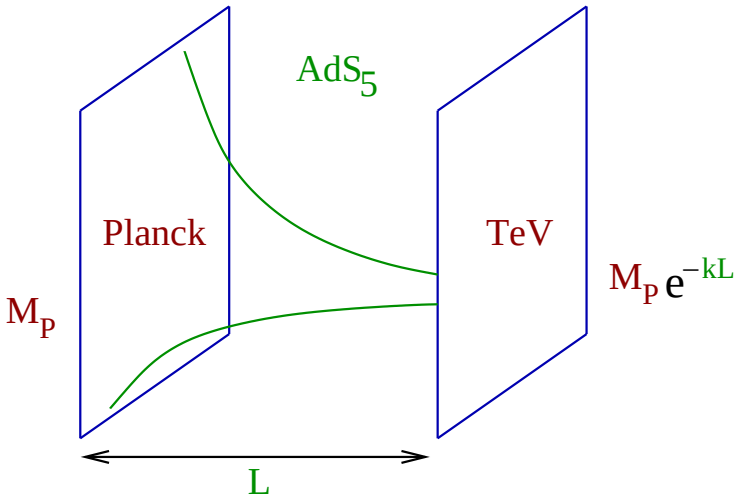
Extra dimensional theories in compact AdS_5 dual to strongly coupled theories in 4D:

- Naturally results in strongly coupled heavy fermions
- Higher-dimensional operators among light fermions suppressed by large UV scale Λ
- Build gauge theory in AdS_5 with one extra chiral generation and no Higgs as *only new elements* .

Solving the Hierarchy Problem in AdS$_5$

Metric in extra dimension $\Rightarrow$ small energy scale from M_P
(Randall, Sundrum '99)

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



4th Generation close to TeV brane

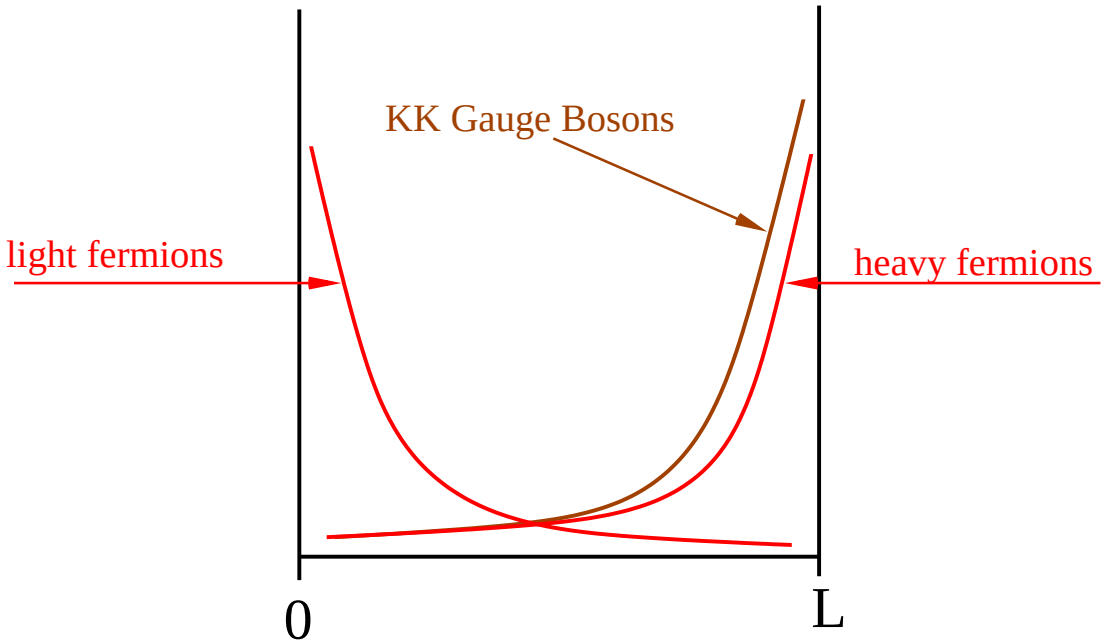
$\Rightarrow$ Composite Higgs IR-localized

Bulk AdS$_5$ Model

- Bulk gauge theory: $SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_X$
- Four generations of SM fermions:
  - UV-localized light SM fermions
  - Q^3, $t_R \sim$ IR-localized
  - IR-localized 4th Generation

Flavor Violation in AdS$_5$ Models

KK Gauge Bosons couple stronger to heavier fermions



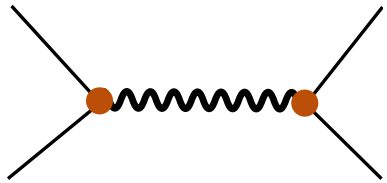
$\Rightarrow$ Tree-level flavor violation is hierarchical:

Only important with the heavier generations

Fermion Condensation in AdS_5

Fourth-Generation Condensation in AdS_5:

- Fourth Generation in the AdS_5 bulk
- Choose zero-mode fermions IR localized $\Rightarrow$ strongly coupled to KK gauge bosons



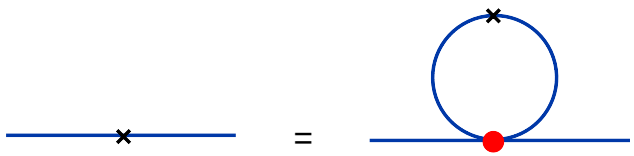
- $\Rightarrow$ 4G zero-mode quarks couple strongly to KK gluon
- We can arrange for at least one 4G to be super-critically coupled. E.g.:

$$\longrightarrow \langle \bar{U}_4 U_4 \rangle \neq 0$$

EWSB from Fourth-Generation in AdS$_5$

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

$\Rightarrow$ Solution to the gap equation:



This implies

- Electroweak Symmetry Breaking
- Dynamical $m_U^{(0)} \simeq 600$ GeV
- A heavy Higgs: $\gtrsim 700$ GeV

Fermion Masses

- Bulk 4-fermion ops. suppressed by M_P :

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

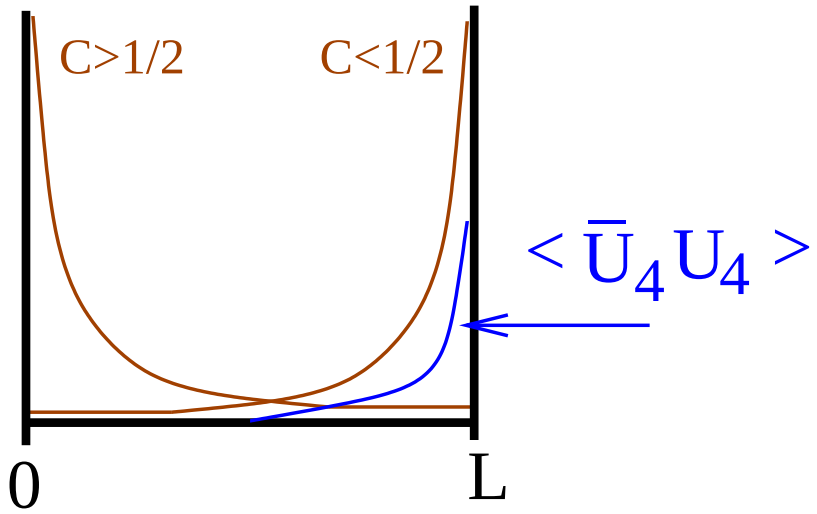
- Zero-mode fermion masses from zero-mode four-fermion operators

$$C^{ij44}\, N^{ij44}\, \frac{e^{k\pi R(4-c_L^i+c_R^j+c_R^4-c_L^4)}}{4-c_L^i+c_R^j+c_R^4-c_L^4}\, \frac{k}{M_P^3}\, \bar{f}_L^i f_R^j\, \bar{U}_R U_L$$

- When $\langle \bar{U}_4 U_4 \rangle \neq 0$ this results in m_{ij}

Flavor Hierarchy

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



TeV localization $\longrightarrow$ larger m_{ij}
Planck localization $\longrightarrow$ suppressed m_{ij}

Constraints

- Tree-level S: $\Rightarrow M_{KK} \gtrsim (2.5)\ \mathrm{TeV}$
- Tree-level FCNCs: can be circumvented with some tweaking.
- Loop-induced S: OK as long as some $T > 0$ induced (Kribs, Plehn, Spannowsky, Tait '07)
- *Heavy Higgs*: EW precision bounds $\Rightarrow m_h \simeq 750$ GeV @ 95 % C.L. (KPST)
- Also, in bulk AdS$_5$ theories, bounds on m_h are affected by divergences (G.B. Da Rold '08):

Phenomenology at the LHC

Phenomenology at the LHC

Heavy Quark Production at the LHC

Production of U_4 and D_4 at the LHC: (G.B., Da Rold, Eboli, Matheus '09)

Consider $m_{U_4} > m_{D_4}$:

$$pp \longrightarrow D_4 \bar{D}_4 \longrightarrow t\bar{t}W^+W^- \Rightarrow 4W\text{'s final state}$$

Two sources:

- SM QCD Production: Same for any theory with a 4th generation
- Production via s-channel KK Gluons (assume $M_{KK} = 2.5$ TeV)

Use $pp \to \ell^{\pm}\ell^{\pm} 6j \not{E}_T$ to beat backgrounds

Cuts in the same-sign dilepton analysis:

$$p_T^{j_{1,2}} > 100 \text{ GeV}; \qquad p_T^{\ell_{1,2}} > 50 \text{ GeV};$$

m_{D_4}	$\sigma_{\mathcal{S}}$[fb]	$\sigma_{\mathcal{B}}$[fb]	$\mathcal{S}/\mathcal{B}$	$\mathcal{L}_{min}$[pb^{-1}]
300 GeV	87.0	6.2	14.	44
450 GeV	54.2	6.2	8.7	84
600 GeV	17.8	6.2	2.9	460

But this is for 14 TeV. What about 7 or 10 TeV ?

Heavy Quark Production at the LHC

Incremental Goals

- ID D_4 signal over background takes $O(1)$ fb^{-1} in same-sign dilepton channel
- Observing U_4 and mass reconstruction: $O(10)'\mathrm{s}$ fb^{-1}
- Separating the KK Gluon contribution from QCD: Signal of presence of new strong interaction

Heavy Quark Production at the LHC

Detecting the New Strong Interaction

The KK Gluon so strongly coupled to 4th generation quarks that

$$\Gamma_G \simeq M_G$$

$\Rightarrow$ KK Gluon too broad to be observed at LHC

Can't see it in Q_4 pair-production: featureless $\sim 10\%$ excess

Observing the New Strong Interaction

Other possible ways

- Flavor violation of KK Gluon interactions (G.B., Lascio, in progress):

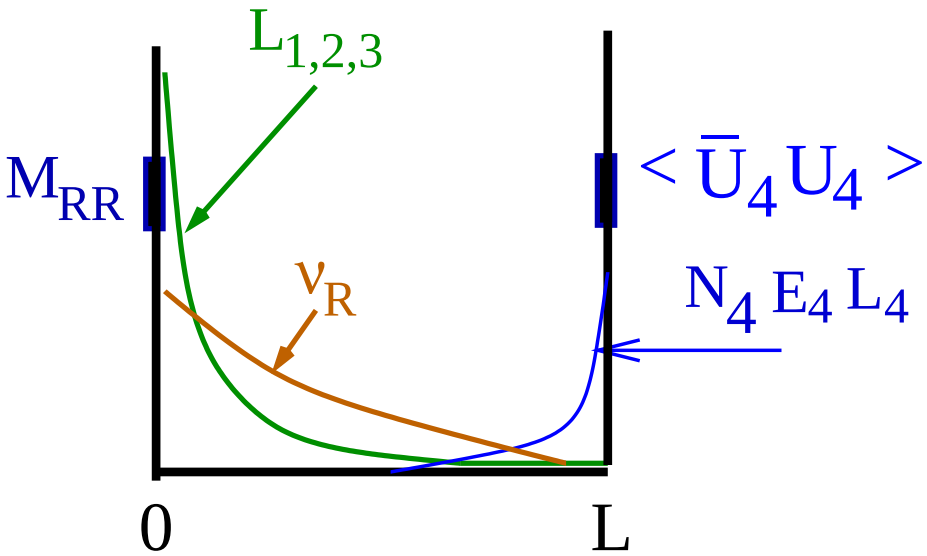
$$G^{(1)} \longrightarrow U_4\ \bar{t} \text{ or } G^{(1)} \longrightarrow D_4\ \bar{b}$$

$$\Rightarrow \text{Single production of fourth-generation quarks}$$

- Observing the strong interactions of the 4G lepton sector (G.B., Da Rold, Eboli, Matheus, in progress)

The Fourth-Generation Lepton Sector

$L_4 = \begin{pmatrix} N_4 \\ E_4 \end{pmatrix}_L$, E_{4R}, N_{4R} Acquire masses $O(m_{U_4})$



The Fourth-Generation Lepton Sector

Neutrino Masses and Mixings

- *See-saw*:
  UV-localized Majorana mass term $\Rightarrow$ usual see-saw for light neutrinos.
  See-saw not affecting IR-localized N_4, remain heavy.
- To obtain correct pattern in V_{MNS} results in
  L_4 coupling $\simeq$ equally to the 3 lighter generations
- $\mu \longrightarrow e\gamma$: $V_{4i} < O(0.01)$

The Fourth-Generation Lepton Sector at the LHC

Heavy Lepton pair-production at the LHC

(G.B., Da Rold, Eboli, Haluch, Matheus in progress)

Assuming $m_{E_4} > m_{N_4}$: $N_4 \to \ell^- W^+$, with $\ell = e, \mu, \tau$

For instance using

$$pp \to N_4 \bar{N}_4 \to e^{\pm}\mu^{\mp} W^+ W^-$$

backgrounds should be manageable

Seeing the Strong Interaction

- Electroweak KK Gauge bosons are narrower than KK gluon
- They represent more than 1/3 of the cross section
- $\sigma(pp \to N_4 \bar{N}_4 \to e^{\pm}\mu^{\mp} W^+ W^-) \simeq O(\text{few})\ fb$

Summary/Outlook

- Existence of 4th Generation would suggest special role in EWSB
- Possible to build viable models of 4th Generation condensation leading to EWSB *and* Fermion masses in AdS$_5$
- Identification of new strong interaction with 4G quarks hard at the LHC.
- Alternatively, use electroweak resonances (narrower than color-octet) in the production of 4G leptons
- Or flavor-violating single production of U_4, or D_4.