Electroweak Symmetry Breaking: The Next Generation

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

Outline

The Problem with the Standard Model

The SM appears to describe well all interactions among all elementary particles

But description of EWSB sector unsatisfactory

- M_W unstable under radiative corrections
  $\Longrightarrow$ Hierarchy Problem
- Origin of fermion mass spectrum

In the last $\sim$ 10 years

Many new ideas proposed to solve the Hierarchy Problem

- Compact Extra Dimensions: Large, Universal, Warped
- Little Higgs, Twin Higgs, ...

The Origin of Electroweak Symmetry Breaking

With some exceptions (e.g. ADD, original RS1),
solution to the HP $\Longleftrightarrow$ origin of EWSB

In these cases:

- EWSB scalar sector is elementary $\leftrightarrow$ SUSY

or

- EWSB scalar sector is composite or absent: Technicolor, Topcolor, Top See-saw, Little Higgs, . . .

The Origin of Electroweak Symmetry Breaking

Composite EWSB Sector:

- Technicolor: Asymptotically free, unbroken gauge interaction

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

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

Strongly Coupled Heavy Fermions

Heavy Chiral Fermions: strongly coupled to EWSB sector

- Top quark:

$$m_t \simeq v \qquad \Rightarrow \qquad y_t \sim 1$$

- If Heavy Fourth Generation $\Rightarrow y_4 > 1$

Higgs sector is strongly coupled

- Natural to assume composite Higgs sector

Top Condensation – Topcolor

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

New interaction at scale Λ

- Coupled strongly to third generation, particularly to the top quark
- Leads to top condensation:

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

Breaks EW symmetry, gives dynamical mass to top

Top Condensation – Topcolor

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

This scenario is as fine-tuned as the SM !

Alternatively, if we want to avoid fine-tuning

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

Top Condensation – Possible Fixes

- Topcolor-assisted Technicolor (Hill '95):
  - TC breaks (most of) EW symmetry
  - ETC gives masses up to $O(1)$ GeV
  - Topcolor interaction $\Rightarrow \langle \bar{t}t \rangle \neq 0$, responsible for m_t.
- Top See-saw (Dobrescu, Hill '97):
  - Topcolor + Singlet fermion without TC
  - χ_L and χ_R have quantum numbers of t_R
  - The actual dynamical mass is 600 GeV, but through mixing results in m_t
- 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:

- Chiral Fourth Generation

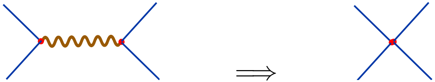
$$Q_L^4 = \begin{pmatrix} U_4 \\ D_4 \end{pmatrix}_L, \qquad U_{4R}, \qquad D_{4R}$$

$$L^4 = \begin{pmatrix} N_4 \\ E_4 \end{pmatrix}_L, \qquad N_{4R}, \qquad E_{4R}$$

EWSB from Fourth Generation Condensation

Ingredients (*cont.*):

- New strong interaction at the $O(1)$ TeV scale:
  - E.g. Broken gauge symmetry $M \sim TeV$
  - Strongly coupled to the fourth generation



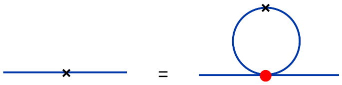
  - Somewhat less to 3rd generation quarks
  - Weakly coupled to light fermions

EWSB from Fourth Generation Condensation

Ingredients (*cont.*):

- At least one of 4G fermions condenses

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



$\Rightarrow$ EWSB, dynamical mass for condensing fermion

$$m_{dyn.} \sim 600 \text{ GeV}$$

Fermion Masses

We need higher dimensional operators like

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

such that $\langle \bar{U}_R U_L \rangle \sim m_U^3$ gives

$$m_{ij} \sim x_{ij}\;m_U\;\left(\frac{m_U}{\Lambda}\right)^2$$

with m_U the dynamically generated mass

Fourth Generation Condensation and AdS_5

Models of 4G Condensation in Compact Extra Dimensions
(G.B., Da Rold '07, top see-saw version in Bai, Carena, Pontón '08)

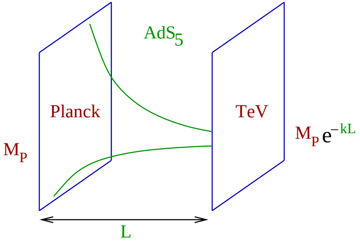
Extra dimensional theories in compact AdS_5 dual to strongly coupled theories in 4D:

- 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 as *only new element*.

Solving the Hierarchy Problem in AdS_5

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

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



Corrections to m_h OK
If Higgs close to TeV brane

Need Higgs IR localization

Bulk AdS_5 Models

Allowing Gauge and Matter fields in 5D bulk

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

The Origin of Flavor Hierarchies

- Fermion Fields in the bulk: 5D fermion field KK decomposition

$$\Psi_{L,R}(x,y) = \frac{1}{\sqrt{2\pi R}} \sum_{n=0} \psi_n^{L,R}(x) e^{2\kappa|y|} f_n^{L,R}(y)$$

- 5D fermion bulk mass term $\longrightarrow$ localization of fermion fields:

$$S_f = \int d^4x\, dy\, \sqrt{g} \left\{ \cdots - c\, \kappa \bar{\Psi}(x,y)\Psi(x,y) \right\} ,$$

with $c \simeq O(1)$.

- $\Rightarrow$ Fermion zero-modes can be localized by choosing c :

$$f_0^{R,L}(y) = \sqrt{\frac{\kappa\pi R\,(1 \pm 2c)}{e^{\kappa\pi R(1\pm 2c)} - 1}}\; e^{\pm c\,\kappa\, y}$$

Flavor in bulk AdS$_5$ Models

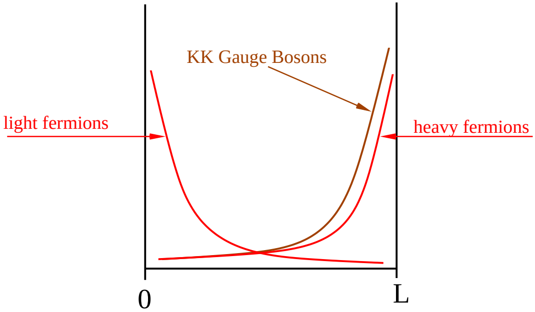
- With proper normalization of zero-mode fermion the zero-mode fermion wave-function is

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

- 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.

Flavor Violation in AdS_5 Models

KK Gauge Bosons couple stronger to heavier fermions



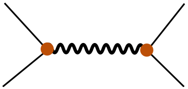
$\Rightarrow$ Tree-level flavor violation is hierarchical:

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



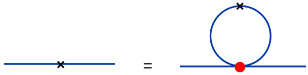
- $\Rightarrow$ 4G zero-mode quarks couple strongly to KK gluon
- We can arrange for at least one 4G to be super-critically coupled. E.g.:

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

EWSB from Fourth-Generation in AdS$_5$

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 $m_U^{(0)} \sim (500 - 700)$ GeV
- A heavy Higgs: $m_h \simeq (600 - 900)$ GeV

Fermion Masses

- Bulk 4-fermion ops. suppressed by M_P :

$$\int dy\,\sqrt{g}\,\frac{C^{ijk\ell}}{M_P^3}\,\bar{\Psi}^i_L(x,y)\Psi^j_R(x,y)\bar{\Psi}^k_R(x,y)\Psi^\ell_L(x,y)\ ,$$

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

$$C^{ij44}\,N^{ij44}\,\frac{e^{k\pi R(4-c^i_L+c^j_R+c^4_R-c^4_L)}}{4-c^i_L+c^j_R+c^4_R-c^4_L}\,\frac{k}{M_P^3}\,\bar{f}^i_L f^j_R\,\bar{U}_R U_L$$

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

Fermion Masses (*cont.*)

Light fermions have small overlap with condensate (TeV)
3rd and 4th generation fermions: more TeV localized

- Light fermions ($\sim$ 1st and 2nd generations): $(c_L^i, -c_R^j) > 1/2$.

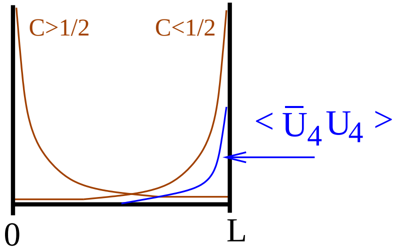
$$m_{ij} \sim e^{k\pi R(1-c_L^i+c_R^j)}\, m_U$$

- Heavy fermions ($\sim$ 3rd and 4th generations): $(c_L^i, -c_R^j) < 1/2$
  Plus at least one of c_L^i or $-c_R^j > -0.12$ to avoid condensation.

$$m_{ij} \sim m_U$$

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}

The full Bulk AdS_5 Picture

Including the Electroweak sector in the bulk:

Needs to be

$$SU(2)_L \times SU(2)_R \times U(1)_X$$

to avoid large isospin violation

Broken down to $\Longrightarrow SU(2)_L \times U(1)_Y$ at UV.

Bounds on Bulk AdS_5 Models

Electroweak precision bounds:

- $T = 0$ at tree-level due to $SU(2)_L \times SU(2)_R$
- Tree-level contributions to S through Z^0 mixing with KK sector:

$$M_{KK} \gtrsim (2.5)\ \mathrm{TeV}$$

- $Z \to \bar{b}b$ require discrete symmetry ($L \leftrightarrow R$) (Agashe, Contino, Da Rold, Pomarol '05)
- Large Flavor Violation effects can be circumvented with some tweaking

Constraints on 4th Generation Model

S parameter:

- PDG quoted "total annihilation" exclusion (99.999% C.L.)
- But re-examination of bounds practically eliminates this (Kribs, Plehn, Spannowsky, Tait '07)

Heavy Higgs:

- EW precision bounds allow $m_h \simeq 750$ GeV @ 95 % C.L. (KPST)
- But in AdS_5 theories bounds on m_h are affected by divergences (G.B. Da Rold '08)

Constraints on 4h Generation Model

Flavor Physics:

- Tree-level FCNCs: Bounds can be safely evaded with minimal model assumptions (E.g. Fitzpatrick, Perez, Randall '07)
- Loop contributions interesting, but not dangerous (E.g. Bobrowski, Lenz, Riedl, Rohrwild '09)

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 $m_{U_4} > m_{D_4}$ (favored by EWPC):

- $pp \to D_4 \bar{D}_4 \to t\bar{t}W^+W^- \Rightarrow 4W$'s final state
- $pp \to U_4 \bar{U}_4 \to D_4 \bar{D}_4 W^+W^- \Rightarrow 6W$'s final state

$\Rightarrow$ Start with the D_4 production

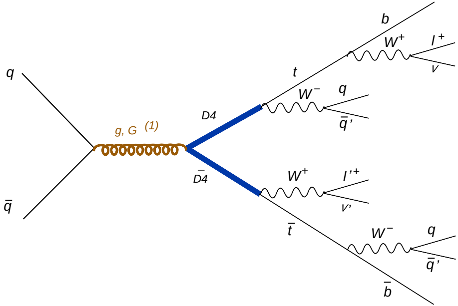
Two sources:

- SM QCD Production: Same for any theory with a 4th generation
- Production via s-channel KK Gluons

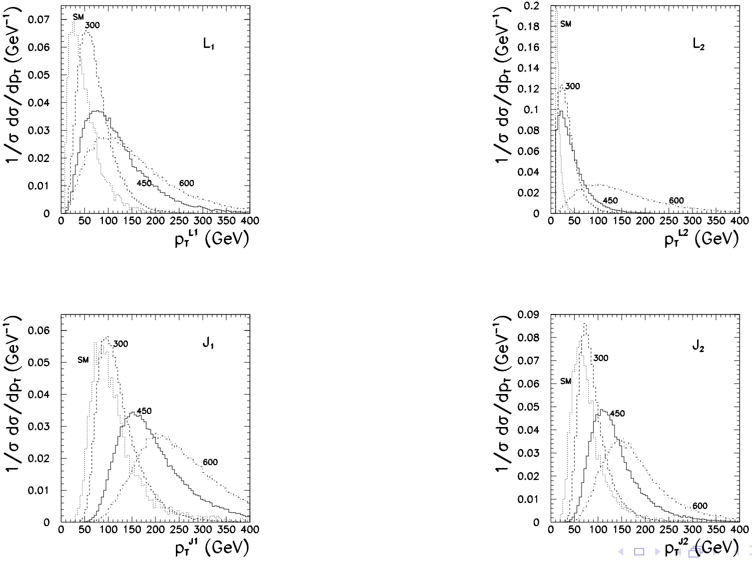
Heavy Quark Production at the LHC

D_4 pair production:

To beat backgrounds ($t\bar{t}$, $V's + j$'s) use same-sign dilepton modes



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

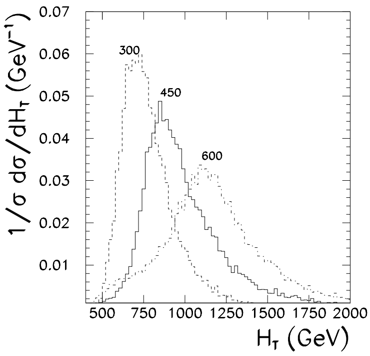

L1
SM
300
450
600
1/σ dσ/dp_T (GeV^-1)
p_T^L1 (GeV)
L2
SM
300
450
600
1/σ dσ/dp_T (GeV^-1)
p_T^L2 (GeV)
J1
SM
300
450
600
1/σ dσ/dp_T (GeV^-1)
p_T^J1 (GeV)
J2
SM
300
450
600
1/σ dσ/dp_T (GeV^-1)
p_T^J2 (GeV)

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

Also $H_T = \sum_i \left(E_T^i + \not{E}_T\right)$ follows m_{D_4}



Ultimately, need to reconstruct m_{D_4}

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

Strongly Coupled Fourth Generation at the LHC

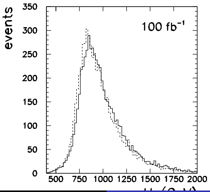
KK Gluon so strongly coupled to 4th generation quarks that

$$\Gamma_G \simeq M_G$$

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

But to validate this picture need to observe strong interaction

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



Observing the New Strong Interaction

Other possible ways

- Flavor violation of KK Gluon interactions:

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

$\Rightarrow$ Single production of fourth-generation quarks

- Observing the strong interactions of the 4G lepton sector

The Fourth-Generation Lepton Sector

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

Neutrino Masses and Mixings

- *See-saw*:
  UV-localized Majorana mass term ⇒ 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
- $\mu \to e\gamma$: $V_{4i} < O(0.01)$

The Fourth-Generation Lepton Sector at the LHC

Heavy Lepton pair-production at the LHC
(G.B., Da Rold, Eboli, Matheus in progress)

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

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

backgrounds should be manageable

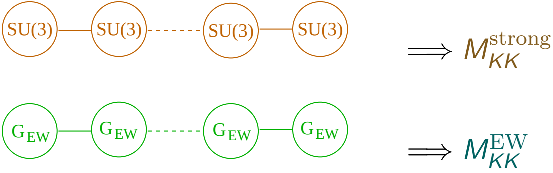
Seeing the Strong Interaction

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

Lowering the New Dynamics Mass Scale

Can the KK-gluon mass be $M_{KK} < 2.5$ TeV ?

- We can *deconstruct* the 5D theory differently for $SU(3)$ than for $SU(2)_L \times SU(2)_R \times U(1)_X$



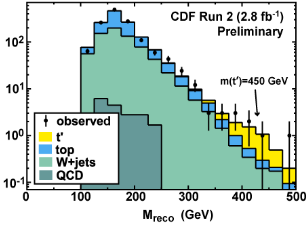
- EWPC $\Longrightarrow M_{KK}^{\rm EW} > 2.5$ TeV
- But $M_{KK}^{\rm strong}$ can be as low as ~ 1 TeV

Lowering the New Dynamics Mass Scale

- KK Gluon exchange in 4G-quark production at LHC now a $O(25\%)$ effect: at LHC $gg \to Q\bar{Q}$ dominates
- But at the Tevatron KK Gluon exchange dominates 4G-quark production for $M_{KK} \simeq 1$ TeV
- What is the Tevatron reach ?

Sensitivity at the Tevatron

Actually, the Tevatron might have seen the U_4 (or D_4)
(Dobrescu, Kong, Mahbubani '09; G.B. Da Rold, Matheus, in progress)



7 Events on a background of 2, consistent with $M_{KK} \simeq 1$ TeV

Summary/Outlook

- TeV Scale could be a window to new strong interactions
- 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
- Identification of new strong interaction with 4G quarks hard at the LHC. The Tevatron could help if $M_{\rm strong} \simeq 1$ TeV.
- 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 (in progress).