The 3-site Higgsless Model

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- General Principles
- A Simple 3-Site Model
- The 3-site model and Experiment
- Conclusions

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hep-ph/0607124
Higgsless Models and Ideal Delocalization: Review of General Principles
Higgsless models are low-energy effective theories of dynamical electroweak symmetry breaking which include the following elements

- massive 4-d gauge bosons arise in the context of a 5-d gauge theory with appropriate boundary conditions

- $WW$ scattering unitarized through exchange of KK modes (instead of Higgs exchange)

- language of Deconstruction allows a 4-d “Moose” representation of the model
Massive Gauge Bosons from Extra-D Theories

Expand 5-D gauge bosons in eigenmodes:

\[ \hat{A}_\mu^a = \frac{1}{\sqrt{\pi R}} \left[ A^{a0}_\mu(x_\nu) + \sqrt{2} \sum_{n=1}^{\infty} A^{an}_\mu(x_\nu) \cos \left( \frac{nx_5}{R} \right) \right] \]

\[ \hat{A}_5^a = \sqrt{\frac{2}{\pi R}} \sum_{n=1}^{\infty} A^{an}_5(x_\nu) \sin \left( \frac{nx_5}{R} \right) \]

4-D gauge kinetic term contains

\[ \frac{1}{2} \sum_{n=1}^{\infty} \left[ M^2_n (A_\mu^{an})^2 - 2M_n A^{an}_\mu \partial^\mu A_5^{an} + (\partial_\mu A_5^{an})^2 \right] \]

i.e., \( A_L^{an} \leftrightarrow A_5^{an} \)
Deconstructed Higgsless Models

- 5th dimension discretized
- \( \text{SU}(2)^N \times U(1) \); general \( f_j \) and \( g_k \) encompass spatially-dependent couplings, warping
- Localized fermions would sit on “branes,” i.e. sites 0, N+1, but these present difficulties

Foadi, et. al. & Chivukula et. al.
Conflict of S & Unitarity

Heavy resonances must unitarize WW scattering (since there is no Higgs!)

This bounds lightest KK mode mass: \( m_{Z_1} < \sqrt{8\pi} \, v \)

... and yields a value of the S-parameter that is

\[
\alpha S \geq \frac{4 s^2_Z c^2_Z M^2_Z}{8\pi v^2} = \frac{\alpha}{2}
\]

too large by a factor of a few!

Independent of warping or gauge couplings chosen...
Delocalized Fermions, i.e., mixing of “brane” and “bulk” modes

\[ \mathcal{L}_f = \bar{J}_L^\mu \cdot \left( \sum_{i=0}^{N} x_i \bar{A}_\mu^i \right) + J_Y^\mu A^{N+1}_\mu \]

Can Reduce Contribution to S!
Ideal Fermion Delocalization

- Recall that the light W's wavefunction is orthogonal to wavefunctions of KK modes
- Choose fermion delocalization profile to match W wavefunction profile along the 5th dimension:
  \[ g_i x_i \propto \nu_i^W \]
- No (tree-level) fermion couplings to KK modes!

\[
\hat{S} = \hat{T} = W = 0
\]
\[
Y = M_W^2 (\Sigma_W - \Sigma_Z)
\]

RSC, HJH, MK, MT, EHS hep-ph/0504114
The 3-site Model:
general principles in action
Three-site model in biology
### 3-Site Model: basic structure

\[ SU(2) \times SU(2) \times U(1) \quad g_0, g_2 \ll g_1 \]

- **Gauge boson spectrum:** photon, Z, Z', W, W'
- **Fermion spectrum:** t, T, b, B (ψ is an SU(2) doublet)
  - and also c, C, s, S, u, U, d, D plus the leptons
3-Site Model: fermion details

\[ SU(2) \times SU(2) \times U(1) \quad g_0, \ g_2 \ll g_1 \]

\[ L_f = \epsilon_L M \bar{\psi}_L \Sigma_1 \psi_R + M \bar{\psi}_R \psi_L + M \bar{\psi}_L \Sigma_2 \begin{pmatrix} \epsilon_{tR} \\ \epsilon_{bR} \end{pmatrix} \begin{pmatrix} t_{R2} \\ b_{R2} \end{pmatrix} + h.c. \]

related to degree of delocalization

Fermion Structure Motivated by 5-D
Flavor Structure Identical to Standard Model
3-Site Ideal Delocalization

General ideal delocalization condition \( g_i(\psi^f_i)^2 = g_W v^w_i \)

becomes \( \frac{g_0(\psi^f_{L0})^2}{g_1(\psi^f_{L1})^2} = \frac{v^0_W}{v^1_W} \) in 3-site model

From \( W \), fermion eigenvectors, solve for

\[ \epsilon^2_L \rightarrow (1 + \epsilon^2_{fR})^2 \left[ \frac{x^2}{2} + \left( \frac{1}{8} - \frac{\epsilon^2_{fR}}{2} \right) x^4 + \frac{5 \epsilon^4_{fR} x^6}{8} + \ldots \right] \]

For all but top, \( \epsilon_{fR} \ll 1 \) and

\[ \epsilon^2_L = 2 \left( \frac{M^2_W}{M^2_{W'}} \right) + 6 \left( \frac{M^2_W}{M^2_{W'}} \right)^2 + \ldots \]

insures \( W' \) and \( Z' \) are fermiophobic!

\[ \hat{S} = \hat{T} = W = 0 \]

\[ Y = M^2_W (\Sigma_W - \Sigma_Z) \]

Use \( WW \) scattering to see \( W' \): Birkedal, Matchev, Perelstein hep-ph/0412278
The 3-site Model and Experiment
Triplet Gauge Vertices

Hagiwara, et al. define:

\[
L_{\text{TGV}} = -ie \frac{c_Z}{s_Z} [1 + \Delta \kappa_Z] W^+ \gamma^\mu Z^\mu - ie [1 + \Delta \kappa_\gamma] W^+ \gamma^\mu A^\mu
\]

\[
- ie \frac{c_Z}{s_Z} [1 + \Delta g_1^Z] (W^{+\mu \nu} W^-_\mu - W^{-\mu \nu} W^+_\mu) Z_\nu
\]

\[
- ie (W^{+\mu \nu} W^-_\mu - W^{-\mu \nu} W^+_\mu) A_\nu
\]

In 3-site model:

\[
\Delta g_1^Z = \Delta \kappa_Z = \frac{M_W^2}{2c^2 M_{W'}^2}, \quad \Delta \kappa_\gamma = 0
\]

LEP II measurement:

\[
\Delta g_1^Z \leq 0.028 \atop @95\%\text{CL}
\]

places lower bound on \( W' \) mass:

\[
M_{W'} \geq 380 \text{ GeV} \sqrt{\frac{0.028}{\Delta g_1^Z}}
\]
... plus unitarity

and recalling \[ \epsilon_L^2 = 2 \left( \frac{M_W^2}{M_{W'}^2} \right) + 6 \left( \frac{M_W^2}{M_{W'}^2} \right)^2 + \ldots \]

this translates into \[ \epsilon_L \approx 0.30 \left( \frac{380 \text{ GeV}}{M_{W'}} \right) \]

As mentioned earlier, maintaining unitarity of WW scattering requires \[ m_{W'} < \sqrt{8\pi} \nu \approx 1.2 \text{ TeV} \]

We conclude: \[ 0.095 \leq \epsilon_L \leq 0.30 \]
$b \rightarrow s\gamma$

To keep this within bounds requires* \[ \frac{g_R^{Wtb}}{g_L^W} < 0.004 \]

which translates into the bound \[ \varepsilon_{tR} < 0.67 \]

Since \[ m_f \approx \frac{\varepsilon_L \varepsilon_{fR} M}{\sqrt{1 + \varepsilon_{fR}^2}} \]

and b-quark mass is small, we can leverage \( \varepsilon_{tR} \) to show \( \varepsilon_{bR} < 0.015 \)

hence, \( b \) is ideally delocalized like light fermions

* Larios, Perez, Yuan, hep-ph/9903394
\[ \Delta \rho \text{ at one loop} \]

In \( \epsilon_L \to 0 \) limit, can calculate leading “new” contribution

- SM contribution vanishes since \( m_t, m_b \propto \epsilon_L \)
- \( \epsilon_L \) is custodially symmetric

From the following W diagrams (and related Z diagrams)

\[ \Delta \rho \approx \frac{1}{16\pi^2} \frac{\epsilon^4_{tR} M^2}{v^2} \]

leading contribution is:
3-Site Parameter Space

Conditions setting boundaries:

\[ m_f \approx \frac{\epsilon_L \epsilon_{fR} M}{\sqrt{1 + \epsilon_{fR}^2}} \]

\[ \Delta \rho \approx \frac{1}{16\pi^2} \frac{\epsilon_{tR}^4 M^2}{v^2} \]

\[ 0.095 \leq \epsilon_L \leq 0.30 \]
3-Site Parameter Space

Rewrite in terms of $W'$ mass:

$$\epsilon_L \approx 0.30 \left( \frac{380 \text{ GeV}}{M_{W'}} \right)$$

$$380 \text{ GeV} \leq M_{W'} \leq 1.2 \text{ TeV}$$

$M_{T,B} \gg M_{W'}$
\( Z \rightarrow b\bar{b} \) at one loop

Involves heavy fermions whose mass (\( M \)) is above the reach of the effective theory. We invoke a benchmark UV completion to estimate the size of effects:

\[
\frac{\delta g_{Zbb}^{1-loop,3-site}}{g_{Zbb}^{SM}} \approx \frac{m_t^2}{16\pi^2 M^2} \approx \frac{v^2}{M^2} \frac{\delta g_{Zbb}^{1-loop,SM}}{g_{Zbb}^{SM}}
\]

This is acceptably small.

Note: ideal delocalization removes a possible obstacle:
Conclusions:
The 3-site model yields a viable effective theory of electroweak symmetry breaking valid up to 1.5 - 2 TeV

• incorporates / illustrates general principles [Higgsless models, deconstruction, ideal delocalization]

• accommodates flavor [e.g. heavy t quark]

• observables calculable at one loop

• extra gauge bosons can be relatively light [hard to find at LHC/ILC since they are fermiophobic]

Precision electroweak corrections discussed in BSM Session talks by Chivukula and Matsuzaki