The 3-site Higgsless Model

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- Review of General Principles
- A Simple 3-Site Model
- S and T at one loop
- LHC Phenomenology
- Conclusions

**hep-ph Refs:**
0607124, 060719, 0708.2588

**Collaborators:**
Belyaev, Chivukula, Coleppa, Di Chiara, He, Kuang, Kurachi, Matsuzaki, Pukhov, Qi, Tanabashi, Zhang
Higgsless Models and Ideal Delocalization: 
Review of General Principles
General Principles:

Higgsless models are low-energy effective theories of dynamical electroweak symmetry breaking including 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

Csaki/Murayama/Terning & Chivukula/He
Massive Gauge Bosons from Extra-D Theories

**KK mode**

Expand 5-D gauge bosons in eigenmodes:
e.g. for $S^1/Z_2$:

\[
\hat{A}_\mu^a = \frac{1}{\sqrt{\pi R}} \left[ A_{\mu}^{a0}(x_\nu) + \sqrt{2} \sum_{n=1}^{\infty} A_{\mu}^{an}(x_\nu) \cos \left( \frac{n x_5}{R} \right) \right]
\]

\[
\hat{A}_5^a = \sqrt{\frac{2}{\pi R}} \sum_{n=1}^{\infty} A_{5}^{an}(x_\nu) \sin \left( \frac{n x_5}{R} \right)
\]

4-D gauge kinetic term contains

\[
\frac{1}{2} \sum_{n=1}^{\infty} \left[ M_n^2 (A^a_{\mu})^2 - 2 M_n A_{\mu}^{an} \partial^\mu A_{5}^{an} + (\partial_\mu A_{5}^{an})^2 \right]
\]

i.e., \( A_{L}^{an} \leftrightarrow A_{5}^{an} \)
Deconstructed Higgsless Models

- 5th dimension discretized
- SU(2)^N x U(1); general f_j and g_k encompass spatially-dependent couplings, warping
- for fixed v, \[ \frac{1}{v^2} = \sum_i \frac{1}{f_i^2} \] means \[ f_i \sim \sqrt{N} v \]
- In simplest models, Localized fermions sit on “branes” [sites 0 and N+1]

Foadi, et. al. & Chivukula et. al.
Generalizations

- by folding, represent SU(2) x SU(2) x U(1) in “bulk”
- modify fermions’ location (brane? bulk?)
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

\[
\alpha S \geq \frac{4s_Z^2 c_Z^2 M_Z^2}{8\pi v^2} = \frac{\alpha}{2}
\]

too large by a factor of a few!

Independent of warping or gauge couplings chosen...
Delocalized Fermions

Delocalized Fermions, i.e., mixing of “brane” and “bulk” modes

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

Can Reduce Contribution to S!

Cacciapaglia, Csaki, Grojean, & Terning

Foadi, Gopalkrishna, & Schmidt
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:

\[ g_i x_i \propto v_i^W \]

• 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
3-Site Model: basic structure

\( SU(2) \times SU(2) \times U(1) \)

\( g_0, g_2 \ll g_1 \)

Gauge boson spectrum: photon, Z, Z', W, W' (as in BESS)

Fermion spectrum: t, T, b, B (\( \psi \) is an SU(2) doublet)

and also c, C, s, S, u, U, d, D plus the leptons

Chivukula hep-ph/0607124
3-Site Model: fermion details

\[ SU(2) \times SU(2) \times U(1) \]

\[ g_0, g_2 \ll g_1 \]

Fermion Structure Motivated by 5-D

Flavor Structure Identical to Standard Model
3-Site Ideal Delocalization

General ideal delocalization condition \[ g_i(\psi_i^f)^2 = g_W v_i^w \]

becomes \[ \frac{g_0(\psi_{L0}^f)^2}{g_1(\psi_{L1}^f)^2} = \frac{v_0^W}{v_1^W} \] in 3-site model

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

\[ \epsilon_L^2 \rightarrow (1 + \epsilon_{fR}^2)^2 \left[ \frac{x^2}{2} + \left( \frac{1}{8} - \frac{\epsilon_{fR}^2}{2} \right) x^4 + \cdots \right] \]

\[ x^2 \equiv \left( \frac{g_0}{g_1} \right)^2 \approx 4 \left( \frac{M_W}{M_W'} \right)^2 \]

For all but top, \( \epsilon_{fR} \ll 1 \) and \[ \epsilon_L^2 = 2 \left( \frac{M_W^2}{M_W'^2} \right) + 6 \left( \frac{M_W^2}{M_W'^2} \right)^2 + \cdots \]

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

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

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

Use WW scattering to see \( W' \): Birkedal, Matchev, Perelstein hep-ph/0412278
3-Site Parameter Space

Heavy fermion mass $M_{T,B}$

Allowed Region $M_{T,B} \gg M_{W'}$

Unitarity violated

WWZ vertex visibly altered

I-loop fermionic EW precision corrections too large

Chivukula hep-ph/0607124
S and T gauge corrections at one loop
**Electroweak Parameters**

EW corrections \((S, T)\) are defined from amplitudes for “on-shell” 4-fermion processes

\[-A_{NC} = e^2 \frac{Q Q'}{Q^2} + \frac{(I_3 - s^2 Q)(I'_3 - s^2 Q')}{(\frac{s^2 c^2}{e^2} - \frac{s}{16\pi}) Q^2} + \frac{1}{4\sqrt{2}G_F} (1 - \alpha T) + \text{flavor dependent}\]

**Universal Corrections Depend only on External Quantum Numbers!**

Gauge-Invariant, **to all orders**, as defined here!

\[S, T: \text{ Peskin & Takeuchi, Altarelli, et. al. and Hagiwara, et. al.} \]
\[\text{Chivukula, Kurachi, He, EHS & Tanabashi hep-ph/0408262 & 0410154} \]
\[\text{Hagiwara, Matsumoto, Haidt, & Kim: hep-ph/9409380} \]
Gauge-invariance of scattering amplitudes arises by addition of vertex and box corrections to the familiar gauge-boson self-energy corrections (which are not gauge-invariant on their own).
Gauge-Boson Self-Energies

Working in 't Hooft-Feynman gauge, the following types of corrections to gauge-boson self-energies appear in the calculation of $S$

The gauge-dependence is canceled by...
Gauge-Dependent Box and Vertex Contributions

Pinch Technique: collect all such contributions in an effective self-energy function.

\[ \propto [gT^+, gT^-] = 2g^2T_3 \]

Cornwall, 1982  Cornwall and Papavassiliou, 1989  Degrassi and Sirlin, 1992
Pinch Contributions to $\mathcal{S}$ in 3-site model

Conventional pinch contributions from 3-point vertex in `t Hooft-Feynman gauge

\[ \mathcal{L}'_f = x_1 \cdot \bar{\psi}_L (i \not{D} \Sigma_{(1)} \Sigma^\dagger_{(1)}) \psi_L \]

Additional piece from delocalization
\[ \alpha S_{3-site} = \frac{4s^2 M_W^2}{M_W'} \left( 1 - \frac{x_1 M_W^2}{2M_W^2} \right) \]

tree; involves ideal delocalization \((x_1)\)

\[ + \frac{\alpha}{12\pi} \ln \frac{M_W^2}{M_{H_{ref}}^2} \]

one-loop; up to \(W'\) mass

\[ - \frac{3\alpha}{2\pi} \left[ \frac{41}{36} - \frac{x_1 M_W^2}{8M_W^2} \right] \ln \left( \frac{\Lambda^2}{M_W'} \right) \]

one-loop; up to cutoff

\[ - 8\pi \alpha \left( c_1(\Lambda) + c_2(\Lambda) \right) \]

counterterms; cf. \(L_{10}\)

\[ c_2 g \tilde{g} Tr(W_1^{\mu\nu} \Sigma_1 W_2_{\mu\nu} \Sigma_1^\dagger) + c_1 g \tilde{g} Tr(W_2^{\mu\nu} \Sigma_2 B_{\mu\nu} \Sigma_2^\dagger) \]

link 1

link 2

Perelstein hep-ph/0408072

Matsuzaki hep-ph/0607191
\[ \alpha T_{3-site} = 0 \]

\[ - \frac{3\alpha}{16\pi c^2} \ln \frac{M_{W'}^2}{M_{H_{ref}}^2} \]

\[ - \frac{3\alpha}{32\pi c^2} \ln \frac{\Lambda^2}{M_W^2} \]

\[ + \frac{4\pi\alpha}{c^2} c_o(\Lambda) \]

\[ + \text{contributions from weak-isospin violation in fermion sector} \]

\[ c_og_2^2 f^2 \left[ \text{Tr} \left( D_\mu \Sigma (2) \frac{T_3}{2} \Sigma^\dagger (2) \right) \right]^2 \]

Matsuzaki hep-ph/0607191
We also used RGE techniques to compute the one-loop corrections to all $O(p^4)$ counter-terms in the three-site model in Landau gauge. 

Chivukula hep-ph/0702218

Our RGE results for $S$ and $T$ agree with those of our Pinch-Technique calculation in 't Hooft-Feynman gauge. Matsuzaki hep-ph/0607191

A subsequent calculation via another approach also agrees with the results presented here. Dawson hep-ph/0703299
LHC Phenomenology
(calculations courtesy of CalcHEP, MADGRAPH, and HANLIB)
Gauge boson widths and branchings

- Fermiophobic nature of the gauge bosons is crucial
- Dominant decay into WW and WZ pairs
- $Z'$ Br does not depend much on deviation from ideal delocalization

\[
\Gamma(Z' \rightarrow W^+W^-) = \frac{e^2 M_{W'}}{192\pi x^2 s_w^2}
\]

\[
\Gamma(Z' \rightarrow e^+e^-) = \frac{5e^2 M_W x^2 s_w^2}{384\pi c_w^4}
\]
$W'$ branching fraction to fermion pairs

- is quite sensitive to deviation from ideal delocalization
- but is always very small

\[
\Gamma(W' \to e^+ e^-) = \frac{e^2 M_{W'} x^2 \left(1 - \frac{2cL}{x^2}\right)^2}{192\pi s_w^2}
\]
**W’ and Z’ bosons at LHC**

**Production**

- **DY**
  \[ pp \rightarrow Z'(W') \]

- **VBF**
  \[ pp \rightarrow W'(Z')j \]

- **AP**
  \[ pp \rightarrow WZ', WW', ... \]

**Decay**

- **Z’**
  \[ Z' \rightarrow \ell^+\ell^-, t\bar{t} \]

- **W’**
  \[ W' \rightarrow \ell\nu, tb \]

- **Z’**
  \[ Z' \rightarrow W^+W^- \rightarrow \ell^+\ell^- \]

\[ W' \rightarrow WZ \rightarrow \ell\ell\nu \]
Vector Boson Fusion ($WZ \rightarrow W'$) and $W'Z$ Associated Production promise large rates and clear signatures.
Example: CalcHEP

computation of $pp \rightarrow W^+ Z jj$

- **No effective WZ approximation.**
- **Complete set of signal and background diagrams including interference.**

in contrast with Birkedal, Matchev & Perelstein 2005
Associated Production (signal in WZZ channel)

500 GeV W' boson

\[ M_{jj} = 80 \pm 15 \text{ GeV}, \quad \Delta R(jj) < 1.5, \quad \sum_z p_T(Z) + \sum_j p_T(j) = \pm 15 \text{ GeV}. \]

\[ p_{T\ell} > 10 \text{ GeV}, \quad |\eta_\ell| < 2.5, \quad p_{Tj} > 15 \text{ GeV}, \quad |\eta_j| < 4.5. \]
Vector Boson Fusion (signal in WZjj channel)
500 GeV W’ boson

Background is 10x larger than estimated in Birkedal, Matchev & Perelstein (2005)

forward jet tag removes WZ background

\[ E_j > 300 \text{ GeV}, \quad p_{Tj} > 30 \text{ GeV}, \quad |\eta_j| < 4.5, \quad |\Delta \eta_{jj}| > 4. \]

\[ p_{T\ell} > 10 \text{ GeV}, \quad |\eta_\ell| < 2.5 \]
Integrated LHC Luminosity required to discover $W'$ in each channel
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]

• extra gauge bosons can be relatively light
  [since they are fermiophobic]

• EW observables calculable at one loop

• $W'$ and $Z'$ promise clean multi-lepton signatures at LHC [gauge invariance is key to accurate calculation of rate]