Deconstructed Higgsless Models at the LHC

Elizabeth H. Simmons
Michigan State University

Introduction
Models
LHC Phenomenology
Conclusions
Introduction
Deconstructed Higgsless Models
Higgsless Models:

Higgsless models are low-energy effective theories of dynamical electroweak symmetry breaking in which:

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

- WW scattering is unitarized through exchange of KK modes (not via Higgs exchange)

The language of Deconstruction allows us to create a 4d “Moose” representation of the model.
Deconstructed Higgsless Models

- Discretize 5th dimension: 4D gauge group at each site; link is non-linear sigma model \( \Sigma(x) = \exp(i \pi^a(x) \sigma^a / v) \)
- Example shown is an SU(2)^N \times U(1); the \( f_j \) and \( g_k \) can encompass spatially-dependent couplings, warping
- for fixed \( v \), relation \( \frac{1}{v^2} = \sum_i \frac{1}{f_i^2} \) means each \( f_i \sim \sqrt{N} v \)
- In the simplest models, localized fermions are charged under groups at sites 0 and N+1 [“live on the branes”]

Foadi, et. al. & Chivukula et. al.
**Conflict: S vs Unitarity**

Heavy gauge boson exchange must unitarize WW scattering in these models (since there is no Higgs)

The **lightest KK mode** mass satisfies: $m_{Z_1} < \sqrt{8\pi} v$

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

$$\alpha S \geq \frac{4s_Z^2 c_Z^2 M_Z^2}{8\pi v^2} = \frac{\alpha}{2} \quad \text{too large!}$$

This applies to any model with brane-localized fermions, independent of warping or gauge couplings chosen...
Solution: Delocalized Fermions

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

\[ L_f = \vec{J}_L^\mu \cdot \left( \sum_{i=0}^{N} x_i \vec{A}_\mu^i \right) + J_{Y}^\mu A_{\mu}^{N+1} \]

Can reduce fermionic contributions to the S-parameter

Cacciapaglia, Csaki, Grojean, & Terning

Foadi, Gopalakrishna, & Schmidt
Ideal Fermion Delocalization

- The light $W$’s wavefunction is orthogonal to the wavefunctions of the higher 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!

$$ \hat{S} = \hat{T} = W = 0 $$

$$ Y = M_W^2 (\Sigma_W - \Sigma_Z) $$

Chivukula, He, Kurachi, Tanabashi, EHS  0504114
Models:
Three-site Model
Top Triangle Moose
The Three-Site Model

Gauge structure: $SU(2) \times SU(2) \times U(1)$

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

Fermion spectrum: $t$, $T$, $b$, $B$; similar for light quarks & leptons

3-site model refs: Chivukula, Coleppa, Di Chiara, He, Kurachi, EHS, & Tanabashi: hep-ph/0607124
Chivukula, He, Kurachi, EHS, & Tanabashi: hep-ph/0504114 and hep-ph/0612070

Related Work: Hidden Local Symmetry: Bando, Kugo, Uehara, Yamawaki, Yanagida 1985
BESS: Casalbuoni, De Curtis, Dominici, Gatto 1985
3-Site Model: fermion masses

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

ideal delocalization sets this value as
\[ \epsilon_L^2 = M_W^2 / 2M_W^2 \]

ordinary fermion masses are of the form
\[ m_f \approx M \epsilon_L \epsilon_{fR} \]

each ordinary fermion mass value is tied to \( \epsilon_{fR} \)

heavy fermion masses are \( \sim M \)
pre-LHC Constraints on 3-Site Model

Chivukula et al. hep-ph/0607124

Heavy fermion mass $M_{T,B}$

Allowed Region $M_{T,B} >> M_{W'}$

Heavy $W'$ mass $M_{W'}$

$\Delta \rho = \frac{M^2 \epsilon_{tR}^4}{16 \pi^2 v^2}$

WWZ vertex visibly altered

I-loop fermionic EW precision corrections too large

Unitarity violated
**The Top Triangle Moose**

**Gauge structure:**

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

\[ g_0, g_2 \ll g_1 \]

**Top-Higgs**

\[ \langle \Phi \rangle = v \sin \omega \]

**Gauge boson spectrum:**

Photon, Z, Z', W, W' (as in 3-site, BESS or HLS)

**Fermion spectrum:**

t, T, b, B; similar for light quarks & leptons; only top couples to \( \Phi \)

f-constants of \( \Sigma_{01}, \Sigma_{12} \) are \( v \sqrt{2} \cos \omega \)

---

R.S. Chivukula, N.Christensen, B. Coleppa, EHS arXiv:0906.5667
Key Mass Terms

Top quark: \(-\lambda_t \bar{\psi}_{L0} \Phi t_R\)

Top-pions: \(4\pi\kappa v^3 \text{Tr} \left( \Phi \Sigma_{01} \Sigma_{12}^\dagger \right)\)

All fermions (including top):

\[
M_D \left[ \epsilon_L \bar{\psi}_{L0} \Sigma_{01} \psi_{R1} + \bar{\psi}_{R1} \psi_{L1} + \bar{\psi}_{L1} \Sigma_{12} \begin{pmatrix} \epsilon_{uR} & 0 \\ 0 & \epsilon_{dR} \end{pmatrix} \begin{pmatrix} u_{R2} \\ d_{R2} \end{pmatrix} \right]
\]

ideal delocalization sets this value as \(\epsilon_L^2 = M_W^2 / 2M_W^2\).

light fermion masses are of the form \(m_f \approx M_D \epsilon_L \epsilon_{fR}\)

each light mass value is tied to the value of \(\epsilon_{fR}\)

Top mass value is different...
Top Mass

\[ M_t = M_D \begin{pmatrix} \epsilon_{tL} & a \\ 1 & \epsilon_{tR} \end{pmatrix} \cdot a \equiv \frac{\lambda_t v \sin \omega}{M_D} \]

Perturbative diagonalization yields...

\[ m_t = \lambda_t v \sin \omega \left[ 1 + \frac{\epsilon_{tL}^2 + \epsilon_{tR}^2 + \frac{2}{a} \epsilon_{tL} \epsilon_{tR}}{2(-1 + a^2)} \right] \]

Top mass depends strongly on \( \lambda_t \), weakly on \( \epsilon_{tR} \)

Therefore, achieving a large top mass does not conflict with making \( \epsilon_{tR} \) small to control the size of \( t_{R2}, b_{R2} \). KK fermions are light enough to produce at LHC
LHC Phenomenology

KK gauge bosons (either model)
KK fermions (top triangle only)

R.S. Chivukula, N.Christensen, B. Coleppa, EHS
W', Z' Production and Decay at LHC (both models)
Vector Boson Fusion ($\text{WZ} \rightarrow \text{W}'$) and $\text{W}'\text{Z}$ Associated Production promise large rates and clear signatures.

$E_j > 300 \text{GeV}, \quad p_{T,j} > 30 \text{GeV}$

$|\eta_j| < 4.5, \quad |\Delta \eta_{jj}| > 4.$

$\sigma (\text{fb})$

$pp \rightarrow W'jj \rightarrow WZjj \rightarrow 3l\nu jj$

$pp \rightarrow W'Z \rightarrow WZZ \rightarrow jj4l$

$M_{W'} \ (\text{GeV})$
Associated Production (signal in WZZ channel)

500 GeV W’ boson

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

$p_{T\ell} > 10$ GeV, \quad |\eta_\ell| < 2.5, \quad p_{Tj} > 15$ 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

![Graph showing the integrated luminosity (fb⁻¹) vs. $M_{W_1}$ (GeV) for $W'_0 Z_0 Z_0$, $W'_0 Z_0 jj$, and $W'_0 Z_0 jj$ channels. The graph includes curves for 5σ and 3σ significance levels.](image-url)
KK Quark Production at LHC
(triangle moose only)

Pair Production

\[ q \quad g \quad Q \]
\[ \bar{q} \quad Q \quad g \]

Single Production

\[ u,d \quad U,D \]
\[ u,d \quad Z,Z' \]
\[ u,d \quad u,d \]
**KK Quark Decay and Detection**

**QQ signature:** \( pp \rightarrow Q\bar{Q} \rightarrow WZqq \rightarrow \ell\ell\ell jj E_T \)

**Qq signature:** \( pp \rightarrow Qq \rightarrow W'qq \rightarrow WZqq \rightarrow \ell\ell\ell jj E_T \)

\( M_{Z'} = 500 \text{ GeV} \)
Pair Production

Combined with basic identification and separation cuts on jets and leptons, a hard jet $p_T$ cut removes nearly all SM background.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T j$</td>
<td>$&gt;100$ GeV</td>
</tr>
<tr>
<td>$p_T l$</td>
<td>$&gt;15$ GeV</td>
</tr>
<tr>
<td>Missing $E_T$</td>
<td>$&gt;15$ GeV</td>
</tr>
<tr>
<td>$</td>
<td>\eta_j</td>
</tr>
<tr>
<td>$</td>
<td>\eta_l</td>
</tr>
<tr>
<td>$\Delta R_{jj}$</td>
<td>$&gt;0.4$</td>
</tr>
<tr>
<td>$\Delta R_{jl}$</td>
<td>$&gt;0.4$</td>
</tr>
<tr>
<td>$M_{ll}$</td>
<td>$89$ GeV $&lt; M_{ll} &lt; 93$ GeV</td>
</tr>
</tbody>
</table>

# events

$M_D = 300$ GeV

$M_D = 700$ GeV
Single Production

Identification and separation cuts on jets and leptons, a hard jet $p_T$ cut, and jet & lepton rapidity cuts control the SM background

<table>
<thead>
<tr>
<th>Variable</th>
<th>Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_{T,j}$ hard</td>
<td>$&gt;200$ GeV</td>
</tr>
<tr>
<td>$p_{T,j}$ soft</td>
<td>$&gt;15$ GeV</td>
</tr>
<tr>
<td>$p_{Tl}$</td>
<td>$&gt;15$ GeV</td>
</tr>
<tr>
<td>Missing $E_T$</td>
<td>$&gt;15$ GeV</td>
</tr>
<tr>
<td>$</td>
<td>\eta_j</td>
</tr>
<tr>
<td>$</td>
<td>\eta_j</td>
</tr>
<tr>
<td>$</td>
<td>\eta_l</td>
</tr>
<tr>
<td>$\Delta R_{jj}$</td>
<td>$&gt;0.4$</td>
</tr>
<tr>
<td>$\Delta R_{jl}$</td>
<td>$&gt;0.4$</td>
</tr>
</tbody>
</table>
Integrated Luminosity for $5\sigma$ detection of KK quarks at LHC (fb$^{-1}$)
Conclusions
Conclusions

• Deconstructed Higgsless models like the 3-site model and top triangle moose use $W'$, $Z'$ to unitarize $W_LW_L$ scattering and ideal fermion delocalization to minimize precision EW corrections.

• The fermiophobic $W'$ bosons of either model will be visible in gauge boson fusion or associated production channels at LHC across their full mass range.

• In the top triangle moose, a topcolor-like mechanism generates the heavy top quark mass. As a result, the KK quarks can be light enough to be detected at LHC.

• Pair and single KK quark production channels at LHC will jointly cover the parameter space.
Library
Massive Gauge Bosons from Extra-D Theories

Expand 5-D gauge bosons in eigenmodes:

\[ \hat{A}_\mu^a = \frac{1}{\sqrt{\pi R}} \left[ A_{\mu 0}^a(x_\nu) + \sqrt{2} \sum_{n=1}^{\infty} A_{\mu n}^a(x_\nu) \cos \left( \frac{nx_5}{R} \right) \right] \]

\[ \hat{A}_5^a = \sqrt{\frac{2}{\pi R}} \sum_{n=1}^{\infty} A_{5 n}^a(x_\nu) \sin \left( \frac{nx_5}{R} \right) \]

4-D gauge kinetic term contains

\[ \frac{1}{2} \sum_{n=1}^{\infty} \left[ M_n^2 (A_{\mu 0}^a)^2 - 2 M_n A_{\mu n}^a \partial^\mu A_5^a + (\partial_\mu A_5^a)^2 \right] \]

i.e., \( A_{\mu 5}^a \leftrightarrow A_5^a \)
Symmetry (breaking) structure at a glance
A familiar example:

\[
\text{SU}(2)_W \times \text{U}(1)_B \rightarrow \text{U}(1)
\]

Each circle is a global SU(2) of which all (solid) or a U(1) subgroup (dashed) is gauged
Low-energy symmetry-breaking sector is described by non-linear sigma-model fields

\[
\sum(x) = \exp(i \pi^a(x) \sigma^a / v)
\]

Solid line linking two circles is an [SU(2) x SU(2) / SU(2)] non-linear sigma model field; at scale v, it breaks the symmetries of the attached circles
\[\sum\] is a 2x2 matrix field transforming as \[\sum \rightarrow L \sum R^\dagger\]
under the SU(2) groups which it connects.
3-Site Ideal Delocalization

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

becomes \( \frac{g_0(\psi_{L0}^f)^2}{g_1(\psi_{L1}^f)^2} = \frac{v_W^0}{v_W^1} \) 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
Electroweak Parameters

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

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

Universal Corrections Depend only on External Quantum Numbers!

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

Hagiwara, Matsumoto, Haidt, & Kim: hep-ph/9409380
Wave functions

Gauge boson properties resemble those in 3-site model, BESS, or HLS:

-- wavefunctions [$W'$, $Z'$ mainly on site 1]
-- couplings to fermions
-- phenomenology

Ideal fermion delocalization:

To minimize tree-level S-parameter, light fermion wave functions mimic $W$ (as in 3-site model)
To avoid tree-level corrections to $Rb$, top delocalizes in same way as light quarks
Fraction of ordinary LH fermion on site 1 is $\propto \frac{M_W}{M_W'}$