Electroweak Symmetry Breaking without a Higgs Boson

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1. Introduction
2. The Origin of Mass (and the Higgs)
3. Chiral Symmetry Breaking: Technicolor
4. Extra Dimensions: Higgsless Models
5. Conclusions

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Introduction:
Fundamental Particles and Fundamental questions
Subatomic Structure

- Electron: \(<10^{-16}\) cm
- Proton (neutron): \(\sim 10^{-13}\) cm
- Quark: \(<10^{-16}\) cm

Atom: \(\sim 10^{-8}\) cm
Nucleus: \(\sim 10^{-12}\) cm
Force Carriers (bosons)

- SU(3)
- QCD
- SU(2)
- U(1)

The particle drawings are simple artistic representations.
Matter Particles (fermions)

Each can exist in LH and RH chirality

LH (RH) version is charged (neutral) under weak interactions
Mass Mysteries

Otherwise similar particles are seen experimentally to have very different masses (e.g. muon & electron).

Plotting masses in units of the proton mass (1 GeV):

<table>
<thead>
<tr>
<th>e</th>
<th>u</th>
<th>d</th>
<th>μ</th>
<th>s</th>
<th>c</th>
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<td>.001</td>
<td>.01</td>
<td>.1</td>
<td>1</td>
<td>10</td>
<td>100</td>
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(← γ, g)  

W Z

Two "symmetry breaking" mysteries emerge:

- **Flavor** Whence the diverse fermion masses?
- **Electroweak** Why are the W & Z heavy while the γ is massless?
The Origin of Mass: Electroweak Symmetry Breaking and the Higgs
From the masses of the electroweak gauge bosons:

\[ m_\gamma = 0 \] (purely transverse)

\[ M_W, M_Z \neq 0 \] (has a longitudinal mode too)

An apparent **contradiction** emerges:

- \( W^\pm \) and \( Z^0 \) are **massive** gauge bosons
- mass implies a Lagrangian term \( M_W^2 W^\mu W_\mu \)
  
  ... but this term is not gauge-invariant!
Resolution: $SU(2)_W$ gauge symmetry is broken at the energies probed by experiment so far.

Furthermore:

- $W$ bosons are electrically charged ($\pm 1$)
  $\Rightarrow$ weak and electromagnetic forces are related
- $U(1)_{EM}$ is the low-energy remnant of a high-energy electroweak gauge symmetry $SU(2)_W \times U(1)_Y$
- how to achieve this symmetry breaking?
is symmetry explicitly broken? 

i.e., just add $W$ mass term into Lagrangian? ....

**No:** look at high-energy $W_L W_L \rightarrow W_L W_L$ scattering

\[ \mathcal{A}_{\text{tree level}} \sim \frac{E_{\text{c.m.}}^2}{M_W^2} \]

unitarity violated by $E_{\text{cm}} \sim 1000$ GeV
must have spontaneous symmetry breaking

- Lagrangian is symmetric; ground state is not
- example: ferromagnetism

\[ \mathcal{H} \sim \sum (-\vec{s}_i \cdot \vec{s}_j) \]
The SM Higgs

A Fundamental Scalar Doublet:

\[ \phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \]

with potential:

\[ V(\phi) = \lambda \left( \phi^\dagger \phi - \frac{v^2}{2} \right)^2 \]

is employed both to break the electroweak symmetry and to generate masses for the fermions in the Standard Model.
The potential is minimized away from the origin, so the scalar acquires a non-zero vacuum expectation value:

\[
\langle \phi \rangle = (0, v/\sqrt{2}) \quad \text{breaks} \quad SU(2)_w \times U(1)_Y \to U(1)_{\text{EM}}
\]

- breaking this symmetry yields 3 Nambu-Goldstone bosons which become the \( W_L^+ \), \( W_L^- \), \( Z_L \) modes
- scalars’ kinetic energy term \( D^\mu \phi^\dagger D_\mu \phi \) includes

\[
\frac{1}{4} g^2 W^\mu \phi^\dagger W_\mu \phi \to \frac{1}{8} g^2 v^2 W^\mu W_\mu \quad \left( \frac{1}{2} M_W^2 \text{ (W mass!)} \right)
\]

The **Nambu-Goldstone bosons** are the key to providing mass for the \( W \) and \( Z \).
The remaining scalar ($H = \text{Higgs Boson}$) resolves the unitarity problem:

\[ g^2 \frac{E^2}{m_W^2} \]

(a) $+ 2 - 6 \cos \theta$

(b) $- \cos \theta$

(c) $- \frac{3}{2} + \frac{15}{2} \cos \theta$

(d + e) $- \frac{1}{2} - \frac{1}{2} \cos \theta$

**Sum including (d+e)** $0$

\[ \mathcal{O}(E^0) \Rightarrow 4d \ m_H \text{ bound: } m_H < \sqrt{16\pi/3} \nu \simeq 1.0 \text{ TeV} \]

\[ \mathcal{O}(E^2) \Rightarrow E < \sqrt{4\pi} \nu \simeq 0.9 \text{ TeV} \]
Bonus: fermion masses are generated too

A fermion mass term in the Lagrangian takes the form

$$m_f (f_L f_R + f_R f_L)$$

- because this term is not a weak singlet ($f_L$ and $f_R$ have different weak charges) it can exist only if the electroweak symmetry is broken

A weak doublet of scalars $\phi$ couples to fermions, $\bar{\lambda} f \phi f$, yielding two effects when the symmetry breaks

- fermion coupling to Goldstone modes produces fermion mass terms with $m_f = \lambda \langle \phi \rangle = \lambda v / \sqrt{2}$
- coupling to remaining $H$ allows the Higgs boson to decay to fermions
Problems with the Higgs Model

• No fundamental scalars observed in nature

• No explanation of dynamics responsible for Electroweak Symmetry Breaking

• Hierarchy or Naturalness Problem

\[ m_H^2 \propto \Lambda^2 \]

• Triviality Problem...

\[ \Rightarrow \beta = \frac{3\lambda^2}{2\pi^2} > 0 \quad \lambda(\mu) < \frac{3}{2\pi^2 \log \frac{\Lambda}{\mu}} \]
Interim Conclusions

• The electroweak symmetry is spontaneously broken

• The Nambu-Goldstone bosons of the broken continuous symmetry become the $W_L$ and $Z_L$

• Additional states must exist in order to unitarize the scattering of $W_L$ and $Z_L$

• The Standard Higgs Model is, at best, a low-energy effective theory valid below a scale $\Lambda$ characteristic of the underlying physics

• What lies beyond the Standard Higgs Model? How can we tell?
A Fork in the Road...

• Make the Higgs Natural: Supersymmetry

• Make the Higgs Composite
  – Little Higgs
  – Twin Higgs

• Eliminate the Higgs
  – Technicolor
  – “Higgsless” Models

“When you come to a fork in the road, take it!”
— Yogi Berra
Chiral Symmetry Breaking: Technicolor
For a new approach to generating mass, we turn to the strong interactions (QCD) for inspiration.

Consider the hadrons composed of up and down quarks:

Why is the pion so light?
Recall that the QCD coupling varies with energy scale
QCD Lagrangian for u, d quarks, neglecting masses,

\[ \mathcal{L} = i \bar{u}_L \gamma^\mu d_L + i \bar{d}_L \gamma^\mu d_L + i \bar{u}_R \gamma^\mu u_R + i \bar{d}_R \gamma^\mu d_R \]

displays $SU(2)_L \times SU(2)_R$ global symmetry when color becomes strong ($\Lambda_{QCD} \sim 1 \text{ GeV}$),

- $\langle \bar{q}_L q_R \rangle \neq 0$ breaks $SU(2)_L \times SU(2)_R \rightarrow SU(2)_{L+R}$
- Pions $(\bar{q}_L q_R)$ are Nambu–Goldstone bosons!

**Bonus:** $q_L$, $q_R$ have different $SU(2) \times U(1)$ charges,

- $q_L$ form weak doublet; $q_R$ are weak singlets
- So $\langle \bar{q}_L q_R \rangle \neq 0$ also breaks electroweak symmetry
- Can QCD pions be our composite Higgs bosons?
**bonus:** $q_L, \ q_R$ have different $SU(2) \times U(1)$ charges,

- $q_L$ form weak doublet; $q_R$ are weak singlets
- so $\langle q_L q_R \rangle \neq 0$ also breaks electroweak symmetry
- can QCD pions be our composite Higgs bosons?

**Not Quite:** $M_W = \frac{1}{2} g \langle \rangle = 80$ GeV requires $\langle \rangle \sim 250$ GeV

- $\langle q_L q_R \rangle$ only supplies $\sim 0.1$ GeV
- need extra source of dynamical symmetry breaking
This line of reasoning inspired Technicolor:

introduce new gauge force with symmetry $SU(N)_{TC}$

(technigluons inspired by QCD gluons)

add technifermions carrying $SU(N)_{TC}$ charge

(techniquarks inspired by QCD quarks)

- e.g. $T_L = (U_L, D_L)$ $U_R$, $D_R$

- $\mathcal{L}$ has global $SU(2)_L \times SU(2)_R$ symmetry

Susskind, Weinberg
if $SU(N)_{TC}$ force were stronger than QCD...

spontaneous symmetry breaking and pion formation would happen at a higher energy scale... e.g.

- gauge coupling becomes large at $\Lambda_{TC} \approx 1000$ GeV
- $\langle \bar{T}_L T_R \rangle \approx 250$ GeV breaks electroweak group
- ‘technipions’ ($\Pi_T$) become $W_L, Z_L$
- $W$ and $Z$ boson masses are the right size

So far, so good...
ρ meson unitarizes $\pi\pi$ scattering in QCD

Data for spin-1 isospin-1 $\pi\pi$ scattering

Donoghue, et. al., PRD 38 (1988) 2195

We expect similar behavior in WW scattering due to the techni-$\rho$ ... which should be ~2500 times heavier

$M_{\rho_{TC}} \approx 2 \text{ TeV} \sqrt{\frac{3}{N_{TC}}}$
Prediction: Techni-$\rho$ in WW scattering at LHC

<table>
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<th>leptonic cuts</th>
<th>jet cuts</th>
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<tr>
<td>$</td>
<td>y(\ell)</td>
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<tr>
<td>$p_T(\ell) &gt; 40$ GeV</td>
<td>$3.0 &lt;</td>
</tr>
<tr>
<td>$p_T^{\text{miss}} &gt; 50$ GeV</td>
<td>$p_T(j_{tag}) &gt; 40$ GeV</td>
</tr>
<tr>
<td>$p_T(Z) &gt; \frac{1}{4} M_T$</td>
<td>$p_T(j_{\text{veto}}) &gt; 60$ GeV</td>
</tr>
<tr>
<td>$M_T &gt; 500$ GeV</td>
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For $M_{\rho TC} = 1.0$ TeV, 2.5 TeV:

*J. Bagger et. al., hep-ph/9306256, 9504426*
Precision Electroweak Corrections

Deviations from Standard Model \((S, T)\) are defined from amplitudes for “on-shell” 4-fermion scattering processes

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

\(S\): size of electroweak symmetry breaking sector

\(T\): tendency of corrections to alter ratio \(M_W/M_Z\)

data are sensitive to quantum corrections; constrain \(S, T\) to be small

S, T: Peskin & Takeuchi
**Fermion Masses**

In extended technicolor* (ETC) models, new heavy gauge bosons couple ordinary and techni- fermions. As a result, fermions acquire mass when technifermions condense. E.g. the top quark’s mass comes from:

\[
\text{and its size is } m_t \approx \frac{g^2}{M^2} \langle T \bar{T} \rangle \times \text{(flavor-dependent factor)}
\]

**Challenge:** ETC would cause rare processes to happen at enhanced rates excluded by data

*Dimpoulous & Susskind; Eichten & Lane*
Walking Technicolor

- Pushes flavor symmetry breaking to higher scale (M), so rare process rates agree with data

- Precision electroweak corrections no longer calculable by analogy with QCD ... smaller?
Extra Dimensions:
Higgsless Models
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.
Massive Gauge Bosons from Extra-D Theories

Expand 5-D gauge bosons in eigenmodes:

\[ 
\hat{A}_\mu^a = \frac{1}{\sqrt{\pi R}} \left[ A_\mu^{a0}(x_\nu) + \sqrt{2} \sum_{n=1}^{\infty} A_\mu^{an}(x_\nu) \cos \left( \frac{nx_5}{R} \right) \right] 
\]
\[ 
\hat{A}_5^a = \sqrt{\frac{2}{\pi R}} \sum_{n=1}^{\infty} A_5^{an}(x_\nu) \sin \left( \frac{nx_5}{R} \right) 
\]

4-D gauge kinetic term contains

\[ 
\frac{1}{2} \sum_{n=1}^{\infty} \left[ M_n^2 (A_\mu^{an})^2 - 2 M_n A_\mu^{an} \partial^\mu A_5^{an} + (\partial_\mu A_5^{an})^2 \right] 
\]
i.e., \( A_L^{an} \leftrightarrow A_{5}^{an} \)
4-D KK Mode Scattering

Cancellation of bad high-energy behavior through exchange of massive vector particles

\[
\begin{array}{c}
\text{graph} & g^2C_{eab}C_{ecd} & g^2C_{eac}C_{edb} & g^2C_{ead}C_{ebc} \\
(a) & 6c(x^4 - x^2) & \frac{3}{2}(3 - 2c - c^2)x^4 & -3(3 + 2c - c^2)x^4 \\
& -3(1 - c)x^2 & +3(1 + c)x^2 \\
(b1) & -2c(x^4 - x^2) & & \\
(c1) & -4cx^4 & & \\
(b2, 3) & \frac{1}{2}(3 - 2c + c^2)x^4 & \frac{1}{2}(3 + 2c - c^2)x^4 & +3(1 - c)x^2 & -3(1 + c)x^2 \\
(c2, 3) & (-3 + 2c - c^2)x^4 & (3 + 2c - c^2)x^4 & -8cx^2 & -8cx^2 \\
\text{Sum} & -8cx^2 & -8cx^2 & -8cx^2 \Rightarrow 0 \\
\end{array}
\]

RSC, H.J. He, D. Dicus
Recipe for a Higgsless Model:

- Choose “bulk” gauge group, fermion profiles, boundary conditions
- Choose $g(x)$
- Choose metric/manifold: $g_{MN}(x)$
- Calculate spectrum & eigenfunctions
- Calculate fermion couplings
- Compare to model to data
- Declare model viable or not ....

Can we do better?
Yes ...
Latticize Fifth Dimension
• Discretize fifth dimension
• 4D gauge group at each site
• Nonlinear sigma model link fields
• To include warping: vary $f_j$
• For spatially dependent coupling: vary $g_k$
• Continuum Limit: take $N \rightarrow \infty$

Arkani-Hamed, Georgi, Cohen & Hill, Pokorski, Wang
Aside: Moose notation

Reveals symmetry (breaking) structure at a glance

A familiar example:

Each circle represents a global SU(2) of which all (solid, left) or a U(1) subgroup (dashed, right) is gauged

Low-energy $\mathcal{L}_{\text{eff}}$ description of symmetry-breaking sector employs non-linear sigma-model fields $\Sigma$

A solid line linking two circles is an $[\text{SU}(2) \times \text{SU}(2) / \text{SU}(2)]$ non-linear sigma model field; at the scale $\nu$ this breaks the gauged or global symmetries of the attached circles

Note: $\Sigma$ is a 2x2 matrix field transforming as $\Sigma \rightarrow L\Sigma R^\dagger$ under the SU(2) groups which it connects.
Deconstructed Higgsless Models with Brane-Localized Fermions

- $SU(2)^N \times U(1)$; general $f_j$ and $g_k$
- Fermions sit on “branes” [sites 0 and $N+1$]
- Many 4-D/5-D theories are limiting cases... study them all at once!
- e.g., $N=1$ equivalent to technicolor/one-Higgs

cf. “BESS” and “HLS”

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

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

Too large by a factor of a few!

Independent of warping or gauge couplings chosen...
Since Higgsless models with localized fermions are not viable, look at:

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

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

How will this affect precision EW observables?
Ideal Fermion Delocalization

- The light W’s wavefunction is orthogonal to wavefunctions of KK modes (charged gauge boson mass-squared matrix is real, symmetric)

- 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!

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

RSC, HJH, MK, MT, EHS hep-ph/0504114
The 3-Site Higgsless Model:

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

$g_0, \ g_2 \ll g_1$

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
Unitarity in the 3-Site Model

\[ A_{I=0}(s, \cos \theta) = 3A(s, t, u) + A(t, s, u) + A(u, t, s) \]

\[ A_{I=J=0}(s) = \frac{1}{64\pi} \int_{-1}^{+1} d\cos \theta A_{I=0}(s, \cos \theta) P_0(\cos \theta) \]

Coupled-Channels

\[ M_{W'} = 400 \text{ GeV} \]

\[ M_{W'} = 600 \text{ GeV} \]

Modest Enhancement of Scale of Unitarity Violation
3-Site Parameter Space

Heavy fermion mass $M_{T,B}$

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

Unitarity violated

WWZ vertex visibly altered

Electroweak precision corrections too large
Conclusions
• The Standard Higgs Model is, at best, a low-energy effective theory of electroweak symmetry breaking that is valid below a scale $\Lambda$ characteristic of the underlying physics.

• Intriguing candidates for the underlying physics include:
  - *technicolor*
    composite Nambu-Goldstone bosons
    techni-rho exchange unitarizes $WW$ scattering
  - *Higgsless models*
    Nambu-Goldstone bosons from extra dimensions
    KK-mode exchange unitarizes $WW$ scattering

• Experiments in this decade at the Large Hadron Collider (CERN) should be able to tell the difference!