Electroweak Symmetry Breaking without a Higgs Boson

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Introduction: Fundamental Particles and Fundamental questions
Subatomic Structure

- Atom: $\sim 10^{-8}$ cm
- Nucleus: $\sim 10^{-12}$ cm
- Proton (neutron): $\sim 10^{-13}$ cm
- Electron: $< 10^{-16}$ cm
- Quark: $< 10^{-16}$ cm
Force Carriers (bosons)
Matter Particles (fermions)

Each can exist in LH and RH chirality

LH (RH) version is charged (neutral) under weak interactions
Questions About Broken Symmetries

Flavor:
Why do fermions with the same charge have different masses?

Electroweak:
Why are the W & Z bosons heavy while the photon is massless?
The Origin of Mass: Electroweak Symmetry Breaking and the Higgs
Gauge Boson Masses

Consider the masses of the electroweak gauge bosons:

\[
M_\gamma = 0 \quad (2 \text{ transverse modes only})
\]

\[
M_W, M_Z \neq 0 \quad (2 \text{ transverse modes, and 1 longitudinal})
\]

An apparent contradiction exists:

- \( W^\pm \) and \( Z^0 \) are massive gauge bosons
- mass implies a Lagrangian term \( M^2_W W^\mu W_\mu \)
  
  ... but such a term is not gauge-invariant
Resolving the contradiction:
The SU(2)_W gauge symmetry is broken at the energies our experiments have probed so far.

Relationship of SU(2) and U(1):

- W bosons are electrically charged \((\pm 1)\), implying that the weak & electromagnetic forces are related

- \(U(1)_{\text{EM}}\) 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 the symmetry explicitly broken? i.e., do we just add a $W$ mass term to the Lagrangian?

No: consider high-energy $W_L W_L \rightarrow W_L W_L$ scattering

Unitarity would be violated (scattering probability > 100%) for scattering energies $E_{c.m.} \sim 1000$ GeV ... so something is still missing.
Must have spontaneous symmetry breaking!

- Lagrangian is symmetric, but ground state is not
- A familiar example: ferromagnetism

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

A fundamental (not composite) complex weak doublet (4 degrees of freedom) of scalar (spin-0) fields

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

with potential energy function

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

is employed both to break the electroweak symmetry and to generate masses for the fermions in the Standard Model.
Nambu-Goldstone bosons provide $M_W$ and $M_Z$

The potential is minimized away from the origin, so the scalar acquires a non-zero vacuum expectation value:

- $\langle \phi \rangle = (0, v/\sqrt{2})$ breaks $SU(2)_W \times U(1)_Y \rightarrow U(1)_{EM}$
- breaking this continuous symmetry yields 3 Nambu-Goldstone bosons which become the $W^+_L$, $W^-_L$, $Z^0_L$
- the scalars’ kinetic energy term includes $D^\mu \phi^\dagger D_\mu \phi$ which now becomes

$$\frac{1}{4} g^2 W^\mu_\phi \phi^\dagger W_\mu \phi \rightarrow \frac{1}{8} g^2 v^2 W^\mu W_\mu \equiv \frac{1}{2} M^2_W W^\mu W_\mu$$

a mass term for the $W$ and $Z$ bosons!
The remaining scalar \((H = \text{Higgs Boson})\) resolves the unitarity problem:

\begin{align*}
\text{Graphs} & \quad g^2 \frac{E^2}{m_w^2} \\
(a) & \quad + 2 - 6 \cos\theta \\
(b) & \quad - \cos\theta \\
(c) & \quad - \frac{3}{2} + \frac{15}{2} \cos\theta \\
(d+e) & \quad - \frac{1}{2} - \frac{1}{2} \cos\theta
\end{align*}

\textbf{Sum including (d+e)}: 0

\textbf{\(\Theta(E^0) \Rightarrow 4d\ m_H\ bound\):} \(m_H < \sqrt{16\pi/3\ v} \approx 1.0 \text{ TeV}\)

\textbf{\(\Theta(E^2)\):} \(E < \sqrt{4\pi\ v} \approx 0.9 \text{ TeV}\)
The scalar doublet $\phi$ couples to fermions as $\lambda \bar{f} \phi f$, yielding two effects when the electroweak symmetry breaks:

- The fermion coupling to Nambu-Goldstone modes produces masses for the fermions

\[ m_f = \lambda \langle \phi \rangle = \lambda v / \sqrt{2} \]

- The coupling of the remaining Higgs Boson ($H$) to fermions allows the Higgs to be produced by or decay to fermion pairs.
Polar Decomposition

Put \( \phi \) in matrix form by defining \( \tilde{\phi} \equiv i\sigma_2 \phi^* \) and \( \Phi \equiv (\tilde{\phi}, \phi) \) so that \( \Phi^\dagger \Phi = \Phi \Phi^\dagger = (\phi^\dagger \phi) \mathcal{I} \)

A polar decomposition of \( \Phi \)

\[
\Phi(x) = \frac{1}{\sqrt{2}} \left( H(x) + v \right) \Sigma(x)
\]

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

neatly separates the radial “Higgs boson” from the “pion” modes (Nambu-Goldstone Bosons).

In unitary gauge, \( \langle \Sigma \rangle = \mathcal{I} \)
Search for the Higgs Particle

Status as of July 2010

Excluded by LEP Experiments 95% confidence level
Excluded by Tevatron Experiments 95% confidence level
Excluded by Indirect Measurements 95% confidence level

Higgs mass

Excluded

100 114 120

140

158 175

185 200 GeV/c²

Excluded

Excluded

Excluded
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 three Nambu-Goldstone bosons of this broken continuous symmetry become the $W_L$ and $Z_L$ states. This process is known as the Higgs Mechanism.

• Additional states must exist in order to unitarize the scattering of the $W_L$ and $Z_L$ bosons. One minimal candidate is the Higgs boson.

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

• What lies beyond the Standard Model?
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:

- Proton: $UUU$ (mass 938 MeV)
- Neutron: $UDD$ (mass 940 MeV)
- $\pi^+$: $UDD$ (mass 140 MeV)
- $\rho^+$: $UDD$ (mass 770 MeV)

Why is the pion so light?
Recall that the QCD coupling varies with energy scale, becoming strong at energies ~ 1 GeV.
The strong-interaction (QCD) Lagrangian for the u and d quarks (neglecting their small masses)

\[ \mathcal{L} = i\bar{u}_L \slashed{D} u_L + i\bar{d}_L \slashed{D} d_L + i\bar{u}_R \slashed{D} u_R + i\bar{d}_R \slashed{D} d_R \]

displays an SU(2)_L \times SU(2)_R global ("chiral") symmetry

When the QCD coupling becomes strong

• \( \langle \bar{q}_L q_R \rangle \neq 0 \) breaks SU(2)_L \times SU(2)_R \rightarrow SU(2)_{L+R}

• pions (\( \bar{q}_L q_R \)) are the associated Nambu-Goldstone bosons!
**Bonus:** from chiral to electroweak symmetry breaking

- $u_L, d_L$ form weak doublet; $u_R, d_R$ are weak singlets
- so $\langle \bar{q}_L q_R \rangle \neq 0$ also breaks electroweak symmetry
- could QCD pions be our composite Higgs bosons?

**Not Quite:**

- $M_W = 0.5g< > = 80$ GeV requires $< > \sim 250$ GeV
- $\langle \bar{q}_L q_R \rangle$ only supplies $\sim 0.1$ GeV
- need extra source of EW symmetry breaking
This line of reasoning inspired **Technicolor**

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

- force carriers are **technigluons**, inspired by QCD gluons

- add **techniquarks** carrying $\text{SU}(N)_{TC}$ charge: i.e., matter particles inspired by QCD quarks

  - e.g. $T_L = (U_L, D_L)$ forms a weak doublet
    $U_R, D_R$ are weak singlets

- Lagrangian has familiar global (chiral) symmetry $\text{SU}(2)_L \times \text{SU}(2)_R$
If $\text{SU}(N)_{TC}$ force is **stronger** than QCD ... then spontaneous symmetry breaking and pion formation will happen at a **higher** energy scale... e.g.

- gauge coupling becomes large at $\Lambda_{TC} \approx 1000$ GeV
- $\langle T_L T_R \rangle \approx 250$ GeV breaks electroweak symmetry
- **technipions** $\Pi_{TC}$ become the $W_L, Z_L$
- $W$ and $Z$ boson masses produced by technicolor match the values seen in experiment!

So far, so good... but what about **unitarization**?
\( \rho \) unitarizes \( \pi \pi \) scattering in QCD

Data for amplitude of spin-1 isospin-1 \( \pi \pi \) scattering

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

We expect similar behavior in \( W_L W_L \) scattering due to the techni-\( \rho \) ... which should be \( \sim \)2500 times heavier

\[ M_{\rho_{TC}} \approx 2 \text{ TeV} \sqrt{\frac{3}{N_{TC}}} \]
Prediction:
Techni-$\rho$ will unitarize $W_LW_L$ scattering at LHC

For $M_{\rho_{TC}} = 1.0$ TeV, 2.5 TeV: (simulations only)

*J. Bagger et. al., hep-ph/9306256, 9504426*
Fermion Masses

In extended technicolor* or ETC models, new heavy gauge bosons connect ordinary and technifermions. The quarks and leptons acquire mass when technifermions condense. The top quark mass, e.g.

\[ m_t \sim \left( \frac{g_{ETC}}{M_{ETC}} \right)^2 \langle \bar{T}T \rangle \]  

* (flavor-dependent factor)

**Challenge:** ETC would cause rare processes that mix quarks of different flavors to happen at enhanced rates excluded by data (e.g. Kaon/anti-Kaon mixing)

*Dimpoulous & Susskind; Eichten & Lane*
Precision Electroweak Corrections

General amplitudes for “on-shell” 2-to-2 fermion scattering include deviations from the Standard Model:

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

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

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

data (e.g. from LEP II, SLC, FNAL) are sensitive to quantum corrections, constraining \(S, T\) to be \(\sim 0.001\)

\(QCD\)-like technicolor models predict larger \(S, T\) values

\(S, T\): Peskin & Takeuchi
Walking Technicolor

- Large TC coupling enhances $m_f \sim \left( \frac{g_{ETC}}{M_{ETC}} \right)^2 \langle \bar{TT} \rangle$
- 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
Overview:

Suppose the universe is a 5-D spacetime including a gauge theory subject to appropriate boundary conditions. What we 4-D folk observe is:

• a light set of bosons identified with the photon, $W$, and $Z$

• towers of heavy replica gauge bosons (called Kaluza-Klein modes)

• $W_L W_L$ scattering being unitarized through exchange of the KK modes (instead of via Higgs or techni-rho exchange)
Massive Gauge Bosons from Extra-D Theories

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

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

$$\hat{A}_5^a = \sqrt{\frac{2}{\pi R}} \sum_{n=1}^{\infty} A_5^{an}(x_\nu) \sin \left( \frac{nx_5}{R} \right)$$

4-D gauge kinetic term contains

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

i.e., $A^{an}_L \leftrightarrow A_5^{an}$
4-D KK Mode Scattering

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

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

- Choose “bulk” gauge group, fermion profiles, boundary conditions
- Choose $g(x^5)$
- Choose metric/manifold: $g_{MN}^{}(x^5)$
- Calculate spectrum & eigenfunctions
- Calculate fermion couplings
- Compare to model to data
- Declare model viable or not ....
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\textbf{Sisyphus (Titian, 1548/9)}
To break the cycle...
Latticize the Fifth Dimension
• Discretize fifth dimension with a 4D gauge group at each site

• Nonlinear sigma model link fields \( \Sigma(x) = \exp(i\pi^a(x)\sigma^a / \nu) \)
  break adjacent groups to diagonal subgroup

• To include warping: vary \( f_j \)

• For spatially dependent coupling: vary \( g_k \)

• Continuum Limit: take \( N \to \infty \)

Arkani-Hamed, Georgi, Cohen & Hill, Pokorski, Wang
• consider a generic $SU(2)^{N+1} \times U(1)$ Higgsless model with generic $f_j$ and $g_k$ values

• simplest case: fermions do not propagate in the 5th dimension, but stay on the 4-D “branes” [sites 0 and N+1] at either end

• Many 4-D/5-D theories are limiting cases [e.g. N=0 related to technicolor]; with this technique we can study them all at once!

cf. “BESS” and “HLS”
Conflict of $S$ & Unitarity for Brane-Localized Fermions

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

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

Too large by a factor of a few!

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

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

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

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:

$$g_i x_i \propto \nu_i^W$$

• 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 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:** \( t, T, b, B \) (\( \psi \) 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

Elastic

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

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

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

Heavy fermion mass $M_{T,B}$

Allowed Region

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

Unitarity violated

WWZ vertex visibly altered

Electroweak precision corrections too large
Vector Boson Fusion ($WZ \rightarrow W'$) and $W'Z$ Associated Production promise large rates and clear signatures.
Integrated LHC Luminosity required to discover $W'$ in each channel.
Conclusions
• The Standard Higgs Model is a low-energy **effective** theory of electroweak symmetry breaking that is valid below a scale characteristic of the **underlying physics**.

• Intriguing candidates for the **underlying physics** include:
  
  **Technicolor**
  
  composite Nambu-Goldstone bosons
techni-rho exchange unitarizes $W_L W_L$ scattering

  **Higgsless models**
  
  Nambu-Goldstone bosons from extra dimensions
  KK-mode exchange unitarizes $W_L W_L$ scattering

• Experiments now underway at the Large Hadron Collider (CERN) should be able to tell the difference!