“Alternative” Theories of Electroweak Breaking

R. Sekhar Chivukula
PANIC 2008
Why Worry About EWSB?
Loss of Unitarity in
SU(2) × U(1) @ E^4

Graphs

\[ g^2 \frac{E^4}{m_w^4} \]

(a) \[ -3 + 6 \cos \theta + \cos^2 \theta \]

(b) \[ -4 \cos \theta \]

(c) \[ +3 - 2 \cos \theta - \cos^2 \theta \]

Sum \[ 0 \]

\[ \epsilon_{\mu \nu}(k) = \frac{k_{\mu}}{m_w} + O\left(\frac{m_w}{E}\right) \]
$SU(2) \times U(1) \ @ \ E^2$

Graphs

(a) $g^2 \frac{E^2}{m_w^2} + 2 - 6 \cos \theta$

(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

$\varTheta(E^0) \Rightarrow 4d \ m_H \ bound: \ m_H < \sqrt{16\pi/3} \nu \simeq 1.0 \ TeV$

If no Higgs $\Rightarrow \varTheta(E^2) \Rightarrow E < \sqrt{4\pi} \nu \simeq 0.9 \ TeV$
Problems with a fundamental Higgs Boson

- No fundamental scalars observed in nature!
- No explanation of Electroweak Symmetry Breaking
- Hierarchy and Naturalness Problem
  \[ m^2_H \propto \Lambda^2. \]
- Triviality Problem
  \[ \beta = \frac{3\lambda^2}{2\pi^2} > 0. \]
A Fork in the Road...

• (Make the Higgs Natural: Supersymmetry)

• Make the Higgs Composite
  – Little Higgs
  – (Twin Higgs)

• Eliminate the Higgs
  – Technicolor
  – “Higgsless” Models
Composite/Little Higgs
Composite Higgs

Higgs as (Pseudo-)Goldstone Boson:

Hard to do!

\[ V(h) = \frac{C g^2}{16 \pi^2} \left( -\eta_2 f^2 |h|^2 + \eta_4 \frac{|h|^4}{2} + \ldots \right) \]

\[ g \ll 1 \]

Decay Constant

Yields: \[ \langle h \rangle^2 \simeq \frac{\eta_2}{\eta_4} f^2 \]

But, EWPT: \[ f > 4 - 5 \text{ TeV} \]

Must suppress \( \eta_2 \) without suppressing \( \eta_4 \)

Georgi & Kaplan; Banks

Chacko et. al., hep-ph/0510273
The Little Higgs

Collective Symmetry Breaking:

For weak springs, masses at end very weakly coupled!

In practice:

\[
\frac{\eta_2}{\eta_4} \sim \frac{g^2}{16\pi^2} \quad \quad m_h^2 \sim \frac{g^2}{16\pi^2} f^2
\]

<table>
<thead>
<tr>
<th>Global Symmetries</th>
<th>Gauge Symmetries</th>
<th>triplet</th>
<th># Higgs</th>
</tr>
</thead>
<tbody>
<tr>
<td>(SU(5)/SO(5))</td>
<td>([SU(2) \times U(1)]^2)</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>(SU(3)^8/SU(3)^4)</td>
<td>(SU(3) \times SU(2) \times U(1))</td>
<td>Yes</td>
<td>2</td>
</tr>
<tr>
<td>(SU(6)/Sp(6))</td>
<td>([SU(2) \times U(1)]^2)</td>
<td>No</td>
<td>2</td>
</tr>
<tr>
<td>(SU(4)^4/SU(3)^4)</td>
<td>(SU(4) \times U(1))</td>
<td>No</td>
<td>2</td>
</tr>
<tr>
<td>(SO(5)^8/SO(5)^4)</td>
<td>(SO(5) \times SU(2) \times U(1))</td>
<td>Yes</td>
<td>2</td>
</tr>
<tr>
<td>(SU(9)/SU(8))</td>
<td>(SU(3) \times U(1))</td>
<td>No</td>
<td>2</td>
</tr>
<tr>
<td>(SO(9)/[SO(5) \times SO(4)])</td>
<td>(SU(2)^3 \times U(1))</td>
<td>Yes</td>
<td>1</td>
</tr>
</tbody>
</table>

Global Symmetry Extended to Third Generation

- Top Yukawa Large and breaks chiral symmetries
- Extra singlet quarks added
- Top mass results from seesaw like mixing between doublet and singlet fermions
- EWSB: radiatively induced
Little Higgs: The Hierarchy

Cancellation of divergences by particles of same spin!
OR ...
Eliminate the Higgs...

Technicolor: Higgsless since 1976!

Eliminate Scalars: Electroweak gauge symmetry broken by the nonzero expectation value of a fermion bilinear, driven by new strong interactions.

Understanding of strongly-interacting gauge theories is extremely limited ⇒ theories constructed by analogy!
From QCD:

Why is the pion so light?

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!
Technicolor Limits:

- Model Dependent
- Just Reaching interesting range!
- Run II & LHC will extend limits substantially

No Run II limits yet?

Narain, Womersley, RSC PDG review

<table>
<thead>
<tr>
<th>Process</th>
<th>Excluded mass range</th>
<th>Decay channels</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p\bar{p} \to \rho_T \to W\pi_T$</td>
<td>$170 &lt; m_{\rho_T} &lt; 190$ GeV for $m_{\pi_T} \approx m_{\rho_T}/2$</td>
<td>$\rho_T \to W\pi_T$ $\pi^0_T \to bb$ $\pi^+_T \to b\bar{c}$</td>
<td>[16]</td>
</tr>
<tr>
<td>$p\bar{p} \to \omega_T \to \gamma\pi_T$</td>
<td>$140 &lt; m_{\omega_T} &lt; 290$ GeV for $m_{\pi_T} \approx m_{\omega_T}/3$ and $M_T = 100$ GeV</td>
<td>$\omega_T \to \gamma\pi_T$ $\pi^0_T \to bb$ $\pi^+_T \to b\bar{c}$</td>
<td>[18]</td>
</tr>
<tr>
<td>$p\bar{p} \to \omega_T/\rho_T$</td>
<td>$m_{\omega_T} = m_{\rho_T} &lt; 203$ GeV for $m_{\omega_T} &lt; m_{\pi_T} + m_W$ or $M_T &gt; 200$ GeV</td>
<td>$\omega_T/\rho_T \to \ell^+\ell^-$</td>
<td>[19]</td>
</tr>
<tr>
<td>$e^+e^- \to \omega_T/\rho_T$</td>
<td>$90 &lt; m_{\rho_T} &lt; 206.7$ GeV $m_{\pi_T} &lt; 79.8$ GeV</td>
<td>$\rho_T \to WW$, $W\pi_T$, $\pi_T\pi_T$, $\gamma\pi_T$, hadrons</td>
<td>[20]</td>
</tr>
<tr>
<td>$p\bar{p} \to \rho_{T8}$</td>
<td>$260 &lt; m_{\rho_{T8}} &lt; 480$ GeV</td>
<td>$\rho_{T8} \to q\bar{q}$, $gg$</td>
<td>[22]</td>
</tr>
<tr>
<td>$p\bar{p} \to \rho_{T8}$</td>
<td>$m_{\rho_{T8}} &lt; 510$ GeV</td>
<td>$\pi_{LQ} \to \ell\nu$</td>
<td>[25]</td>
</tr>
<tr>
<td>$p\bar{p} \to \rho_{T8}$</td>
<td>$m_{\rho_{T8}} &lt; 600$ GeV</td>
<td>$\pi_{LQ} \to \nu\nu$</td>
<td>[25]</td>
</tr>
<tr>
<td>$p\bar{p} \to \rho_{T8}$</td>
<td>$m_{\rho_{T8}} &lt; 465$ GeV</td>
<td>$\pi_{LQ} \to \tau\nu$</td>
<td>[24]</td>
</tr>
<tr>
<td>$p\bar{p} \to g_t$</td>
<td>$0.3 &lt; m_{g_t} &lt; 0.6$ TeV for $0.3m_{g_t} &lt; \Gamma &lt; 0.7m_{g_t}$</td>
<td>$g_t \to b\bar{b}$</td>
<td>[30]</td>
</tr>
<tr>
<td>$p\bar{p} \to Z'$</td>
<td>$m_{Z'} &lt; 480$ GeV for $\Gamma = 0.012m_{Z'}$</td>
<td>$Z' \to t\bar{t}$</td>
<td>[31]</td>
</tr>
<tr>
<td>$p\bar{p} \to Z'$</td>
<td>$m_{Z'} &lt; 780$ GeV for $\Gamma = 0.04m_{Z'}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
WZ Scattering at SLHC

\[ p_T(\ell_1) > 150 \text{ GeV}, \quad p_T(\ell_2) > 100 \text{ GeV}, \quad p_T(\ell_3) > 50 \text{ GeV} \]

\[ |m(\ell_1\ell_2) - m_Z| < 10 \text{ GeV} \]

\[ E_T^{\text{miss}} > 75 \text{ GeV} \]

+ forward jets

F. Gianotti, et. al., hep-ph/0204087
What about the S-parameter?
Why are we still talking about technicolor?

- Technicolor may be there
  - No “computations” of S in non-QCD like theories

- Technicolor has interesting experimental signatures
  - Complementary to other BSM theories

- AdS/CFT Correspondence:
  - Some 4D strongly-coupled theories “dual” to weakly-coupled 5D theories
  - New model building ideas
  - Address S parameter issues
AdS/CFT Duality

Conjecture: Equivalence of 5D theory in AdS and 4D CFT

\[ ds^2 = \left( \frac{R}{z} \right)^2 \left[ \eta_{\mu\nu} dx^\mu dx^\nu - dz^2 \right] \]

\( R < z < R' \)

NB: Rescaling Invariance!

Strong evidence for N=4 SUSY YM string theory on AdS

Strongly-coupled CFT \( \Leftrightarrow \) Weakly-coupled 5D Theory!

“Walking Technicolor” \( \Leftrightarrow \) Higgsless Models
From Technicolor to Extra-Dimensions
... and Back Again: Higgsless Models
**Extra-D Theories and Massive Vector Boson Scattering**

Expand 5-D gauge bosons in eigenmodes: e.g.

for $S^1/Z_2$:

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

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

4-D gauge kinetic term contains

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

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

Can we apply this to W and Z?

RSC, H.J. He, D. Dicus

<table>
<thead>
<tr>
<th>graph</th>
<th>$g^2 C^{eab} C^{ecd}$</th>
<th>$g^2 C^{eac} C^{edb}$</th>
<th>$g^2 C^{ead} C^{ebc}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>$6c(x^4 - x^2)$</td>
<td>$\frac{3}{2}(3 - 2c - c^2)x^4$</td>
<td>$\frac{3}{2}(3 + 2c - c^2)x^4$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$-3(1-c)x^2$</td>
<td>$+3(1+c)x^2$</td>
</tr>
<tr>
<td>(b1)</td>
<td>$-2c(x^4 - x^2)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(c1)</td>
<td></td>
<td>$-4cx^4$</td>
<td></td>
</tr>
<tr>
<td>(b2, 3)</td>
<td>$\frac{1}{2}(3 - 2c + c^2)x^4$</td>
<td>$\frac{1}{2}(3 + 2c - c^2)x^4$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$+3(1-c)x^2$</td>
<td>$-3(1+c)x^2$</td>
</tr>
<tr>
<td>(c2, 3)</td>
<td>$(-3</td>
<td>2c</td>
<td>c^2)x^4$</td>
</tr>
<tr>
<td></td>
<td>$-8cx^2$</td>
<td>$-8cx^2$</td>
<td>$-8cx^2 \Rightarrow 0$</td>
</tr>
</tbody>
</table>
Associated Production (signal in WZZ channel)

\[ pp \rightarrow W^* \rightarrow W'Z \rightarrow WZZ \]

500 GeV \( W' \) boson

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

\[
p_{T\ell} > 10 \text{ GeV}, \quad |\eta_\ell| < 2.5, \quad p_{Tj} > 15 \text{ GeV}, \quad |\eta_j| < 4.5.
\]

See talk by E. Simmons
Higgsless Models

- Can we use Extra-D/AdS-CFT in EWSB?
- Unitarize TeV-scale $W_LW_L$ scattering using vector bosons?
- If KK modes exist, $M_W \ll M_{KK}$!!
- Luckily, unitarization generalizes to a large class of 5-d manifolds and boundary conditions!

Csaki, Grojean, Murayama, Pilo, Terning
Energy Scales and Couplings

\( g_4^4 = g_5^5 \sqrt{\frac{1}{\pi R}} \)

\[ M_n = \frac{n}{R} \]

\[ \Lambda_{UV} \propto \frac{1}{g_5^2} \]
Crazy Wild Ideas?

“Higgs” as portal to the unknown

Higgs - Unparticle Mixing: \[ V_0 = m^2 |H|^2 + \lambda |H|^4 + \kappa_U |H|^2 \mathcal{O}_U \]

New “conformally-invariant” sector

A. Delgado, et. al., arxiv: 0802.2680

A. Delgado, et. al., arxiv: 0802.2680
## EWSB Theory Summary

<table>
<thead>
<tr>
<th>Theory</th>
<th>WW Scattering</th>
<th>Hierarchy Problem</th>
<th>“Calculable” @ LHC?</th>
<th>Precision EW</th>
<th>$\Lambda_{UV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamental Higgs</td>
<td>I=J=0</td>
<td>YES!</td>
<td>✓</td>
<td>✓</td>
<td>1 TeV - $M_{GUT}$</td>
</tr>
<tr>
<td>SUSY</td>
<td>I=J=0</td>
<td>No</td>
<td>✓</td>
<td>✓</td>
<td>$M_{GUT}$?</td>
</tr>
<tr>
<td>Composite Higgs</td>
<td>I=J=0</td>
<td>No</td>
<td>✓</td>
<td>f &gt; 5 TeV</td>
<td>50 TeV</td>
</tr>
<tr>
<td>Higgsless</td>
<td>I=J=1</td>
<td>No</td>
<td>✓</td>
<td>Ideal fermions</td>
<td>10 TeV</td>
</tr>
<tr>
<td>Technicolor</td>
<td>I=J=1</td>
<td>No</td>
<td>??</td>
<td>Non-QCD</td>
<td>few TeV</td>
</tr>
</tbody>
</table>
Conclusions

• What unitarizes WW scattering?

• Two new mechanisms, and one old, to address EWSB
  • Technicolor
  • Composite/Little/Twin Higgs
  • Higgsless Models

• All predict new TeV Scale particles, two new predict
  • Extended Electroweak Gauge Symmetries
  • Extended Fermion Sector

• Much Phenomenology Left to be done!
Observations

• Our standards have changed
  • We are content with a low-energy effective theory valid to \( \sim \) few TeV
  • This is a good thing in preparation for the LHC ...

• Fine-tuning is in the eye of the beholder
  • \( S = O(1) \) in QCD-like technicolor; experimental bound \( O(0.1) \) - hence need 10% fine-tuning?
  • Dynamics matters: Inflation makes fine-tuning of flatness problem irrelevant.
Extra Slides
Twin Higgs

• Global SU(4) Symmetry, H in fundamental

  \[ V(H) = -m^2 H^\dagger H + \lambda (H^\dagger H)^2 \]

  \[ \langle H \rangle, \text{SU}(4) \text{ breaks to SU}(3); 7 \text{ GBs} \]

• Weakly Gauge SU(2)_W \times SU(2)_H, H=\(H_W, H_H\)

  \[ 3 \text{ GBs eaten, 4 remaining are “higgs”} \]

  \[ \Delta V^{(2)} = \frac{9g_A^2\Lambda^2}{64\pi^2} H_W^\dagger H_W + \frac{9g_B^2\Lambda^2}{64\pi^2} H_H^\dagger H_H \]

• \(Z_2\) symmetry: \(g_A=g_B\)

  \[ \text{Accidental SU(4) symmetry of} \quad \Delta V^{(2)} \]

  \[ \text{No mass generated for higgs boson to } O(g^2) \]

Chacko, Go, and Harnick hep-ph/0506256
Twin Higgs (cont’d)

- Self-coupling

\[ \Delta V^{(4)} \propto \frac{g^4}{16\pi^2} \log \left( \frac{\Lambda}{g f} \right) \left( |H_W|^4 + |H_H|^4 \right) \]

- Extend SU(4) global symmetry to top-quark sector

- EWSB: Radiatively induced

- Hierarchy: like Little Higgs