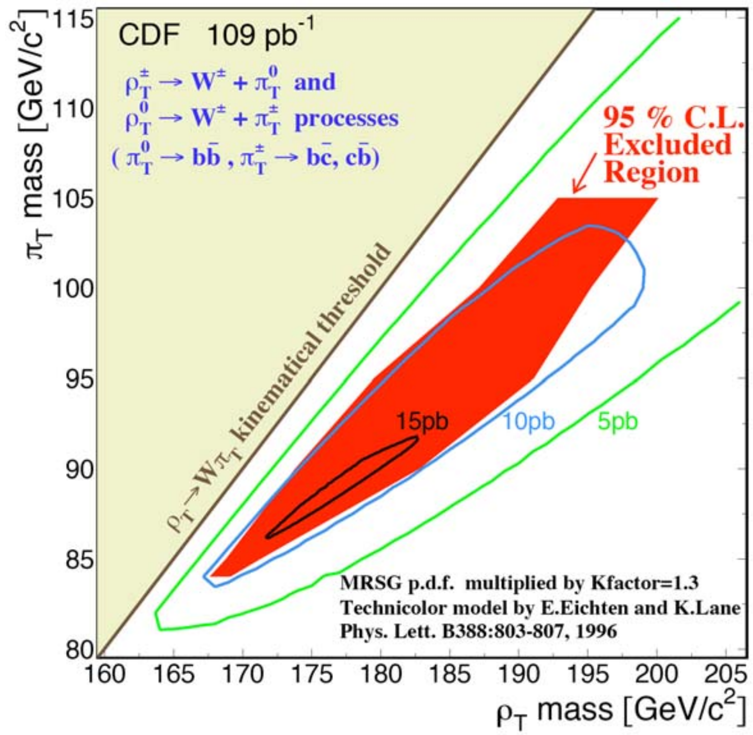

Electroweak Symmetry Breaking:
with Dynamics

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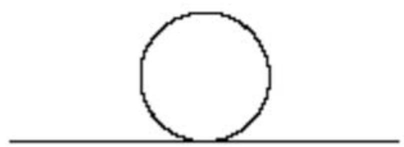
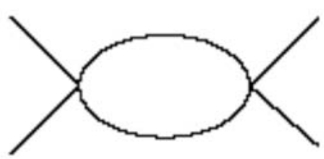
Problems with the Higgs

- No fundamental scalars observed in nature!
- No explanation of Electroweak Symmetry Breaking
- Hierarchy and Naturalness Problem



$$\Rightarrow \; m_H^2 \propto \Lambda^2 \; .$$

- Triviality Problem



$$\Rightarrow \beta = \frac{3\lambda^2}{2\pi^2} > 0 \quad .$$

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 $\Rightarrow$ theories constructed by analogy!

New Models in this decade from Extra D

Technicolor Limits:

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

Narain, Womersley, RSC
PDG review

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

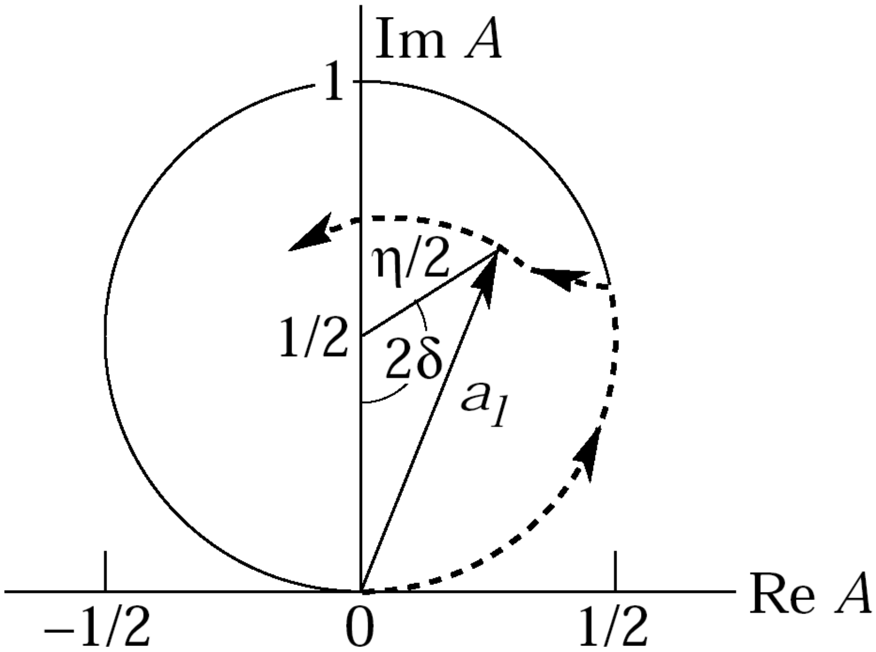
Why worry about EWSB?

Unitarity!

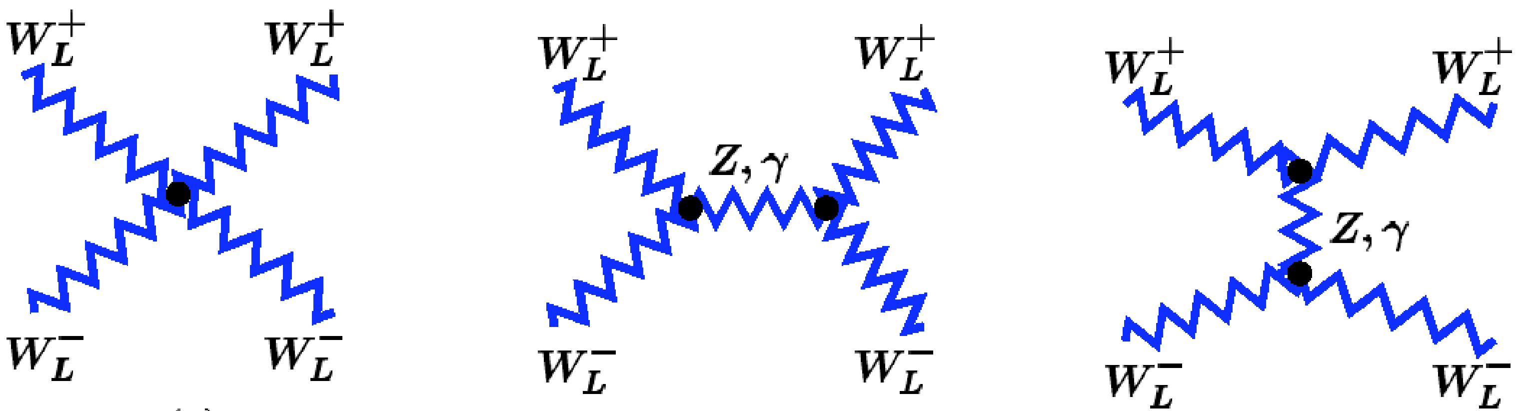
$$\mathscr{M} = -8\pi\sqrt{s}\, f(k,\theta)$$

$$f(k,\theta) = \frac{1}{k}\sum_{\ell}(2\ell+1)a_\ell P_\ell(\cos\theta)$$

$$\sigma_{\rm tot} = \frac{4\pi}{k}\,\mathrm{Im}\, f(k,0)$$



SU(2)xU(1) @ E^4

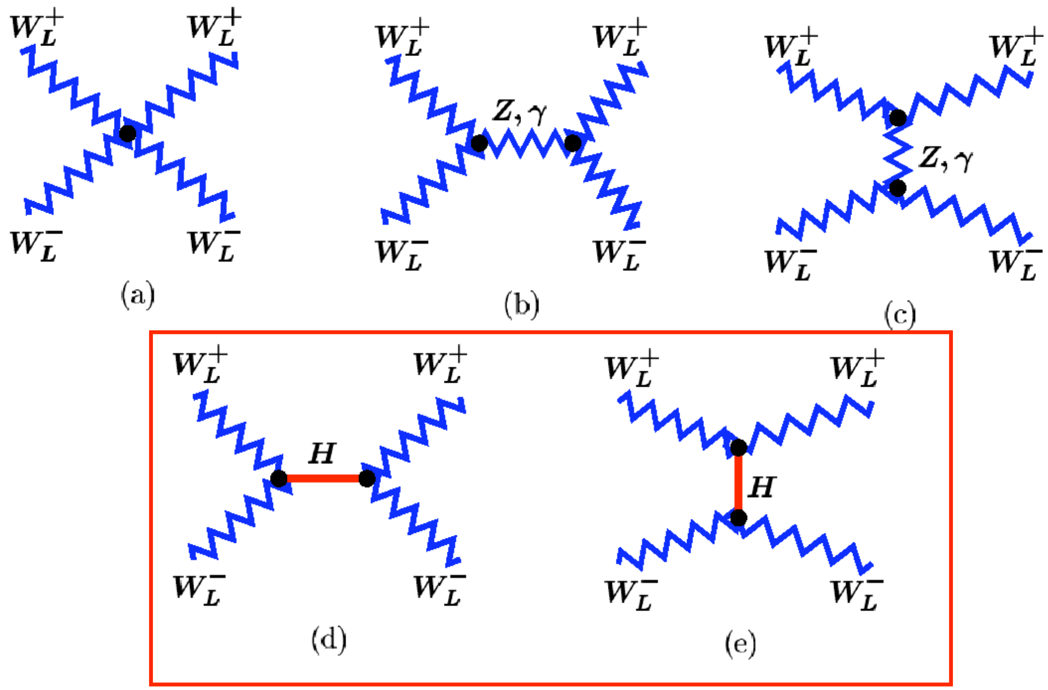


(a) (b) (c)

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**

$$\epsilon_L^\mu(k) = \frac{k^\mu}{m_w} + \mathcal{O}\left(\frac{m_w}{E}\right)$$

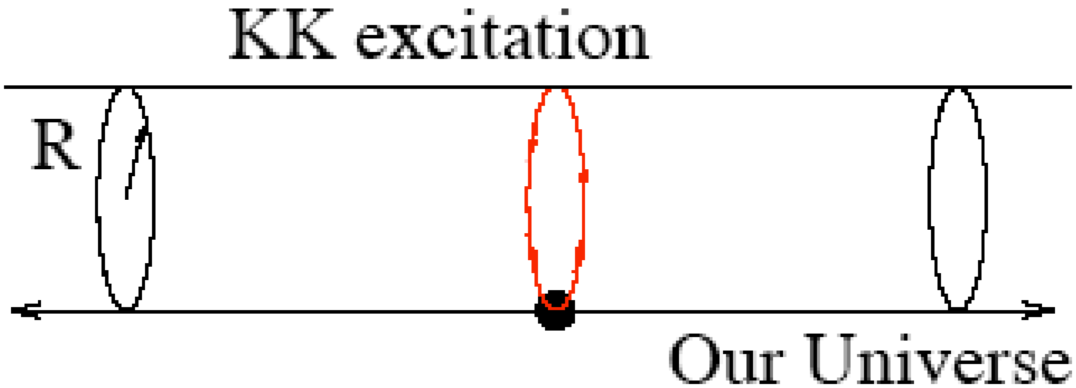
SU(2)xU(1) @ E²



Graphs	$g^2 \frac{E^2}{m_w^2}$
(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	**0**

- $\mathcal{O}(E^0) \Rightarrow$ 4d m_H bound: $m_H < \sqrt{16\pi/3}\, v \simeq 1.0$ TeV
- If no Higgs $\Rightarrow \mathcal{O}(E^2) \Rightarrow\; E < \sqrt{4\pi}\, v \simeq 0.9$ TeV

Massive Gauge Bosons from Extra-D Gauge Theories



Expand gauge field in eigenmodes, e.g. for S^1/Z_2:

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

$$\widehat{A}^a_5 = \sqrt{\frac{2}{\pi R}}\sum_{n=1}^{\infty} A^{an}_5(x_\nu)\sin\left(\frac{n x_5}{R}\right)$$

KK Masses: "Higgs Mechanism"

- 4d kinetic gauge term contains:

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

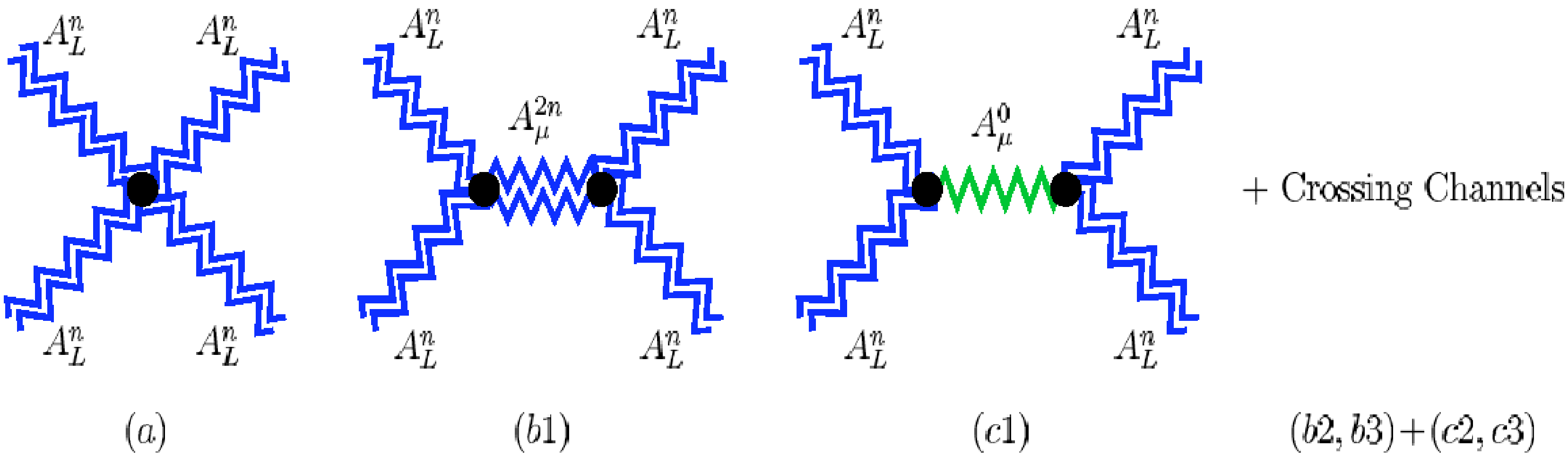
Geometric KK Mass Spectrum: $\mathrm{M_n = n/R}$

- Geometric Higgs Mechanism: $A_L^{an} \Longleftrightarrow A_5^{an}$!

- Exact 5d YM Gauge Symm broken to 4d YM Gauge Symm by Compactification of x^5

and choice of Boundary Conditions!

4-D KK Mode Scattering



$c = \cos\theta,\ x = E/M_n$

Cancellation of bad high-energy behavior due to exchange of massive vector particles.

graph	$g^2 C^{eab}C^{ecd}$	$g^2 C^{eac}C^{edb}$	$g^2 C^{ead}C^{ebc}$
(a)	$6c(x^4-x^2)$	$\frac{3}{2}(3-2c-c^2)x^4$ $-3(1-c)x^2$	$\frac{-3}{2}(3+2c-c^2)x^4$ $+3(1+c)x^2$
$(b1)$	$-2c(x^4-x^2)$		
$(c1)$	$-4cx^4$		
$(b2,3)$		$\frac{-1}{2}(3-2c+c^2)x^4$ $+3(1-c)x^2$	$\frac{1}{2}(3+2c-c^2)x^4$ $-3(1+c)x^2$
$(c2,3)$		$(-3+2c+c^2)x^4$ $-8cx^2$	$(3+2c-c^2)x^4$ $-8cx^2$
Sum	$-8cx^2$	$-8cx^2$	$-8cx^2 \Rightarrow$ **0**

RSC, H.J. He, D. Dicus

No Free Lunch: Coupled-Channel Analysis

▶ How does BAD high energy behavior of 5d YM manifest via KK scattering in effective C5d YM ?

▶ Consider a state with KK-pairs up to N_0,

$$\left|\Psi^{ab}\right\rangle = \frac{1}{\sqrt{N_0}} \sum_{\ell=1}^{N_0} \left|A_L^{a\ell} A_L^{b\ell}\right\rangle$$

▶ Compute S-matrix: $\quad (N_0 \gg 1)$

$$\mathcal{T}\left[\left|\Psi^{ab}\right\rangle \to \left|\Psi^{cd}\right\rangle\right] = \cdots \simeq N_0 \mathcal{T}\left[A_5^{an} A_5^{bn} \to A_5^{c\ell} A_5^{d\ell}\right]$$

Limit on Number of KK Modes

For large N_0, 4d s-wave in gauge-singlet channel:

$$a_\Psi^{00} = \frac{1}{32\pi}\int_{-1}^{1} d\cos\theta \, \frac{1}{k^2-1}\sum_{a,c=1}^{k^2-1} \mathcal{T}\left[|\Psi^{aa}\rangle \to |\Psi^{cc}\rangle\right]$$

$$= N_0 \frac{kg^2}{8\pi}\mathcal{O}(1) = \frac{N_0}{R}\frac{kg_5^2}{8\pi^2}\mathcal{O}(1),$$

▶ Unitarity bounds $|a_\Psi^{00}|$ and requires a truncation of KK-level at $N_0 = N$,

$$\frac{N}{R} \lesssim \frac{\sqrt{32}\pi^2}{k}\frac{\mathcal{O}(1)}{g_5^2} = \mathcal{O}\left(\frac{1}{g_5^2}\right) \quad \Rightarrow \quad \text{indep of radius } R\,!$$

Consistent with 5-d intuition!

Moral: You can delay unitarity, but you can't avoid it!

- $g_{su(2)} \sim 1$; could potentially add several vector mesons and delay unitarity

- Generalizes to a large class of 5-d manifolds and boundary conditions
  (Csaki, Grojean, Murayama, Pilo, Terning)

- Generalizes, in the limit of zero "4d" coupling to form a unitarization of chiral perturbation theory
  (Son and Stephanov in QCD; cf. CWZC 1969)

Simplest TC-inspired Model

$$\mathcal{L} = -\frac{1}{4g_5^2} W^{a\,MN} W^a_{MN}$$

$$-\delta(y - \pi R)\frac{1}{4g^2} W^{a\,\mu\nu} W^a_{\mu\nu}$$

$$-\delta(y)\frac{1}{4g'^2} W^{3\,\mu\nu} W^3_{\mu\nu}$$

$$\delta(x_5, x_5 - \pi R) \equiv \lim_{\varepsilon \to 0^+} \delta(x_5 - \varepsilon, x_5 - \pi R + \varepsilon)$$

$$\frac{dW^a_\mu}{dx_5}|_{x_5=\pi R} = 0\,, \quad \frac{dW^3_\mu}{dx_5}|_{x_5=0} = 0 \;\;\&\;\; W^{1,2}_\mu(0) = 0$$

Foadi, Gopalkrishna, Schmidt hep-ph/0312324

Carena, Tait, Wagner hep-ph/0207056

Power Counting and Scales

Standard Model Recovered in limit: $g,\ g' \ll \frac{g_5}{\sqrt{\pi R}}$

$$M_W \approx \frac{g}{g_5\sqrt{\pi R}}, \quad M_Z \approx \frac{\sqrt{g^2 + g'^2}}{g_5\sqrt{\pi R}}$$

$$M_{W^*} \simeq \frac{1}{R}$$

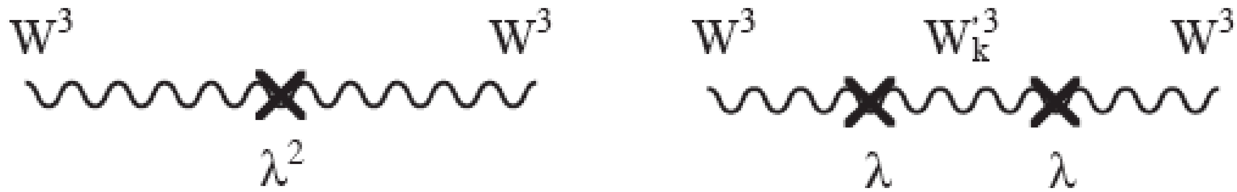
Need moderately strong g_5 in order to gain anything!

$$\Lambda_5 \simeq \frac{2\sqrt{2}\pi^2}{g_5^2} \gg \sqrt{4\pi} v$$

$$\frac{\pi^{3/2}}{\sqrt{2}} \gg \frac{g_5}{\sqrt{\pi R}} \gg g \simeq \mathcal{O}(1)$$

Just barely OK?

S, again!



$$\alpha S = \frac{2e^2}{3}\,\frac{\pi R}{g_5^2} \simeq \frac{e^2}{3\pi\sqrt{2}}\,\frac{\Lambda_5}{M_{W^*}}$$

$$\alpha S < \mathcal{O}(10^{-3}) \Rightarrow \frac{M_{W^*}}{\Lambda_5} > 7$$

INCONSISTENT

Conclusions, Connections and Speculations

- A fundamental SM Higgs is unnatural, unattractive, and (so far) unobserved.
- Strong Dynamics/Technicolor provides an elegant "explanation" for EWSB, but is challenged by precision electroweak tests.
- Models inspired by gauge theories in 5-d can accommodate EWSB in a manner reminiscent of Technicolor -- perhaps too reminiscent!
- QCD Connections: CWZC, unitarized chiral perturbation theory, "mended symmetries"…