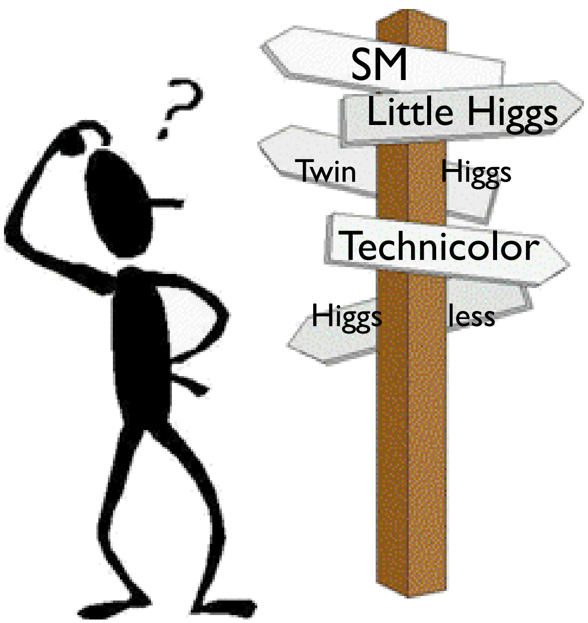
New Approaches to Electroweak Symmetry Breaking

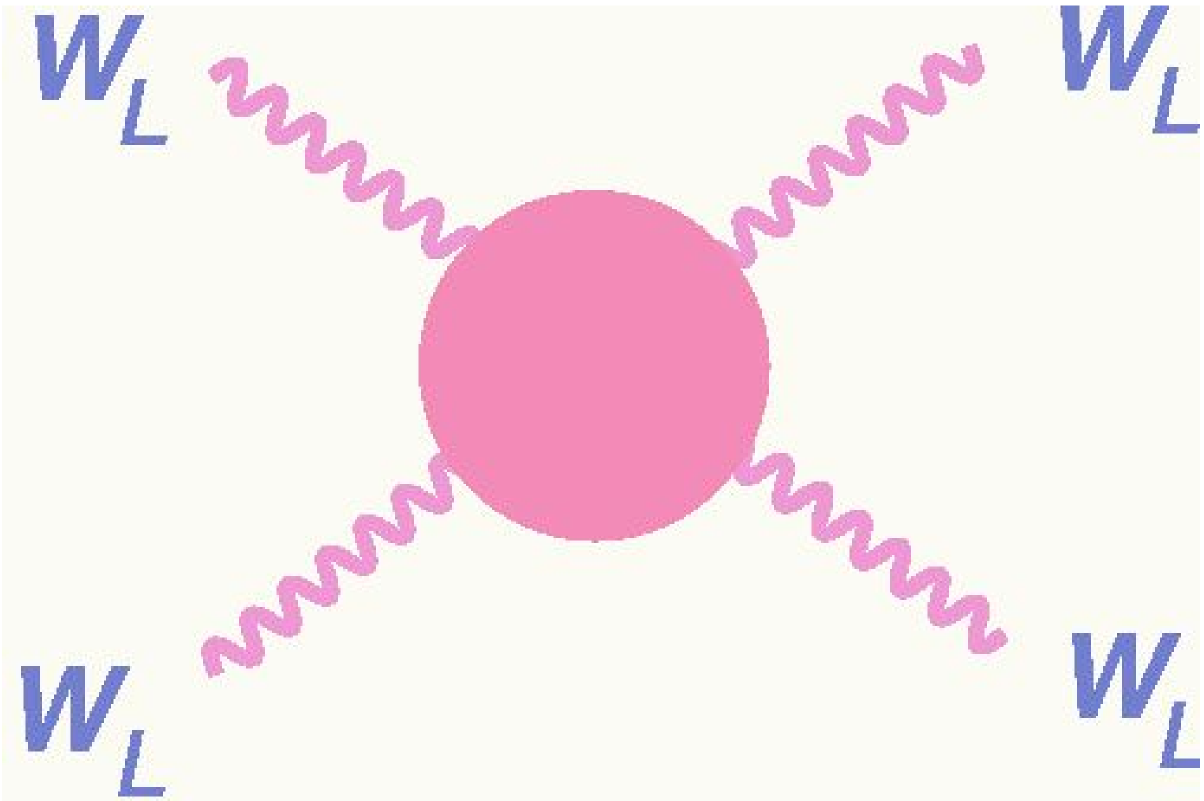


R. Sekhar Chivukula
Michigan State University

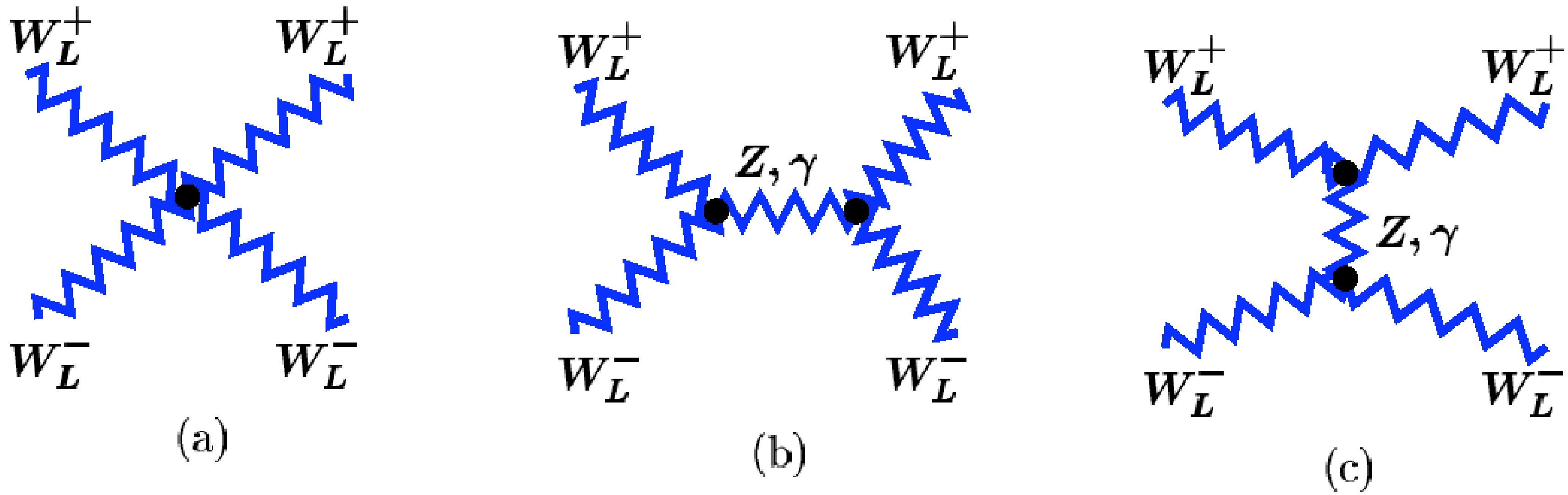
Pheno 06 Symposium
Madison, Wisconsin
May 17, 2006

Why Worry About EWSB?

Loss of Unitarity in



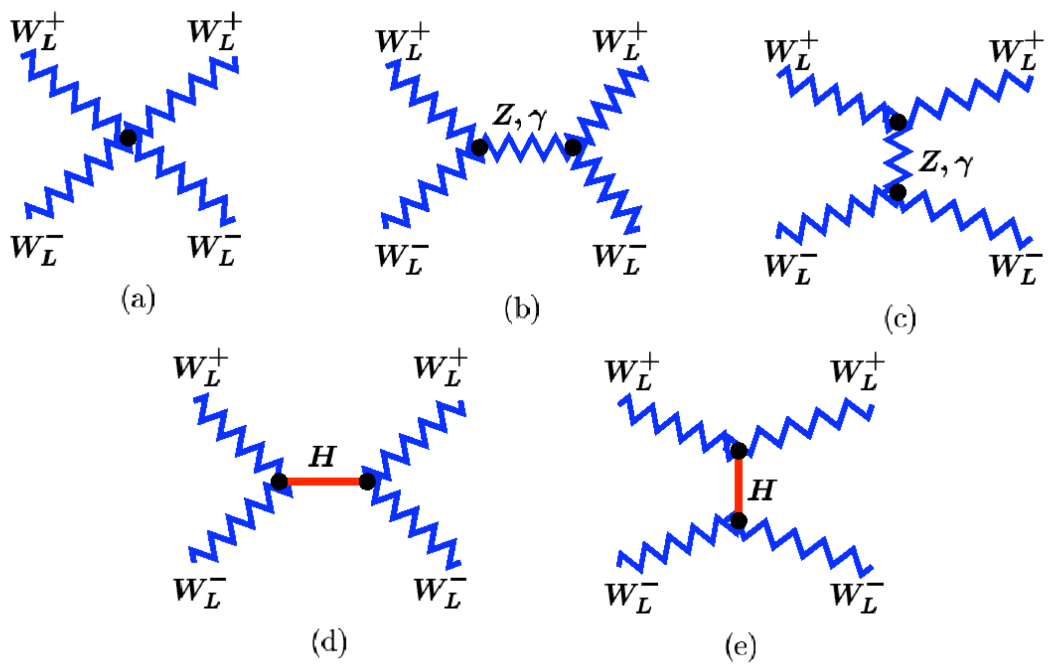
SU(2) x U(1) @ E^4



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

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

SU(2) x U(1) @ E^2

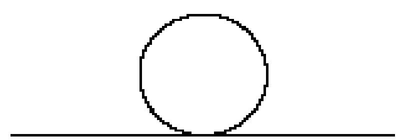


Graphs	$g^2 \frac{E^2}{m_w^2}$
(a)	$+2 - 6\cos\theta$
(b)	$-\cos\theta$
(c)	$-\frac{3}{2} + \frac{15}{2}\cos\theta$
(d + e)	$-\frac{1}{2} - \frac{1}{2}\cos\theta$
Sum including (d+e)	**0**

- ▶ $\mathcal{O}(E^0) \Rightarrow$ 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

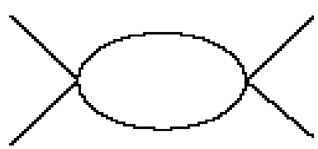
Problems with a fundamental Higgs Boson

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



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

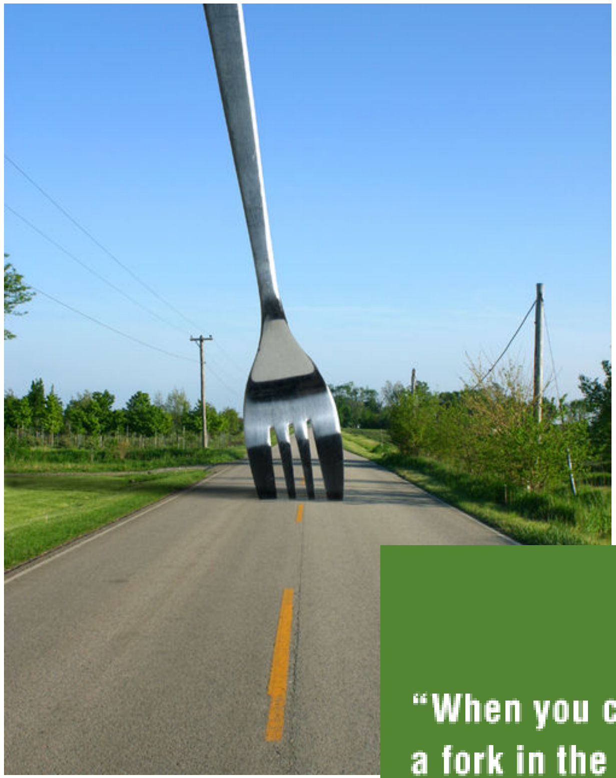
- Triviality Problem



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

A Fork in the Road...

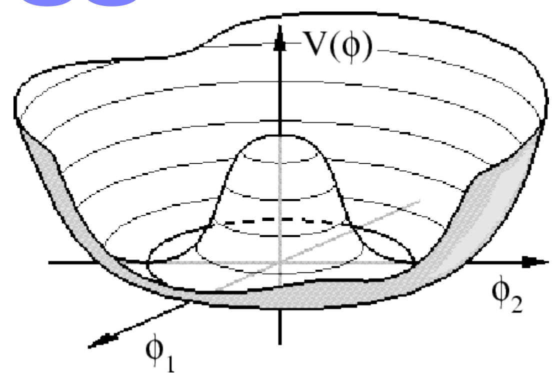
- (Make the Higgs Natural: Supersymmetry)
- Make the Higgs Composite
  - Little Higgs
  - Twin Higgs
- Eliminate the Higgs
  - Technicolor
  - "Higgsless" Models



"When you come to a fork in the road, take it!"
— Yogi Berra

Composite Higgs

Higgs as (Pseudo-)Goldstone Boson:



Hard to do!

$$V(h) = \frac{Cg^2}{16\pi^2}\left(-\eta_2 f^2|h|^2 + \eta_4\frac{|h|^4}{2} + \ldots\right)$$

$g \ll 1$ Decay Constant

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

But, EWPT: $f > 4 - 5\,\mathrm{TeV}$

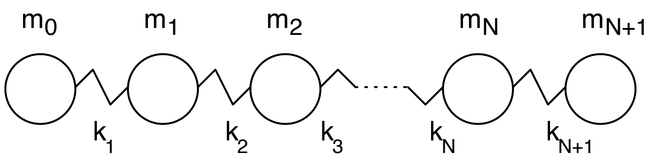
Must suppress η_2 without suppressing η_4

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: $\frac{\eta_2}{\eta_4} \simeq \frac{g^2}{16\pi^2}$ $\qquad m_h^2 \simeq \frac{g^2}{16\pi^2} f^2$

Global Symmetries	Gauge Symmetries	triplet	# Higgs
$SU(5)/SO(5)$	$[SU(2) \times U(1)]^2$	Yes	1
$SU(3)^8/SU(3)^4$	$SU(3) \times SU(2) \times U(1)$	Yes	2
$SU(6)/Sp(6)$	$[SU(2) \times U(1)]^2$	No	2
$SU(4)^4/SU(3)^4$	$SU(4) \times U(1)$	No	2
$SO(5)^8/SO(5)^4$	$SO(5) \times SU(2) \times U(1)$	Yes	2
$SU(9)/SU(8)$	$SU(3) \times U(1)$	No	2
$SO(9)/[SO(5) \times SO(4)]$	$SU(2)^3 \times U(1)$	Yes	1

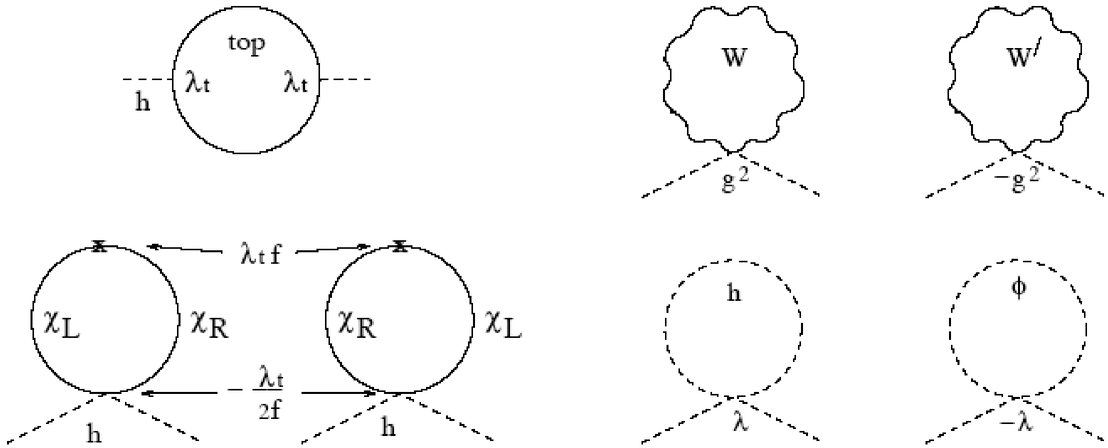
Arkani-Hamed, Cohen, Georgi

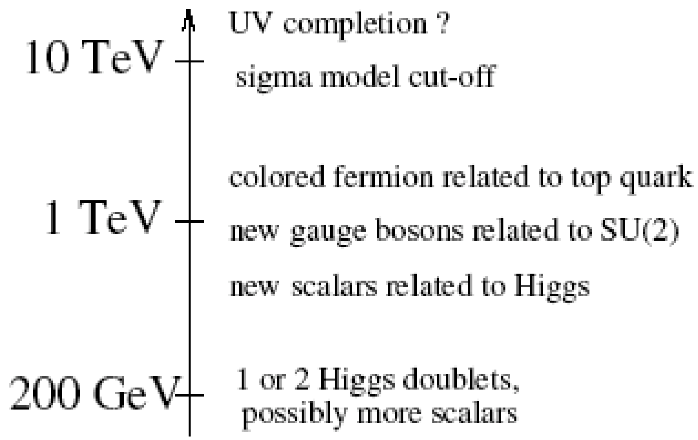
Meade, hep-ph/0402036

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!

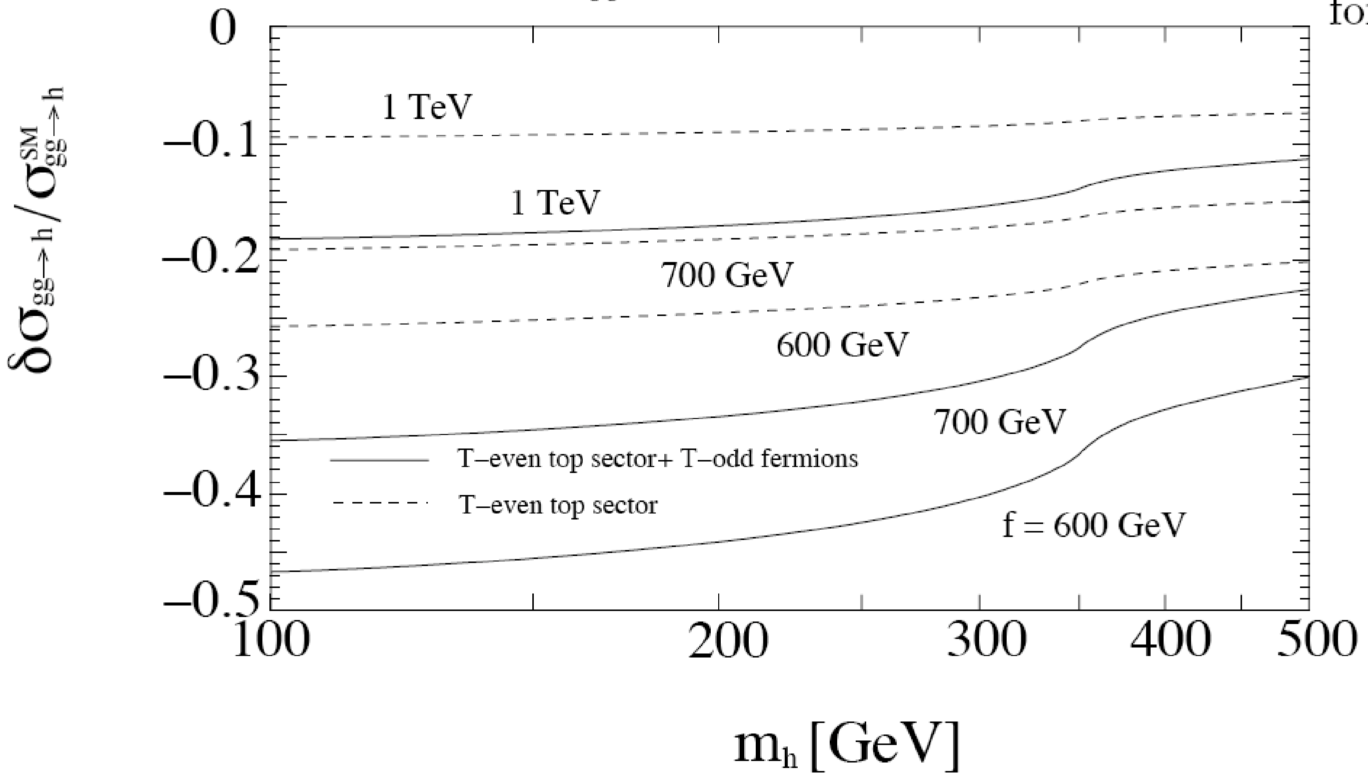
Schmaltz hep-ph/0210415

Correction to Higgs production cross section via gluon fusion process

$$\frac{\delta\sigma_{gg\to h}}{\sigma^{\rm SM}_{gg\to h}} \quad (\text{where } \delta\sigma_{gg\to h} = \sigma^{\rm LH}_{gg\to h} - \sigma^{\rm SM}_{gg\to h})$$

$$\frac{\delta\sigma_{gg\to h}}{\sigma^{\rm SM}_{gg\to h}} \simeq -3\frac{v^2_{SM}}{f^2} \simeq \begin{cases} -37\% \text{ for } f = 700 \text{ GeV}, \\ -18\% \text{ for } f = 1000 \text{ GeV}. \end{cases}$$

for small m_h



The production cross section can be significantly suppressed

Chen, Tobe, Yuan - see Tobe talk

Twin Higgs

- Global SU(4) Symmetry, H in fundamental
  - $V(H) = -m^2 H^\dagger H + \lambda (H^\dagger H)^2$
  - <H>, SU(4) breaks to SU(3); 7 GBs
- Weakly Gauge $SU(2)_W$ x $SU(2)_H$, $H=(H_W,H_H)$
  - 3 GBs eaten, 4 remaining are "higgs"
  - $\Delta V^{(2)} = \frac{9 g_A^2 \Lambda^2}{64\pi^2} H_W^\dagger H_W + \frac{9 g_B^2 \Lambda^2}{64\pi^2} H_H^\dagger H_H$
- Z_2 symmetry: $g_A=g_B$
  - Accidental SU(4) symmetry of $\Delta V^{(2)}$
  - No mass generated for higgs boson to $O(g^2)$

Chacko, Go, and Harnick hep-ph/0506256

Twin Higgs (cont'd)

- Self-coupling $\Delta V^{(4)} \propto \frac{g^4}{16\pi^2} \log\left(\frac{\Lambda}{gf}\right) (|H_W|^4 + |H_H|^4)$
- Extend SU(4) global symmetry to top-quark sector
- EWSB: Radiatively induced
- Hierarchy : like Little Higgs

Goh, Argonne Workshop 2006

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 $\Rightarrow$ theories constructed by analogy!

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

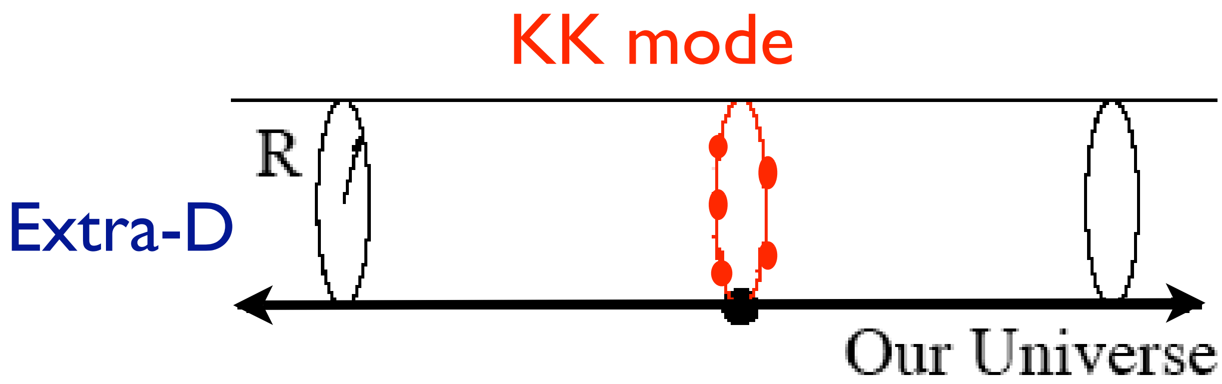
Process	Excluded mass range	Decay channels	Ref.
$p\bar{p} \to \rho_T \to W\pi_T$	$170 < m_{\rho_T} < 190$ GeV for $m_{\pi_T} \approx m_{\rho_T}/2$	$\rho_T \to W\pi_T$ $\pi_T^0 \to b\bar{b}$ $\pi_T^\pm \to b\bar{c}$	[16]
$p\bar{p} \to \omega_T \to \gamma\pi_T$	$140 < m_{\omega_T} < 290$ GeV for $m_{\pi_T} \approx m_{\omega_T}/3$ 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	$\pi_{LQ} \to c\nu$	[25]
	$m_{\rho_{T8}} < 600$ GeV	$\pi_{LQ} \to b\nu$	[25]
	$m_{\rho_{T8}} < 465$ GeV	$\pi_{LQ} \to \tau q$	[24]
$p\bar{p} \to g_t$	$0.3 < m_{g_t} < 0.6$ TeV for $0.3 m_{g_t} < \Gamma < 0.7 m_{g_t}$	$g_t \to b\bar{b}$	[30]
$p\bar{p} \to Z'$	$m_{Z'} < 480$ GeV for $\Gamma = 0.012 m_{Z'}$ $m_{Z'} < 780$ GeV for $\Gamma = 0.04 m_{Z'}$	$Z' \to t\bar{t}$	[31]

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

Extra-D Theories and Massive Vector Boson Scattering



Expand 5-D gauge bosons in eigenmodes:

e.g. for S^1/Z_2:

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

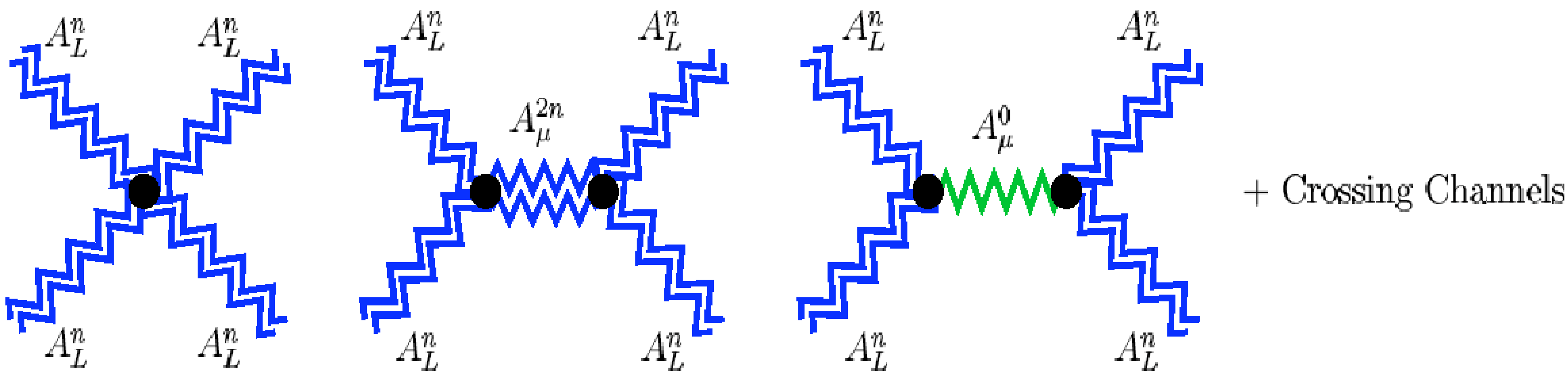
$$\widehat{A}^a_5 = \sqrt{\frac{2}{\pi R}}\sum_{n=1}^{\infty} A^{an}_5(x_\nu)\sin\left(\frac{nx_5}{R}\right)$$

4-D gauge kinetic term contains

$$\frac{1}{2}\sum_{n=1}^{\infty}\left[M_n^2(A^{an}_\mu)^2 - 2M_n A^{an}_\mu \partial^\mu A^{an}_5 + (\partial_\mu A^{an}_5)^2\right]$$

i.e., $A^{an}_L \leftrightarrow A^{an}_5$

4-D KK Mode Scattering



(a) $(b1)$ $(c1)$ $(b2,b3)+(c2,c3)$

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

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	$-8cx^2$	$-8cx^2$	$-8cx^2 \Rightarrow 0$

No Free Lunch

Non-renormalizability of 5-D YM implies lingering unitarity issues ... how is this manifest in KK scattering?

Consider a state composed of KK pairs with $n \leq N_0$

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

Find 4-D s-wave, gauge-singlet amplitude of $|\psi^{aa}\rangle \to |\psi^{cc}\rangle$

$$a_\psi^{00} = \frac{N_0}{R} \frac{k g_5^2}{8\pi^2} \mathcal{O}(1)$$

Grows with N_0!

Moral: Unitarity can be delayed, but not avoided!

- unitary bound on a_ψ^{00} implies highest KK mode number is bounded from above:

$$\frac{N_0}{R} < \frac{\sqrt{32}\pi^2}{k} \frac{\mathcal{O}(1)}{g_5^2}$$

(consistent with 5-d intuition)

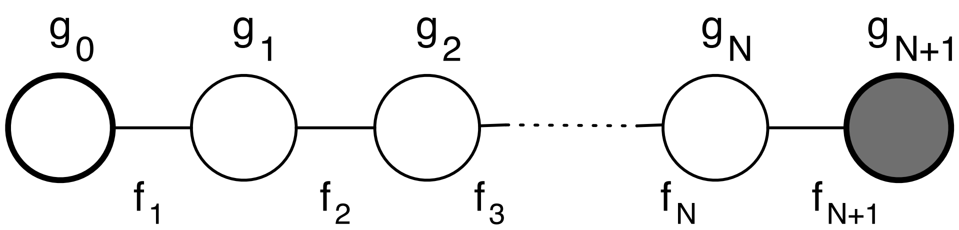
- $g_{SU(2)} \sim 1$; thus, one can potentially add a few vector mesons and delay unitarity onset

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

Recipe for a Higgsless Model:

- Choose "bulk" gauge group, location of fermions, and boundary conditions
- Choose $g(x_5)$
- Choose metric/manifold: $g_{MN}(x_5)$
- Calculate spectrum & eigenfunctions
- Calculate fermion couplings
- Compare to Standard Model: S, T, U, ...

Deconstructed Higgsless Models

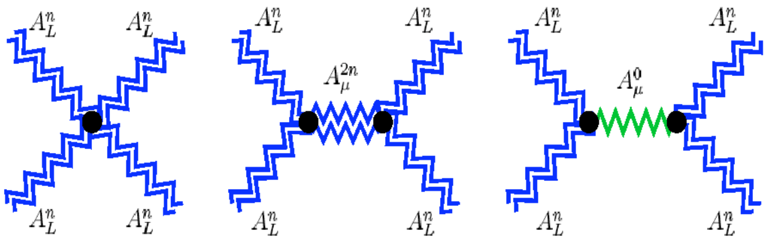


- $SU(2)^N \times U(1)$;   general f_j and g_k
- Fermions sit on "branes" [sites 0 and N+1]
- Many 4-D/5-D theories are limiting cases...
  study them all at once!
- e.g., N=1 equivalent to technicolor/one-Higgs

Foadi, *et. al.*   &   Chivukula *et. al.*

Conflict of S & Unitarity

Heavy resonances must unitarize WW scattering (since there is no Higgs!)



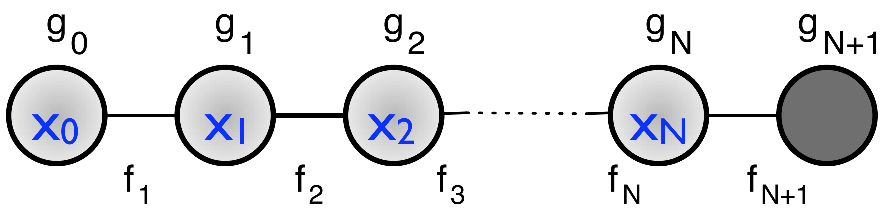
This bounds lightest KK mode mass: m$_{Z_1} < \sqrt{8}\pi v$

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

Too large by a factor of a few!

Independent of warping or gauge couplings chosen...

A New Hope?



Since Higgsless models with localized fermions are not viable, look at:

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

$$\mathcal{L}_f = \vec{J}_L^{\mu} \cdot \left(\sum_{i=0}^{N} x_i \vec{A}_{\mu}^{i} \right) + J_Y^{\mu} A_{\mu}^{N+1}$$

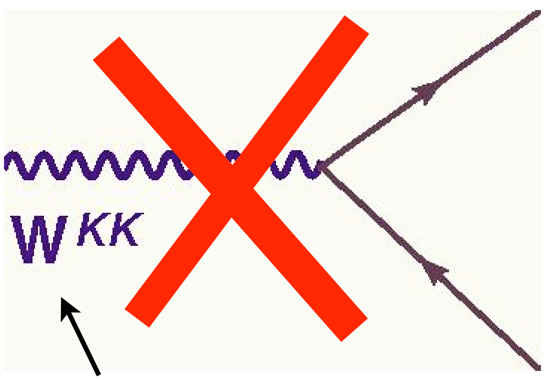
How will this affect precision EW observables?

Cacciapaglia et. al.

Foadi & Schmidt: see Schmidt talk

Ideal Delocalization

- Choose delocalization related to W wavefunction: $g_i x_i \propto v_i^W$
- NB: $x_i = |\psi_f(i)|^2 > 0$
- W-wavefunction orthogonal to KK wavefunctions.
- No (tree-level) couplings to heavy modes!



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

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

RSC, HJH, MK, MT, EHS hep-ph/0504114

LEP II Constraints

LEP II measurements of WWZ vertex yield

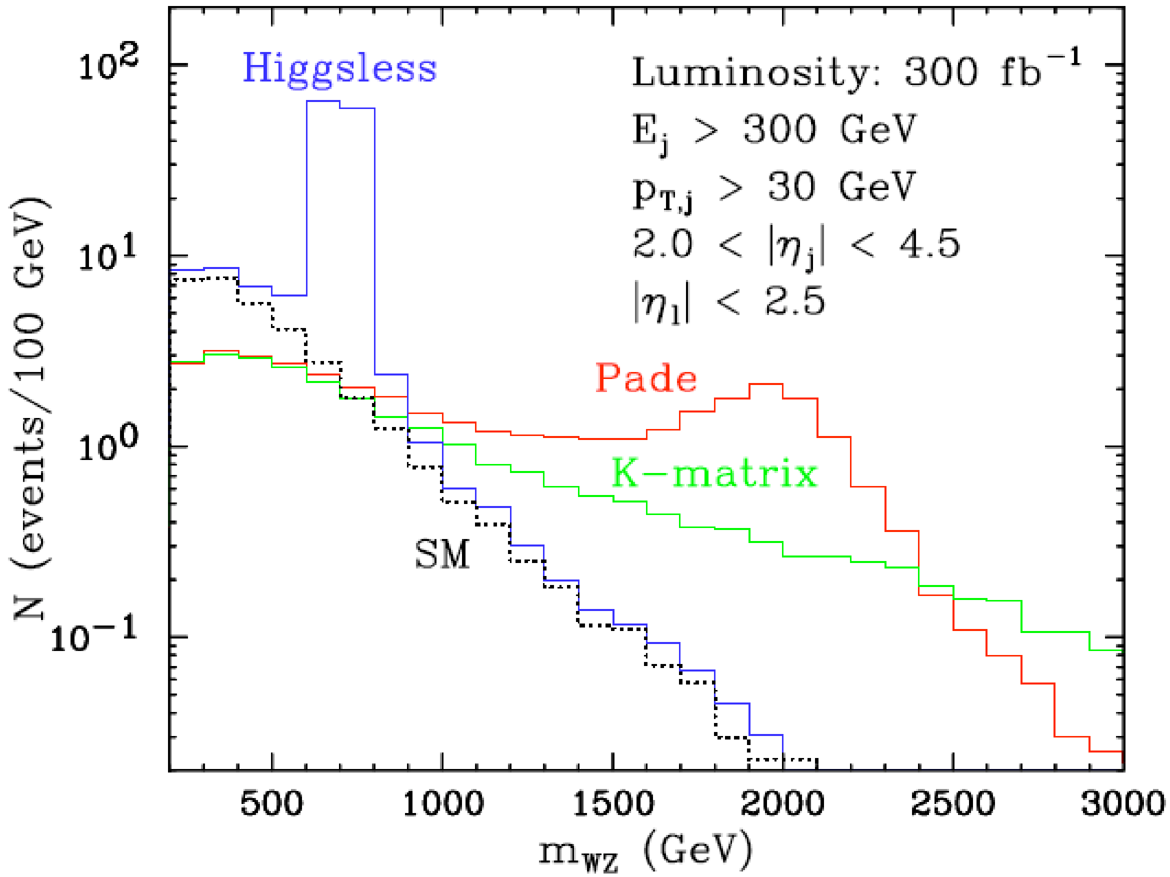
$$\Delta g_1^Z \leq 0.028 \quad @ \quad 95\%\mathrm{CL}$$

In a flat space SU(2) x SU(2) x U(1) model

$$\Delta g_1^Z = \frac{\pi^2}{12c^2}\left(\frac{M_W}{M_{W_1}}\right)^2\left[\frac{1}{4}\cdot\frac{7+\kappa}{1+\kappa}\right]$$

$$M_{W_1} \geq 500\ \mathrm{GeV}\cdot\sqrt{\frac{0.028}{\Delta g_{max}}\ \left[\frac{1}{4}\cdot\frac{7+\kappa}{1+\kappa}\right]}$$

LHC Phenomenology



Birkedal, et.al., hep-ph/0412278

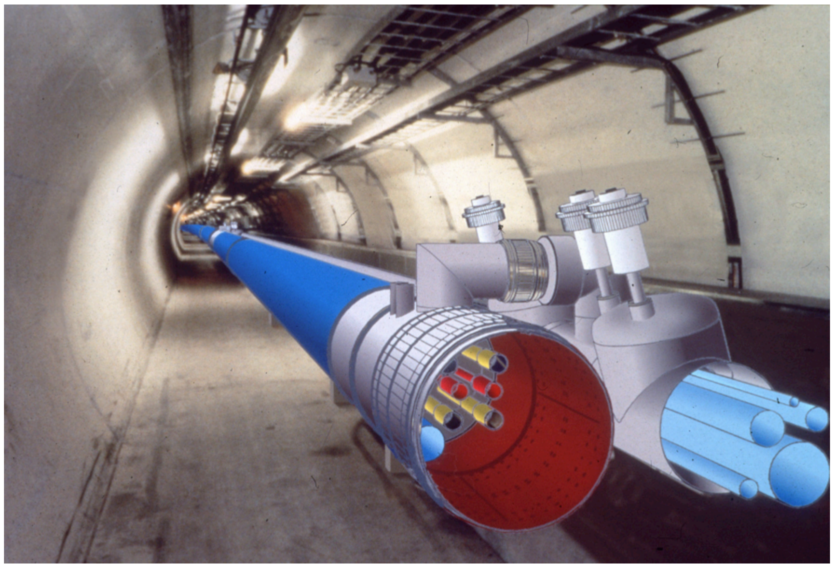
Observations

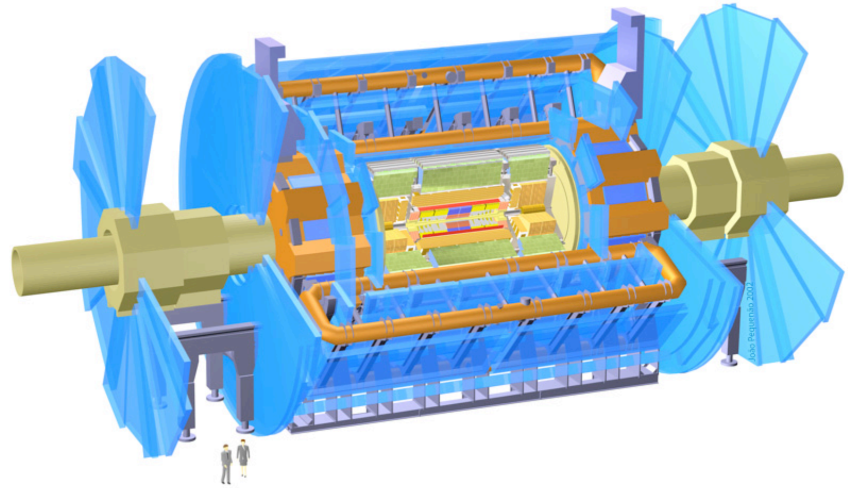
- Our standards have changed
  - We are content with a low-energy effective theory valid to ~ few TeV
  - This is a good thing in preparation for the LHC ...
- Fine-tuning is in the eye of the beholder
  - S=O(1) in QCD-like technicolor; experimental bound O(0.1) - hence need 10% fine-tuning?
  - Dynamics matters: Inflation makes fine-tuning of flatness problem irrelevant.

Conclusions

- Two new mechanisms to address hierarchy problem
  - Composite/Little/Twin Higgs
  - Higgsless Models
- Both predict new TeV Scale particles
  - Extended Electroweak Gauge Symmetries
  - Extended Fermion Sector
- Much Phenomenology Left to be done!

LHC-TI Town Meeting





TODAY, 2:00pm -- 4:30pm CDT
Pyle Center, Room 227
702 Langdon Street
University of Wisconsin
Madison, Wisconsin

Extra Slides

Electroweak Parameters I

EW corrections $(S,\ T,\ \Delta\rho,\ \delta)$ defined from amplitudes for "on-shell" 4-fermion processes

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

$$+ \quad \sqrt{2}G_F \frac{\alpha\delta}{s^2c^2} I_3 I_3' + 4\sqrt{2}G_F\left(\Delta\rho - \alpha T\right)(\mathcal{Q} - I_3)(\mathcal{Q}' - I_3')$$

$$-\mathcal{A}_{\mathrm{CC}} = \frac{(I_+ I_-' + I_- I_+')/2}{\left(\frac{s^2}{e^2} - \frac{S}{16\pi}\right) Q^2 + \frac{1}{4\sqrt{2}G_F}\left(1 + \frac{\alpha\delta}{4s^2c^2}\right)} + \sqrt{2}G_F \frac{\alpha\delta}{s^2c^2} \frac{(I_+ I_-' + I_- I_+')}{2} \ .$$

S,T: Peskin & Takeuchi

Electroweak Parameters II

Alternative formulation defined at zero momentum

$$\hat{S} = \frac{1}{4s^2}\left(\alpha S + 4c^2(\Delta\rho - \alpha T) + \frac{\alpha\delta}{c^2}\right)$$

$$\hat{T} = \Delta\rho$$

$$Y = \frac{c^2}{s^2}(\Delta\rho - \alpha T)$$

$$W = \frac{\alpha\delta}{4s^2c^2}$$

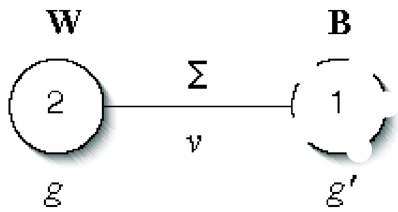
Barbieri, Pomarol, Rattazzi, Strumia

Aside: Moose notation

Reveals symmetry (breaking) structure at a glance

A familiar example:

$SU(2)_W \times U(1)_B \longrightarrow U(1)$ ↔



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 Σ

A solid line linking two circles is an [SU(2) x SU(2) / SU(2)] non-linear sigma model field; at the scale v this breaks the gauged or global symmetries of the attached circles

Note: Σ is a 2x2 matrix field transforming as $\Sigma \rightarrow L\Sigma R^{\dagger}$ under the SU(2) groups which it connects.

An SU(2)xSU(2)xU(1)xU(1) model with the following symmetry-breaking pattern:

$$SU(2)_L \times SU(2)_W \times U(1)_B \times U(1)_R$$

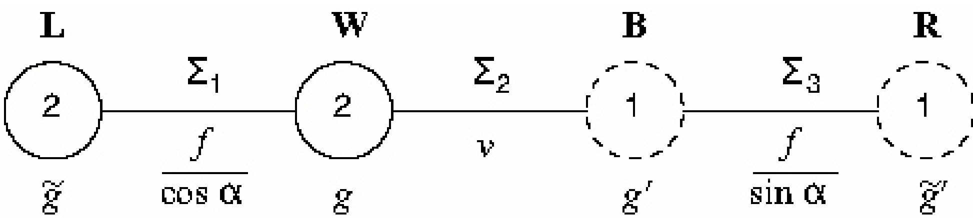
$$\Downarrow \; f$$

$$SU(2)_{weak} \times U(1)_Y$$

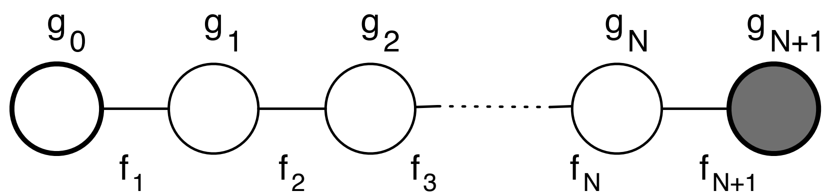
$$\Downarrow \; v$$

$$U(1)_{EM}$$

Can be represented compactly in Moose notation



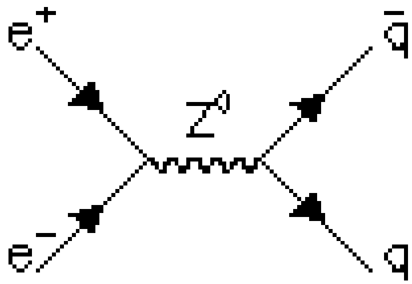
Mass Matrix & Spectrum



$$M_Z^2 = \frac{1}{4}\left(\begin{array}{c|c|c|c|c|c}
g_0^2 f_1^2 & -g_0 g_1 f_1^2 & & & & \\ \hline
-g_0 g_1 f_1^2 & g_1^2(f_1^2+f_2^2) & -g_1 g_2 f_2^2 & & & \\ \hline
 & -g_1 g_2 f_2^2 & g_2^2(f_2^2+f_3^2) & -g_2 g_3 f_3^2 & & \\ \hline
 & & \ddots & \ddots & \ddots & \\ \hline
 & & & -g_{N-1} g_N f_N^2 & g_N^2(f_N^2+f_{N+1}^2) & -g_N g_{N+1} f_{N+1}^2 \\ \hline
 & & & & -g_N g_{N+1} f_{N+1}^2 & g_{N+1}^2 f_{N+1}^2
\end{array}\right).$$

- $\boldsymbol{M}_Z^2$ as above; Spectrum: Photon, Z, heavy Z's
- $\boldsymbol{M}_W^2$ has $g_{N+1} = 0$; Spectrum: W, heavy W's
- EM coupling as expected: $\dfrac{1}{e^2} = \dfrac{1}{g_0^2} + \dfrac{1}{g_1^2} + \ldots + \dfrac{1}{g_{N+1}^2}$

Correlation Functions I



e.g., weak-hypercharge correlation function for Z exchange is within

$$[G(Q^2)]_{0,N+1} \equiv g_0 g_{N+1} \langle 0 | \frac{1}{Q^2 + M_Z^2} | N+1 \rangle$$

$$Q^2 + M_Z^2 = \begin{pmatrix} Q^2+g_0^2 f_1^2/4 & -g_0 g_1 f_1^2/4 & & & & \\ -g_0 g_1 f_1^2/4 & Q^2+g_1^2(f_1^2+f_2^2)/4 & -g_1 g_2 f_2^2/4 & & & \\ & -g_1 g_2 f_2^2/4 & Q^2+g_2^2(f_2^2+f_3^2)/4 & -g_2 g_3 f_3^2/4 & & \\ & & \ddots & \ddots & \ddots & \\ & & & -g_{N-1} g_N f_N^2/4 & Q^2+g_N^2(f_N^2+f_{N+1}^2)/4 & -g_N g_{N+1} f_{N+1}^2/4 \\ & & & & -g_N g_{N+1} f_{N+1}^2/4 & Q^2+g_{N+1}^2 f_{N+1}^2/4 \end{pmatrix}.$$

By considering the (0,N+1) co-factor, we deduce the form of the correlation function

Correlation Functions II

$$[G(Q^2)]_{0,N+1} = \frac{C}{Q^2(Q^2+M_Z^2)\prod_{n=1}^{N}(Q^2+\mathsf{m}_{Z_n}^2)}$$

We know the residue of $Q^2=0$ pole must be e^2 ...

$$[G(Q^2)]_{0,N+1} = \frac{e^2 M_Z^2 \prod_{n=1}^{N}\mathsf{m}_{Z_n}^2}{Q^2(Q^2+M_Z^2)\prod_{n=1}^{N}(Q^2+\mathsf{m}_{Z_n}^2)}$$

Other residues are also informative.

S parameter: Brane Fermions

Correlation function residue at $Q^2 = -M^2_Z$

gives "$J_3\ J_Y$" coupling of light Z-boson

$$[\xi_Z]_{WY} = -e^2 \prod_{n=1}^{N} \frac{1}{1 - \frac{M_Z^2}{\mathrm{m}_{Z_n}^2}} = -e^2 \left(1 + \frac{\alpha S}{4 s_Z^2 c_Z^2}\right)$$

Requiring $M_Z << m_{Z_n}$ yields

$$\alpha S \approx 4 s_Z^2 c_Z^2 \sum_{n=1}^{N} \frac{M_Z^2}{\mathrm{m}_{Z_n}^2}$$

for the entire class of models!