Electroweak Corrections in Higgsless Models

R. Sekhar Chivukula
Michigan State University

Aspen Center for Physics
Feb. 15, 2005

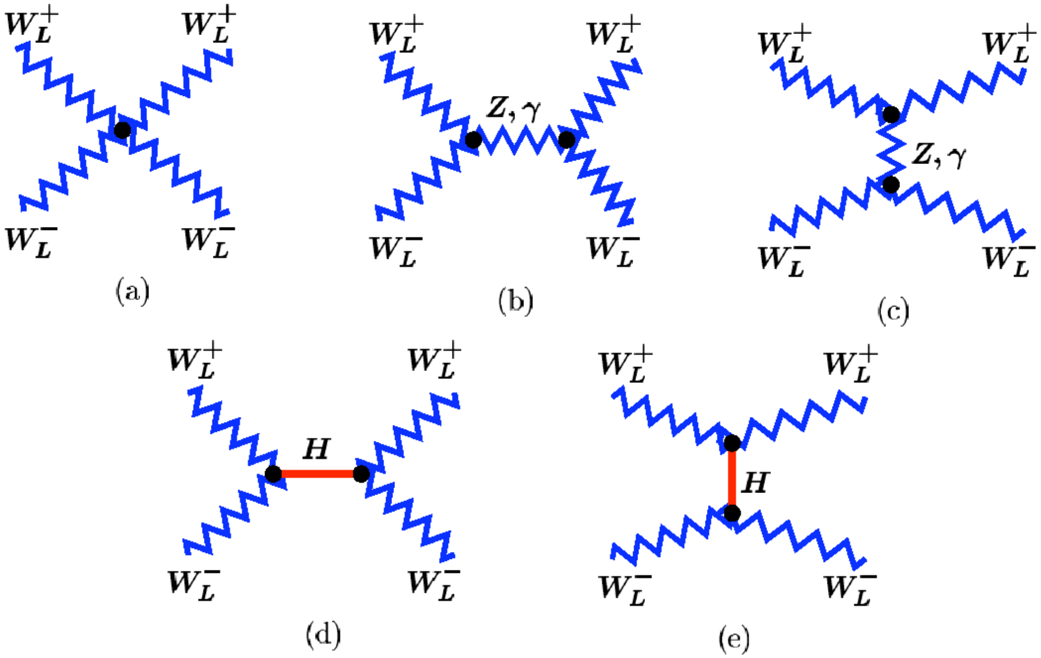
Outline

- Why do we care about EWSB?
- What are Higgsless Models?
- Deconstructed Higgsless Models
- S > 0.5 for Localized Fermions!
- Delocalized Fermons
- Conclusions

References

- Chivukula, He, Kurachi, Simmons, Tanabashi: hep-ph/0406077,0408262,0410154
- Csaki, Grojean, Murayama, Pilo, Terning, Cacciapaglia
- Foadhi, Gopalkrishna, Schmidt
- Davoudiasl, Hewett, Lillie, Rizzo
- Non-commuting ETC, Ununified SM, "Top-Flavor"

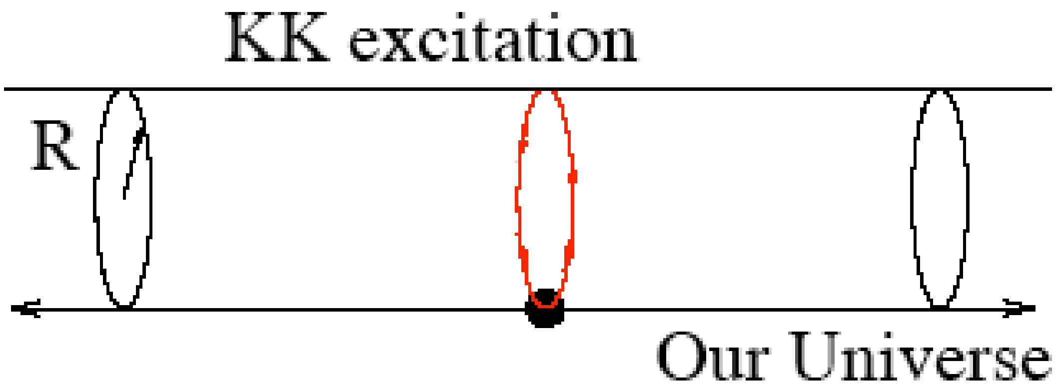
SU(2) x U(1) @ E^2



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	**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 Theories



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

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

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

KK Masses: "Higgs Mechanism"

- 4d kinetic gauge term contains:

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

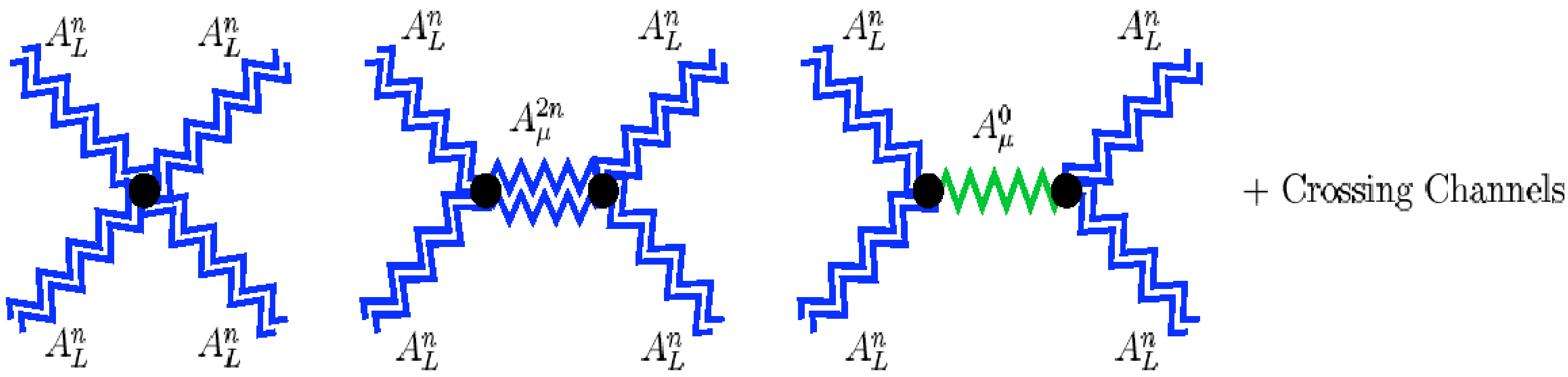
Geometric KK Mass Spectrum: $M_n = n/R$

- 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 boundary conditions!

4-D KK Mode Scattering



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

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

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

RSC, H.J. He, D. Dicus

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

- Generalizes to a large class of 5-d manifolds and boundary conditions - Higgsless Models (Csaki, Grojean, Murayama, Pilo, Terning)
- $g_{SU(2)} \sim 1$; can potentially add several vector mesons and delay unitarity.
- Vanishing gauge coupling - unitarized chiral perturbation theory (Son and Stephanov)

Recipe for a Higgsless Model:

- Choose "bulk" gauge group, position of fermions, boundary conditions
- Choose $g(x_5)$
- Choose metric/manifold: $g_{ab}(x_5)$
- Calculate spectrum & eigenfunctions
- Calculate fermion couplings
- Compare to SM: S, T,...

Can we do better? Yes, using deconstruction!

Electroweak Parameters: I

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

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

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

S, T: Peskin & Takeuchi

Electroweak Parameters: II

Barbieri, et. al. Parameters

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

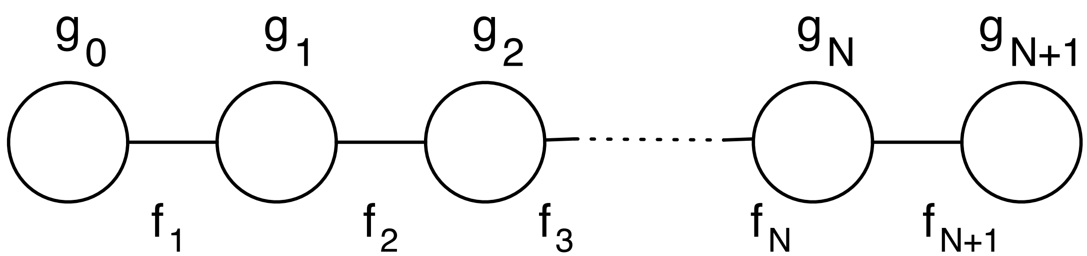
$$\hat{T} = \Delta\rho$$

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

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

Barbieri, Pomarol, Rattazzi, and Strumia

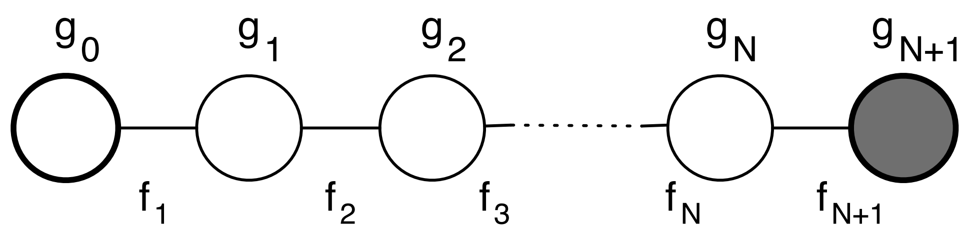
Deconstruction



- Discretize fifth dimension
- 4D gauge group at each site
- Nonlinear Sigma Model Link Fields
- Warping: vary f_j
- Spatially dependent coupling: vary g_k
- Continuum Limit: N to infinity

Arkani-Hamed, Georgi, Cohen & Hill, Pokorski, Wang

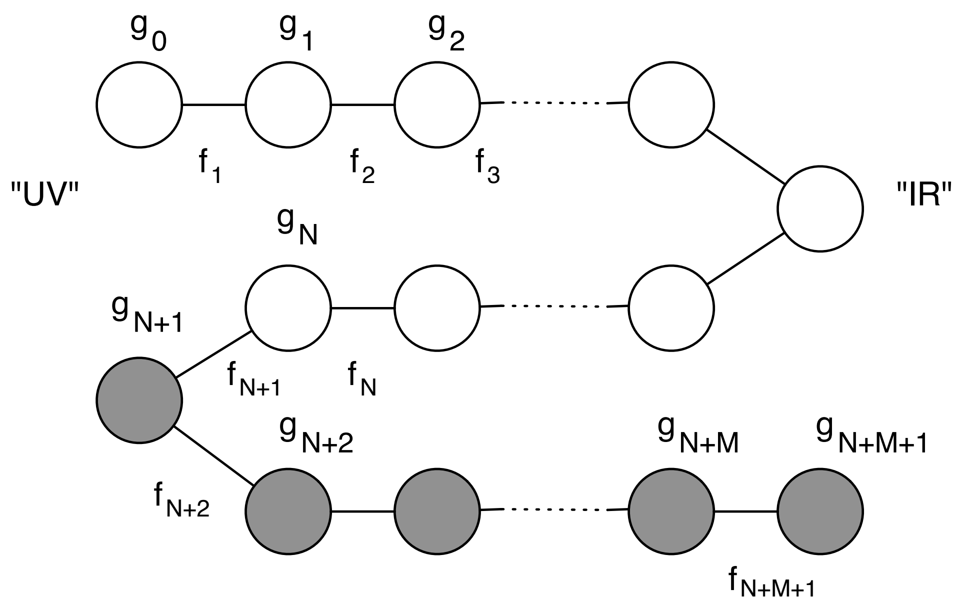
A Deconstructed Higgsless Model



- $SU(2)^N \times U(1)$
- Fermions on “branes”, sites 0 and N+1
- N=0 equivalent to technicolor/one-Higgs
- Many 4-D/5-D theories at once!

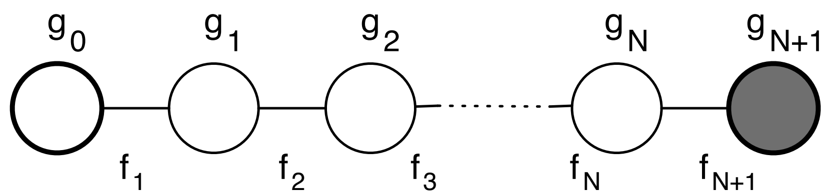
Foadhi, *et. al.* & RSC *et. al.*

Generalizations



- SU(2) x SU(2) x U(1) in “bulk”
- modify fermion location, etc...
- In this talk, will stick with simplest moose

Mass Matrix

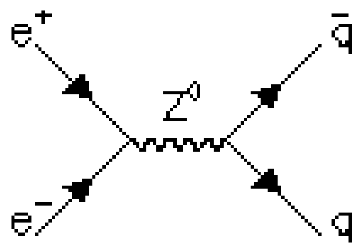


$$M_Z^2 = \frac{1}{4}\left(\begin{array}{cccccc}
g_0^2 f_1^2 & -g_0 g_1 f_1^2 & & & & \\
-g_0 g_1 f_1^2 & g_1^2(f_1^2+f_2^2) & -g_1 g_2 f_2^2 & & & \\
 & -g_1 g_2 f_2^2 & g_2^2(f_2^2+f_3^2) & -g_2 g_3 f_3^2 & & \\
 & & \ddots & \ddots & \ddots & \\
 & & & -g_{N-1} g_N f_N^2 & g_N^2(f_N^2+f_{N+1}^2) &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

- Photon, Z, heavy Z's
- M^2_W with $g_{N+1}=0$: W, heavy W's

$$\frac{1}{e^2} = \frac{1}{g_0^2} + \frac{1}{g_1^2} + \ldots + \frac{1}{g_{N+1}^2}$$

Correlation Functions: I



e.g

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

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

- Consider (0,N+1) co-factor

Correlation Functions: II

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

- Residue of $Q^2=0$ pole is e^2

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

S parameter

- Residue at $Q^2 = -M^2_Z$ gives "$J_3\, J_Y$" Z-coupling

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

Require that $M_Z \ll m_{Z_n}$

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

For entire class of models!

Connection to Unitarity

- Resonances must unitarize WW scattering

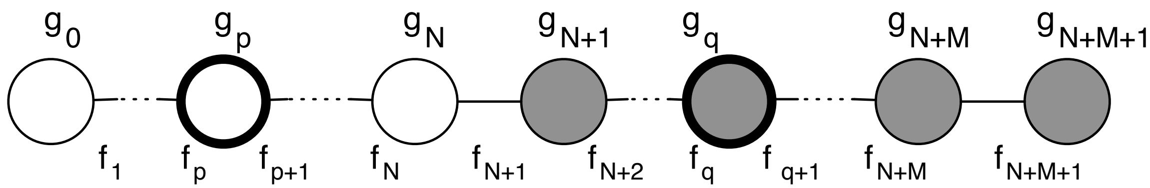
$$\text{m}_{Z_1} < \sqrt{8}\pi v$$

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

Too large by a factor of a few!

Independent of warping or gauge couplings chosen...

Generalizations

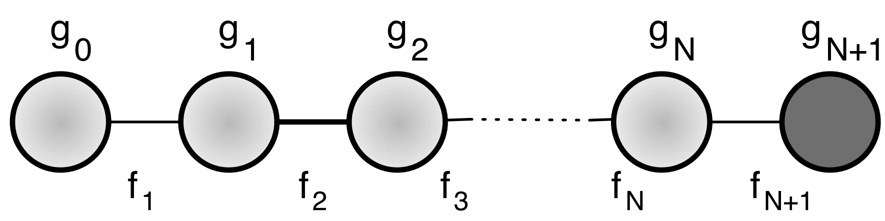


- Any model of this kind
  - with localized fermions
  - has only a light photon, W, and Z
  - and is unitary

Have $\hat{S} > 5 \times 10^{-3}$!

$\hat{S}$ as defined by Barbieri, Pomarol, Rattazzi, and Strumia

A New Hope?



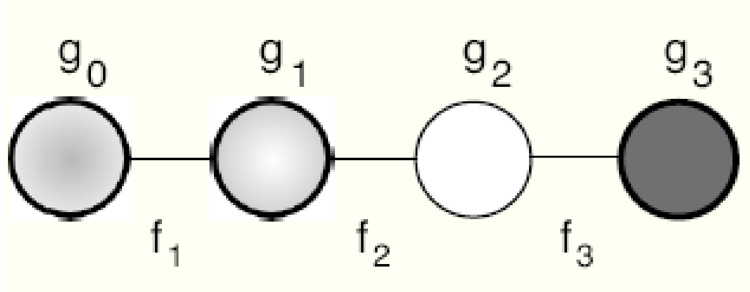
- Delocalized Fermions
  - Mixing of "brane" and "bulk" modes

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

Can tune value of S...
...can this occur naturally?

Analogous to some ETC-induced effects

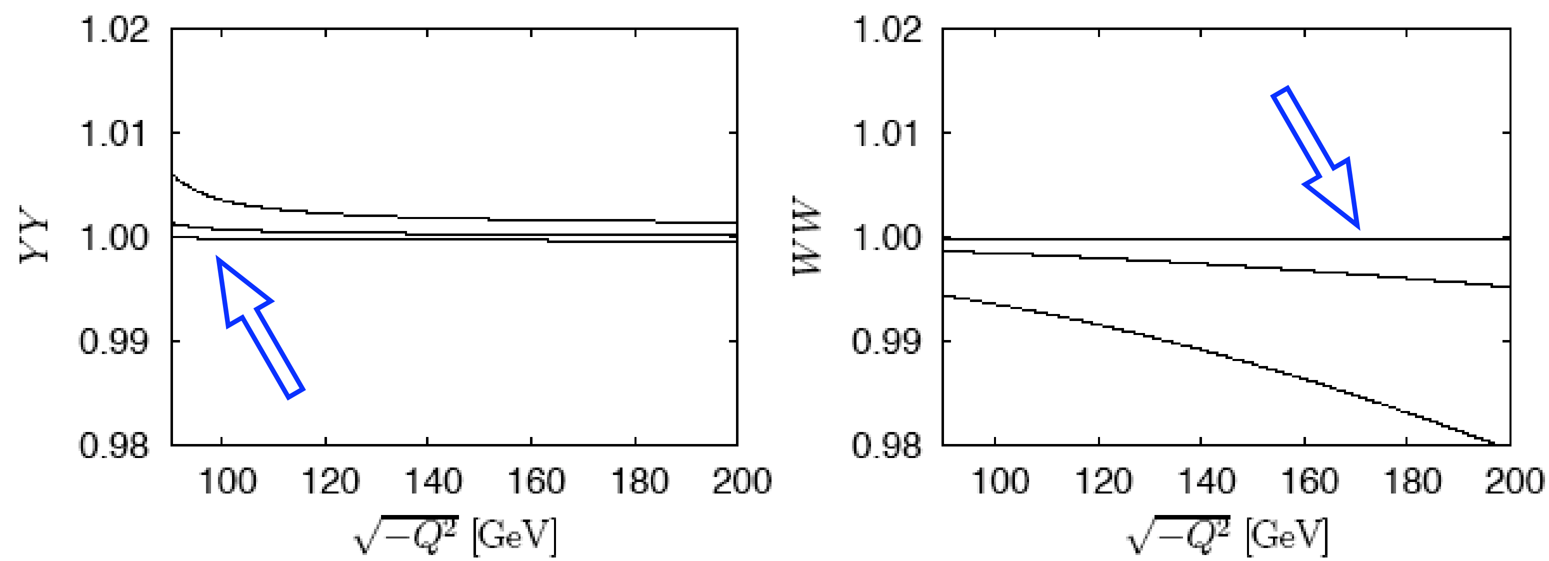
A Toy Model



Massless Fermions!

	Set 1	Set 2	Set 3
Inputs			
f_1	1000 GeV	2000 GeV	300 GeV
$f_2 = f_3$	356.303 GeV	348.922 GeV	591.850 GeV
g_0	0.664421	0.663478	0.657164
$g_1 = g_2$	4.0	4.0	4.0
g_3	0.356505	0.356651	0.357650
x_1	0.139231	0.480892	0.014771
Calculated Physical Masses			
M_W	79.9486 GeV	79.9080 GeV	79.9599 GeV
m_{Z1}	976.990 GeV	983.725 GeV	892.459 GeV
m_{W1}	975.913 GeV	982.737 GeV	888.827 GeV
m_{Z2}	2162.17 GeV	4114.49 GeV	1944.08 GeV
m_{W2}	2162.17 GeV	4144.49 GeV	1943.39 GeV

Correlation Functions at LEP-I and II



Ratio to Standard Model

RSC, HJH, MK, MT, EHS in progress

Conclusions

- Unitary Higgsless models with localized fermions give rise to $\hat{S} > 5 \times 10^{-3}$ ... like QCD-like technicolor
- Fermion delocalization can be used to cancel these effects -- can this happen naturally?