Two Brief Sketches

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- An Effective Higgsless Model
- Z' Bosons Coupled to the 3rd Generation

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Sketch #1:
An Effective Higgsless Model

- Higgsless Models and Ideal Delocalization
- A Simple 3-Site Model
- Experimental Bounds and Signatures
- Conclusions

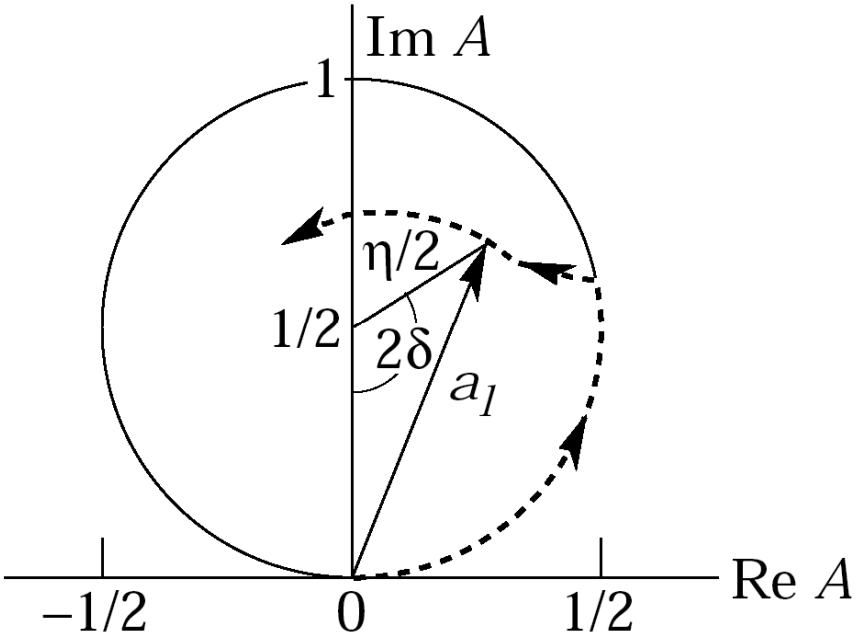
Symptom of Problems in EWSB?

Unitarity!

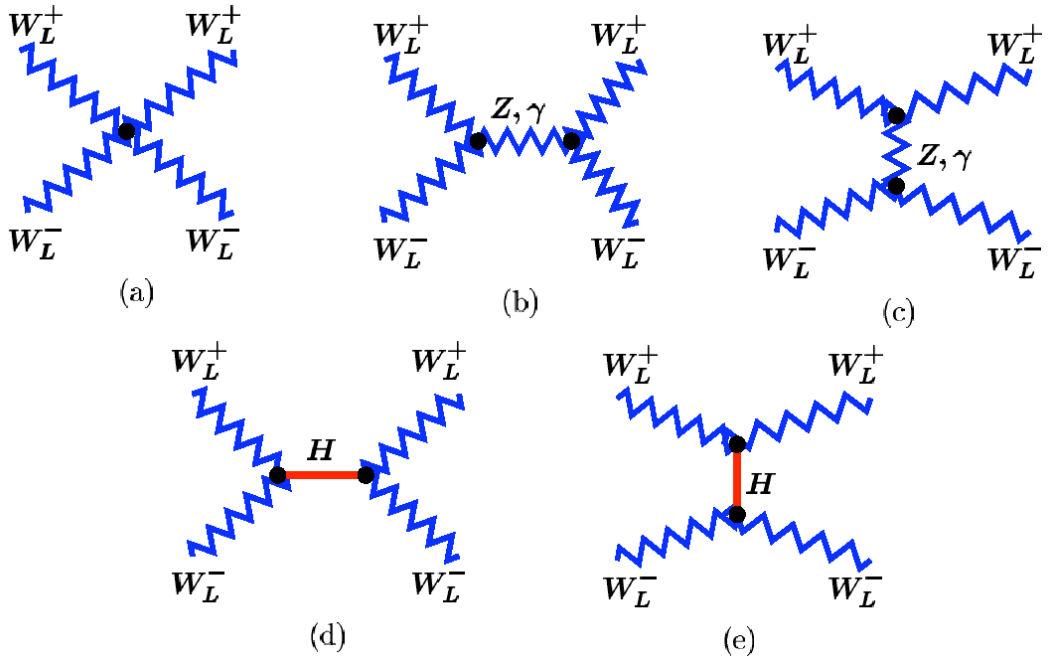
$$\mathscr{M} = -8\pi\sqrt{s}\; f(k,\theta)$$

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

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



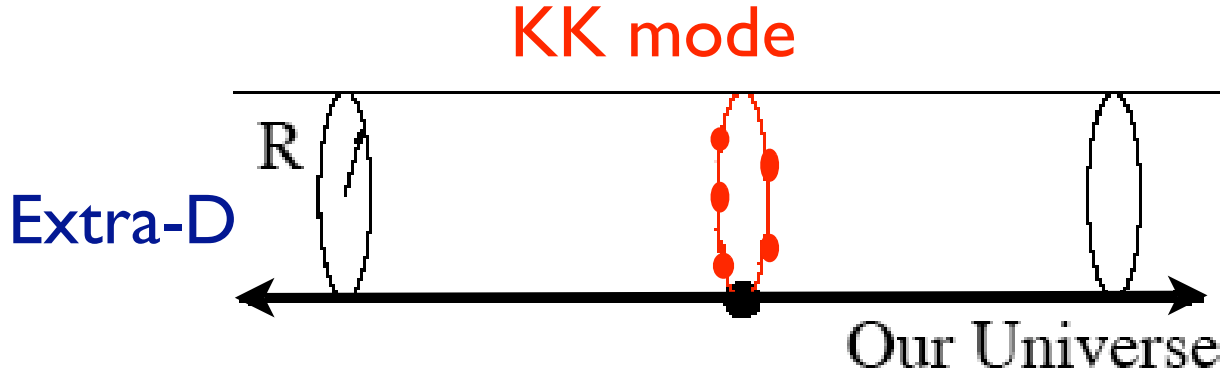
SU(2) x U(1) @ E^2



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

Massive Gauge Bosons from Extra-D Theories



Expand 5-D gauge bosons in eigenmodes:

e.g. for S^1/Z_2:

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

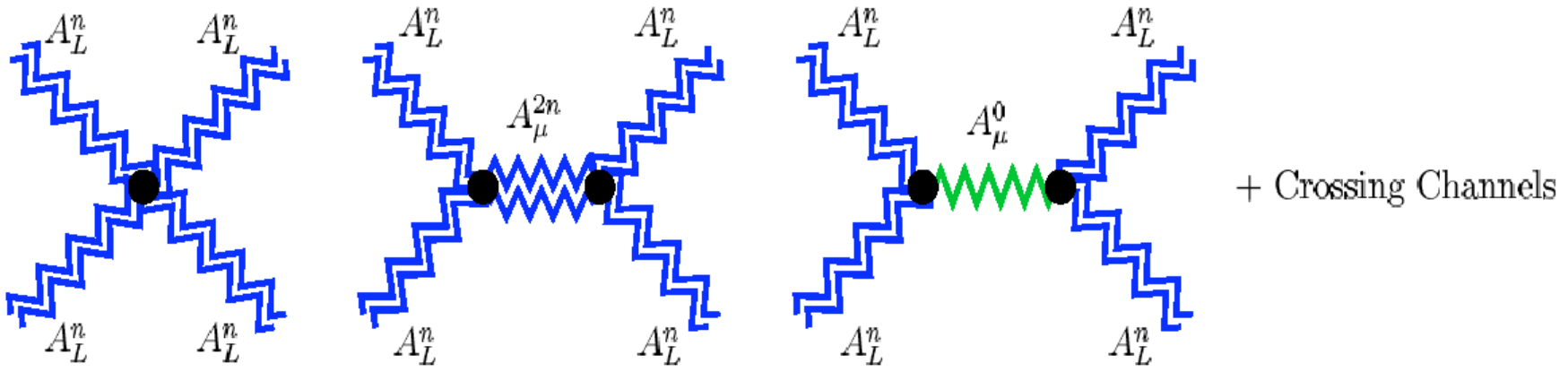
$$\widehat{A}^a_5 = \sqrt{\frac{2}{\pi R}}\sum_{n=1}^{\infty} A^{an}_5(x_\nu)\sin\left(\frac{nx_5}{R}\right)$$

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



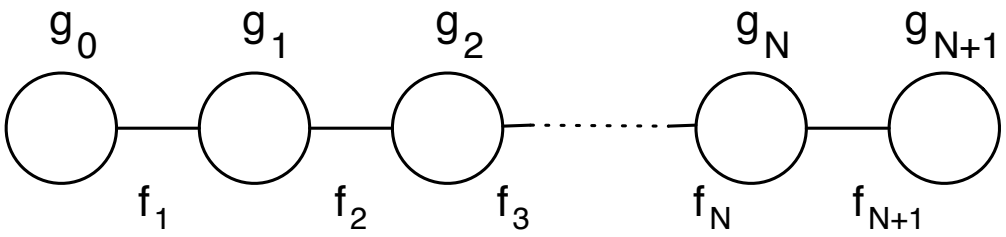
Cancellation of bad high-energy behavior through exchange of massive vector particles ...

But the more modes added, the faster the coupled-channel unitarity bound is reached.

RSC, H.J. He, D. Dicus

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

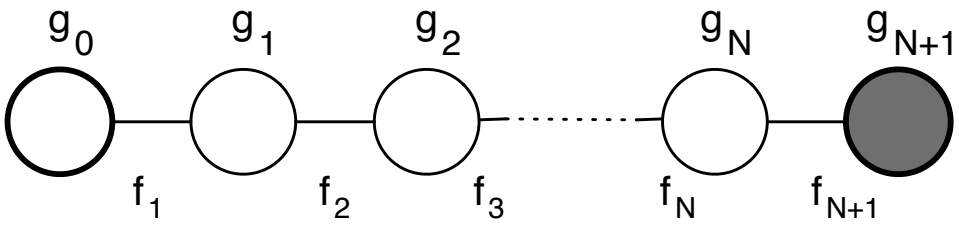
A 4-D Option: Deconstruction



- Discretize fifth dimension
- 4D gauge group at each site
- Nonlinear sigma model link fields
- To include warping: vary f_j
- For spatially dependent coupling: vary g_k
- Continuum Limit: take N → infinity

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

Deconstructed Higgsless Models

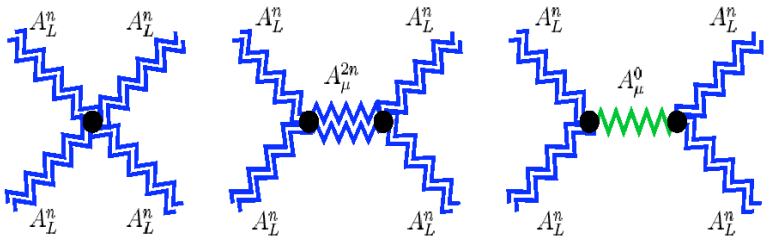


- $SU(2)^N \times U(1)$; general f_j and g_k
- Fermions sit on "branes" [sites 0 and N+1]
- Many 4-D/5-D theories are limiting cases... study them all at once!
- e.g., N=1 equivalent to technicolor/one-Higgs

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

Conflict of S & Unitarity

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



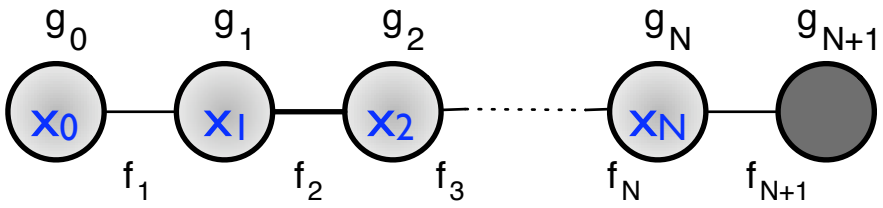
This bounds lightest KK mode mass: $m_{Z_1} < \sqrt{8}\pi v$

... and yields a value of the S-parameter that is

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

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

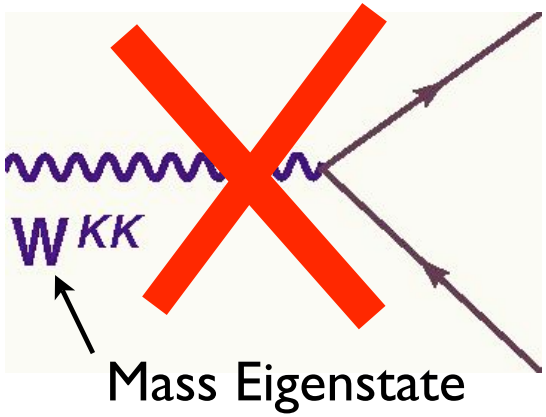
Can Eliminate Contribution to S!

Cacciapaglia, Csaki, Grojean, & Terning

Foadi, Gopalkrishna, & Schmidt

Ideal Delocalization

- Choose fermion delocalization profile 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!



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

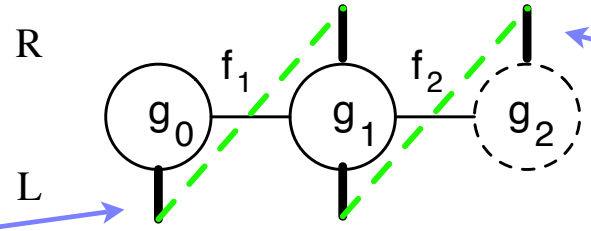
$$Y = M_W^2(\Sigma_W - \Sigma_Z)$$

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

A Simple 3-Site Model

$SU(2) \times SU(2) \times U(1)$

$g_0,\ g_2 \ll g_1$



RH Boundary Fermion

LH Boundary Fermion

"Bulk Fermion"

$$\mathcal{L}_f = \varepsilon_L\, M\, \bar{\psi}_{L0}\Sigma_1\psi_{R1} + M\, \bar{\psi}_{R1}\psi_{L1} + M\, \bar{\psi}_{L1}\Sigma_2 \begin{pmatrix} \varepsilon_{tR} & \\ & \varepsilon_{bR} \end{pmatrix} \begin{pmatrix} u_{R2} \\ d_{R2} \end{pmatrix} + h.c.$$

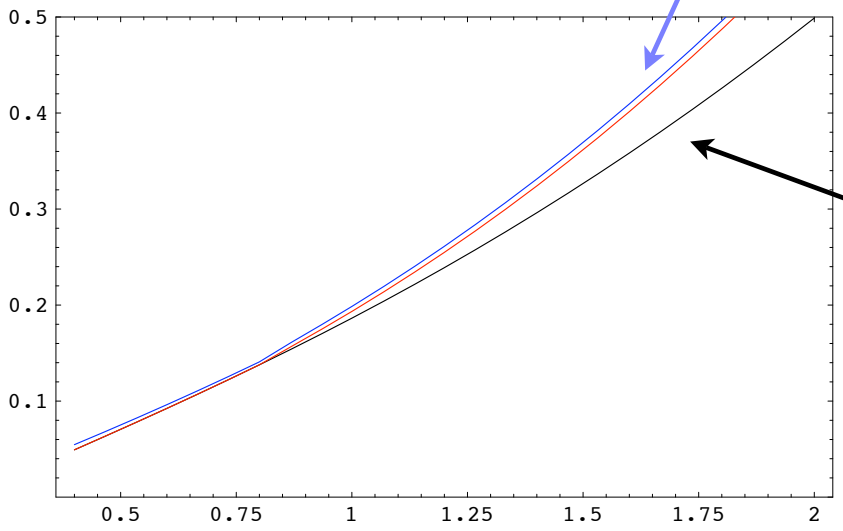
Fermion Structure Motivated by 5-D

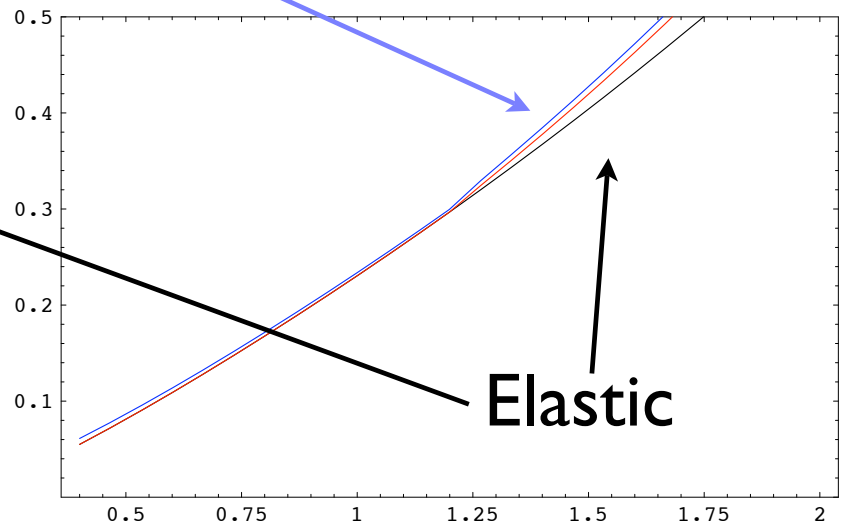
Flavor Structure Identical to Standard Model

Particles: photon, W, W', Z, Z', t, T, b, B
(c, C, s, S, u, U, d, D & leptons)

3-Site Coupled-Channel Unitarity

Coupled-Channel Amplitude





Elastic

$M_{W'} = 400\,\mathrm{GeV}$

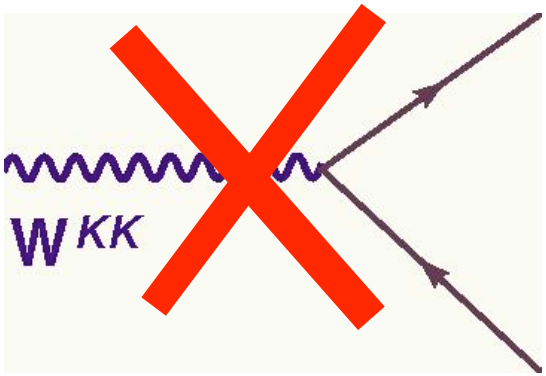
$M_{W'} = 600\,\mathrm{GeV}$

Modest Unitarity Delay : 1.5 - 1.75 TeV

3-Site Ideal Delocalization

$$\varepsilon_L^2 = 2\left(\frac{M_W^2}{M_{W'}^2}\right) + 6\left(\frac{M_W^2}{M_{W'}^2}\right)^2 + \ldots$$

Insures:



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

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

W' and Z' are fermiophobic!

Must rely on WW scattering: Birkedal et. al. hep-ph/0412278

TGVs in 3-Site Model

Hagiwara, *et. al.* define:

$$\begin{aligned}\mathcal{L}_{TGV} &= -ie\frac{c_Z}{s_Z}\left[1+\Delta\kappa_Z\right]W^+_\mu W^-_\nu Z^{\mu\nu} - ie\left[1+\Delta\kappa_\gamma\right]W^+_\mu W^-_\nu A^{\mu\nu} \\ &- ie\frac{c_Z}{s_Z}\left[1+\Delta g_1^Z\right](W^{+\mu\nu}W^-_\mu - W^{-\mu\nu}W^+_\mu)Z_\nu \\ &- ie(W^{+\mu\nu}W^-_\mu - W^{-\mu\nu}W^+_\mu)A_\nu \ ,\end{aligned}$$

$$\Delta g_1^Z = \Delta\kappa_Z = \frac{M_W^2}{2c^2 M_{W'}^2} \qquad \Delta\kappa_\gamma = 0$$

LEP II measurement: $\Delta g_1^Z \leq 0.028 \ \ @ \ \ 95\%\mathrm{CL}$

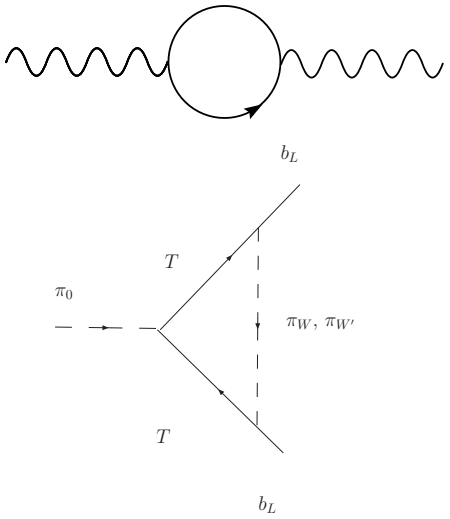
$$M_{W'} \geq 380\,\mathrm{GeV}\sqrt{\frac{0.028}{\Delta g_1^Z}}$$

Fermionic Constraints

$$m_t \approx \varepsilon_L \varepsilon_{tR} M$$

$$b \to s\gamma : \varepsilon_{tR} < 0.60$$

$$\text{Unitarity and } \Delta g_1^Z : 0.095 \leq \varepsilon_L \leq 0.30$$

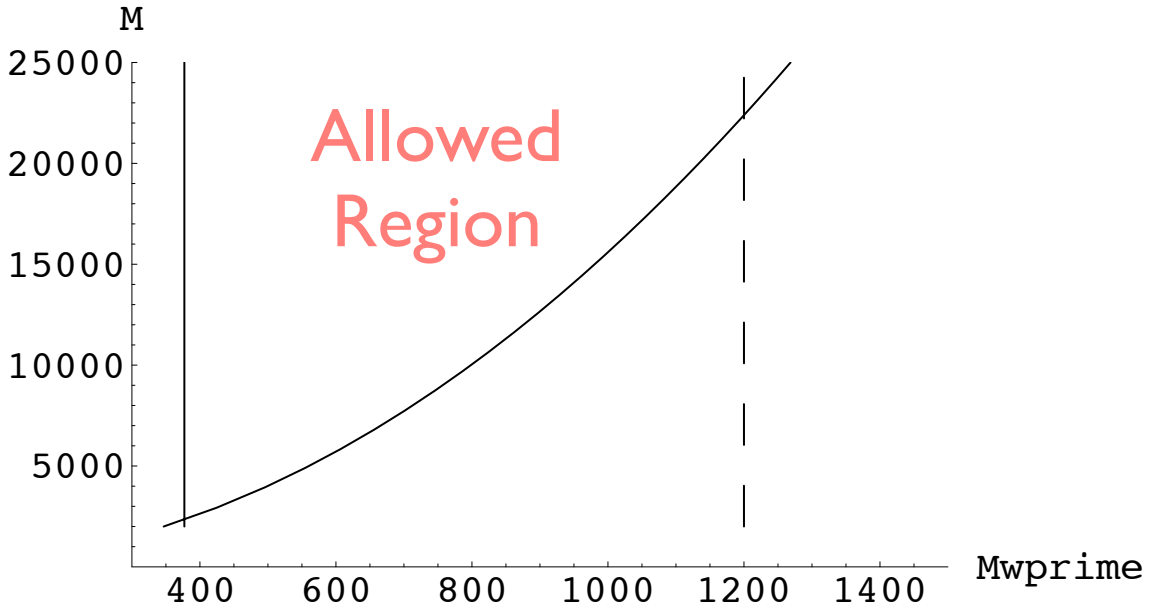


$$\Delta\rho \approx \frac{1}{16\pi^2} \frac{\varepsilon_{tR}^4 M^2}{v^2}$$

$$\delta g_{Zb\bar{b}} \approx 0.25\,(\delta g_{Zb\bar{b}}^{SM})$$

(preliminary...)

3-Site Parameter Space



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

Conclusions

- Higgsless models are intriguing candidate solutions to the puzzle of EWSB.
- Deconstruction gives framework for studying 5-d gauge theories as consistent effective field theories.
- Ideal Fermion Delocalization: $\hat{S}$, $\hat{T}$, W vanish; Y is small
- A simple 3-site model yields a viable effective theory valid up to 1.5 - 2.0 TeV

Some References

- Chivukula, He, Kurachi, Simmons, Tanabashi:
  0406077, 0408262, 0410154, 0502162, 0504114, 0508147, & 0509110
- Cacciapaglia, Csaki, Grojean, Murayama, Pilo, Reece, Skiba, Terning
  0305237, 0308038, 0310355, 0401160, 0409126, 0505001, 0602154
- Foadi, Gopalkrishna, Schmidt
  0312324, 0409266, & 0509071
- Georgi 0408067 & 0508014
- Non-commuting ETC, Ununified SM, "Top-Flavor"

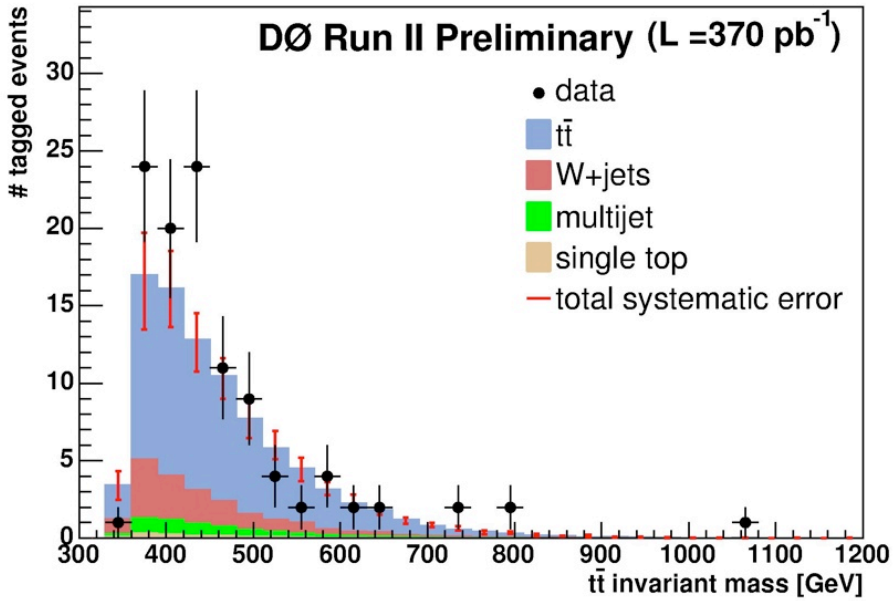
Numbers are hep-ph/

Sketch #2: Z' Bosons Coupled to the 3rd Generation

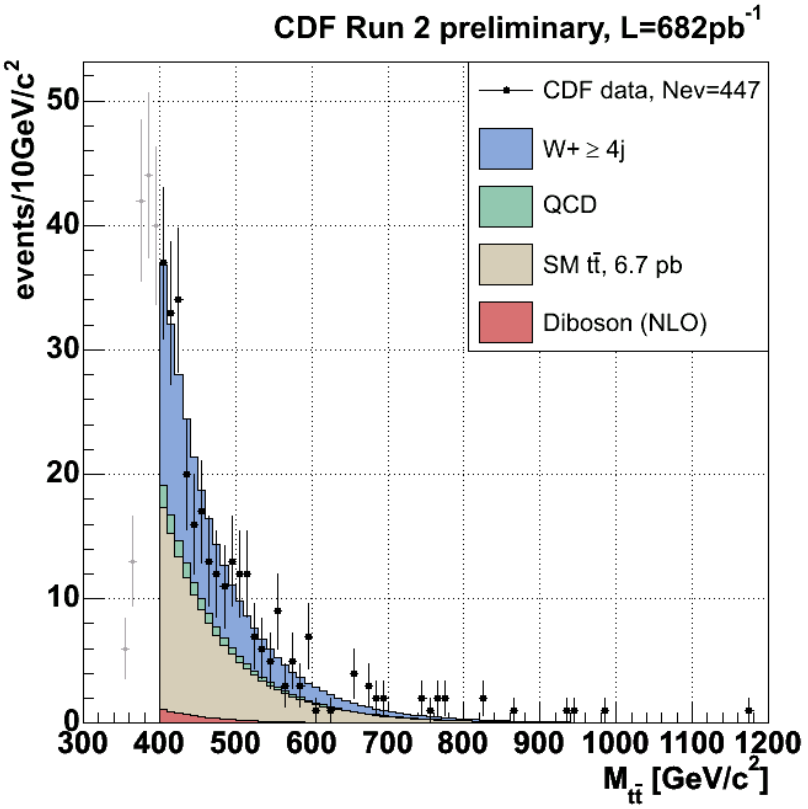
- Recent FNAL Bounds on t t-bar resonances
- Typical FNAL Bounds on Sequential Z'
- Comparison of Sequential Z' with those coupled to the 3rd generation
- Suggestions

Work in progress with R.S. Chivukula and K. Tobe

FNAL Bounds on t t-bar states

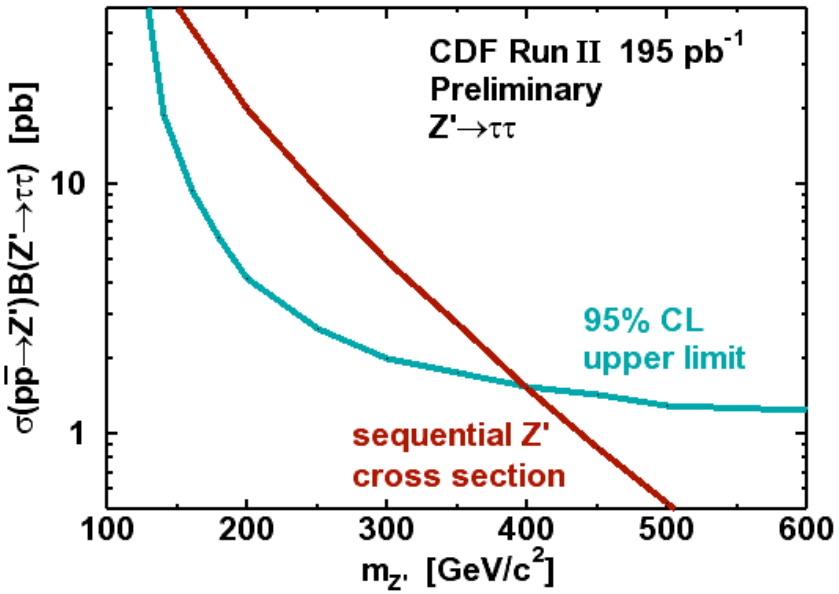


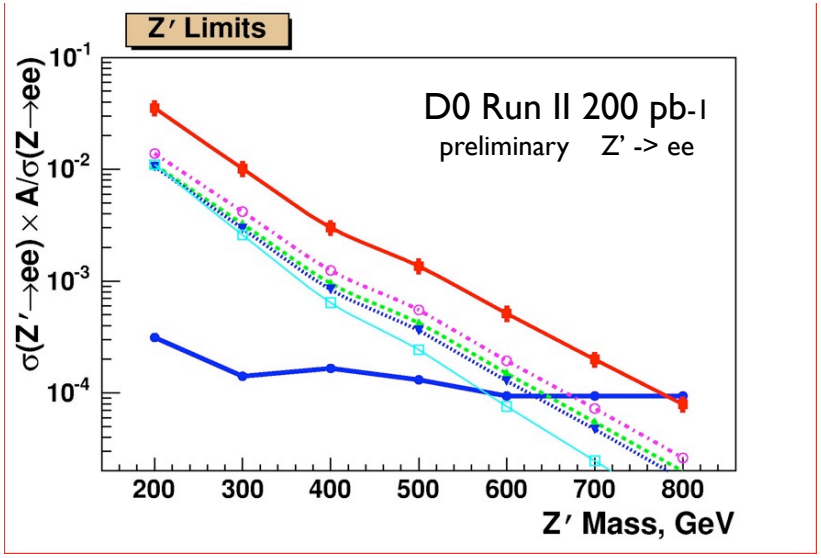
Recently, a tantalizing hint appeared in t t-bar invariant mass plots ... but with a larger data set, it has since evaporated.

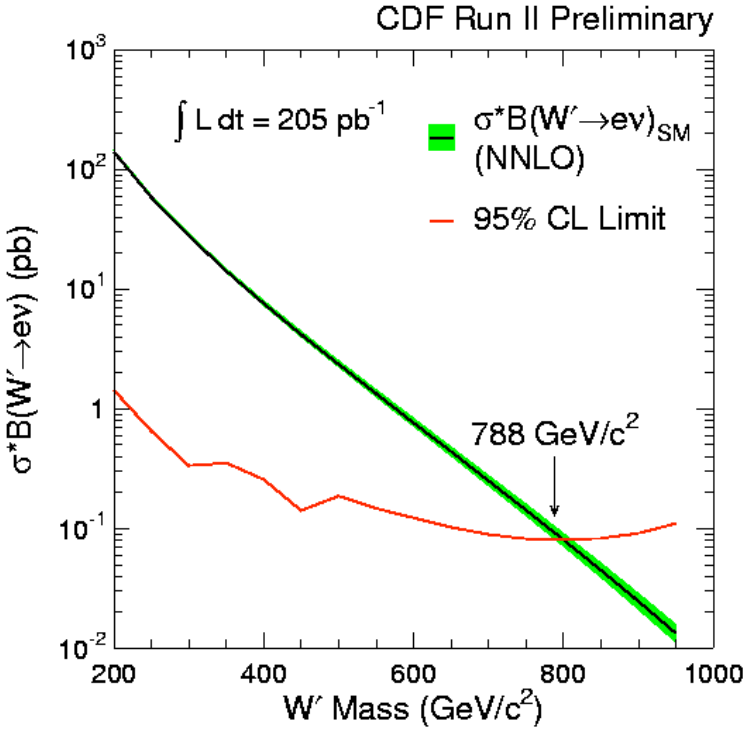


Had it persisted, what could have been the meaning?

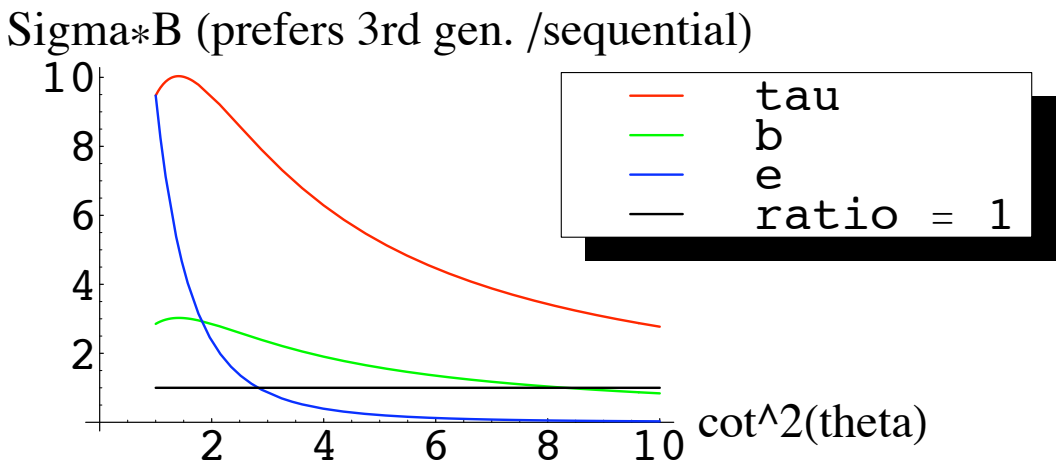
Typical FNAL Sequential Z' Bounds



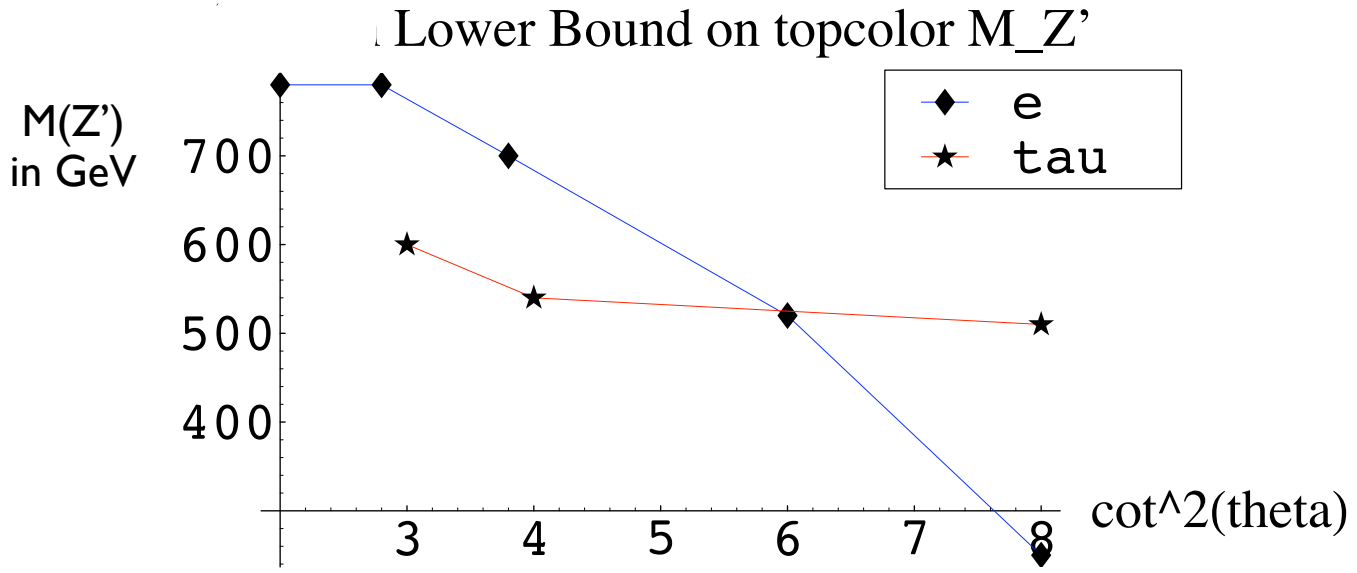




Comparison of Sequential Z' with Z' coupled to the 3rd Generation



Cot^2(theta) is the factor by which Z' coupling to 3rd (light) generation fermions is enhanced (suppressed) compared to SM Z or sequential Z'



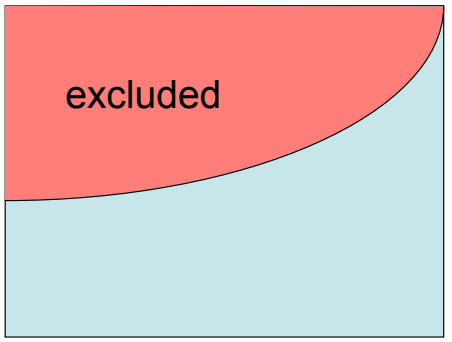
For Z' arising from an extra U(1) group, cot^2(theta) < 10 to keep Landau pole well above symmetry-breaking scale

Suggestions

- Apply current bounds (dilepton, tau pair, top pair, b-jet pair, t/b, tau/nu ...) to non-sequential Z', W'
- Include benchmark Z', W' coupled to 3rd generation in computer-based tools (MC4BSM ?)
- Report bounds in the additional format shown here to facilitate their application to new models

$$\text{Ratio} = \frac{\text{Sigma * B (any Z')}}{\text{Sigma * B (sequential Z')}}$$

Values of Ratio excluded as a function of Z' boson mass



Mass of Z' boson [GeV]