The 3-site Higgsless Model

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- General Principles
- A Simple 3-Site Model
- The 3-site model and Experiment
- Conclusions

Joint Meeting of Pacific Region Particle Physics Communities
(APS-DPF2006 + JPS2006...)

hep-ph/0607124

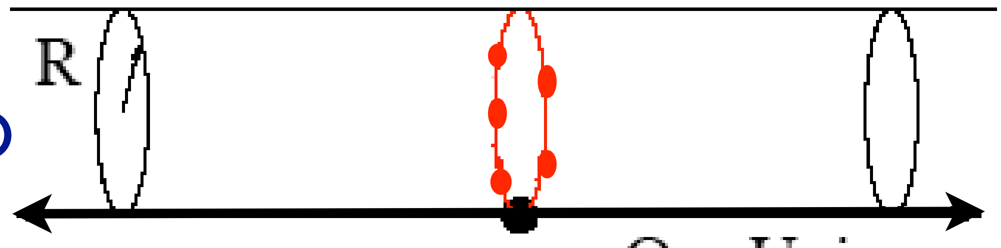
Higgsless Models and Ideal Delocalization:

Review of General Principles

Higgsless models are low-energy effective theories of dynamical electroweak symmetry breaking which include the following elements

- massive 4-d gauge bosons arise in the context of a 5-d gauge theory with appropriate boundary conditions
- WW scattering unitarized through exchange of KK modes (instead of Higgs exchange)
- language of Deconstruction allows a 4-d “Moose” representation of the model

Massive Gauge Bosons from Extra-D Theories



Expand 5-D gauge bosons in eigenmodes:

e.g. for S^1/Z_2:

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

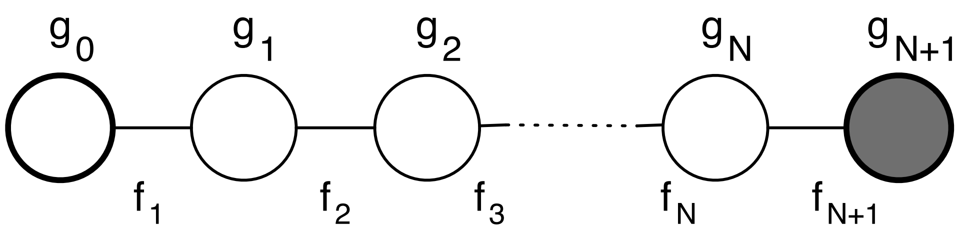
$$\widehat{A}^a_5 = \sqrt{\frac{2}{\pi R}} \sum_{n=1}^{\infty} A^{an}_5(x_\nu) \sin\left(\frac{n x_5}{R}\right)$$

4-D gauge kinetic term contains

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

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

Deconstructed Higgsless Models

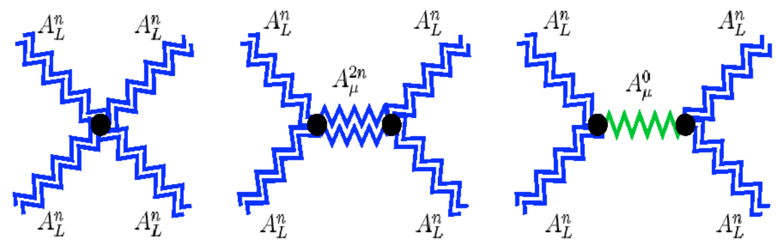


- 5th dimension discretized
- $SU(2)^N \times U(1)$; general f_j and g_k encompass spatially-dependent couplings, warping
- Localized fermions would sit on "branes," i.e. sites 0, N+1, but these present difficulties

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

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

too large by a factor of a few!

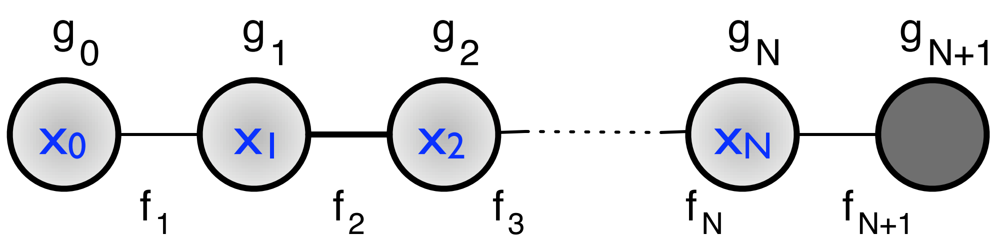
Independent of warping or gauge couplings chosen...

Delocalized Fermions

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

$$\mathcal{L}_f = \vec{J}^\mu_L \cdot \left(\sum_{i=0}^{N} \mathbf{x_i} \vec{A}^i_\mu \right) + J^\mu_Y A^{N+1}_\mu$$

Can Reduce Contribution to S!



Cacciapaglia, Csaki, Grojean, & Terning

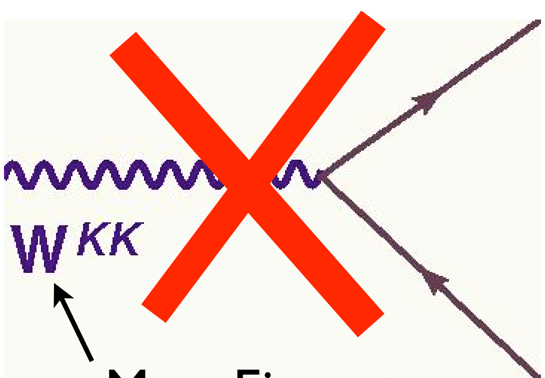
Foadi, Gopalkrishna, & Schmidt

Ideal Fermion Delocalization

- Recall that the light W's wavefunction is orthogonal to wavefunctions of KK modes
- Choose fermion delocalization profile to match W wavefunction profile along the 5th dimension:

$$g_i x_i \propto v_i^W$$

- No (tree-level) fermion couplings to KK modes!



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

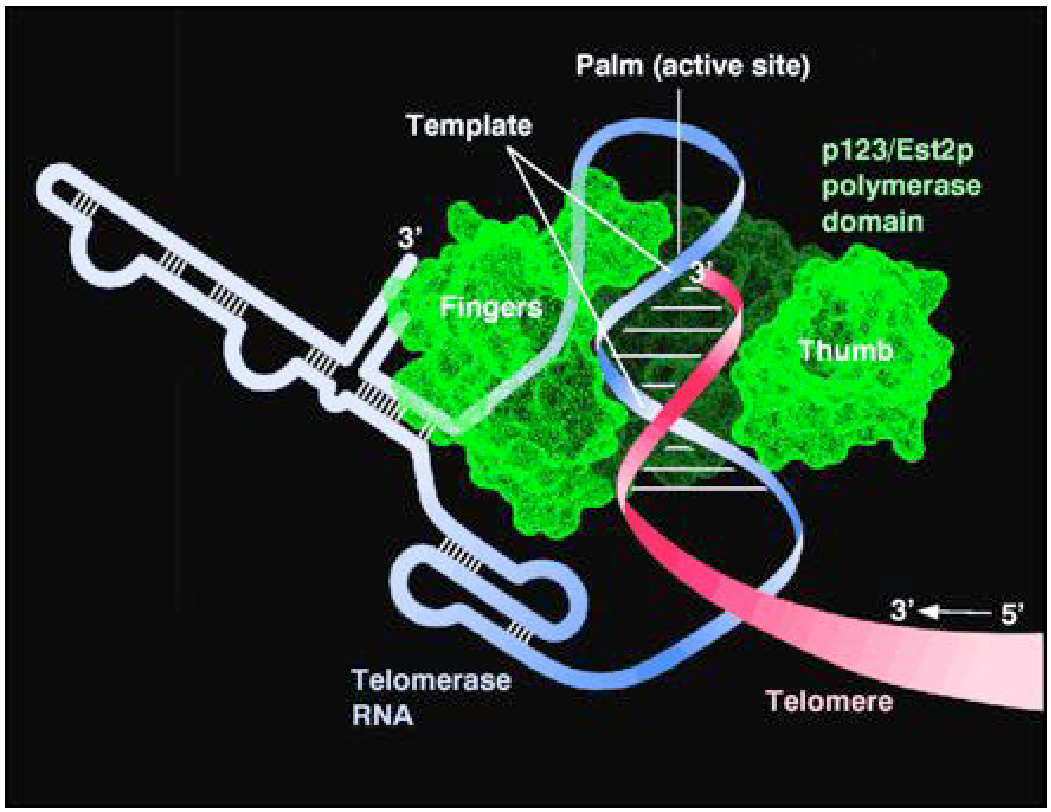
$$Y = M_W^2 (\Sigma_W - \Sigma_Z)$$

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

The 3-site Model:

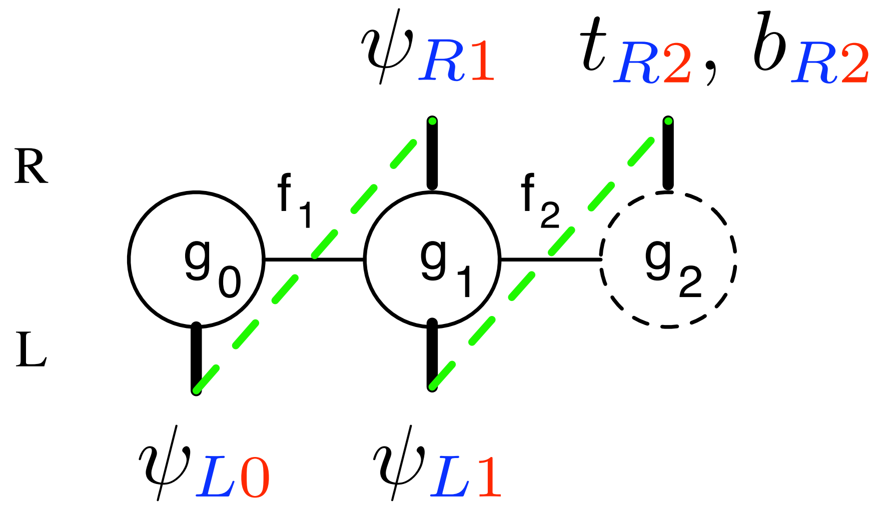
general principles in action

Three-site model in biology



3-Site Model: basic structure

$SU(2) \times SU(2) \times U(1)$ $\qquad g_0,\ g_2 \ll g_1$



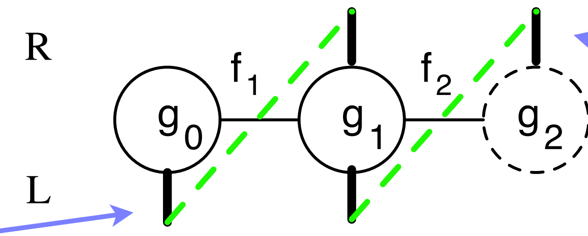
Gauge boson spectrum: photon, Z, Z', W, W'

Fermion spectrum: t, T, b, B (ψ is an SU(2) doublet)

and also c, C, s, S, u, U, d, D plus the leptons

3-Site Model: fermion details

$SU(2) \times SU(2) \times U(1)$ $\qquad g_0,\ g_2 \ll g_1$



RH Boundary Fermion

LH Boundary Fermion

"Bulk Fermion"

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

related to degree of delocalization

Fermion Structure Motivated by 5-D

Flavor Structure Identical to Standard Model

3-Site Ideal Delocalization

General ideal delocalization condition $g_i(\psi_i^f)^2 = g_W v_i^w$

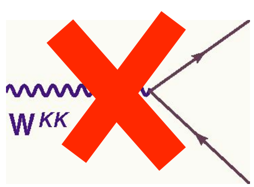
becomes $\frac{g_0(\psi_{L0}^f)^2}{g_1(\psi_{L1}^f)^2} = \frac{v_W^0}{v_W^1}$ in 3-site model

From W, fermion eigenvectors, solve for

$$\epsilon_L^2 \to (1+\epsilon_{fR}^2)^2 \left[\frac{x^2}{2} + \left(\frac{1}{8} - \frac{\epsilon_{fR}^2}{2} \right) x^4 + \frac{5\,\epsilon_{fR}^4\,x^6}{8} + \ldots \right]$$

For all but top, $\epsilon_{fR} \ll 1$ and $\varepsilon_L^2 = 2\left(\frac{M_W^2}{M_{W'}^2}\right) + 6\left(\frac{M_W^2}{M_{W'}^2}\right)^2 + \ldots$

insures W' and Z' are fermiophobic!



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

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

Use WW scattering to see W': Birkedal, Matchev, Perelstein hep-ph/0412278

The 3-site Model and Experiment

Triple Gauge Vertices

Hagiwara, *et al.* define:

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

In 3-site model: $\Delta g_1^Z = \Delta\kappa_Z = \dfrac{M_W^2}{2c^2 M_{W'}^2}$ $\qquad \Delta\kappa_\gamma = 0$

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

places lower bound on W' mass:

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

... plus unitarity

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

this translates into $$\epsilon_L \approx 0.30\ \left(\frac{380\,\mathrm{GeV}}{M_{W'}}\right)$$

As mentioned earlier, maintaining unitarity of WW scattering requires

$$m_{W'} < \sqrt{8\pi}\, v \approx 1.2\,\mathrm{TeV}$$

We conclude: $$0.095 \leq \epsilon_L \leq 0.30$$

$b \to s\gamma$

To keep this within bounds requires* $g_R^{Wtb}/g_L^W < .004$

which translates into the bound $\varepsilon_{tR} < 0.67$

Since $m_f \approx \dfrac{\epsilon_L \epsilon_{fR} M}{\sqrt{1+\epsilon_{fR}^2}}$ and b-quark mass is small,

we can leverage ϵ_{tR} to show $\epsilon_{bR} < .015$

hence, b is ideally delocalized like light fermions

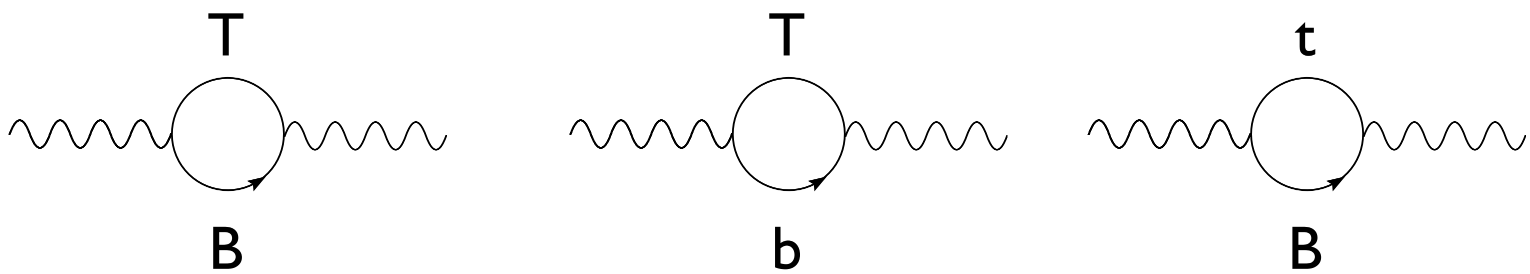
* Larios, Perez, Yuan, hep-ph/9903394

$\Delta\rho$ at one loop

In $\epsilon_L \to 0$ limit, can calculate leading "new" contribution

- SM contribution vanishes since $m_t, m_b \propto \epsilon_L$
- ϵ_L is custodially symmetric

From the following W diagrams (and related Z diagrams)



leading contribution is:

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

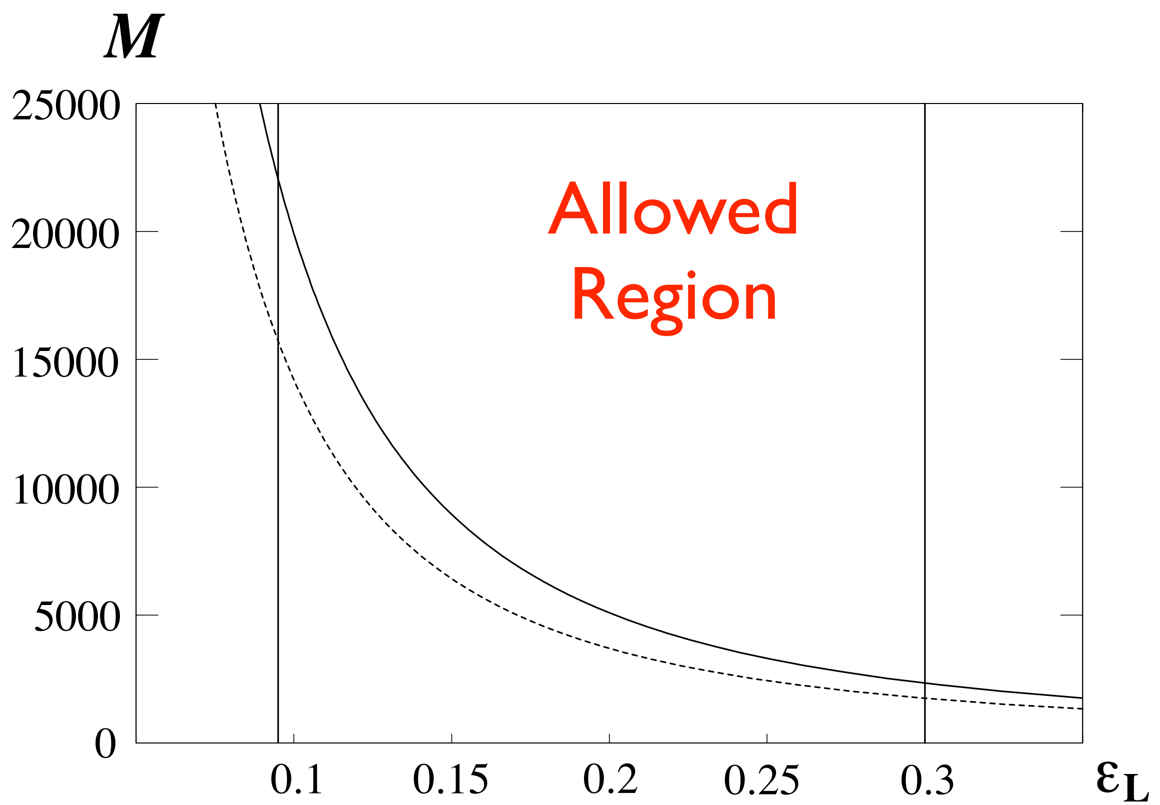
3-Site Parameter Space

Conditions setting boundaries:

$$m_f \approx \frac{\epsilon_L \epsilon_{fR} M}{\sqrt{1+\epsilon_{fR}^2}}$$

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

$$0.095 \leq \epsilon_L \leq 0.30$$

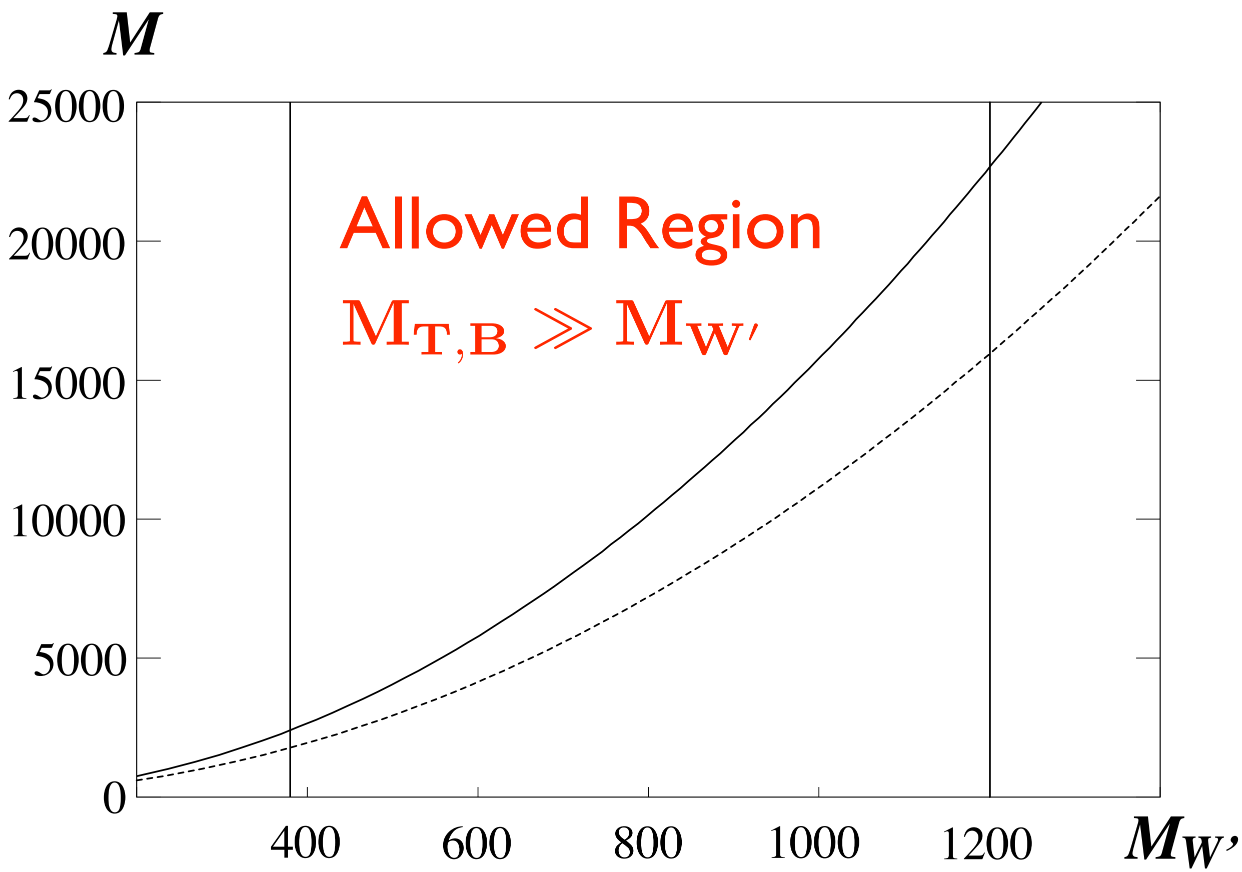


3-Site Parameter Space

Rewrite in terms of W' mass:

$$\epsilon_L \approx 0.30 \left(\frac{380\,\mathrm{GeV}}{M_{W'}} \right)$$

$$380\,\mathrm{GeV} \leq M_{W'} \leq 1.2\,\mathrm{TeV}$$



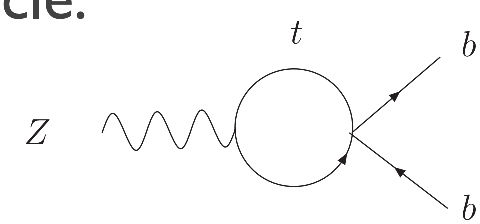
$Z \to b\bar{b}$ at one loop

Involves heavy fermions whose mass (M) is above the reach of the effective theory. We invoke a benchmark UV completion to estimate the size of effects:

$$\frac{\delta g_{Zbb}^{1-loop,3-site}}{g_{Zbb}^{SM}} \sim \frac{m_t^2}{16\pi^2 M^2} \approx \frac{v^2}{M^2}\,\frac{\delta g_{Zbb}^{1-loop,SM}}{g_{Zbb}^{SM}}$$

This is acceptably small.

Note: ideal delocalization removes a possible obstacle:



$$\frac{\delta g_{Zbb}}{g_{Zbb}^{SM}} \approx \frac{g^2 v^2}{16\pi^2 M_{W'}^2} \ln\left(\frac{M_{W'}^2}{m_t^2}\right)$$

Conclusions:

The 3-site model yields a viable effective theory of electroweak symmetry breaking valid up to 1.5 - 2 TeV

- incorporates / illustrates general principles
[Higgsless models, deconstruction, ideal delocalization]

- accommodates flavor [e.g. heavy t quark]

- observables calculable at one loop

- extra gauge bosons can be relatively light
[hard to find at LHC/ILC since they are fermiophobic]

Precision electroweak corrections discussed in BSM Session talks by Chivukula and Matsuzaki