The 3-site Higgsless Model

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- Review of General Principles
- A Simple 3-Site Model
- S and T at one loop
- LHC Phenomenology
- Conclusions

hep-ph Refs:
0607124, 060719, 0708.2588

Collaborators:
Belyaev, Chivukula, Coleppa, Di Chiara, He, Kuang, Kurachi, Matsuzaki, Pukhov, Qi, Tanabashi, Zhang

Higgsless Models and Ideal Delocalization:

Review of General Principles

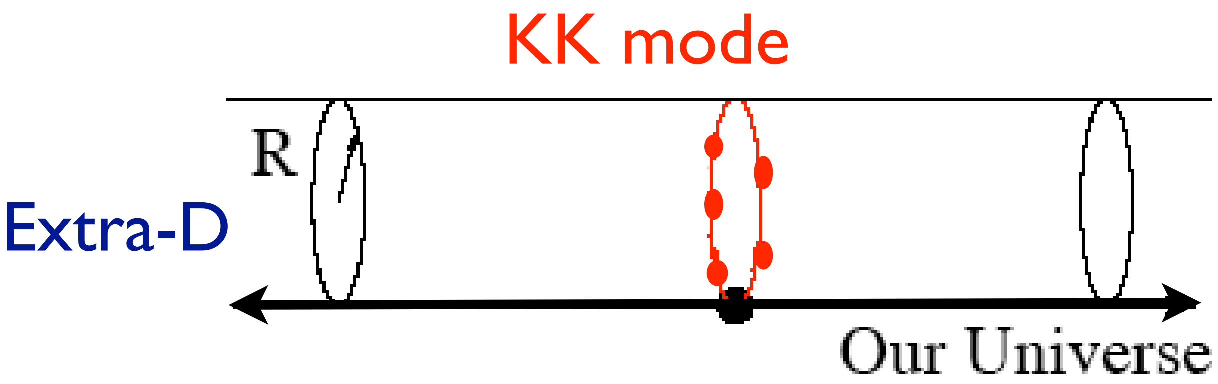
General Principles :

Higgsless models are low-energy effective theories of dynamical electroweak symmetry breaking including 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

Csaki/Murayama/Terning & Chivukula/He

Massive Gauge Bosons from Extra-D Theories



Expand 5-D gauge bosons in eigenmodes:

e.g. for S^1/Z_2:

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

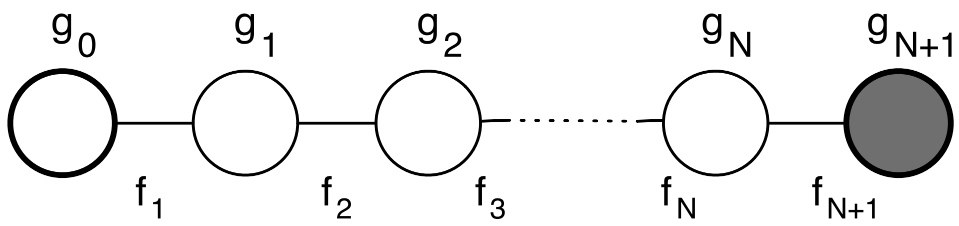
$$\widehat{A}^a_5 = \sqrt{\frac{2}{\pi R}}\sum_{n=1}^{\infty} A^{an}_5(x_\nu)\sin\left(\frac{nx_5}{R}\right)$$

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

Deconstructed Higgsless Models

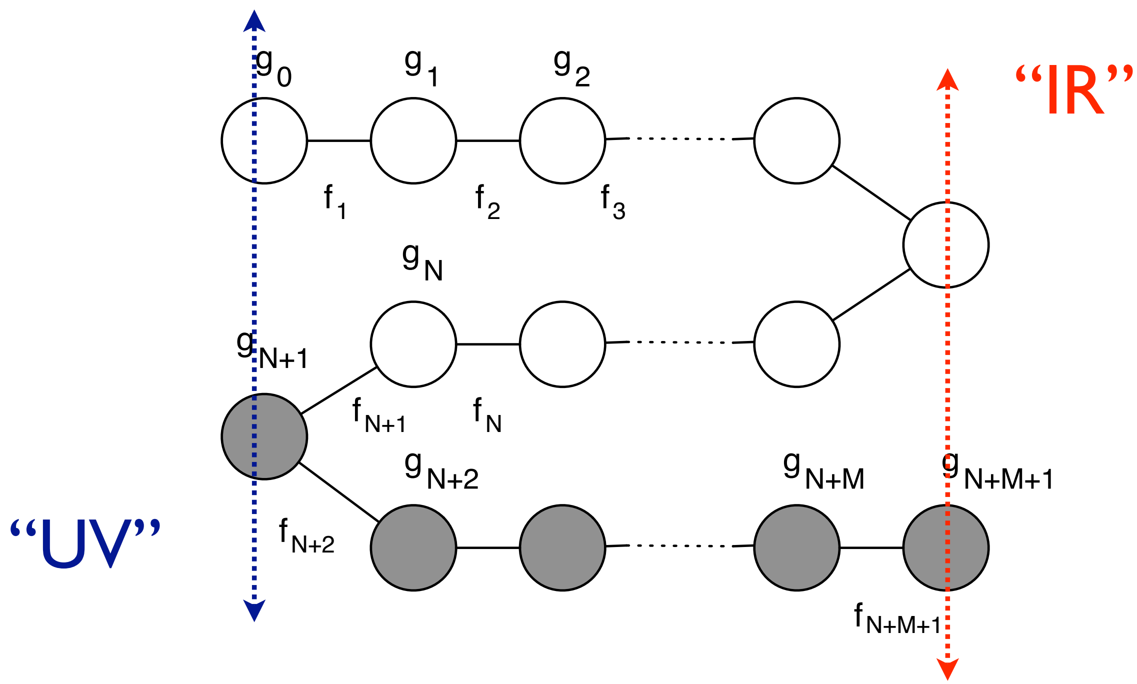


- 5th dimension discretized
- $SU(2)^N \times U(1)$; general f_j and g_k encompass spatially-dependent couplings, warping
- for fixed v, $\frac{1}{v^2} = \sum_i \frac{1}{f_i^2}$ means $f_i \sim \sqrt{N} v$
- In simplest models, Localized fermions sit on "branes" [sites 0 and N+1]

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

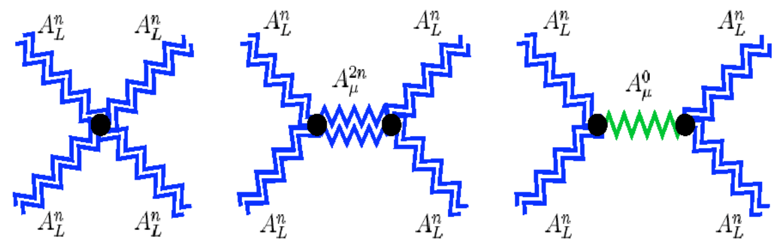
Generalizations

- by folding, represent SU(2) x SU(2) x U(1) in “bulk”
- modify fermions’ location (brane? bulk?)



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!

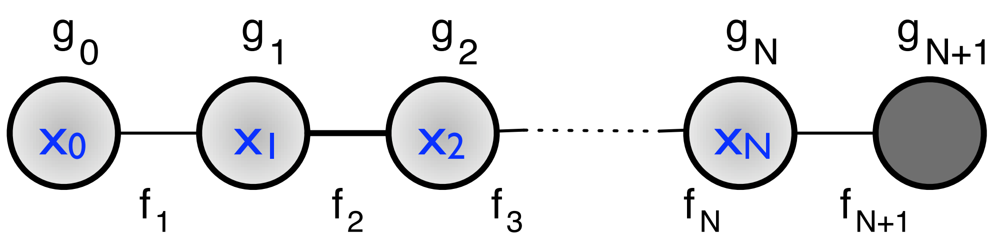
Independent of warping or gauge couplings chosen...

Delocalized Fermions

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

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

Can Reduce Contribution to S!



Cacciapaglia, Csaki, Grojean, & Terning

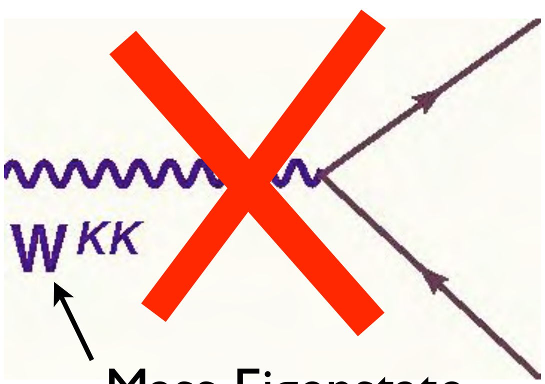
Foadi, Gopalkrishna, & Schmidt

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!



Mass Eigenstate

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

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

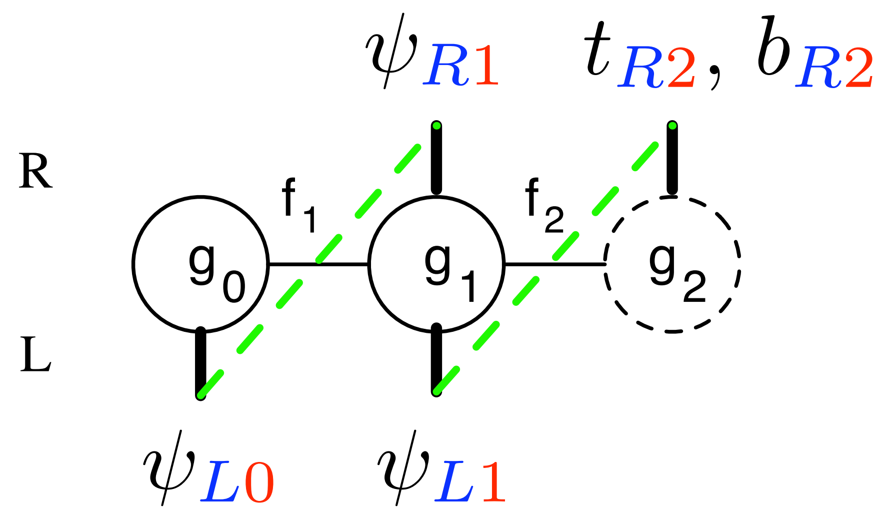
RSC, HJH, MK, MT, EHS hep-ph/0504114

The 3-site Model:

General Principles in Action

3-Site Model: basic structure

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



Gauge boson spectrum: photon, Z, Z', W, W' (as in BESS)

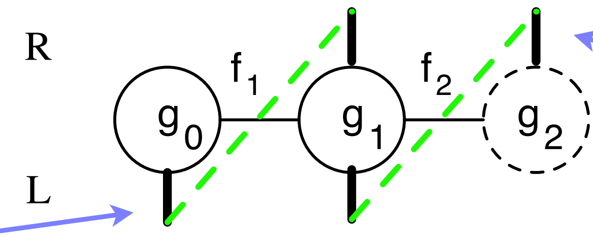
Fermion spectrum: t, T, b, B (ψ is an SU(2) doublet)

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

Chivukula hep-ph/0607124

3-Site Model: fermion details

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



LH Boundary Fermion

"Bulk Fermion"

RH Boundary 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 $g_i(\psi_i^f)^2 = g_W v_i^w$

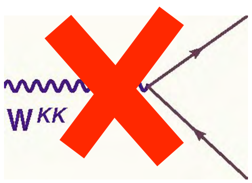
becomes $\frac{g_0(\psi_{L0}^f)^2}{g_1(\psi_{L1}^f)^2} = \frac{v_W^0}{v_W^1}$ in 3-site model

From W, fermion eigenvectors, solve for

$$\epsilon_L^2 \to (1+\epsilon_{fR}^2)^2 \left[\frac{x^2}{2} + \left(\frac{1}{8} - \frac{\epsilon_{fR}^2}{2}\right) x^4 + \cdots \right] \qquad x^2 \equiv \left(\frac{g_0}{g_1}\right)^2 \approx 4\left(\frac{M_W}{M'_W}\right)^2$$

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!



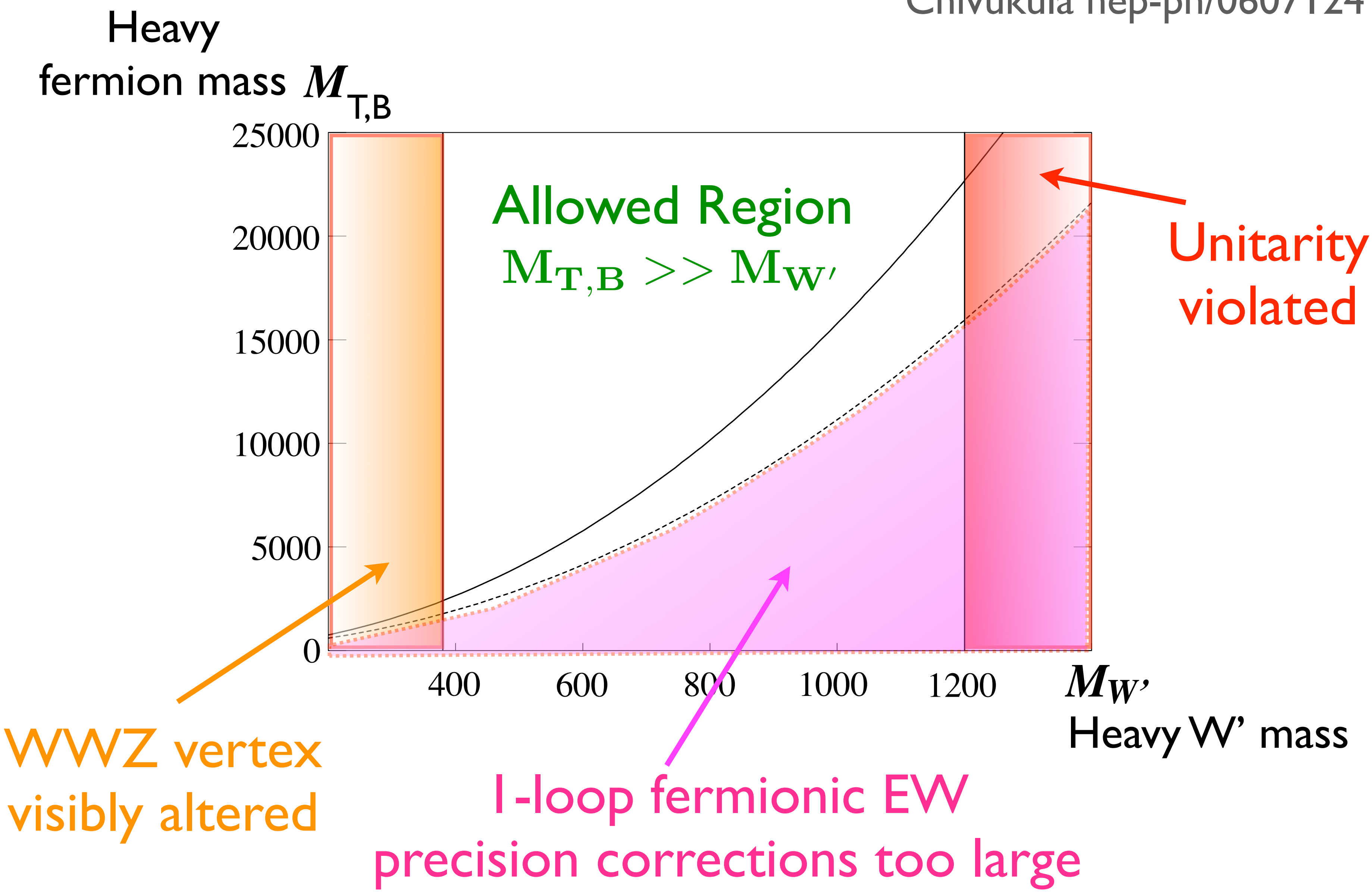
$$\hat{S} = \hat{T} = W = 0$$

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

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

3-Site Parameter Space

Chivukula hep-ph/0607124



S and T gauge corrections at one loop

Electroweak Parameters

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

$$-\mathcal{A}_{NC} = e^2 \frac{\mathcal{Q}\mathcal{Q}'}{Q^2} + \frac{(I_3 - s^2\mathcal{Q})(I'_3 - s^2\mathcal{Q}')}{\left(\frac{s^2c^2}{e^2} - \frac{S}{16\pi}\right) Q^2 + \frac{1}{4\sqrt{2}G_F}(1-\alpha T)} + \ flavor\ dependent$$

Universal Corrections Depend only on External Quantum Numbers!

Gauge-Invariant, to all orders, as defined here!

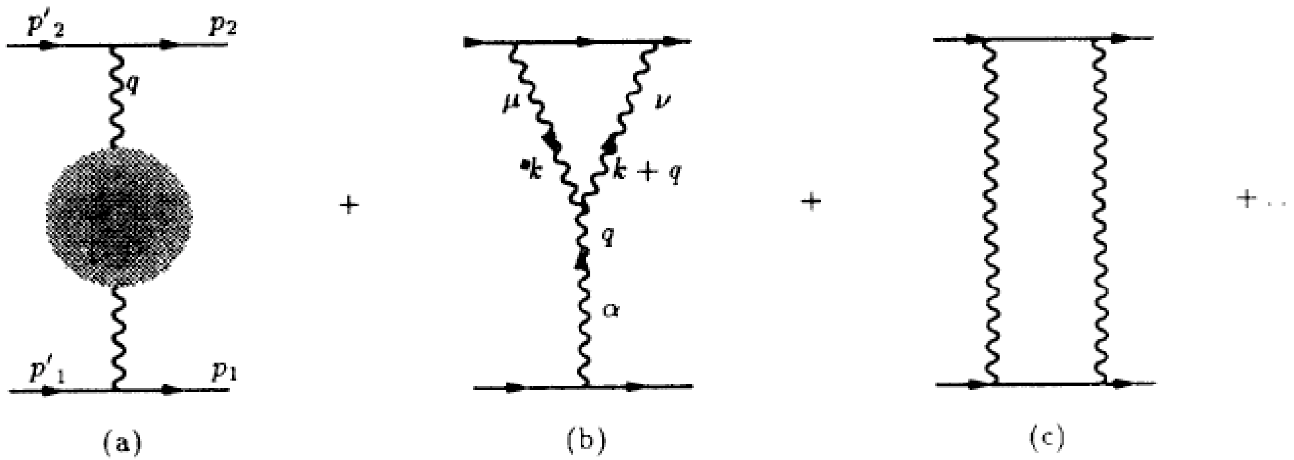
S,T: Peskin & Takeuchi Altarelli, et. al. and Hagiwara, et. al.

Chivukula, Kurachi, He, EHS & Tanabashi hep-ph/0408262 & 0410154

Hagiwara, Matsumoto, Haidt, & Kim: hep-ph/9409380

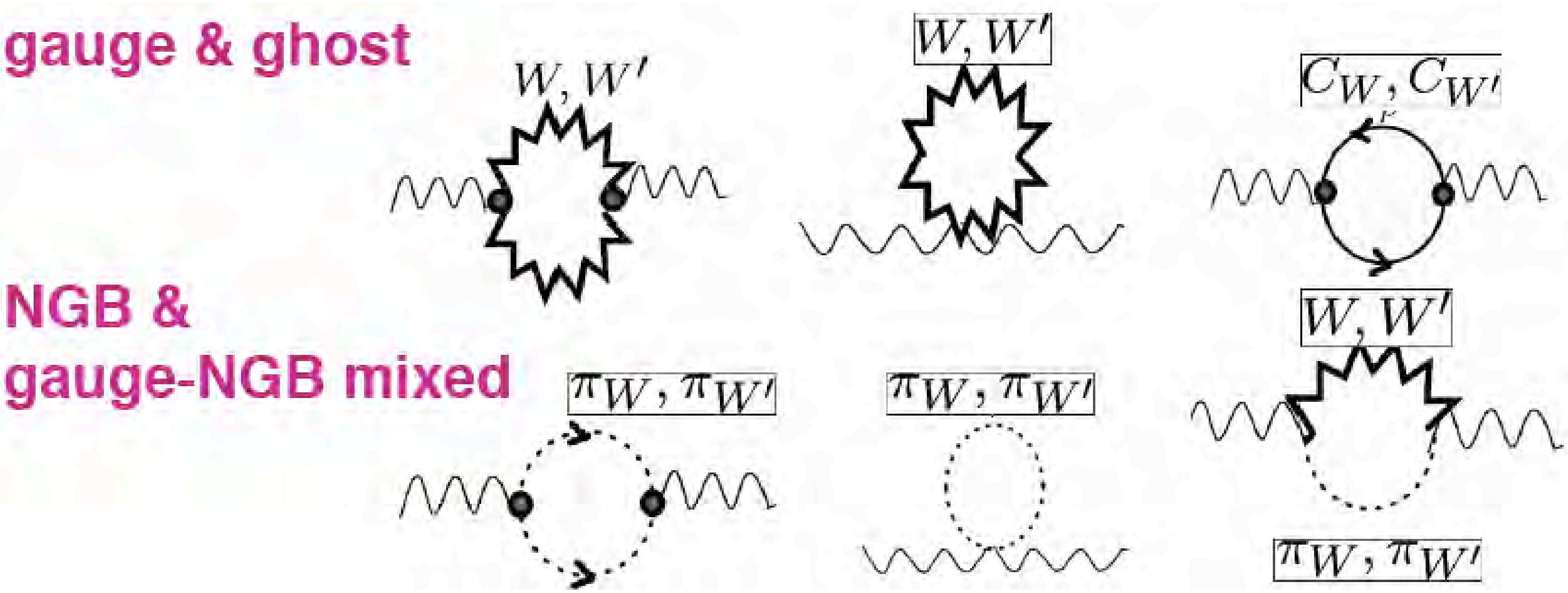
Propagator, Vertex and Box Corrections

Gauge-invariance of scattering amplitudes arises by addition of vertex and box corrections to the familiar gauge-boson self-energy corrections (which are not gauge-invariant on their own).



Gauge-Boson Self-Energies

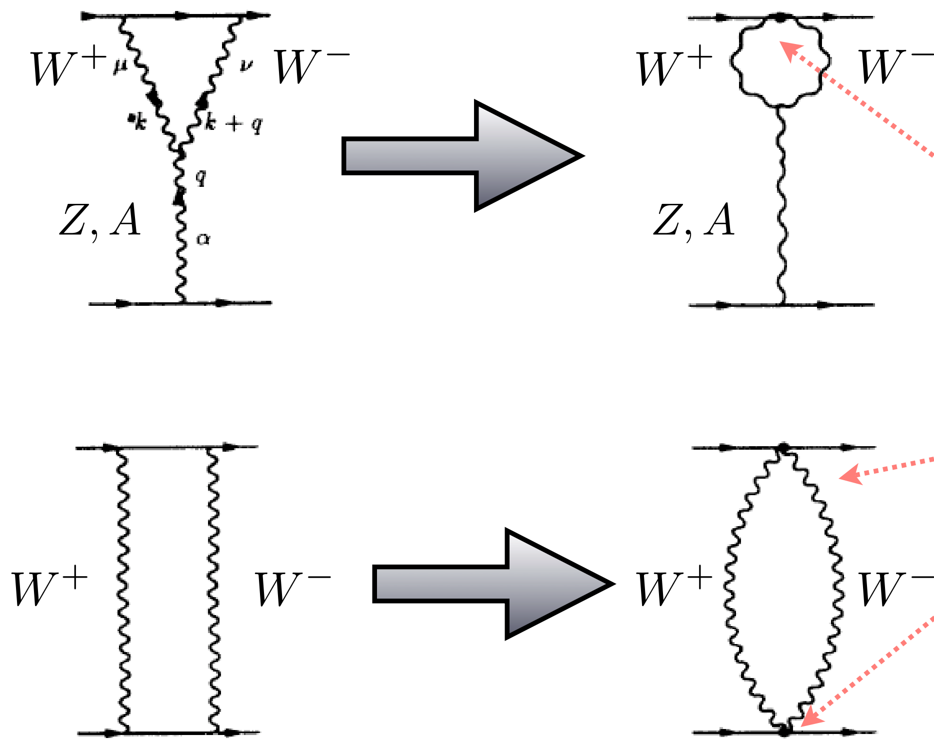
Working in `t Hooft-Feynman gauge, the following types of corrections to gauge-boson self-energies appear in the calculation of S



The gauge-dependence is canceled by...

Gauge-Dependent Box and Vertex Contributions

Pinch Technique: collect all such contributions in an effective self-energy function



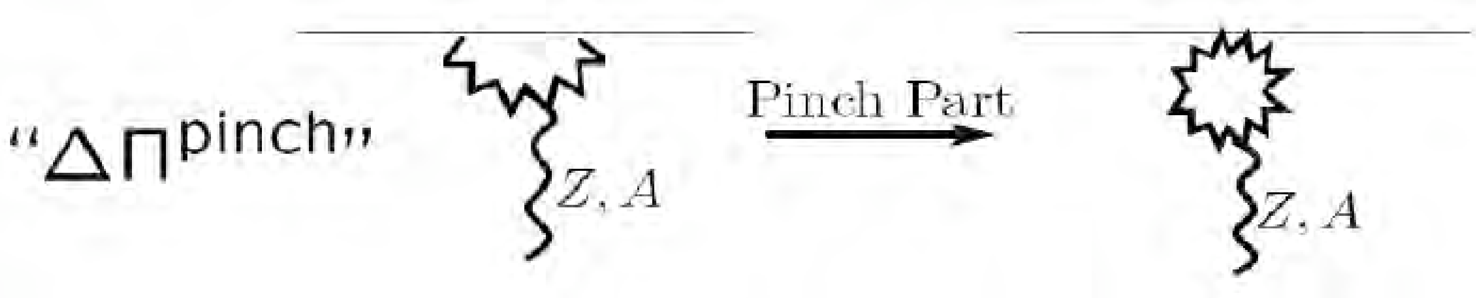
Contributions universal:

$$\propto [gT^+, gT^-] = 2g^2 T_3$$

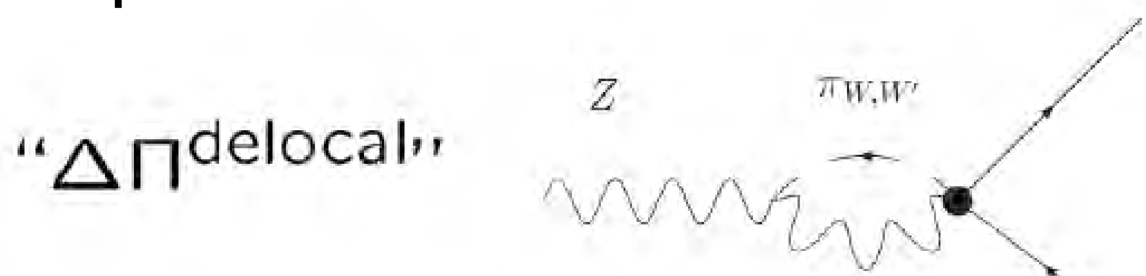
Cornwall, 1982 Cornwall and Papavassiliou, 1989 Degrassi and Sirlin, 1992

Pinch Contributions to S in 3-site model

Conventional pinch contributions from 3-point vertex in `t Hooft-Feynman gauge



Additional piece from delocalization



$$\mathcal{L}'_f = x_1 \cdot \bar{\psi}_L (i \not{D} \Sigma_{(1)} \Sigma^\dagger_{(1)}) \psi_L$$

S at one loop: results

$$\alpha S_{3-site} = \frac{4s^2 M_W^2}{M_{W'}^2}\left(1 - \frac{x_1 M_{W'}^2}{2M_W^2}\right)$$

tree; involves ideal delocalization (x_1)

$$+ \frac{\alpha}{12\pi} \ln \frac{M_{W'}^2}{M_{Href}^2}$$

one-loop; up to W' mass

$$- \frac{3\alpha}{2\pi}\left[\frac{41}{36} - \frac{x_1 M_{W'}^2}{8M_W^2}\right] \ln\left(\frac{\Lambda^2}{M_{W'}^2}\right)$$

one-loop; up to cutoff

$$- 8\pi\alpha\left(c_1(\Lambda) + c_2(\Lambda)\right)$$

counterterms; cf. L_{10}

Perelstein hep-ph/0408072

$$c_2 g\tilde{g} Tr(W_1^{\mu\nu}\Sigma_1 W_{2\,\mu\nu}\Sigma_1^\dagger) + c_1 g\tilde{g} Tr(W_2^{\mu\nu}\Sigma_2 B_{\mu\nu}\Sigma_2^\dagger)$$

link 1 link 2

Matsuzaki hep-ph/0607191

T at one loop: results

$$\alpha T_{3-site} = 0$$ tree

$$- \frac{3\alpha}{16\pi c^2} \ln \frac{M^2_{W'}}{M^2_{Href}}$$ one-loop; up to W' mass

$$- \frac{3\alpha}{32\pi c^2} \ln \frac{\Lambda^2}{M^2_{W'}}$$ one-loop; up to cutoff

$$+ \frac{4\pi\alpha}{c^2} c_o(\Lambda)$$ counterterm; $O(p^4)$

$$c_o g_2^2 f^2 \left[Tr(D_\mu \Sigma_{(2)} \frac{\tau_3}{2} \Sigma^\dagger_{(2)}) \right]^2$$

+ contributions from weak-isospin violation in fermion sector

Matsuzaki hep-ph/0607191

Confirmation

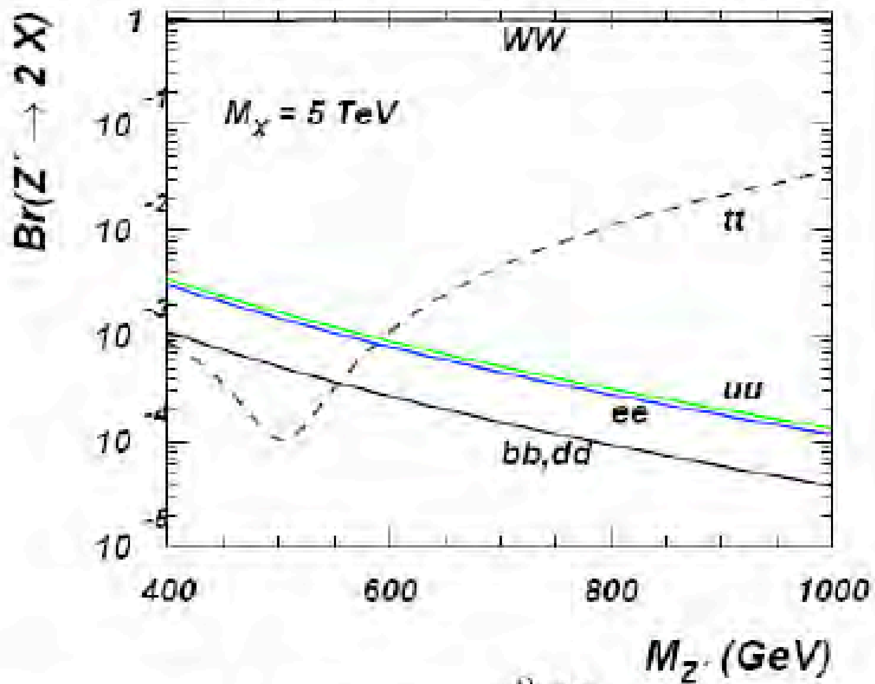
- We also used RGE techniques to compute the one-loop corrections to all O(p^4) counter-terms in the three-site model in Landau gauge.
  Chivukula hep-ph/0702218
- Our RGE results for S and T agree with those of our Pinch-Technique calculation in `t Hooft-Feynman gauge. Matsuzaki hep-ph/0607191
- A subsequent calculation via another approach also agrees with the results presented here.
  Dawson hep-ph/0703299

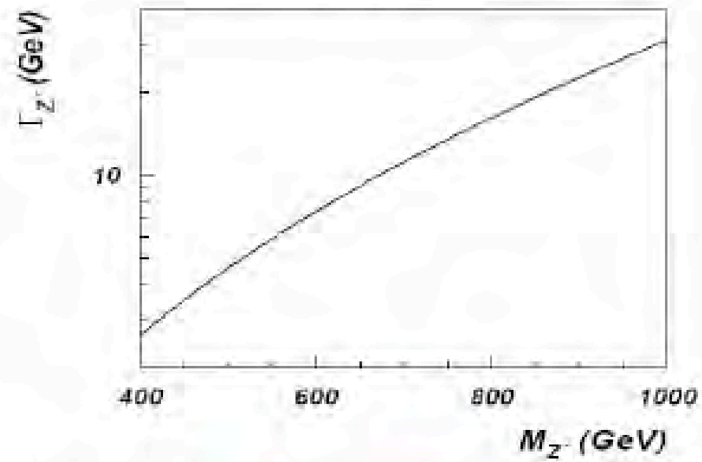
LHC Phenomenology

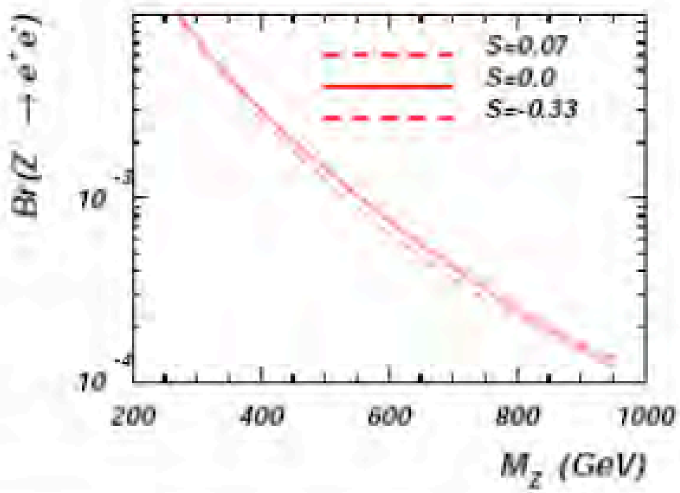
(calculations courtesy of
CalcHEP, MADGRAPH, and HANLIB)

Gauge boson widths and branchings

- Fermiophobic nature of the gauge bosons is crucial
- Dominant decay into WW and WZ pairs
- Z' Br does not depend much on deviation from ideal delocalization





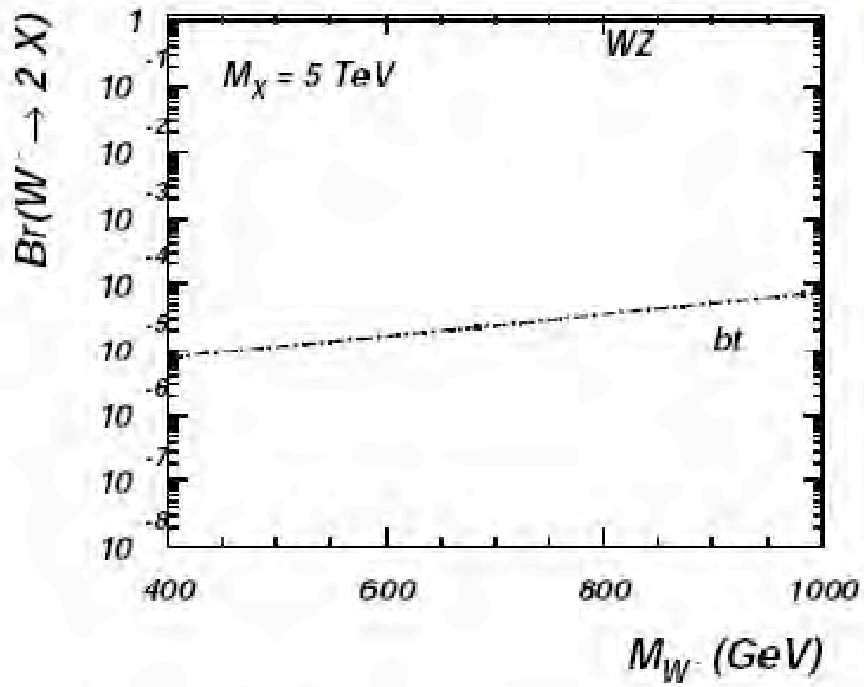


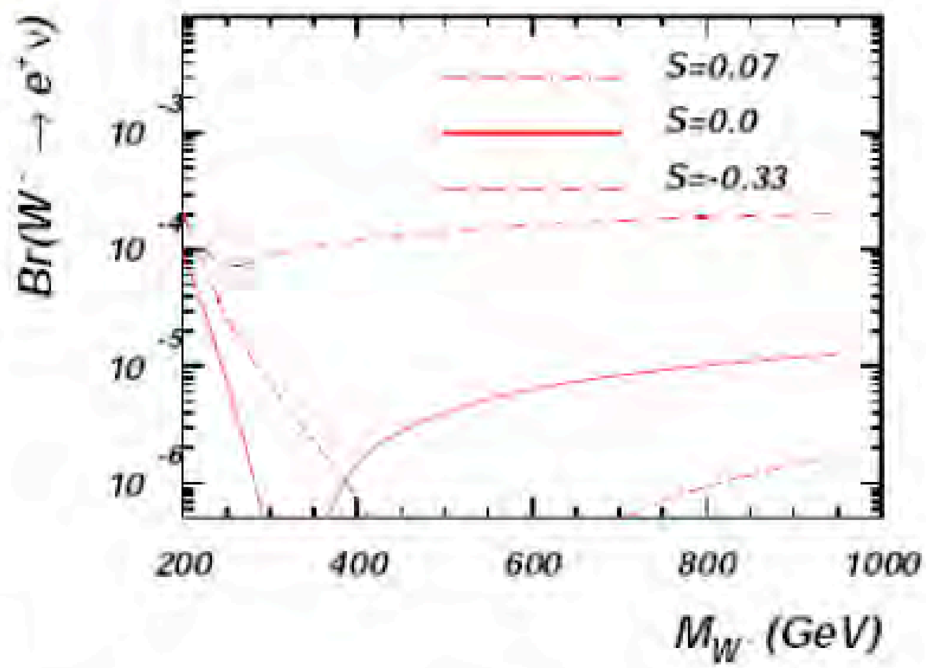
$$\Gamma(Z' \to W^+W^-) = \frac{e^2 M_{W'}}{192\pi x^2 s_w^2}$$

$$\Gamma(Z' \to e^+e^-) = \frac{5e^2 M_{W'} x^2 s_w^2}{384\pi c_w^4}$$

W' branching fraction to fermion pairs

- is quite sensitive to deviation from ideal delocalization
- but is always very small

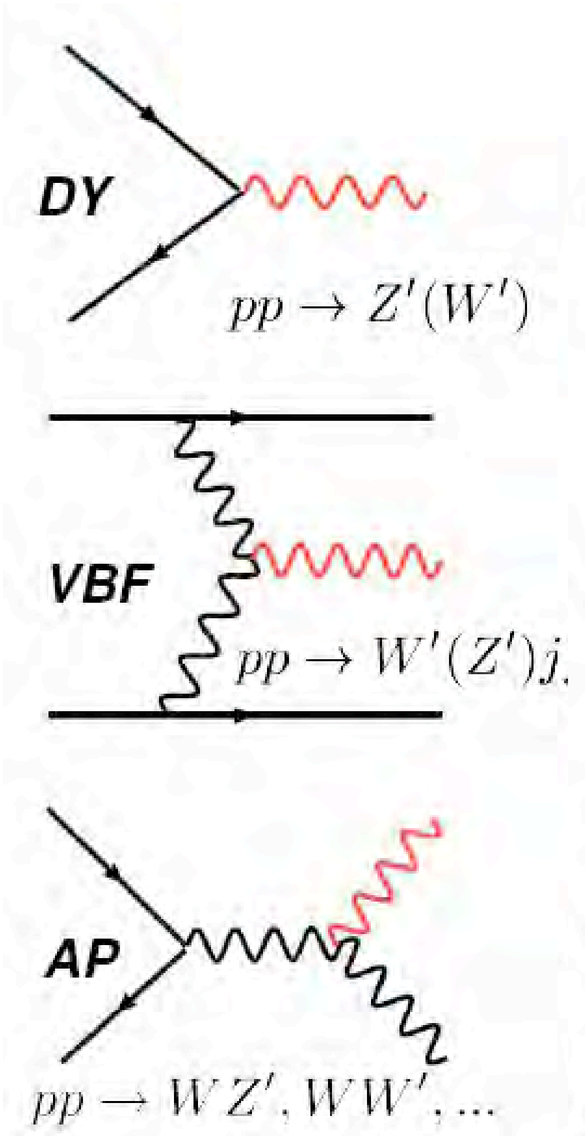




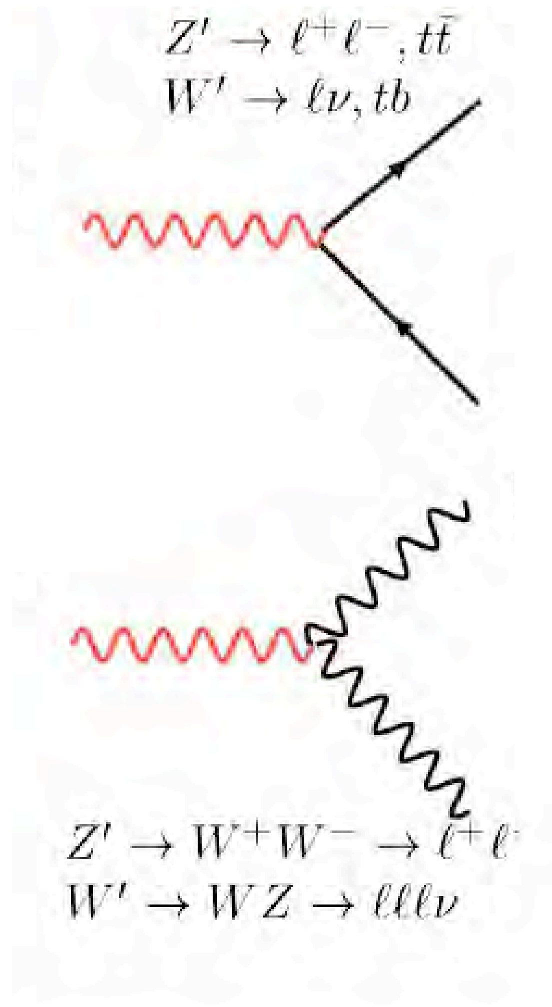
$$\Gamma(W' \to e^+ e^-) = \frac{e^2 M_{W'} x^2 \left(1 - \frac{2\epsilon_L^2}{x^2}\right)^2}{192\pi s_w^2}$$

W' and Z' bosons at LHC

Production

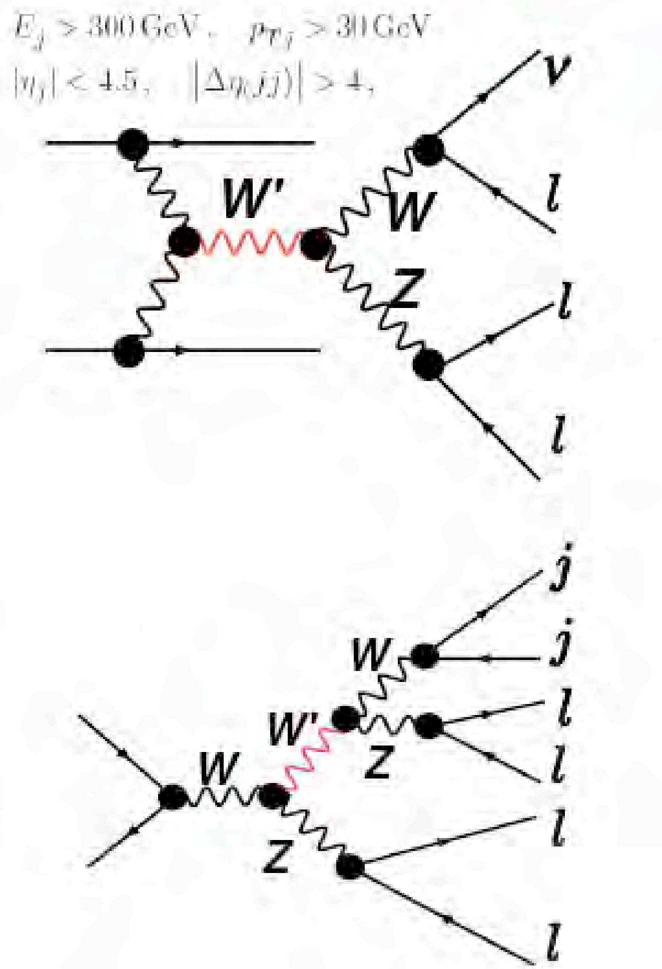


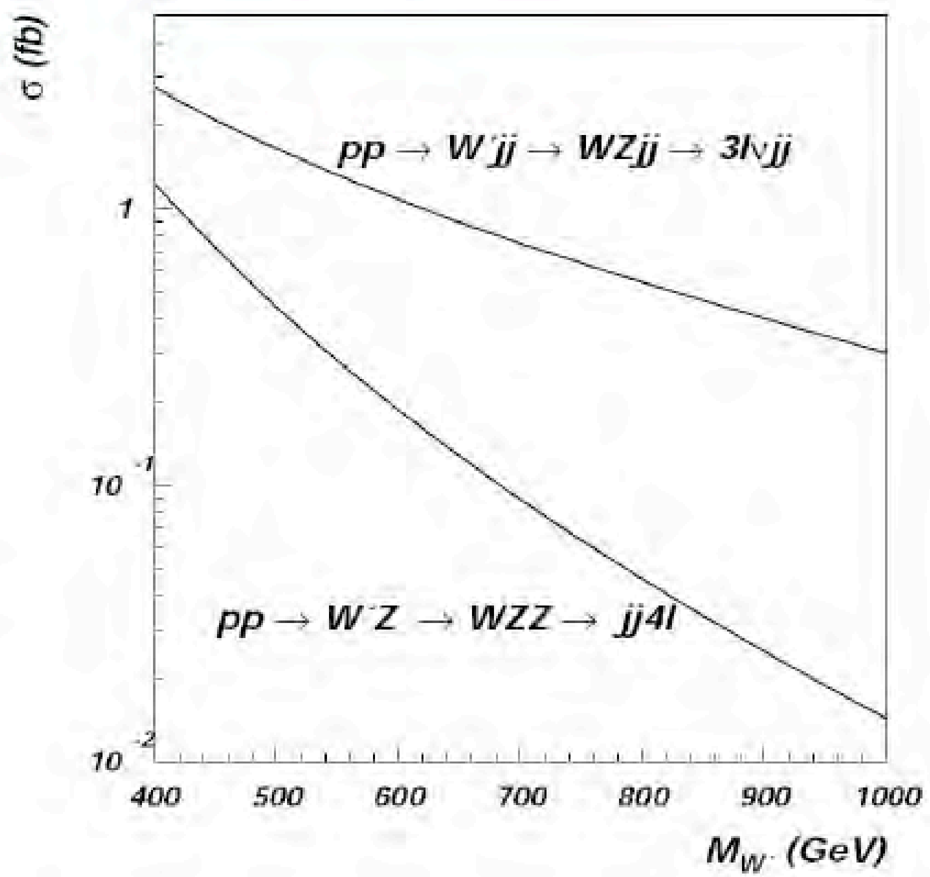
Decay



Vector Boson Fusion (WZ → W') and W'Z Associated Production

promise large rates and clear signatures





Example: CalcHEP

computation of $pp \to W^+ Zjj$

- ***No effective WZ approximation.***
- ***Complete set of signal and background diagrams including interference.***

in contrast with Birkedal, Matchev & Perelstein 2005

CalcHEP/symb

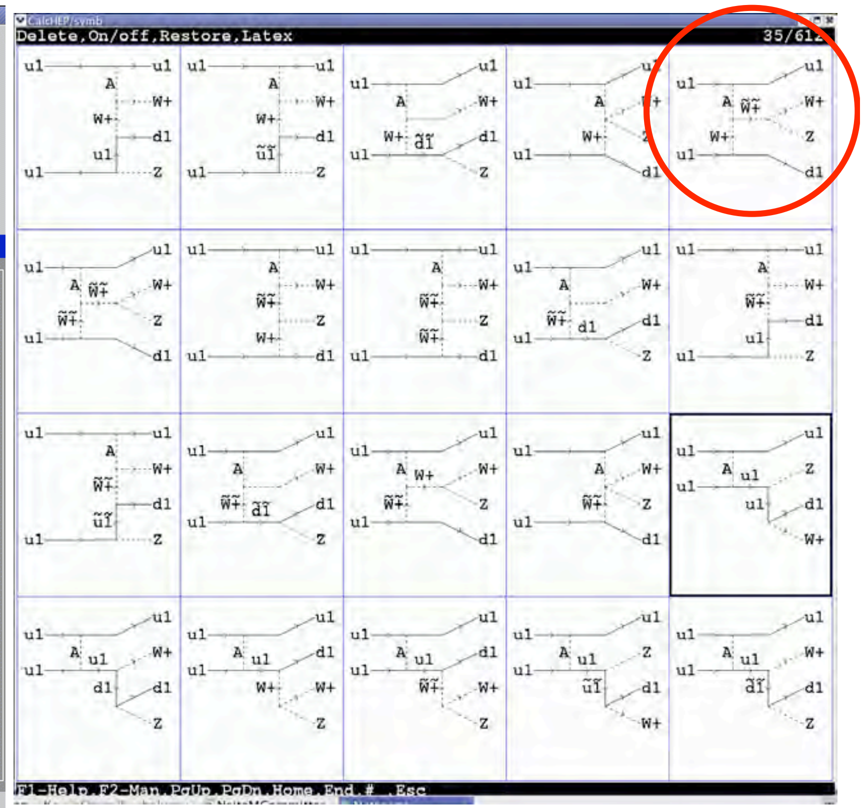
Model: 3-site-tfg

Process: p,p->W+,Z,j,j

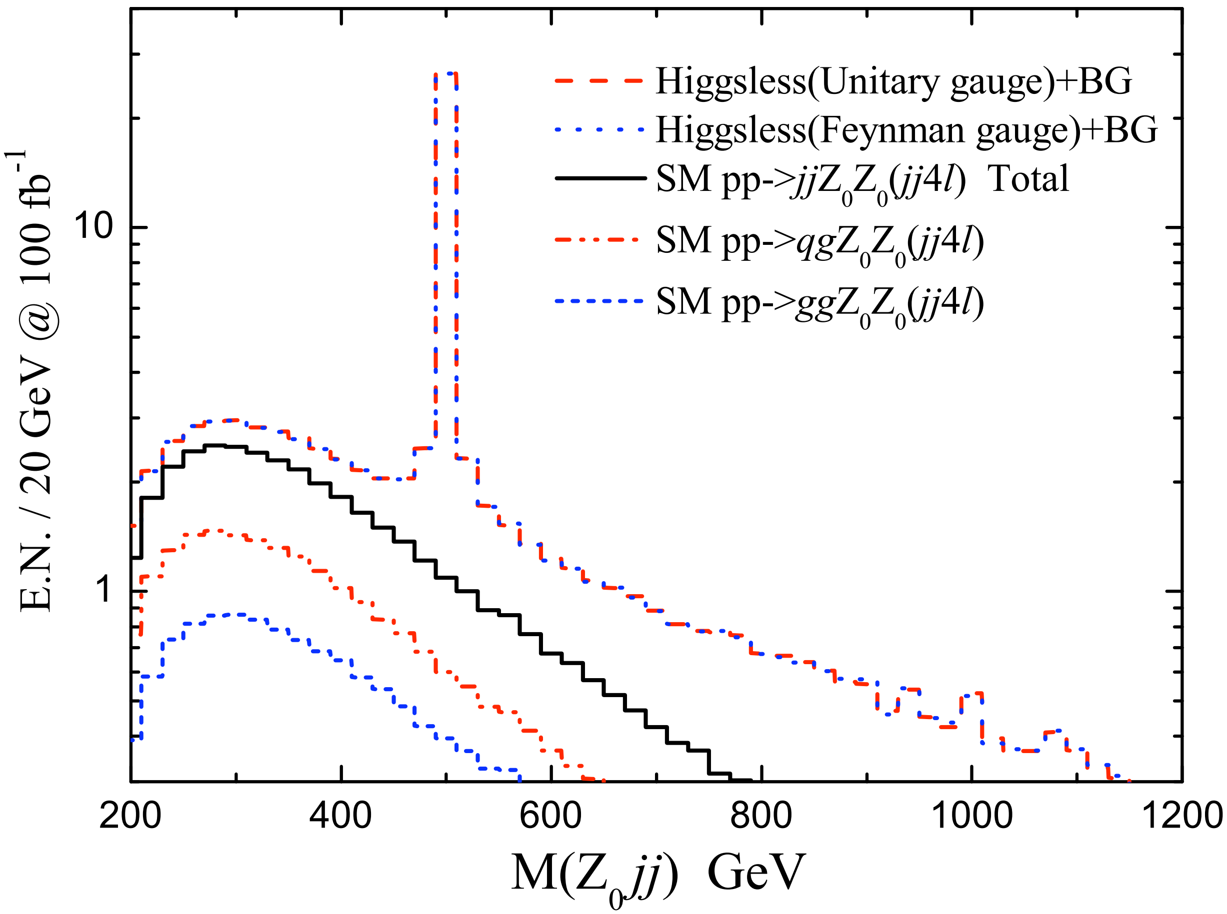
Feynman diagrams

7816 diagrams in 21 subprocesses are constructed.
0 diagrams are deleted.

NN	Subprocess	Del	Rest
1	u1,u1 -> Z,W+,u1,d1	0	612
2	u1,U1 -> Z,W+,U1,d1	0	612
3	u1,d1 -> Z,W+,d1,d1	0	306
4	u1,D1 -> Z,W+,u1,U1	0	612
5	u1,D1 -> Z,W+,d1,D1	0	612
6	u1,D1 -> Z,W+,G,G	0	46
7	u1,G -> Z,W+,G,d1	0	76
8	U1,u1 -> Z,W+,U1,d1	0	612
9	U1,D1 -> Z,W+,U1,U1	0	306
10	d1,u1 -> Z,W+,d1,d1	0	306
11	d1,D1 -> Z,W+,U1,d1	0	612
12	D1,u1 -> Z,W+,u1,U1	0	612
13	D1,u1 -> Z,W+,d1,D1	0	612
14	D1,u1 -> Z,W+,G,G	0	46
15	D1,U1 -> Z,W+,U1,U1	0	306
16	D1,d1 -> Z,W+,U1,d1	0	612
17	D1,D1 -> Z,W+,U1,D1	0	612
18	D1,G -> Z,W+,G,U1	0	76
19	G,u1 -> Z,W+,G,d1	0	76
20	G,D1 -> Z,W+,G,U1	0	76
21	G,G -> Z,W+,U1,d1	0	76



Associated Production (signal in WZZ channel)
500 GeV W' boson

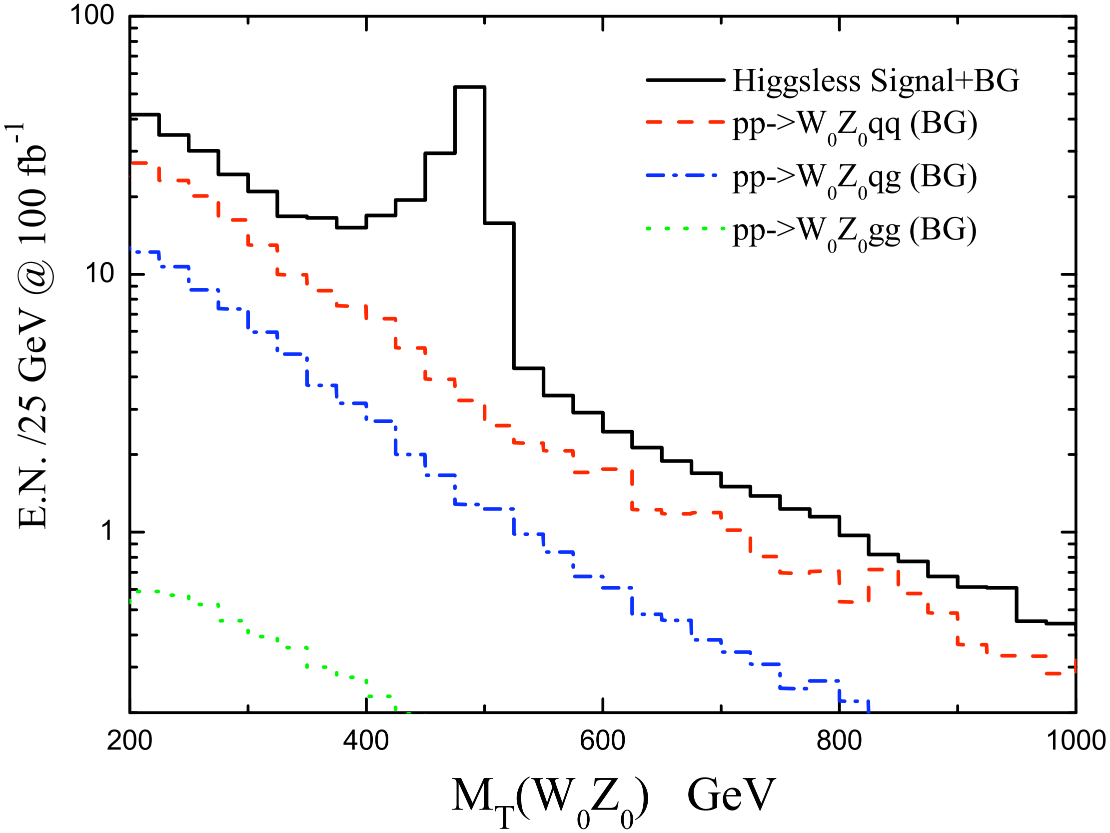


$$M_{jj} = 80 \pm 15\,\mathrm{GeV}, \qquad \Delta R(jj) < 1.5\,, \qquad \sum_Z p_T(Z) + \sum_j p_T(j) = \pm 15\ \mathrm{GeV}.$$

$$p_{T\ell} > 10\,\mathrm{GeV}, \qquad |\eta_\ell| < 2.5\,, \qquad p_{Tj} > 15\,\mathrm{GeV}, \qquad |\eta_j| < 4.5\,.$$

Vector Boson Fusion (signal in WZjj channel)

500 GeV W' boson



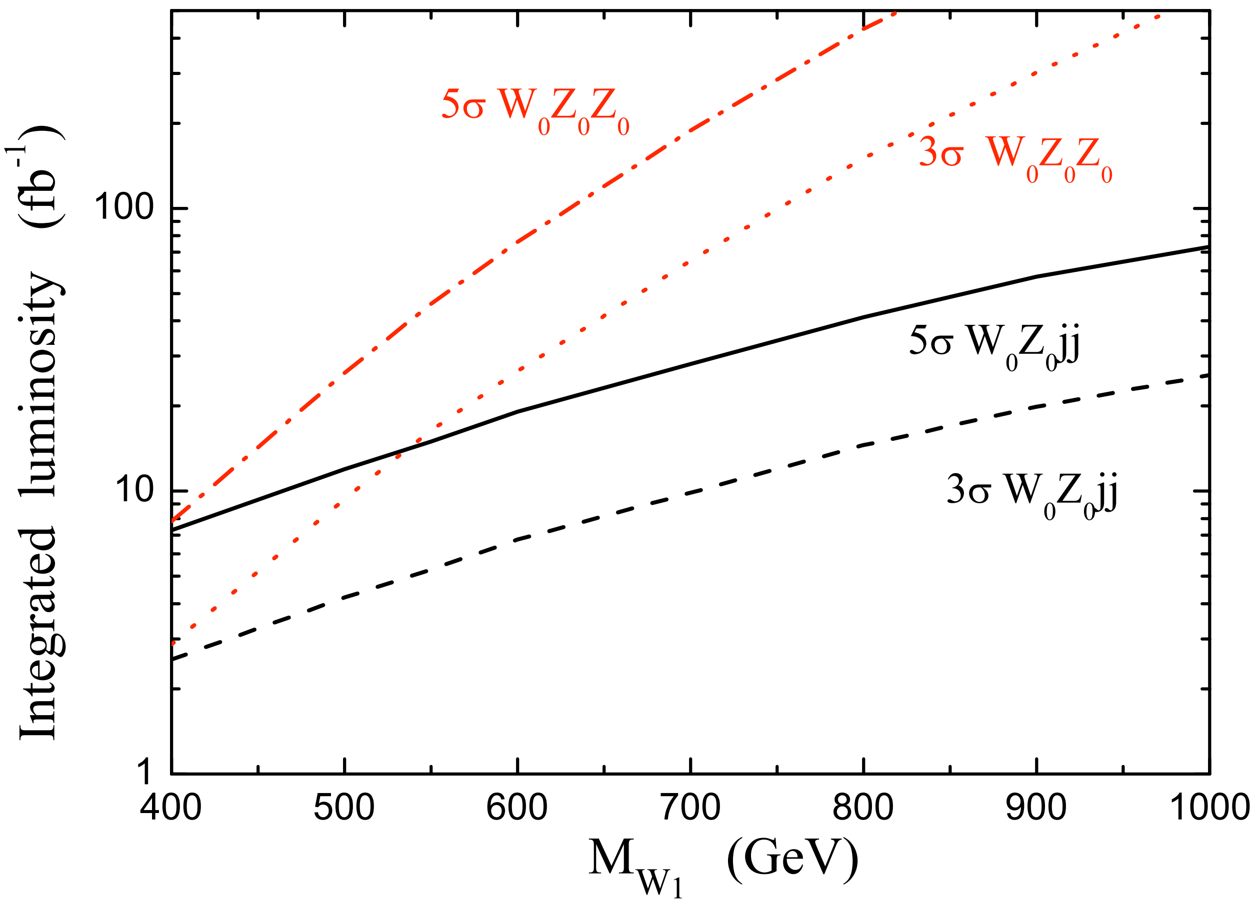
Background is 10x larger than estimated in Birkedal, Matchev & Perelstein (2005)

forward jet tag removes WZ background

$$E_j > 300\,\text{GeV}\,, \qquad p_{Tj} > 30\,\text{GeV}\,, \qquad |\eta_j| < 4.5\,, \qquad |\Delta\eta_{jj}| > 4\,,$$

$$p_{T\ell} > 10\,\text{GeV}\,, \qquad |\eta_\ell| < 2.5\,.$$

Integrated LHC Luminosity required to discover W' in each channel



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]
- extra gauge bosons can be relatively light [since they are fermiophobic]
- EW observables calculable at one loop
- W' and Z' promise clean multi-lepton signatures at LHC [gauge invariance is key to accurate calculation of rate]