LHC Phenomenology of the 3-site Higgsless Model

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- Deconstructed Higgsless Models
- The 3-Site Model
- LHC Phenomenology (W' and Z')
- Conclusions

hep-ph Refs:
0607124, 060719, 0708.2588

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

Deconstructed Higgsless Models

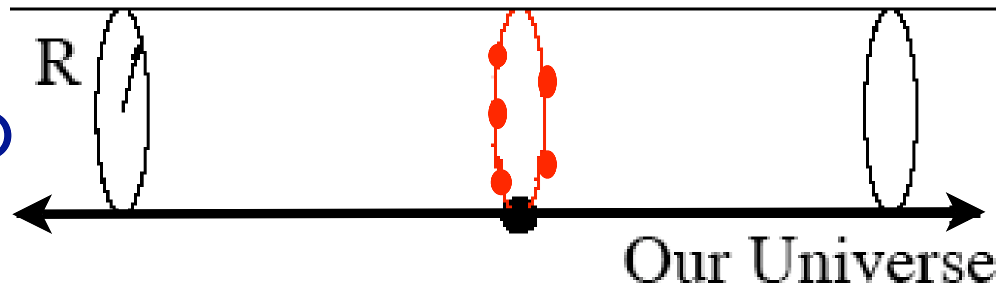
General Principles :

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:

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

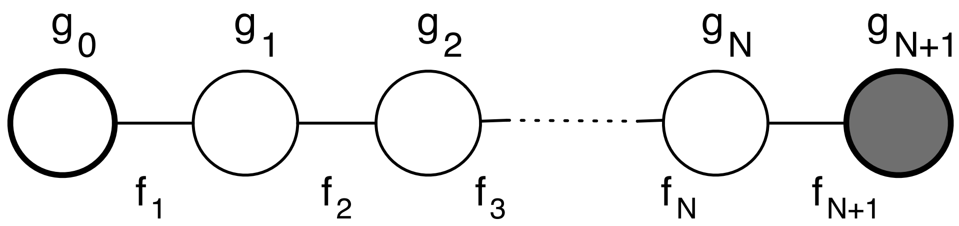
$$\widehat{A}^a_5 = \sqrt{\frac{2}{\pi R}}\sum_{n=1}^{\infty} A^{an}_5(x_\nu)\sin\left(\frac{n x_5}{R}\right)$$

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

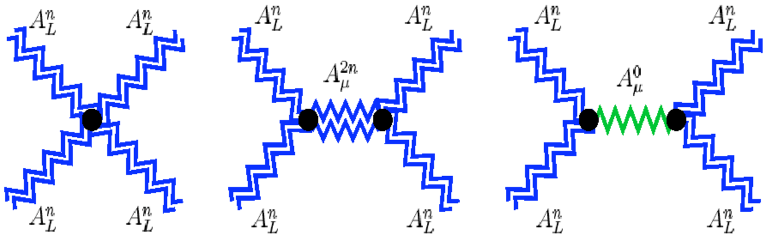


- 5th dimension discretized
- $SU(2)^N$ x U(1); general f_j and g_k encompass spatially-dependent couplings, warping
- for fixed v, $\frac{1}{v^2} = \sum_i \frac{1}{f_i^2}$ means $f_i \sim \sqrt{N} v$
- In simplest models, Localized fermions sit on "branes" [sites 0 and N+1]

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

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!

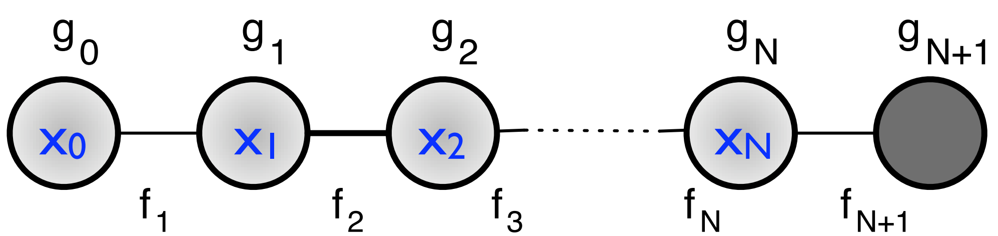
Independent of warping or gauge couplings chosen...

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

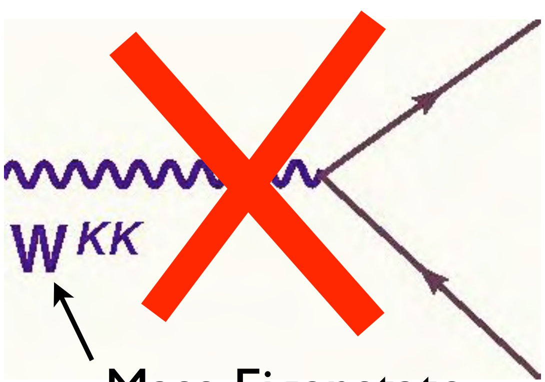
Foadi, Gopalkrishna, & Schmidt

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!



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

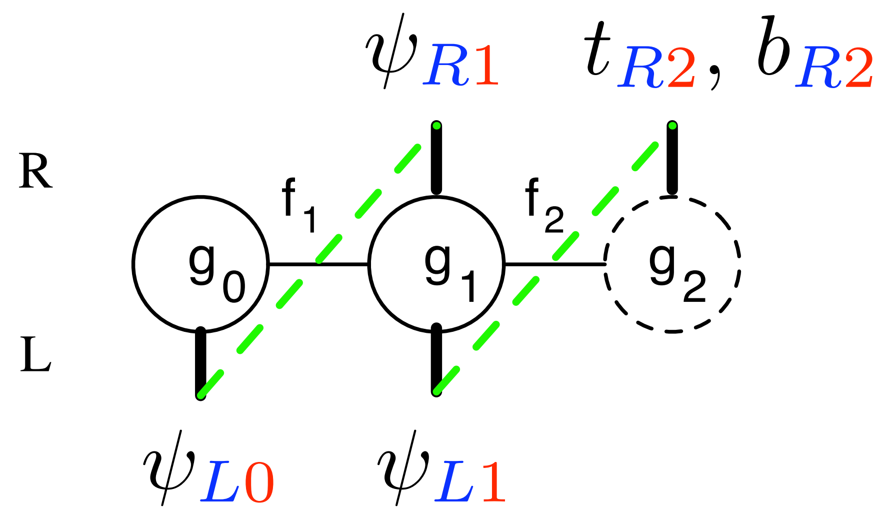
$$Y = M_W^2 (\Sigma_W - \Sigma_Z)$$

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

The 3-site Model

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' (as in BESS)

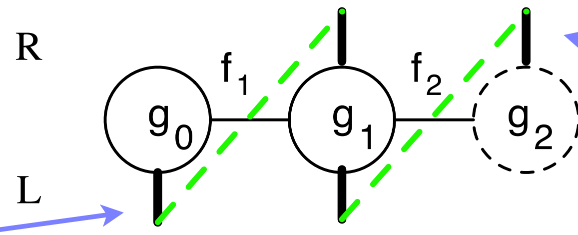
Fermion spectrum: t, T, b, B (ψ is an SU(2) doublet)

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

Chivukula hep-ph/0607124

3-Site Model: fermion details

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



LH Boundary Fermion

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

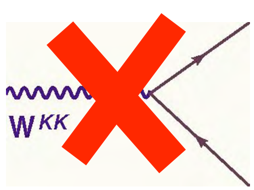
becomes $\frac{g_0(\psi_{L0}^f)^2}{g_1(\psi_{L1}^f)^2} = \frac{v_W^0}{v_W^1}$ in 3-site model

From W, fermion eigenvectors, solve for

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

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

insures W' and Z' are fermiophobic!



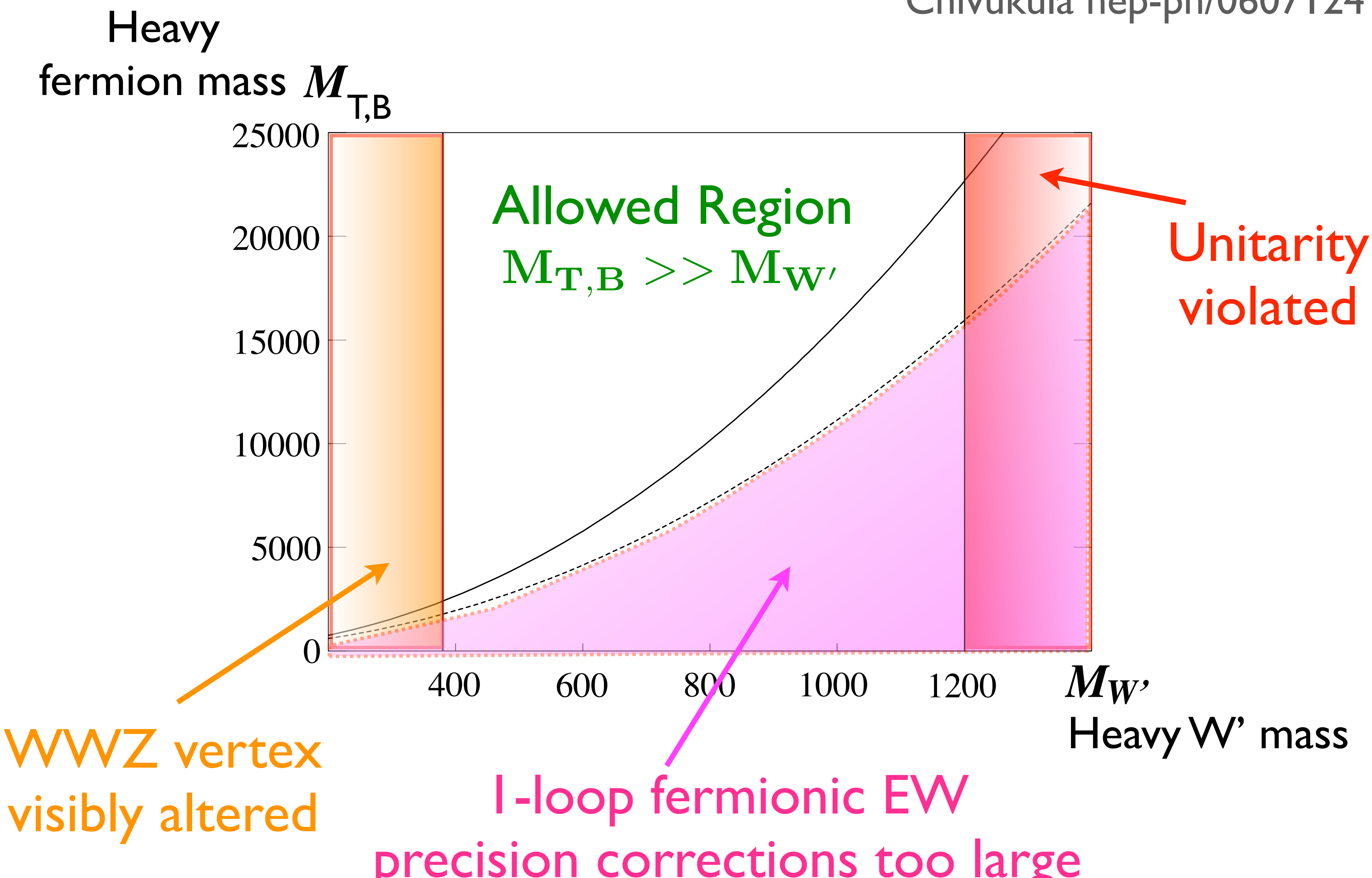
$$\hat{S} = \hat{T} = W = 0$$

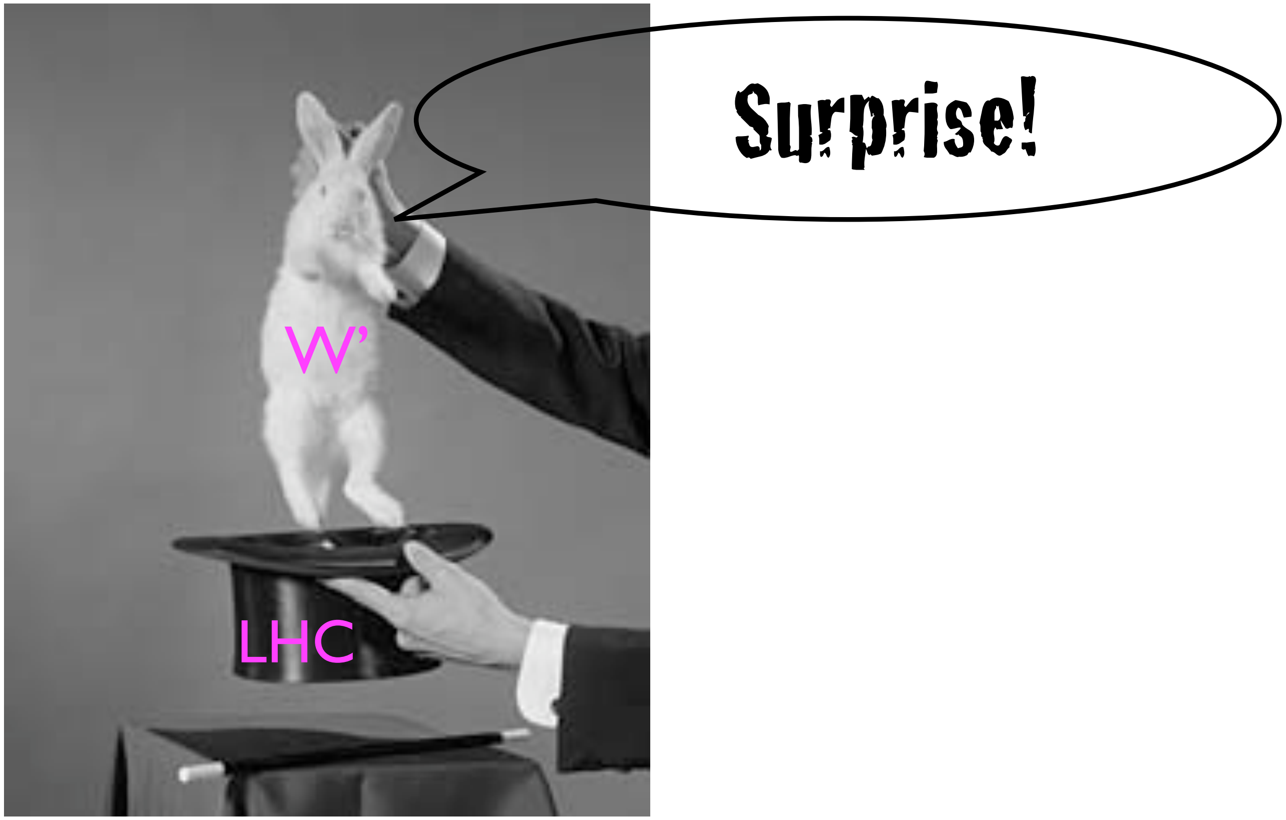
$$Y = M_W^2(\Sigma_W - \Sigma_Z)$$

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

3-Site Parameter Space

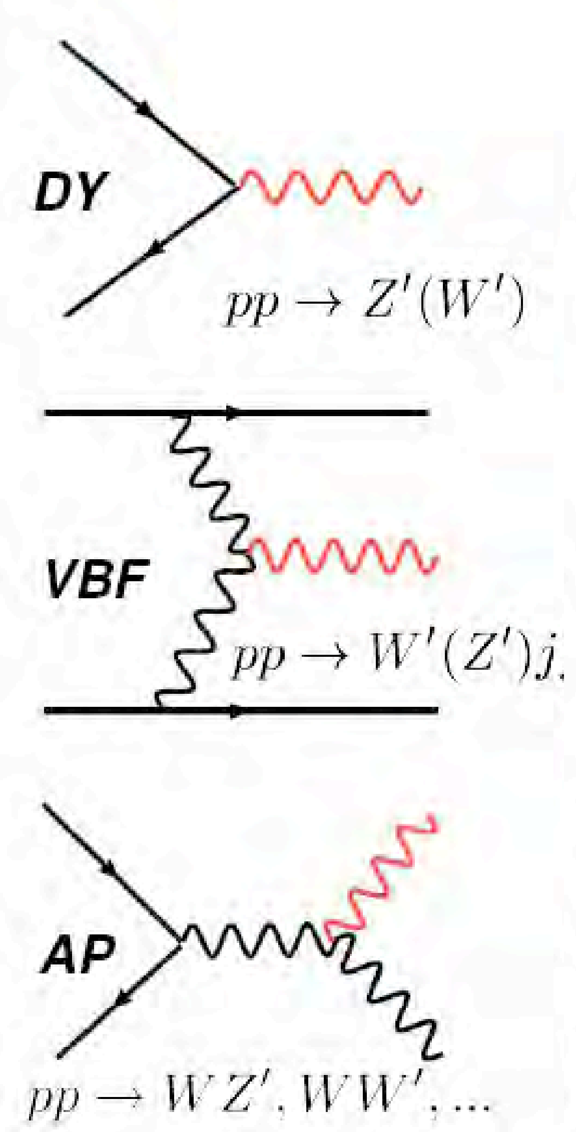
Chivukula hep-ph/0607124

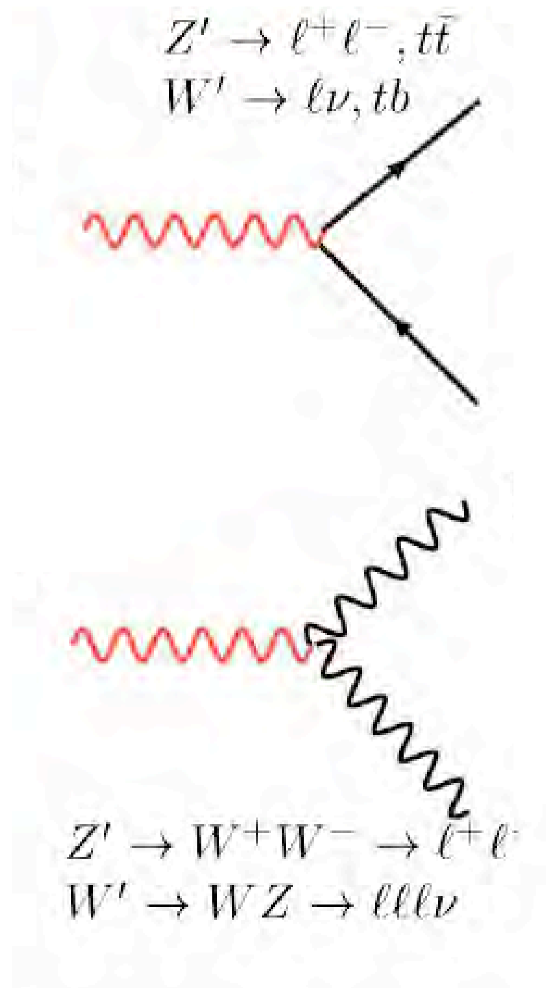




LHC Phenomenology

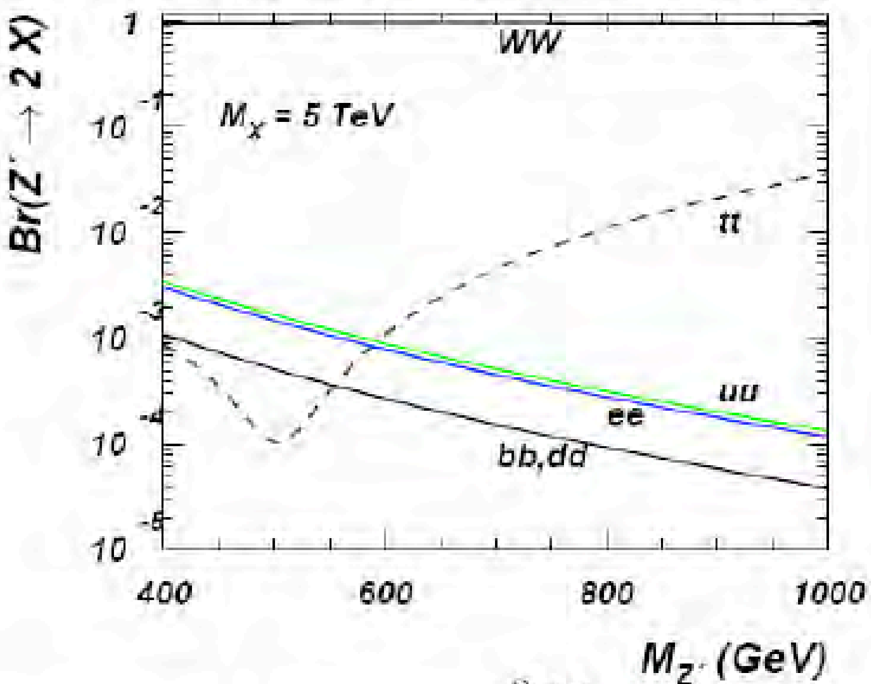
Production and Decay of W’ and Z’ bosons at LHC

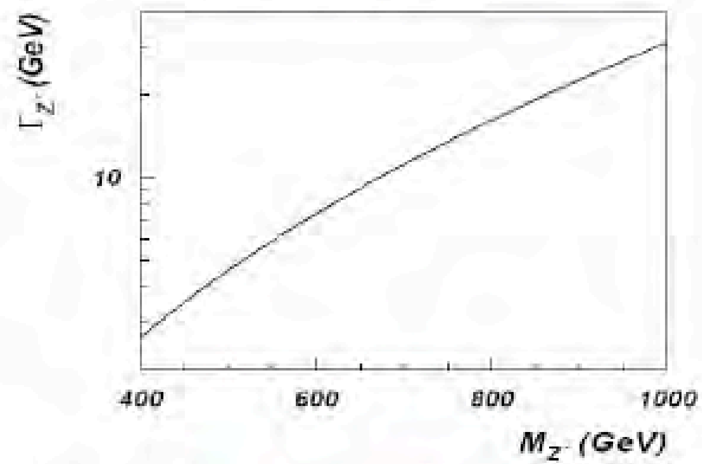


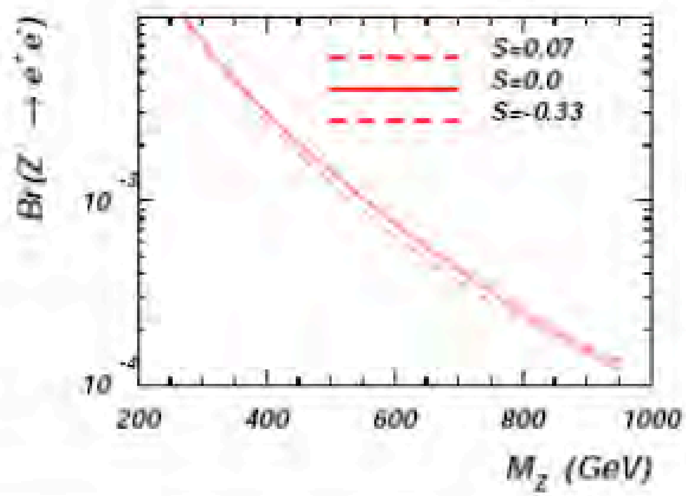


Z' decay modes

- dominant decay is to gauge boson pairs
- BR to fermions not sensitive to deviation from ideal delocalization





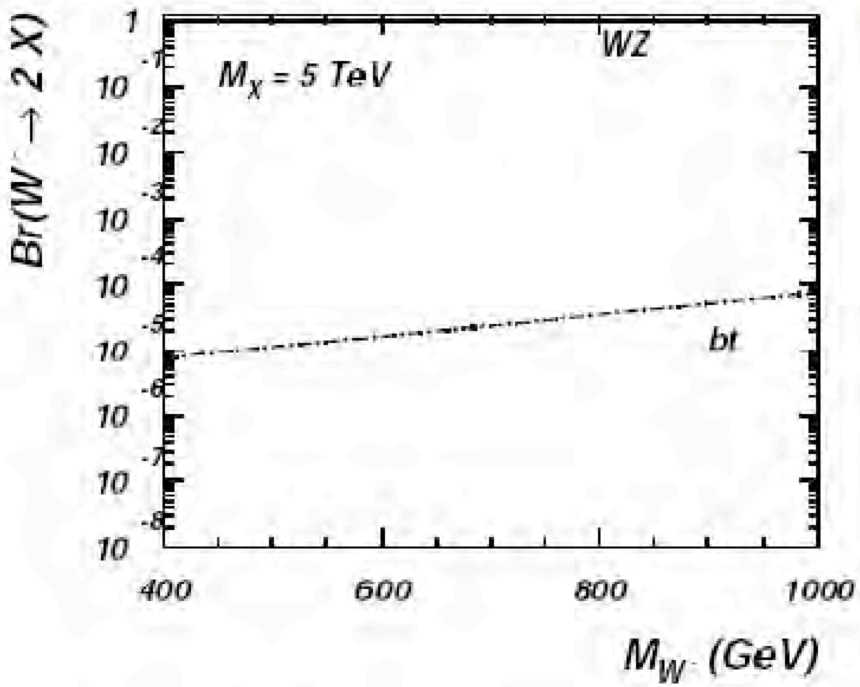


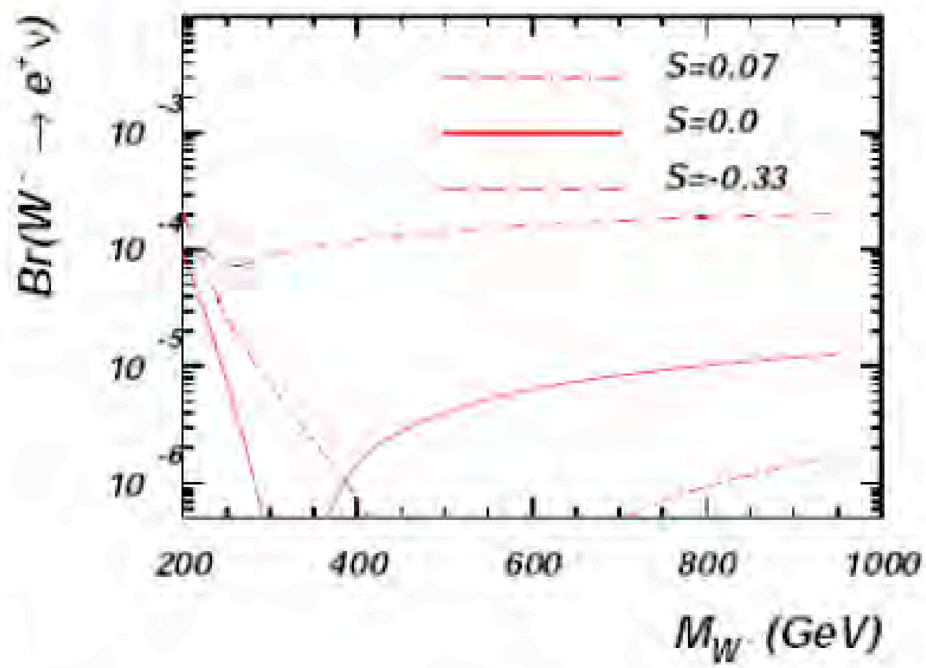
$$\Gamma(Z' \to W^+W^-) = \frac{e^2 M_{W'}}{192\pi x^2 s_w^2}$$

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

W' decay modes

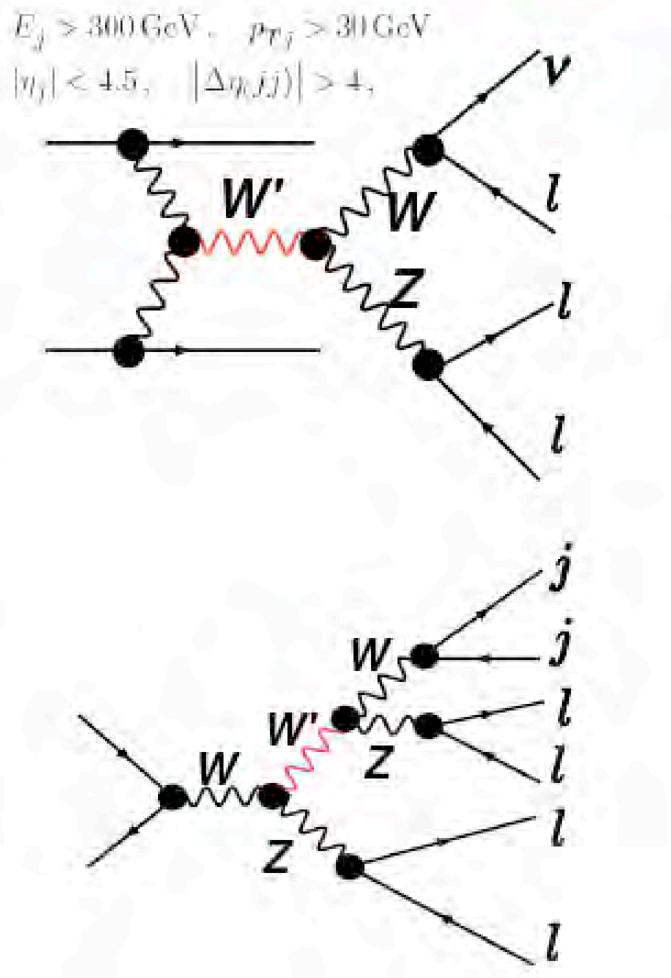
- dominant decay is, again, to gauge boson pairs
- BR to fermions is small -- but sensitive to delocalization

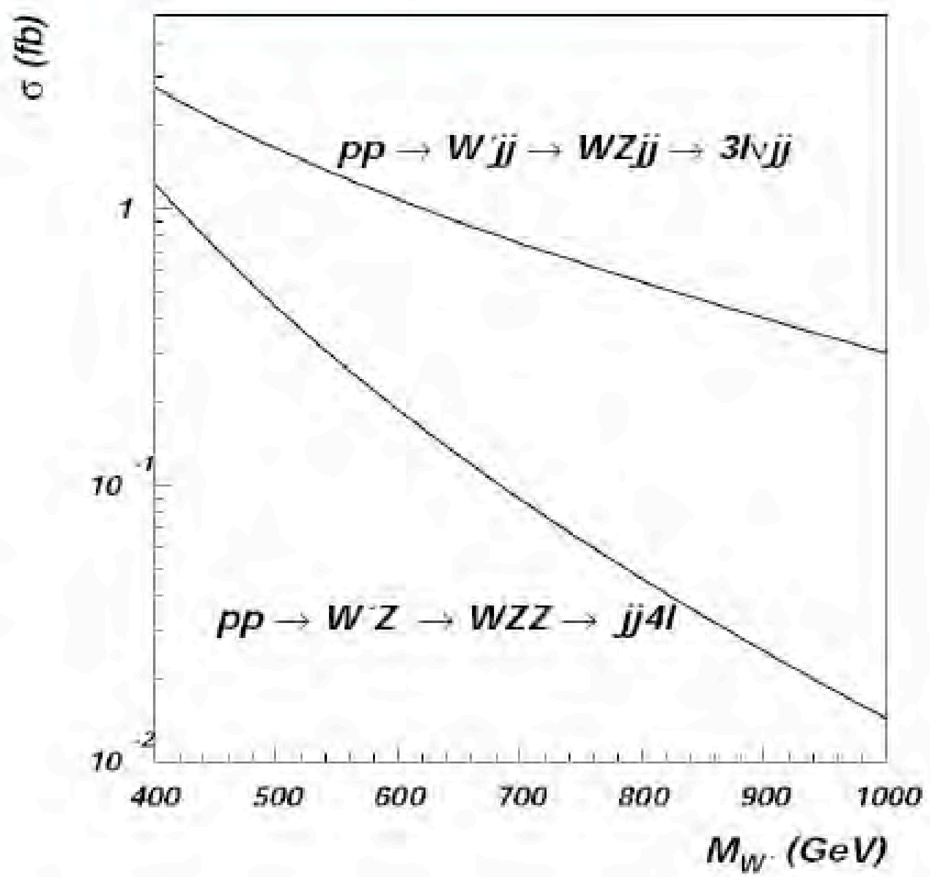




$$\Gamma(W' \to e^+ e^-) = \frac{e^2 M_{W'} x^2 \left(1 - \frac{2\epsilon_L^2}{x^2}\right)^2}{192\pi s_w^2}$$

Vector Boson Fusion (WZ → W') and W'Z Associated Production promise large rates and clear signatures





Example: CalcHEP
computation of $pp \to W^+ Zjj$

MADGRAPH, and HANLIB also used

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

in contrast with Birkedal, Matchev & Perelstein 2005

CalcHEP/symb

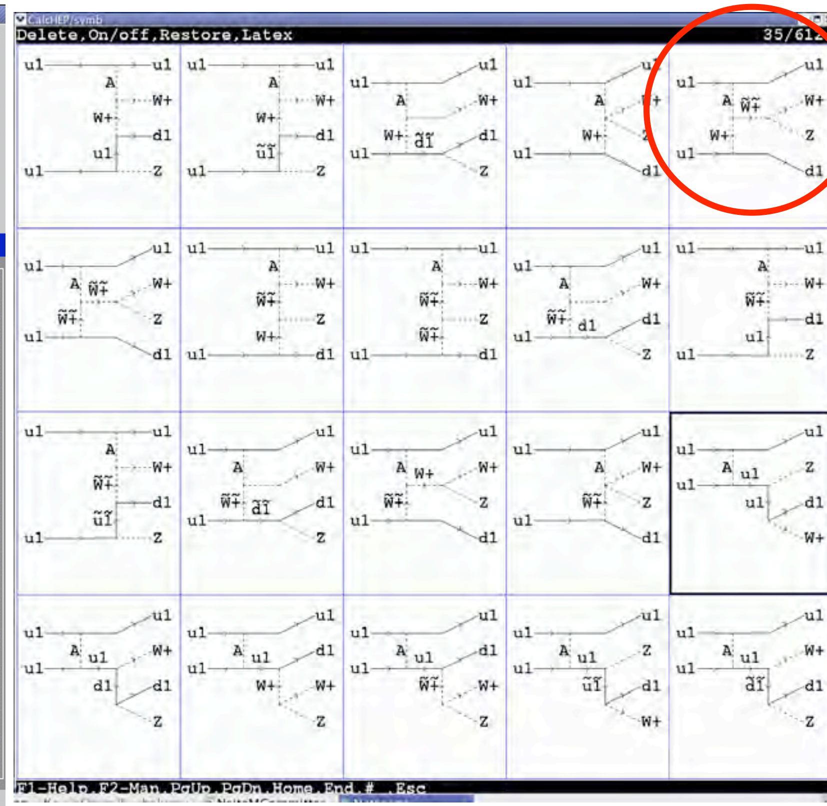
Model: 3-site-tfg

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

Feynman diagrams

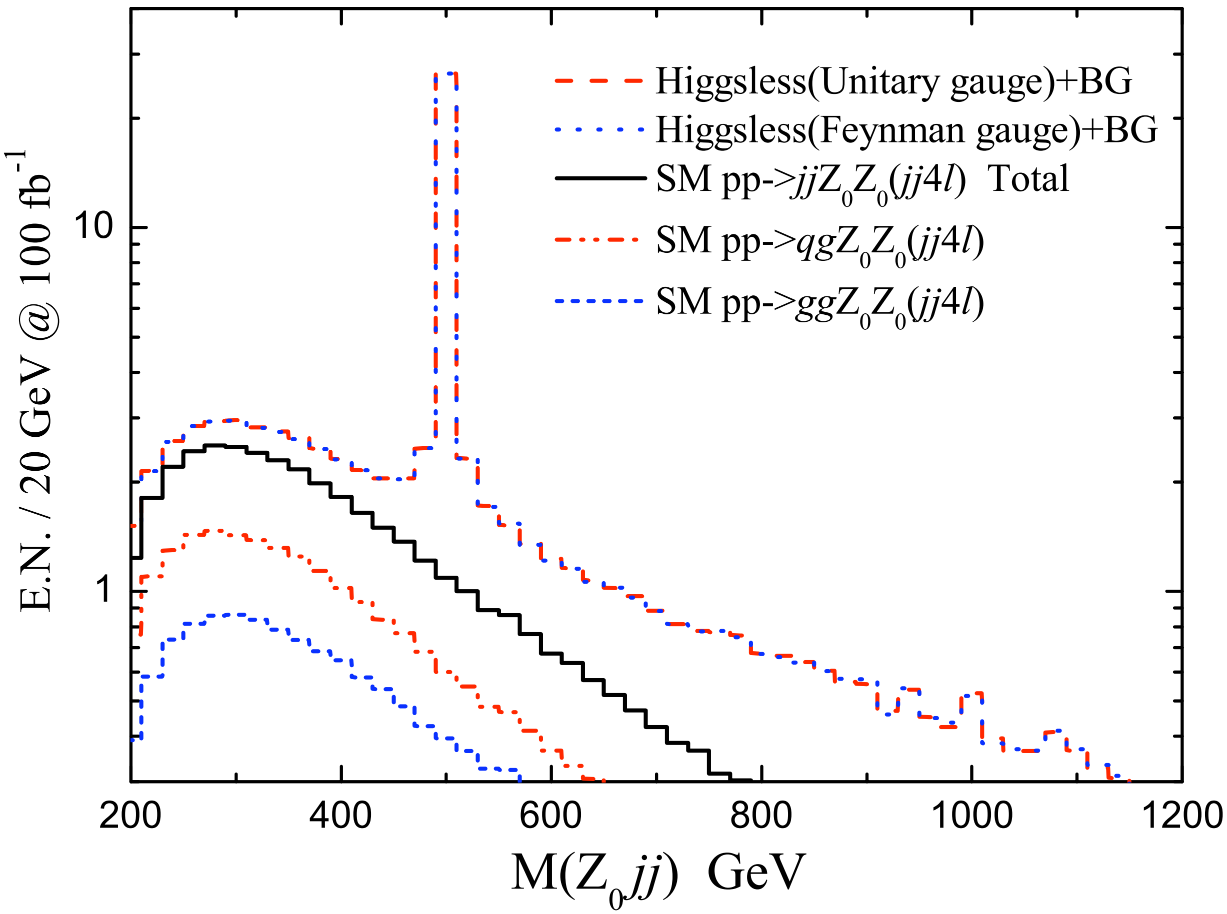
7816 diagrams in 21 subprocesses are constructed.
0 diagrams are deleted.

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

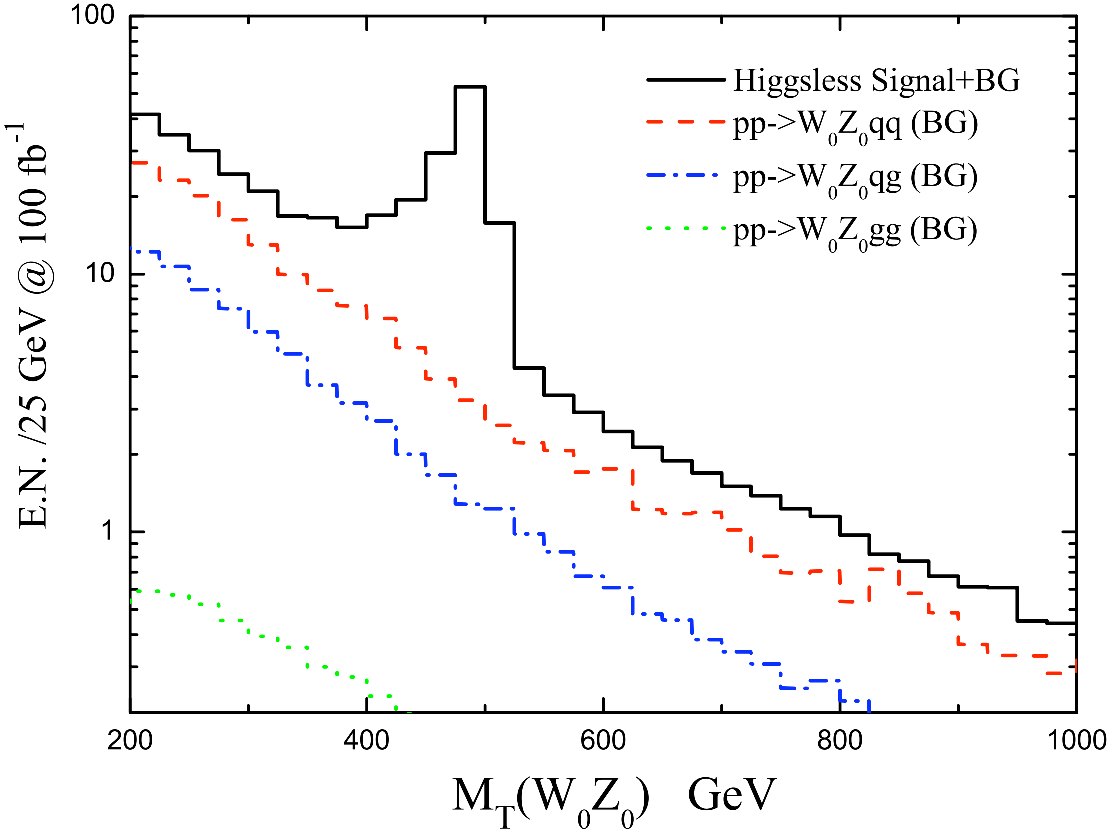


$$M_{jj} = 80 \pm 15\,\text{GeV}, \qquad \Delta R(jj) < 1.5\,, \qquad \sum_Z p_T(Z) + \sum_j p_T(j) = \pm 15\ \text{GeV}.$$

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

Vector Boson Fusion (signal in WZjj channel)

500 GeV W' boson



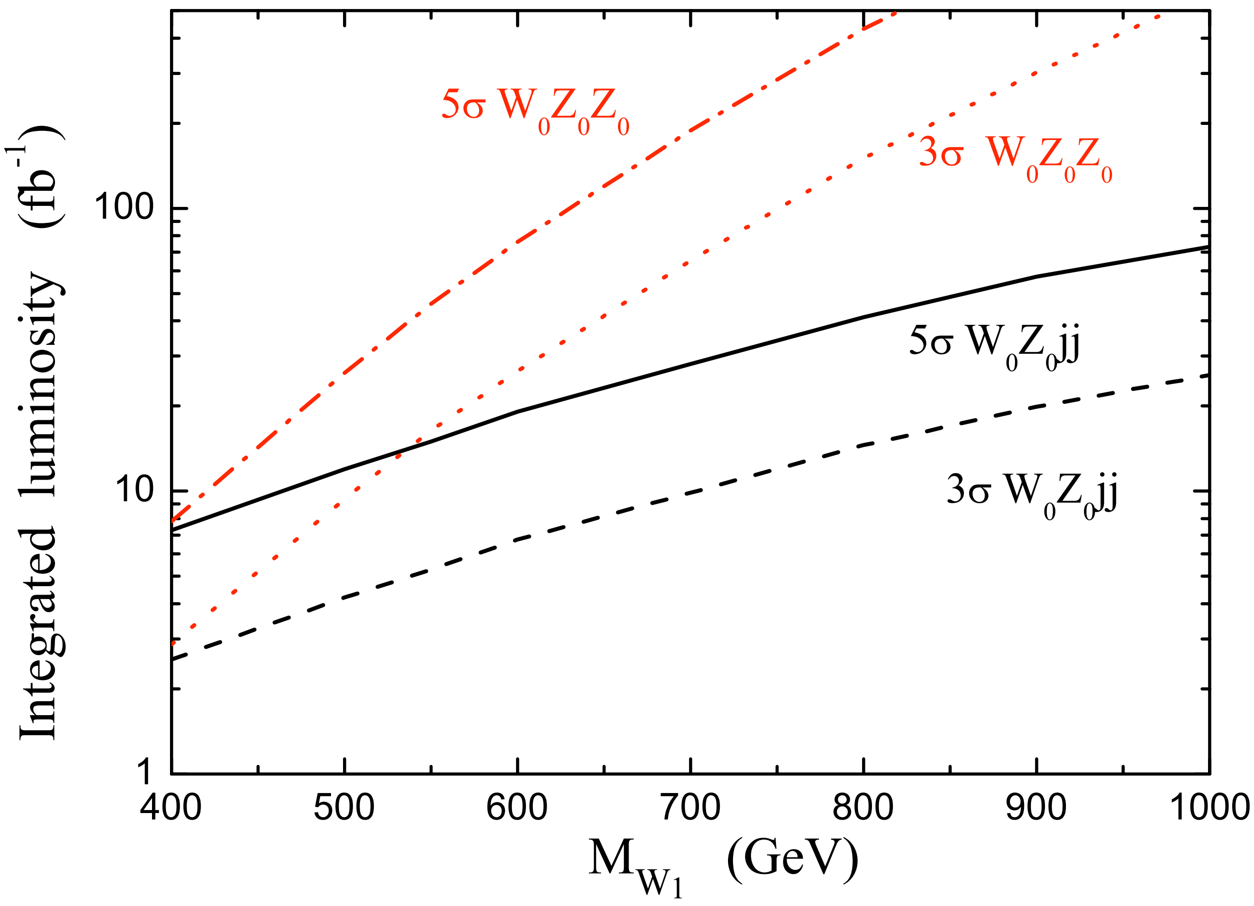
Background is 10x larger than estimated in Birkedal, Matchev & Perelstein (2005)

forward jet tag removes WZ background

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

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

Integrated LHC Luminosity required to discover W' in each channel



Conclusions

The 3-site Higgsless model is a viable effective theory of EWSB up to ~ 2 TeV with interesting LHC signatures

- illustrates general principles of deconstructed Higgsless models and ideal delocalization
- accommodates flavor
- fermiophobic extra gauge bosons can be light
- W' and Z' have clean multi-lepton LHC signatures

<u>NEXT</u>: Heavy Fermions from Higgsless Models at the LHC