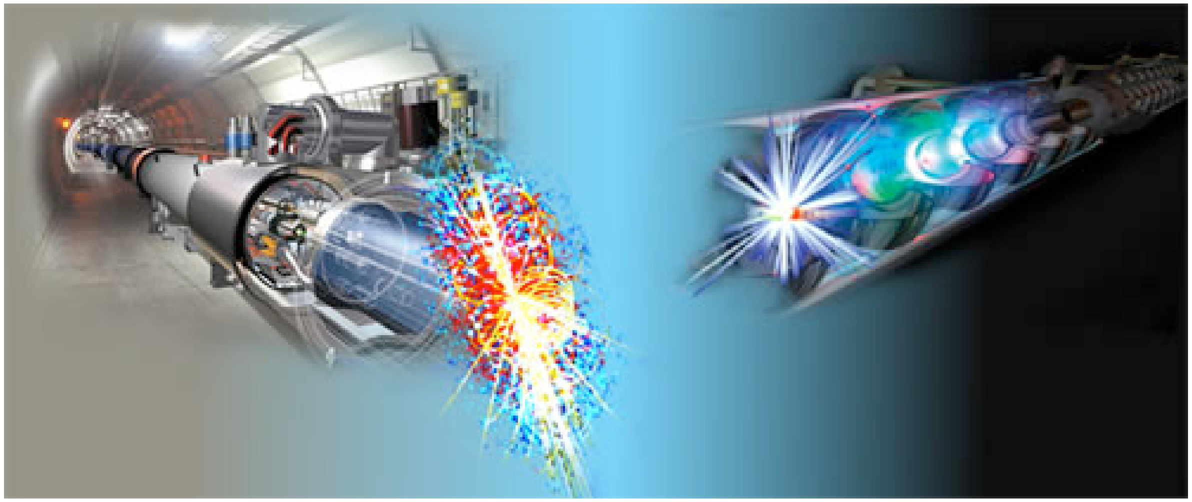
A No Higgs Example: The Three Site Model

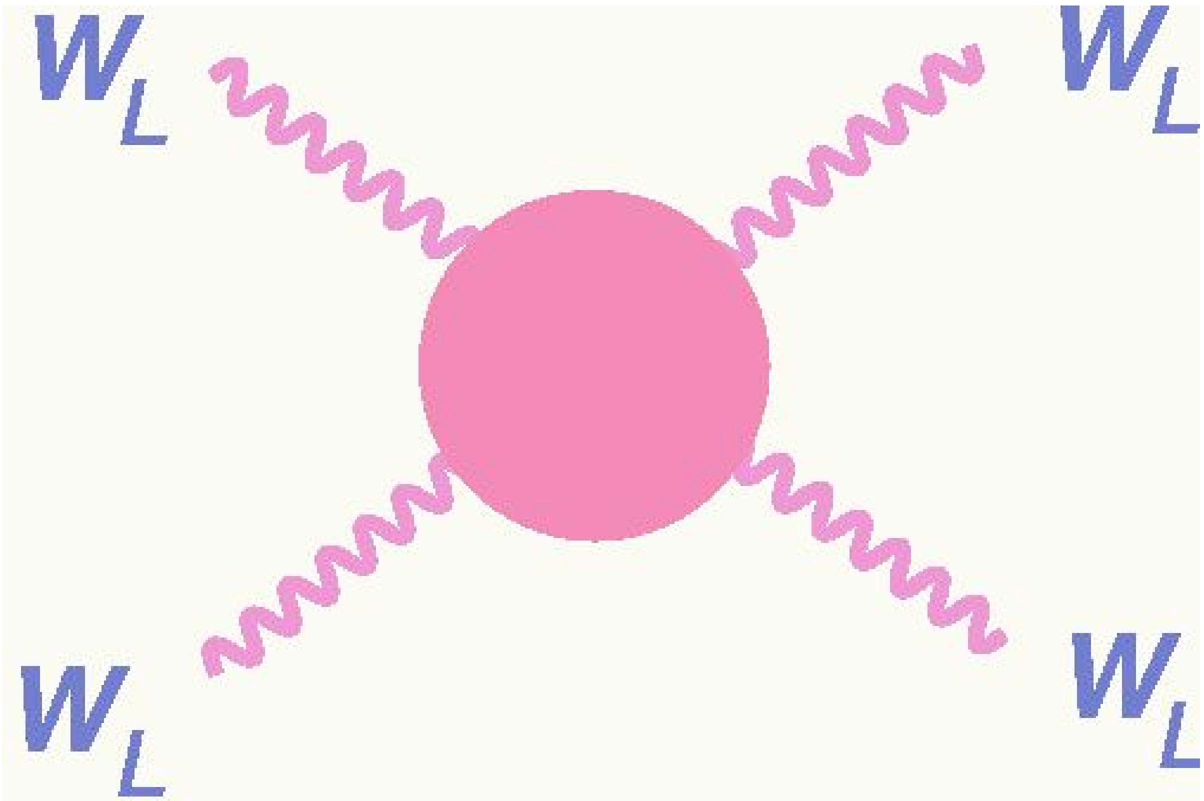
R. Sekhar Chivukula
Michigan State University



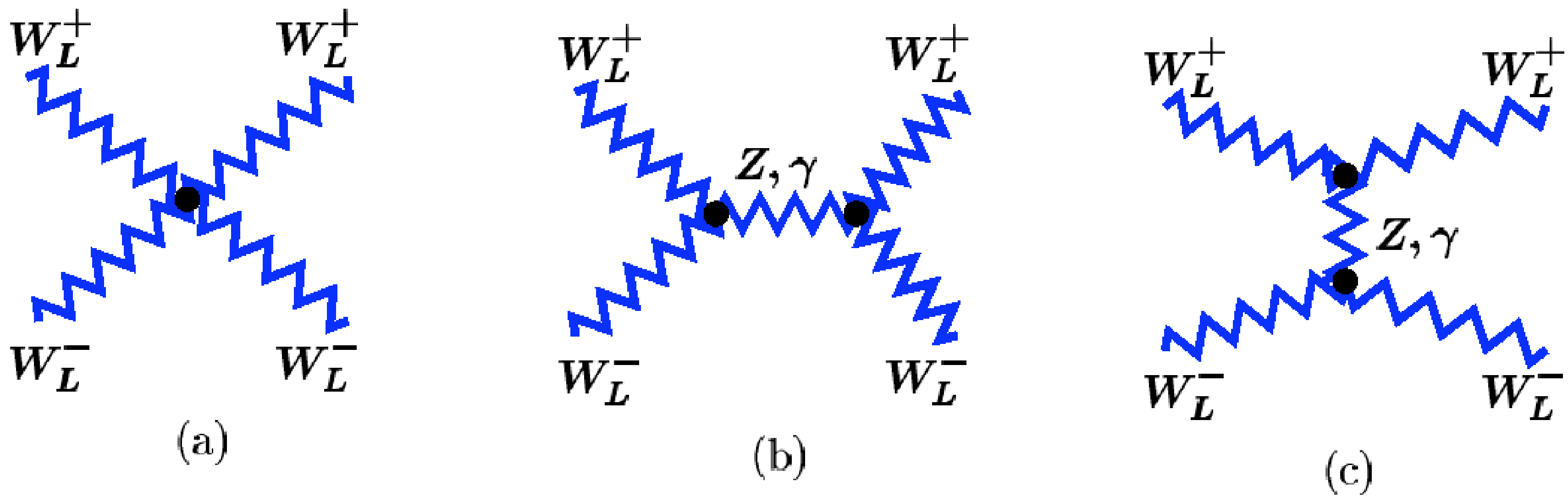
The LHC Early Phase for the ILC
Fermilab, April 12, 2007

Why Worry About EWSB?

Loss of Unitarity in



SU(2) x U(1) @ E^4

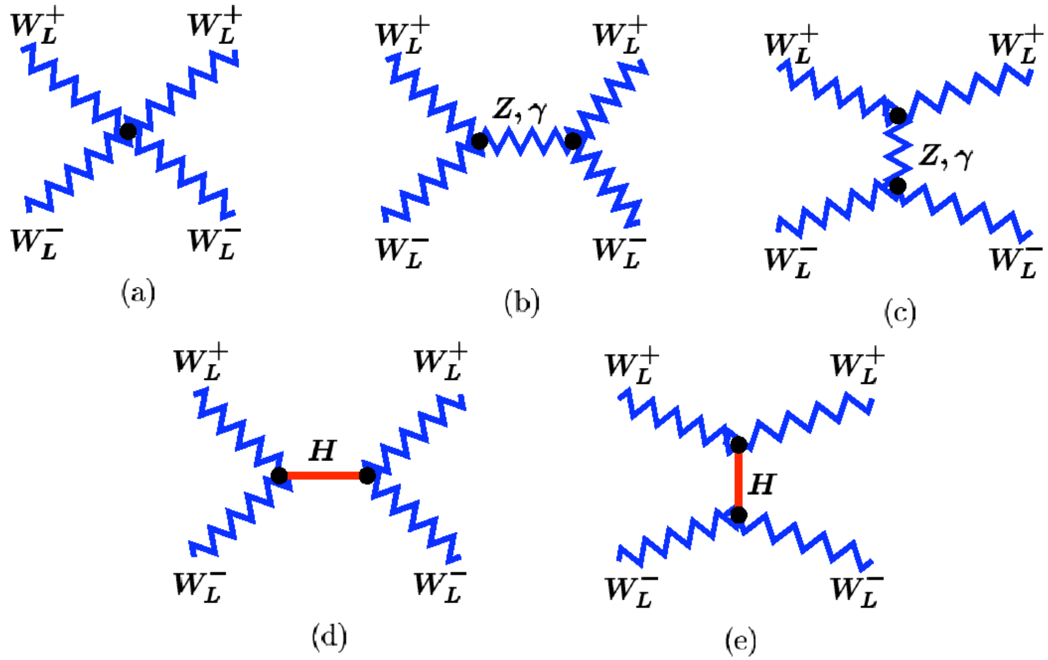


Graphs	$g^2 \frac{E^4}{m_w^4}$
(a)	$-3 + 6\cos\theta + \cos^2\theta$
(b)	$-4\cos\theta$
(c)	$+3 - 2\cos\theta - \cos^2\theta$
Sum	0

$$\epsilon_L^\mu(k) = \frac{k^\mu}{m_w} + \mathcal{O}\left(\frac{m_w}{E}\right)$$

Why a Higgs?

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

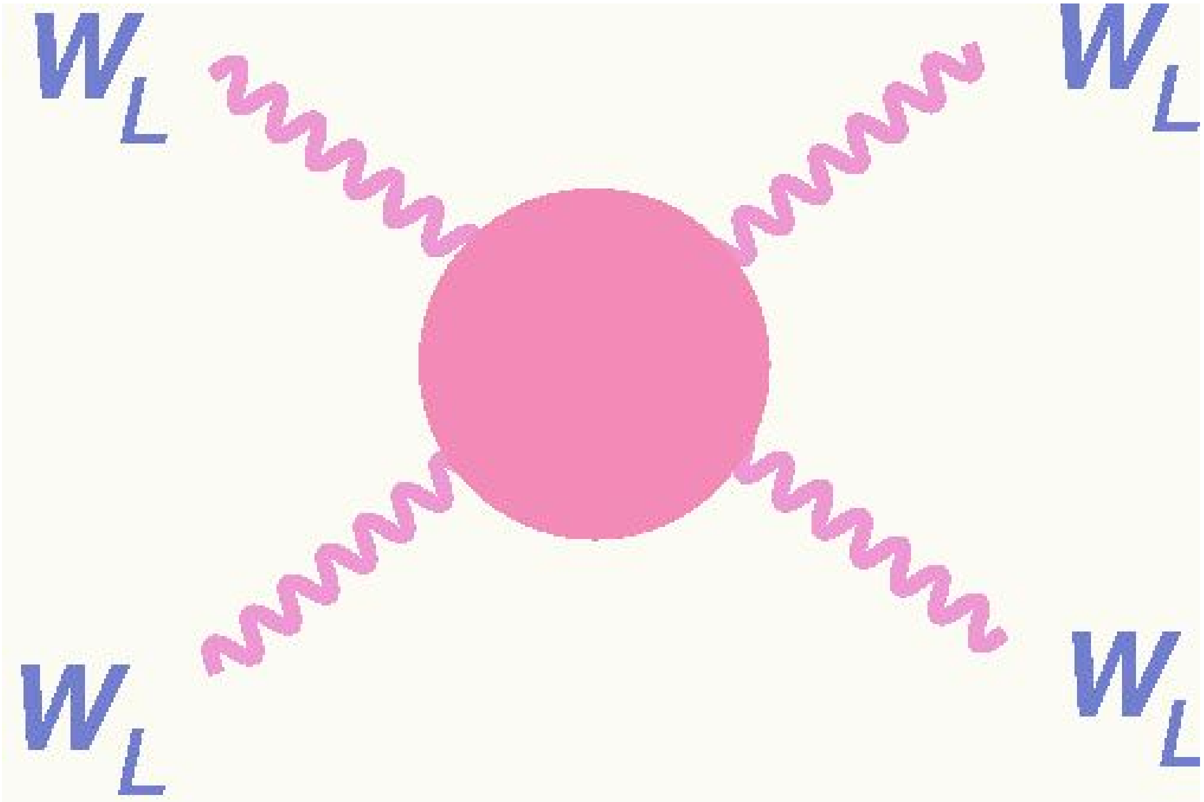


Graphs	$g^2 \frac{E^2}{m_w^2}$
(a)	$+2 - 6\cos\theta$
(b)	$-\cos\theta$
(c)	$-\frac{3}{2} + \frac{15}{2}\cos\theta$
$(d+e)$	$-\frac{1}{2} - \frac{1}{2}\cos\theta$
Sum including (d+e)	**0**

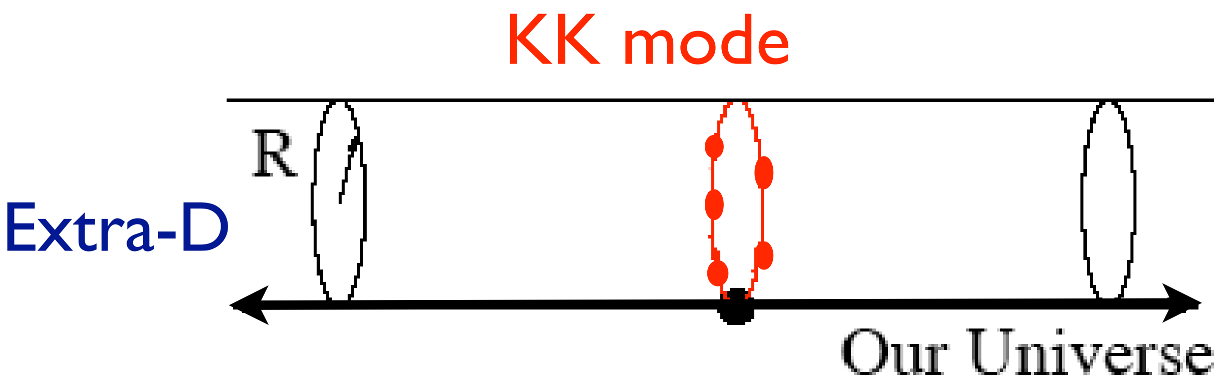
- $\mathcal{O}(E^0) \Rightarrow$ 4d m_H bound: $m_H < \sqrt{16\pi/3}\, v \simeq 1.0$ TeV
- If no Higgs $\Rightarrow \mathcal{O}(E^2) \Rightarrow E < \sqrt{8\pi} v \simeq 1.2\,\mathrm{TeV}$

Can Extra-D be related to EWSB?

Consider Loss of Unitarity in



Extra-D Theories and Massive Vector Boson Scattering



Expand 5-D gauge bosons in eigenmodes:

e.g. for S^1/Z_2:

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

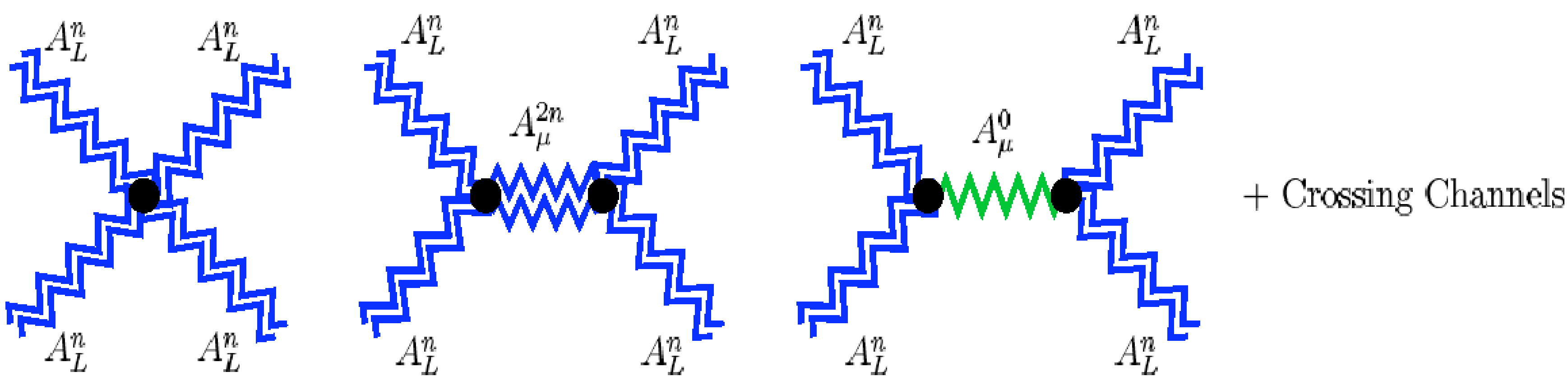
$$\widehat{A}^a_5 = \sqrt{\frac{2}{\pi R}}\sum_{n=1}^{\infty} A^{an}_5(x_\nu)\sin\left(\frac{n x_5}{R}\right)$$

4-D gauge kinetic term contains

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

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

4-D KK Mode Scattering



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

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

Can we apply this to W and Z?

RSC, H.J. He, D. Dicus

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

Higgsless Models

- Can we use Extra-D/AdS-CFT in EWSB?
- Unitarize TeV-scale $W_L W_L$ scattering using vector bosons?
- If KK modes exist, $M_W << M_{KK}$
- Luckily, unitarization generalizes to a large class of 5-d manifolds and boundary conditions!

Csaki, Grojean, Murayama, Pilo, Terning

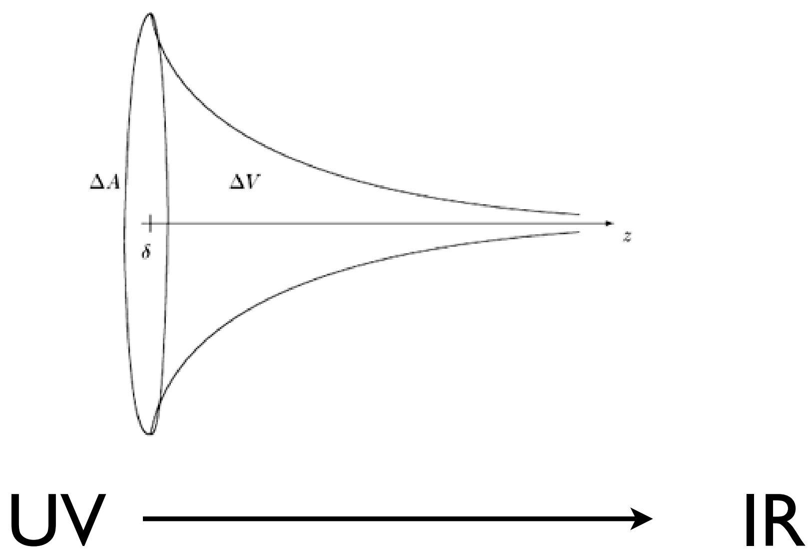
Technicolor: Higgsless since 1976!

Eliminate Scalars: Electroweak gauge symmetry broken by the nonzero expectation value of a fermion bilinear, driven by new strong interactions.

Understanding of strongly-interacting gauge theories is extremely limited $\Rightarrow$ theories constructed by analogy

AdS/CFT Duality

Conjecture: Equivalence of 5D theory in AdS and 4D CFT



$$ds^2 = \left(\frac{R}{z}\right)^2 \left[\eta_{\mu\nu} dx^\mu dx^\nu - dz^2\right]$$

$$R < z < R'$$

NB: Rescaling Invariance!

Strong evidence for N=4 SUSY YM string theory on AdS

Strongly-coupled CFT ⇔ Weakly-coupled 5D Theory

"Walking Technicolor" ⇔ Higgsless Models

Energy Scales and Couplings with AdS/CFT

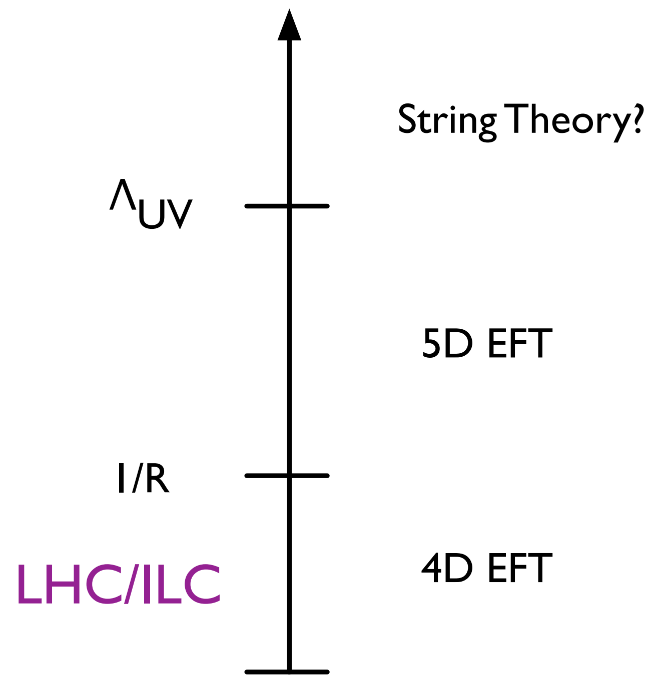
Quantum Corections in 5D KK Theory:

$$\mathcal{O}\left(\frac{g_4^2}{16\pi^2}\right) = \mathcal{O}\left(\frac{1}{N_{CFT}}\right)$$

$$g_4^2 = \frac{g_5^2}{R \log \frac{R'}{R}} \qquad M_{KK} \approx \frac{\pi}{4R'}$$

Naive Dimensional Analysis:

$$\Lambda_{NDA} = \frac{24\pi^3}{g_5^2} \simeq \frac{6\ N_{CFT}\ M_{KK}}{\log \frac{R'}{R}}$$



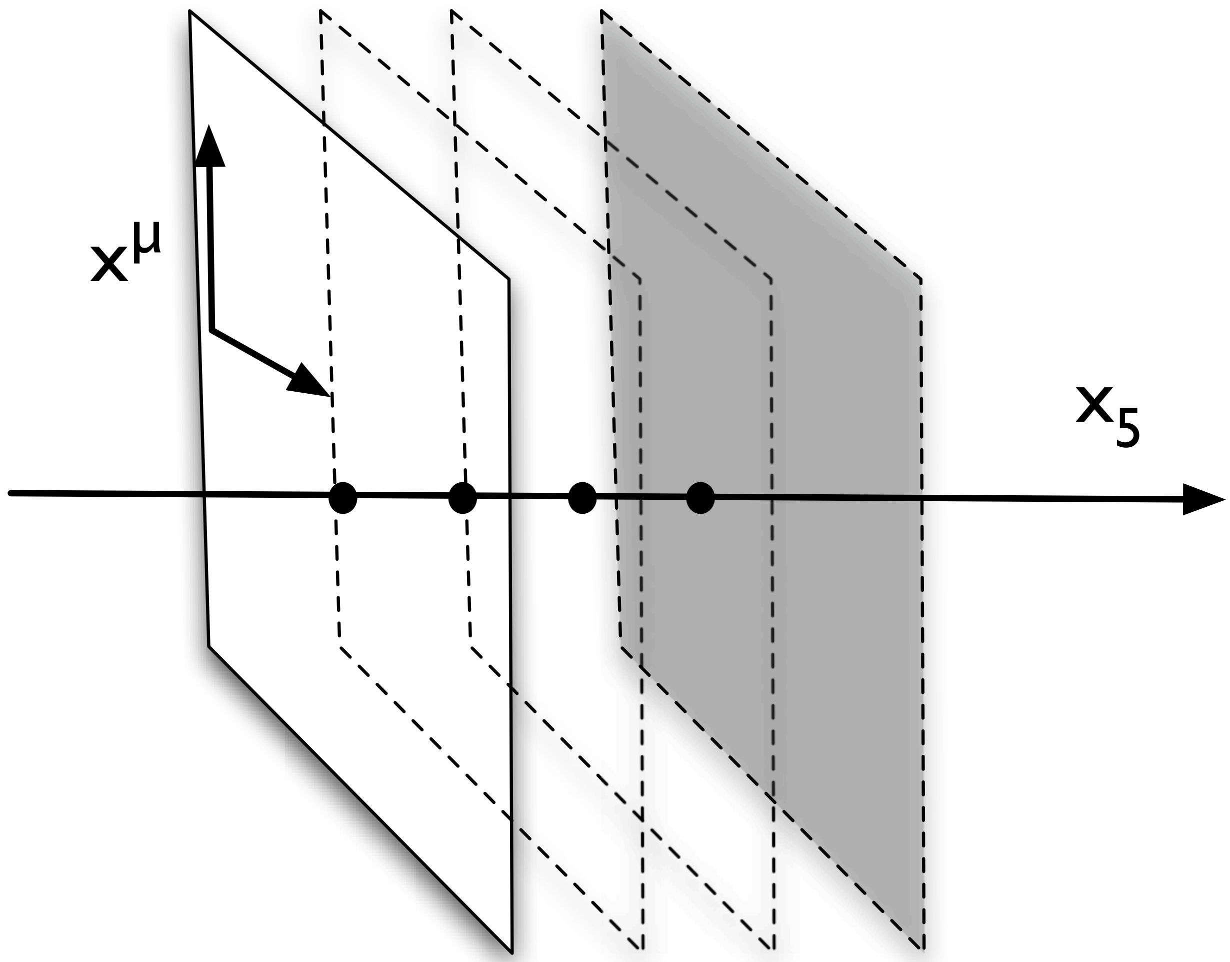
Can we construct the 4D EFT?

Deconstruction

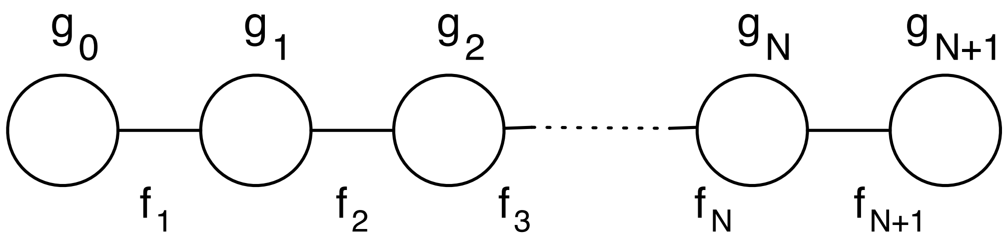
van Gogh

Wolff

Latticize Fifth Dimension



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
- Finite N, a 4D theory w/o 5D constraints

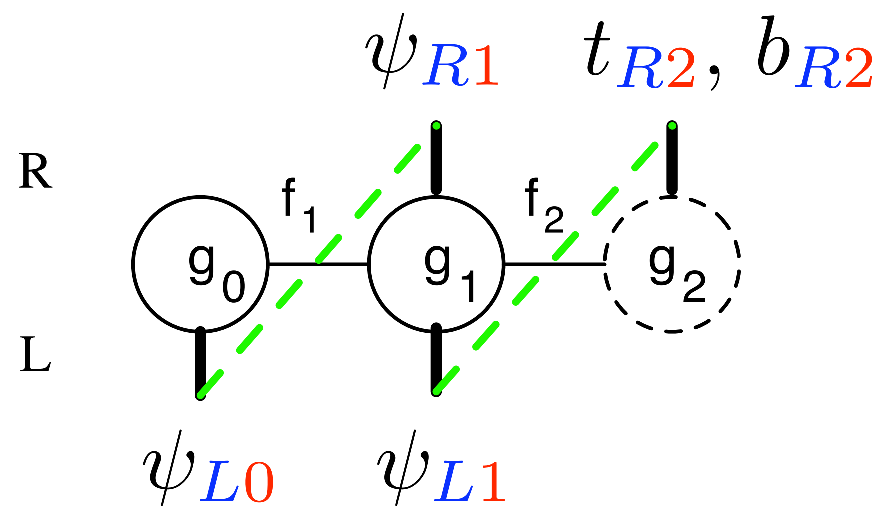
Arkani-Hamed, Georgi, Cohen & Hill, Pokorski, Wang

The 3-site Model:

general principles in action
in a <u>highly</u> deconstructed model

3-Site Model: basic structure

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



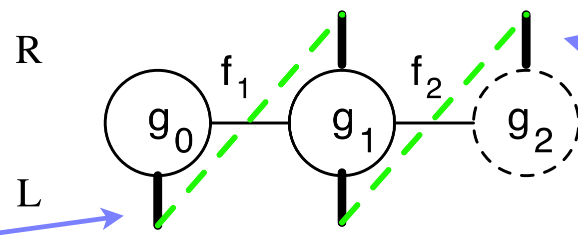
Gauge boson spectrum: photon, Z, Z', W, W' (BESS/HLS)

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

BESS - Casalbuoni, et. al. PLB155 (1985) 95, HLS - Bando, et. al. PRL54 (1985) 1215

3-Site Model: fermion details



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

Flavor Structure Identical to Standard Model

"Theory Space": Fermion dimension smaller than Gauge dimension in "continuum"	Foadi, et.al. hep-ph/0509071

3-Site Ideal Delocalization

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

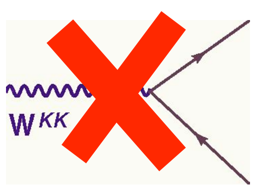
becomes $\frac{g_0(\psi_{L0}^f)^2}{g_1(\psi_{L1}^f)^2} = \frac{v_W^0}{v_W^1}$ in 3-site model

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:
Current Constraints

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: $\Delta g_1^Z = \Delta\kappa_Z = \dfrac{M_W^2}{2c^2M_{W'}^2}$ $\quad\Delta\kappa_\gamma = 0$

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

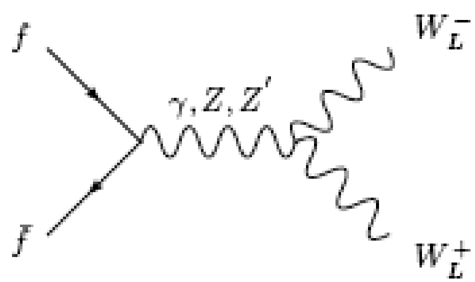
places lower bound on W' mass:

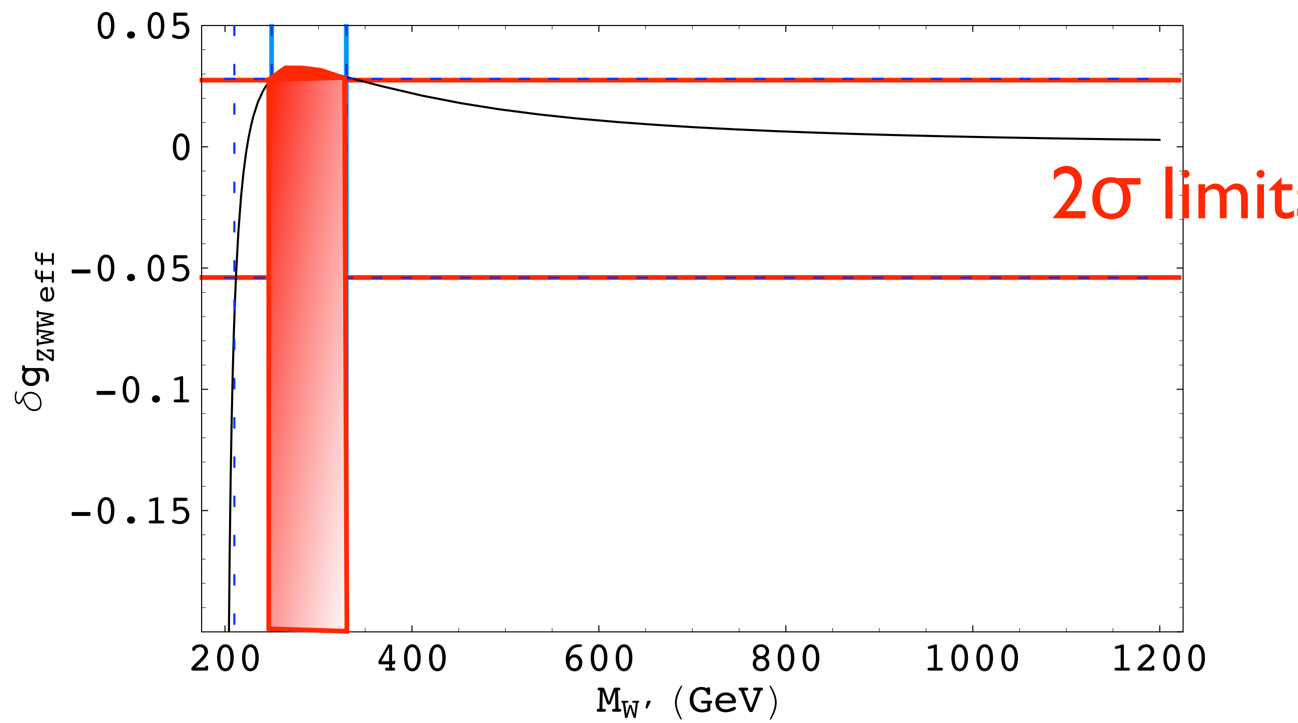
$$M_{W'} \geq 380\,\mathrm{GeV}\sqrt{\frac{0.028}{\Delta g_1^Z}}$$

Warning: See next slide

Bound on $M_{W'}$ is "soft"

Effective
Δg^Z_1
at LEPII





The W' could be very light:

<u>W' could be an early LHC discovery</u>

<u>and ILC target</u>

... 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

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

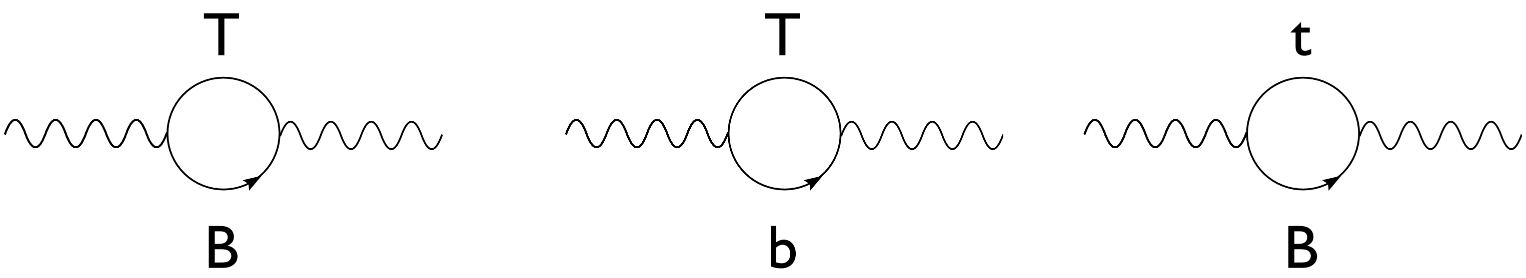
We conclude: $$0.095 \leq \epsilon_L \leq 0.30$$

$\Delta\rho$ 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

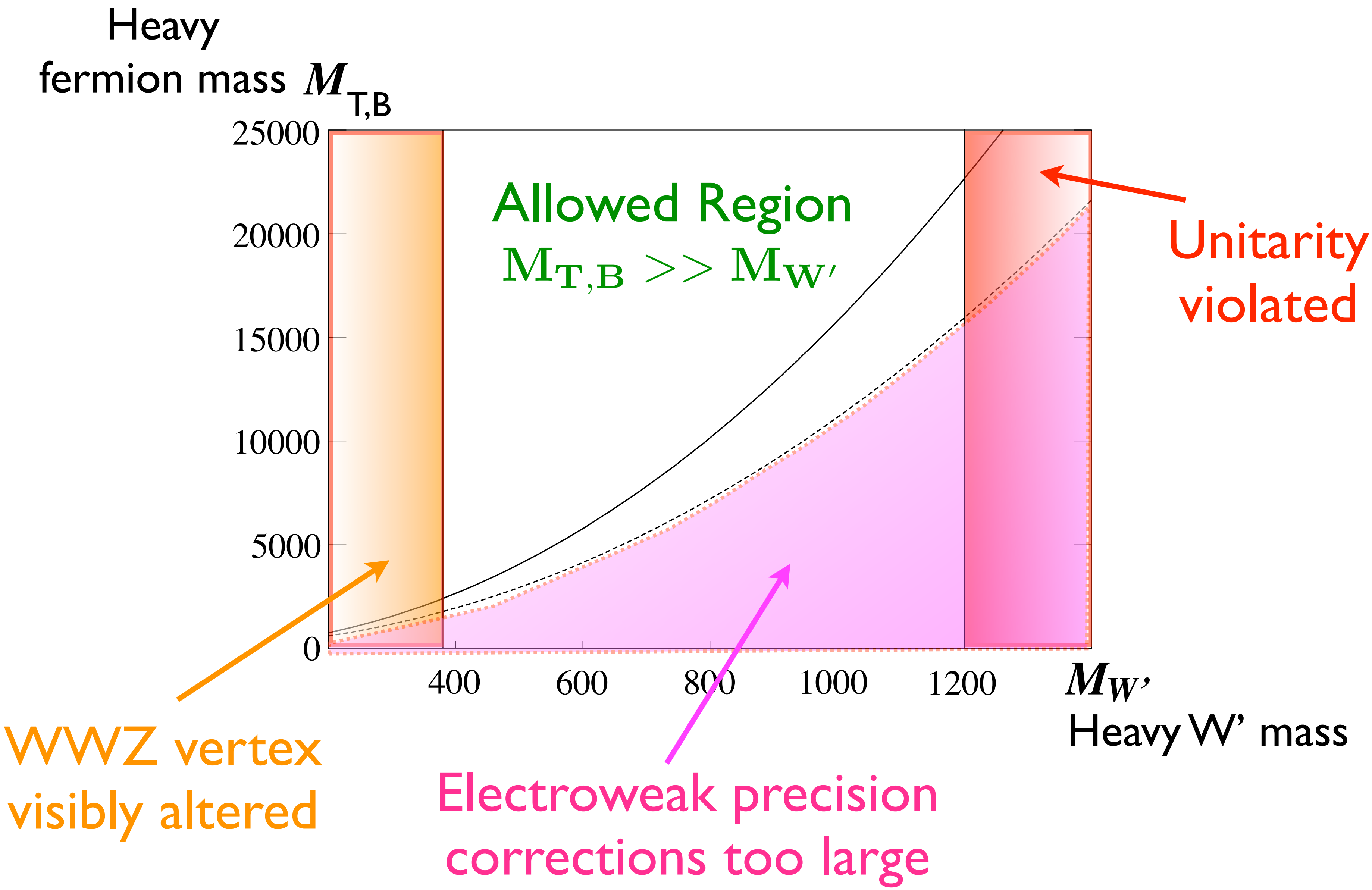
From the following W diagrams (and related Z diagrams)



leading contribution is:

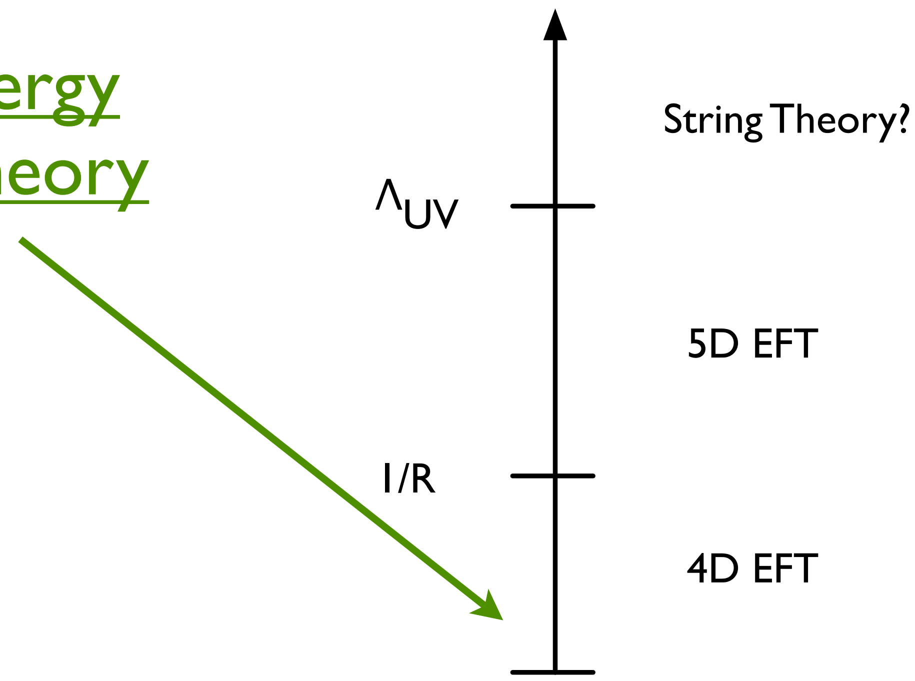
$$\Delta\rho \approx \frac{1}{16\pi^2}\frac{\varepsilon_{tR}^4 M^2}{v^2}$$

3-Site Parameter Space



The 3-site model:

- A consistent low-energy effective Higgsless theory
  - αS under control
  - Gauge-invariant & consistent power-counting scheme



3-site Model: Collider Phenomenology

- Resonances in WZ scattering (ρ_{TC} mesons)
- Potentially light fermiophobic W' and Z'
- Deviations in g_{ZWW}
- Deviations in "F_π"

In a consistent effective theory!

(Includes correlations with αS)

An implementation of

The Three Site Model in CalcHEP

Alexander Belyaev and Neil Christensen

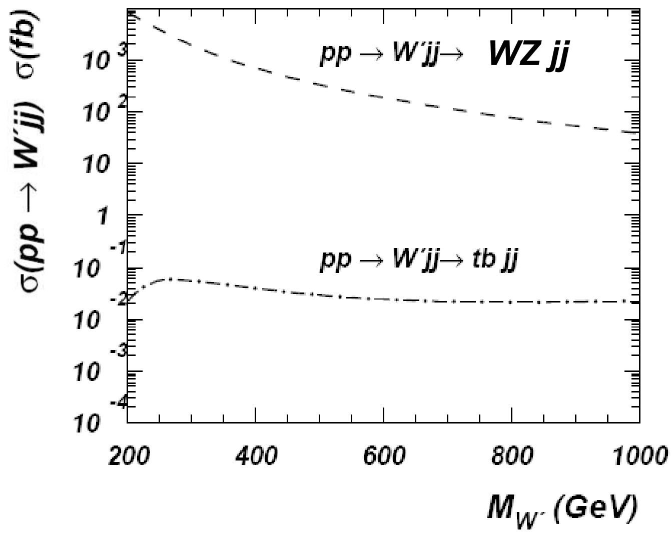
In collaboration with
S. Chivukula and E. Simmons (MSU)
H.-J. He, Y.-P. Kuang and B. Zhang (Tsinghua University)

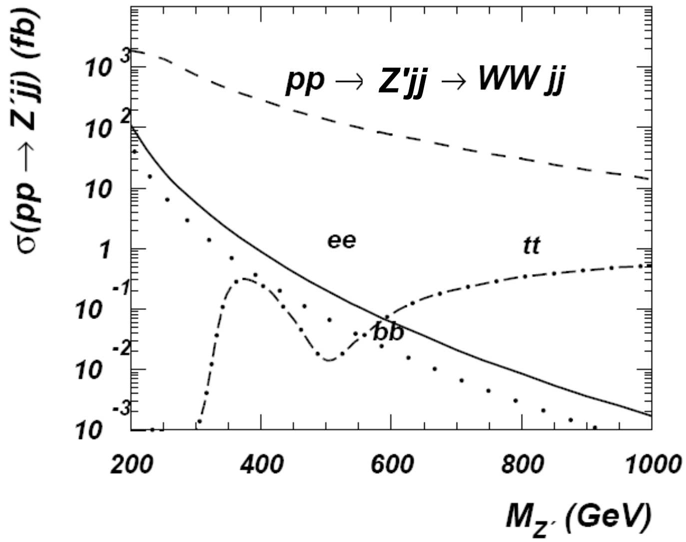
Department of Physics and Astronomy
Michigan State University

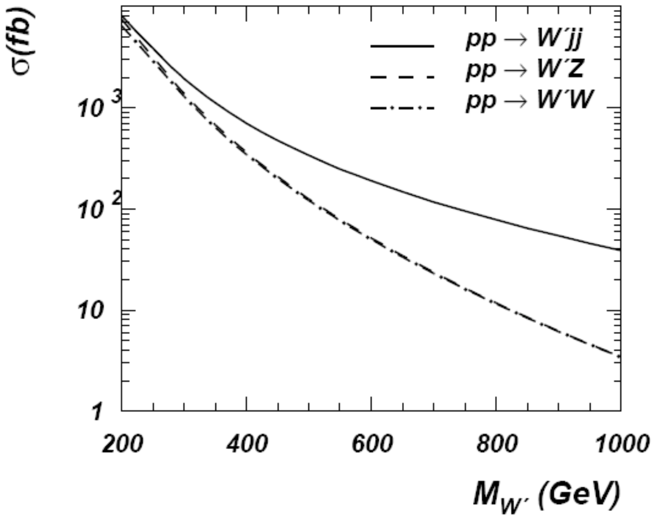
http://hep.pa.msu.edu/people/belyaev/public/3-site/

Preliminary

WW → Z' and WZ → W' Fusion



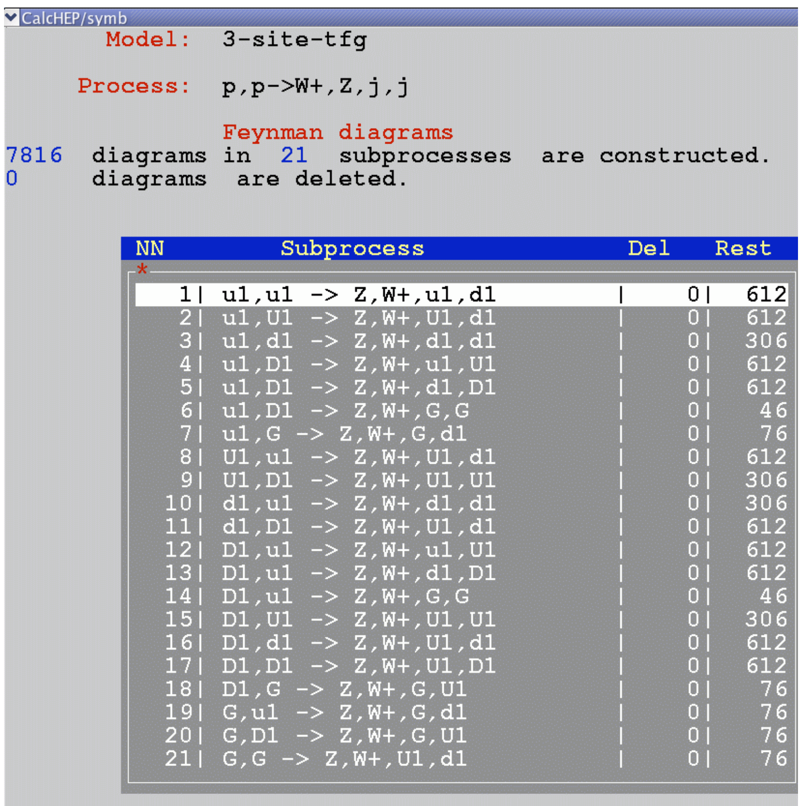




Preliminary

$$pp \to W^+ Zjj$$

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



CalcHEP/symb

Model: 3-site-tfg

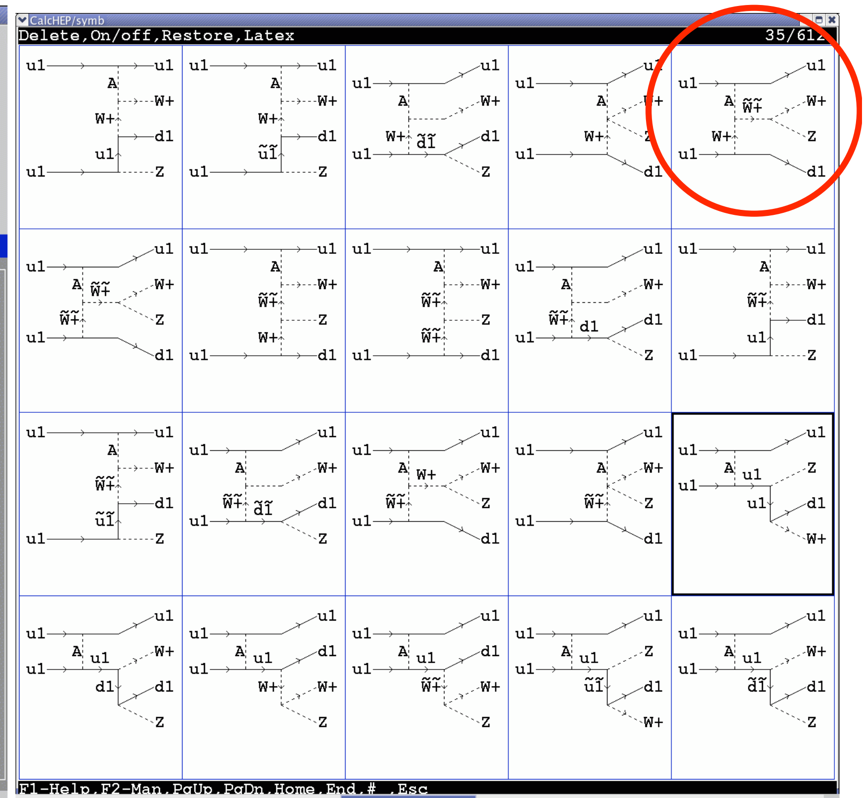
Process: p,p->W+,Z,j,j

Feynman diagrams

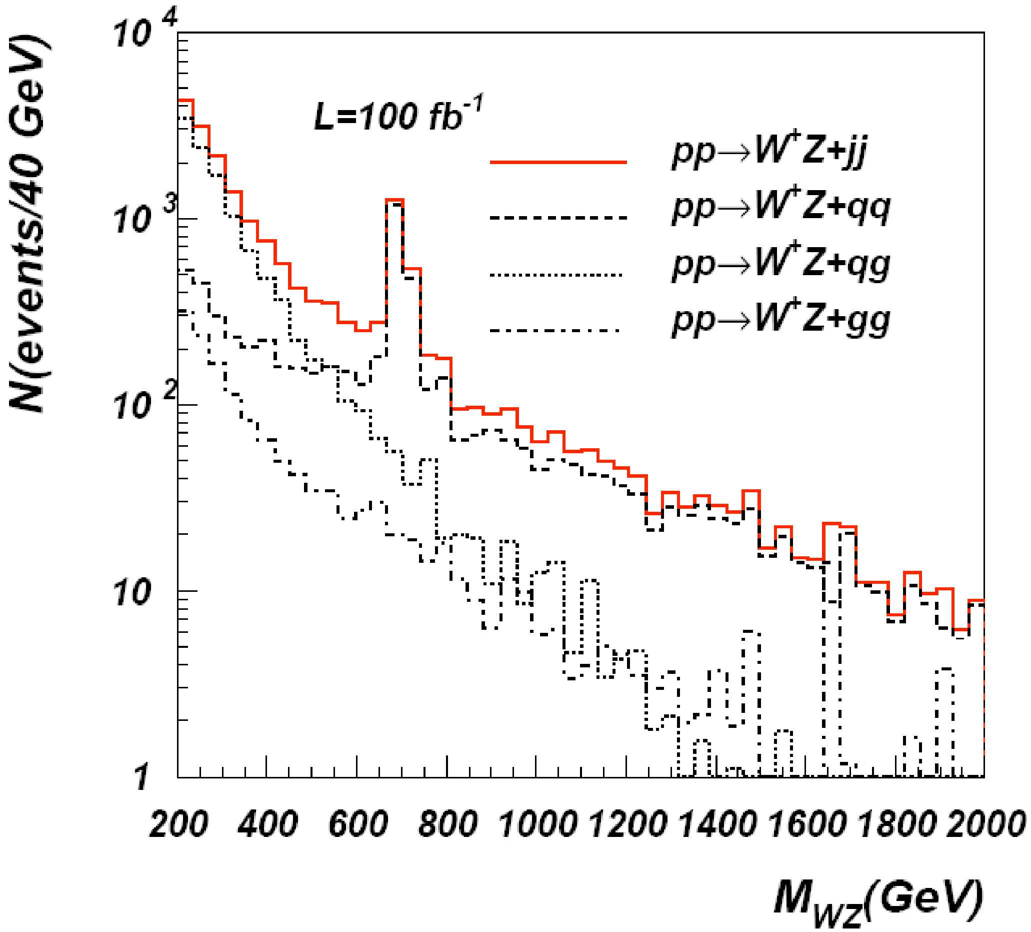
7816 diagrams in 21 subprocesses are constructed.

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



Preliminary $pp \to W^+Zjj$



$p_T^j > 30$ GeV

$2 < |\eta^j| < 4.5$

$E^j > 300$ GeV

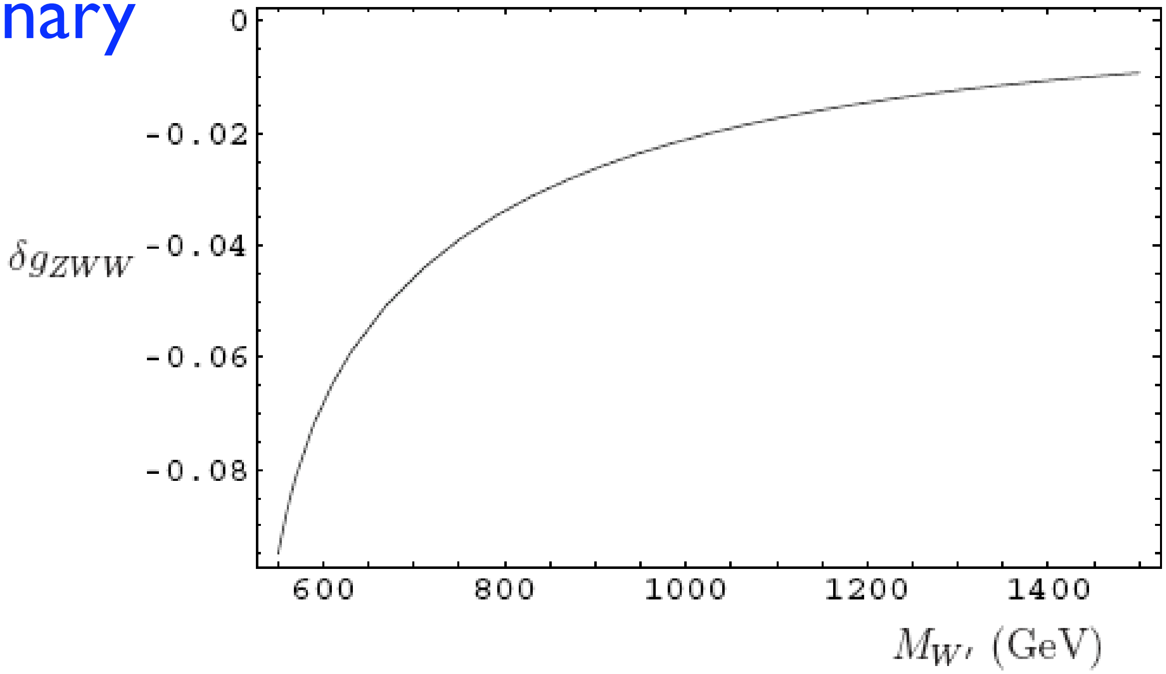
$E^{W,Z} > 200$ GeV

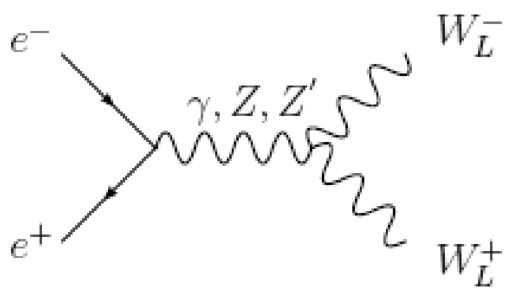
$\Delta Rjj > 0.5.$

To be compared with Birkedal, Matchev, Perelstein: PRL 94, 191803 (2005).

ILC: g_{ZWW} @ 500 GeV

Preliminary



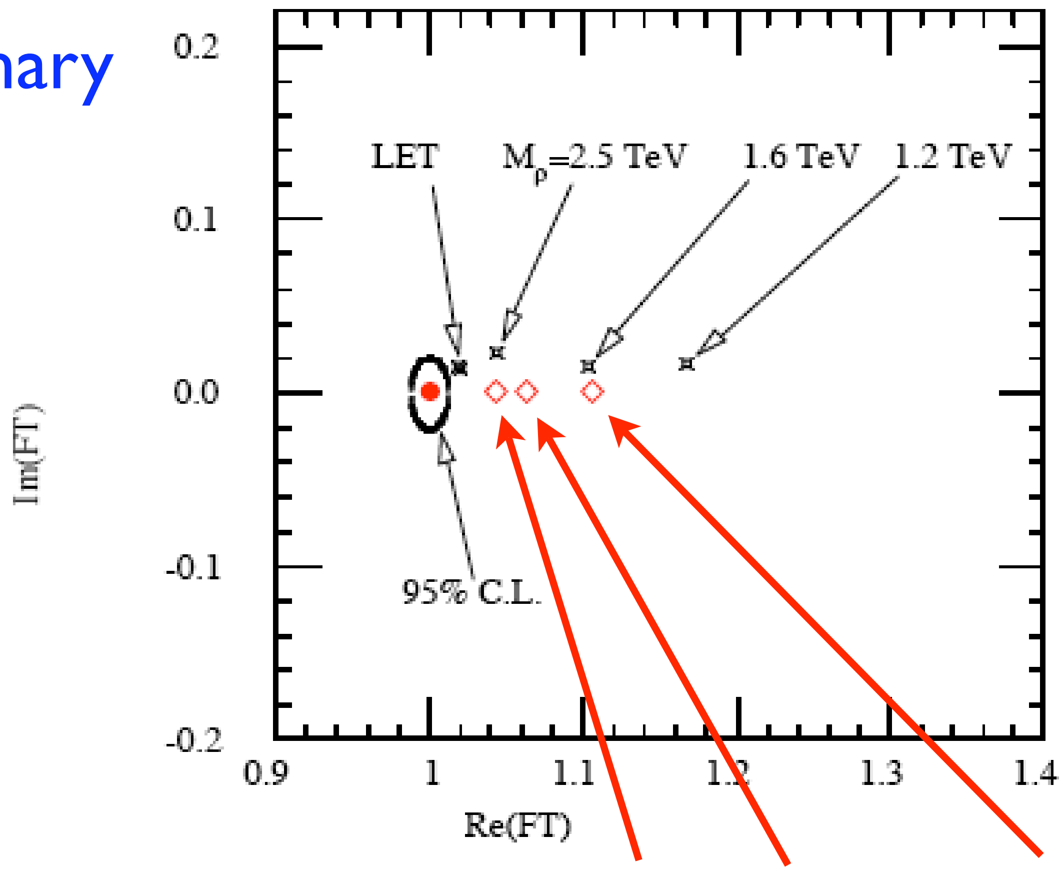


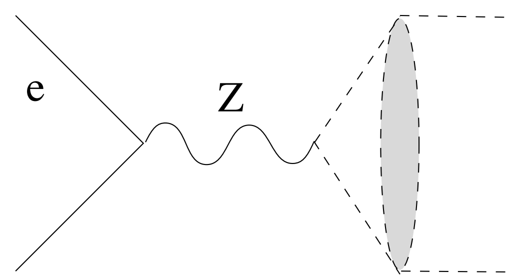
$$\delta g_{ZWW} = \frac{g_{LeZ}\, g_{ZWW}}{g_{LeZ}^{sm}\, g_{ZWW}^{sm}} + \frac{g_{LeZ'}\, g_{Z'WW}}{g_{LeZ}^{sm}\, g_{ZWW}^{sm}} \left(\frac{s - M_Z^2}{s - M_{Z'}^2} \right) - 1$$

ILC sensitivity ~4 x 10^{-4} with 500 fb^{-1}

OR: F_π at ILC

Preliminary



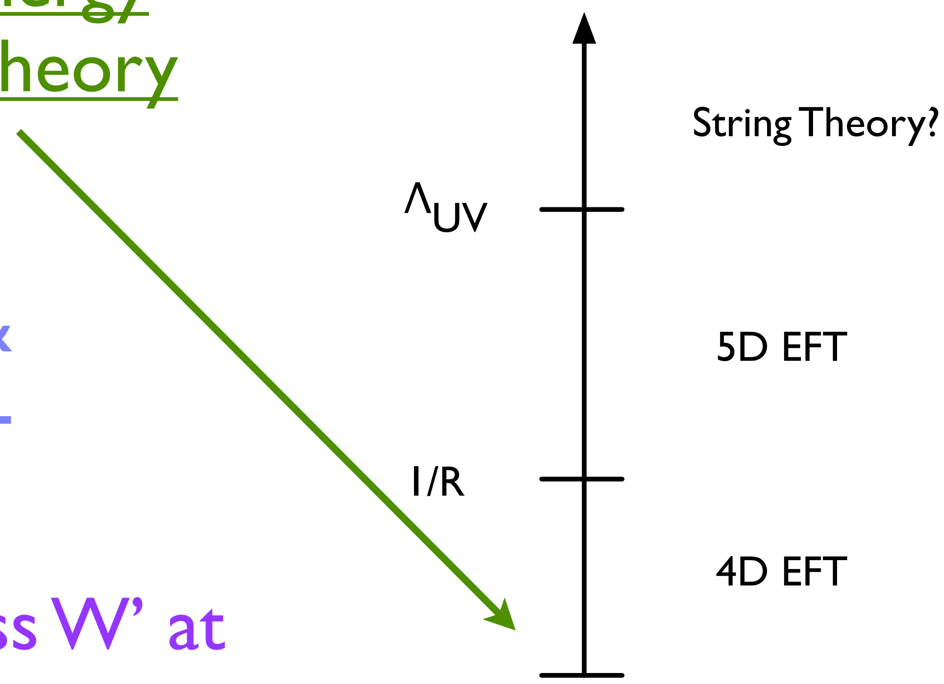


3-site model with $M_{W'}$= 1500, 1200, and 775 GeV

Comparison: TC estimate by T. Barklow in hep-ph/0106057

The 3-site model:

- A consistent low-energy effective Higgsless theory
  - αS under control
  - Gauge-invariant & consistent power-counting scheme
  - Potential low-mass W' at LHC and ILC



References

- Chivukula, He, Kurachi, Simmons, Tanabashi:
  0406077, 0408262, 0410154, 0502162, 0504114, 0508147, & 0509110
- Matsuzaki, Chivukula, Simmons, Tanabashi:
  0607191, 0702218
- Csaki, Grojean, Murayama, Pilo, Terning
  0305237, 0308038, 0401160, 0409126, 0505001
- Foadi, Gopalkrishna, Schmidt
  0312324, 0409266, & 0509071
- Georgi 0408067 & 0508014
- Non-commuting ETC, Ununified SM, "Top-Flavor"

Numbers are hep-ph/