Z1 production via Vector Boson Fusion at the LHC in the four-site Higgsless Model

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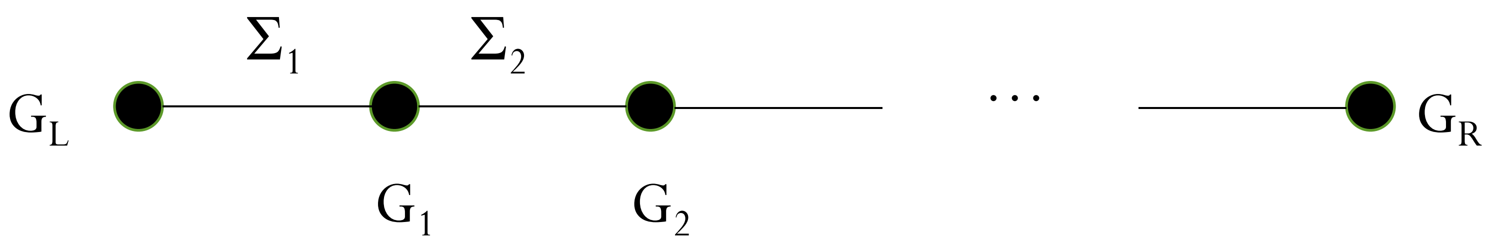
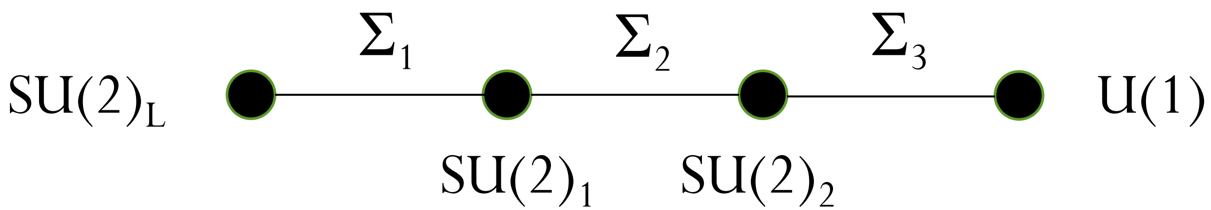
Deconstructed Higgsless Models

- In Higgsless Models, Electroweak Symmetry Breaking occurs through boundary conditions on 5 dimensional gauge fields.
- Lead to extra copies of gauge fields
- Theories with discrete 5^{th} dimension called Deconstructed, can cut off KK towers in gauge invariant way
- Effective theories, so can include possible scalars in UV completion
- Use Moose Diagrams



Four-Site Model



- G_i is group with transformation U_i
- Non-linear sigma fields (Σ_i) come from 5th dimension gauge field component
- Σ_i fields transform according to $\Sigma_i \rightarrow U_{i-1}\Sigma_i U_i^\dagger$
- Unitary gauge ($\Sigma_i \rightarrow 1$) leads to copies of W, Z bosons
- Two new sets of bosons, $W^{\pm}_{1,2}$ and $Z_{1,2}$ in the 350 GeV to few TeV range
- Unitarity violation delayed to about 5 TeV

Four-Site Gauge Lagrangian

$$\mathcal{L}_{gauge} = -\frac{1}{2} Tr\left[F_{\mu\upsilon}(\widetilde{W}_{\mu})^2\right] - \frac{1}{2} Tr\left[F_{\mu\upsilon}(\tilde{Y}_{\mu})^2\right]$$

$$-\frac{1}{2}\sum_{i=1}^{2} Tr\left[F^{i}_{\mu\upsilon} F^{i\,\mu\upsilon}\right] + \sum_{i=1}^{3} f_i^{\,2} Tr\left[\left(D_\mu \Sigma_i^\dagger\right)\left(D^\mu \Sigma_i\right)\right]$$

- Similar to SM but with extra terms for inner groups and sigma fields
- Here f_1, f_2, f_3 are link coupling constants [Energy]. They parameterize distances in the extra dimension (we set $f_1 = f_3$).
- No Higgs!

Four-Site Fermion Lagrangian

$$\mathcal{L}_{fermions} = \bar{\psi}_L i\gamma^\mu \partial_\mu \psi_L + \bar{\psi}_R i\gamma^\mu \partial_\mu \psi_R$$

$$-\frac{1}{1+b_1+b_2}\bar{\psi}_L i\gamma^\mu \tilde{g}\tilde{W}_\mu \psi_L$$

$$-\sum_{i=1}^{2}\frac{b_i}{1+b_1+b_2}\bar{\psi}_L i\gamma^\mu g_1 \tilde{A}_\mu^i \psi_L$$

$$-\bar{\psi}_R\gamma^\mu\left(\tilde{g}'\tilde{Y}_\mu + \frac{1}{2}\tilde{g}'(B-L)\tilde{\mathbf{Y}}_\mu\right)\psi_R - \bar{\psi}_L\gamma^\mu\frac{1}{2}\tilde{g}'(B-L)\tilde{\mathbf{Y}}_\mu\psi_L$$

- Inner gauge couplings set equal
- The b_i parametrize couplings to new gauge fields/movement in new dimensions: $0 \le b_i < 1$.
- Here: $\tilde{Y}_\mu = \tilde{\mathbf{Y}}_\mu \tau^3/2$

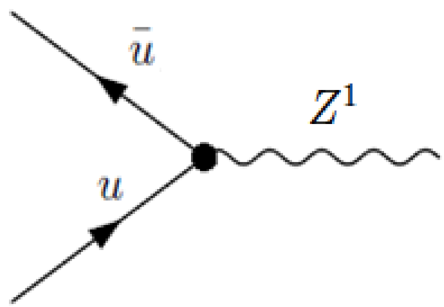
Model Parameters

- Starting parameters are f_1, f_2, $\tilde{g}$, $\tilde{g}'$, g_1 and b_1,b_2
- SM parameters (e, G_f, etc.) depend on the new parameters
- Set SM parameters to their measured values partially constrains new parameters
- Left with two new boson mass scales ($M_1 / M_2 = z$) and fermion couplings

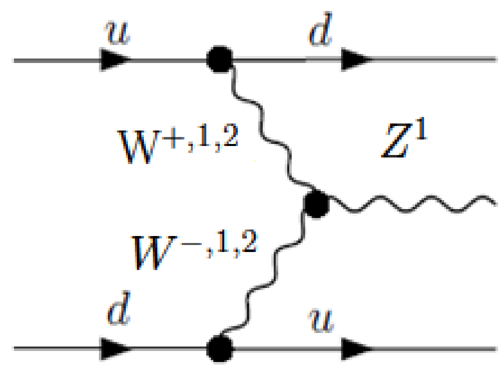
Z_1 Production

- The new gauge bosons are produced through quark and SM gauge boson couplings

Drell-Yan



Gauge Boson Fusion



- Drell-Yan production has been calculated (Accomando, De Curtis, Dominici, and Fedeli), and is assumed to be the dominant mode.
- Vector Boson Fusion suppressed from propagators, couplings and phase space

Couplings

$$z = \frac{f_1}{(f_1^2 + 2f_2^2)} = \frac{M_1}{M_2}$$

$$x = \frac{M_W}{M_1}\sqrt{\frac{2}{1 - z^2}}$$

$$b_{\pm} = b_1 \pm b_2$$

$$b = \frac{b_+ - b_- z^2}{(1 + b_+)}$$

$$a_0 = -\frac{\tilde{g}}{\sqrt{2}}\left(1 - \frac{b}{2}\right)\left(1 - \frac{\tilde{g}^2}{{g_1}^2}\frac{(1 + z^4)}{4}\right)$$

$$a_1^c = \frac{g_1}{2(1 + b)}\left(b_+ - \frac{\tilde{g}^2}{{g_1}^2}\right)$$

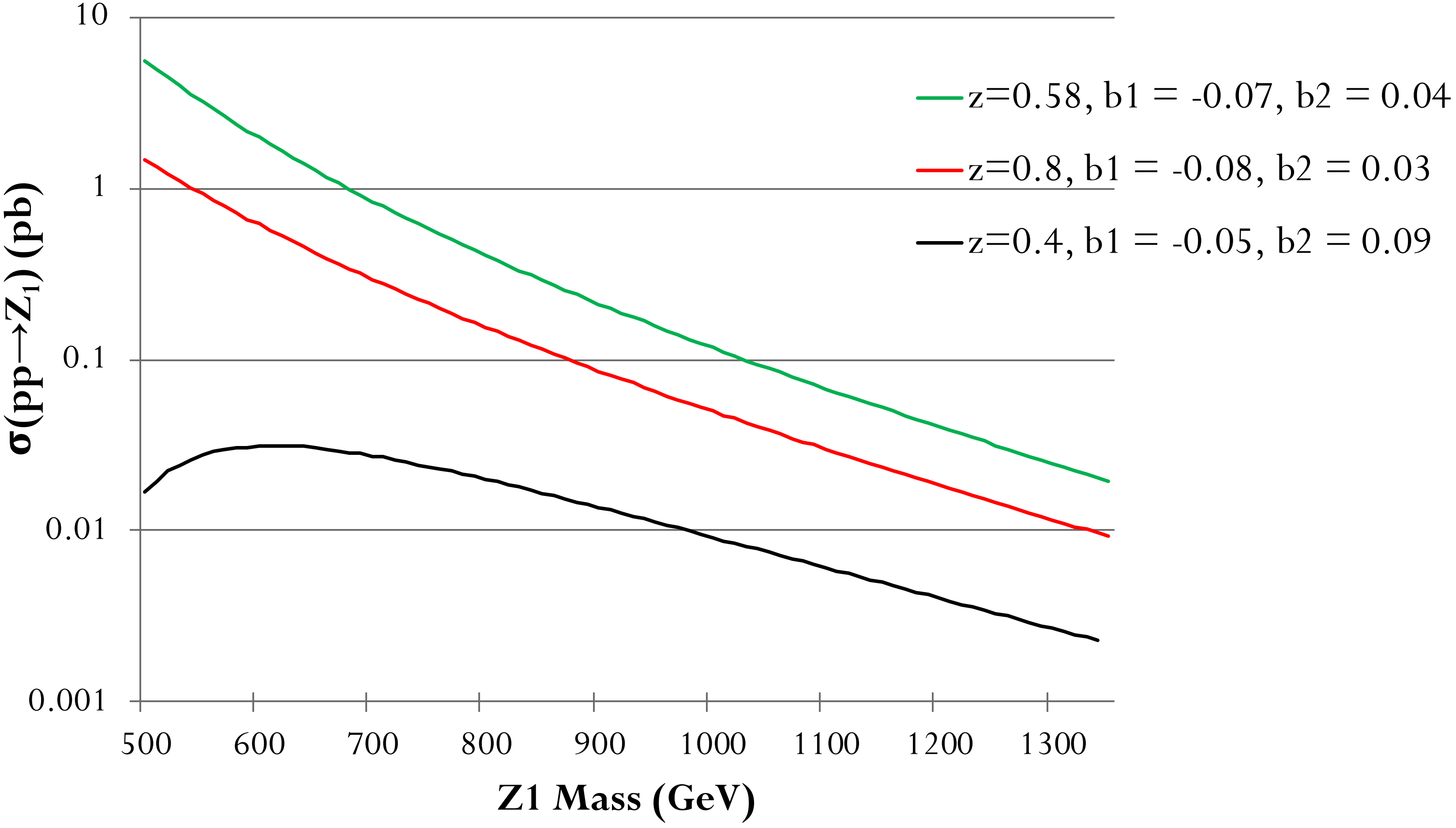
$$a_2^c = \frac{g_1}{2(1 + b)}\left(b_- - \frac{\tilde{g}^2}{{g_1}^2}z^2\right)$$

The couplings of Z_1 bosons to the fermions are:

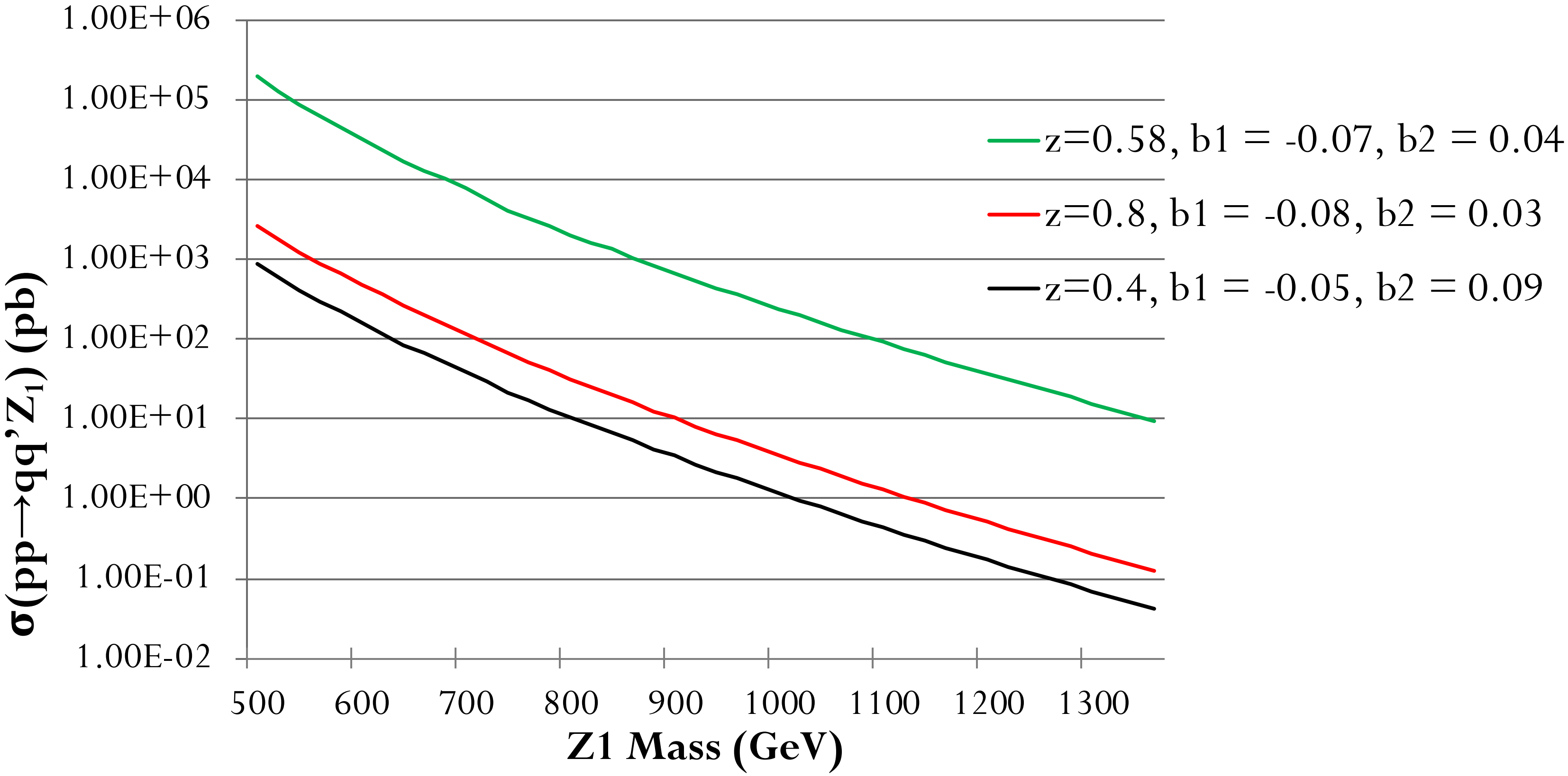
$$a_{1L}^f = -\frac{\tilde{g}x}{\sqrt{2}(1+b_+)}\left(\frac{b_+}{x^2} - \frac{cos2\theta}{cos^2\theta}\right)\frac{\tau_3^f}{2} + \frac{\tilde{g}x\, tan^2\theta}{\sqrt{2}}Q^f$$

$a_{1R}^f = \frac{\tilde{g}x\, tan^2\theta}{\sqrt{2}}Q^f$; where τ_3^f and Q^f are the isospin and charge of that particular fermion, and θ is the mixing angle ($\tan\theta = \frac{\tilde{g}'}{\tilde{g}}$). Notice the τ_3^f and Q^f structure, similar to the SM.

Drell Yan Z_1 production at 7 TeV LHC



Vector Boson Fusion (7 TeV LHC)



- Preliminary
- Higher cross section than DY

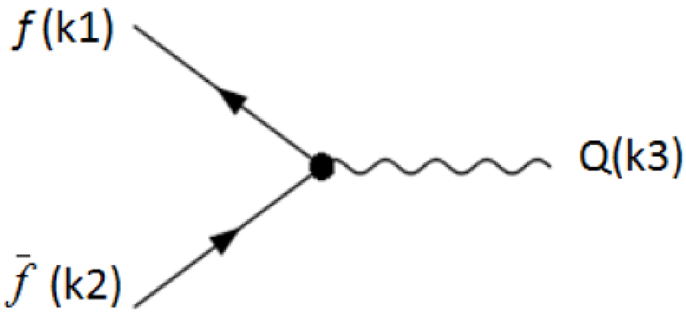
Conclusions

- Higgsless Models break EWS without a physical Higgs
- Gauge Boson Fusion ends up being competitive with Drell-Yan
- Dominant decays of Z_1 are to W bosons when available
- Signals could be seen or ruled out at the LHC soon

Extra Slides

Feynman Rules

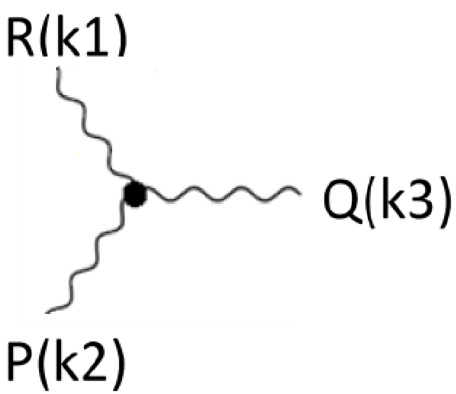
- Coupling to fermions



$$= i\, a_i^c\, \gamma^\mu \frac{(1-\gamma^5)}{2} \;;\ \text{charged}$$

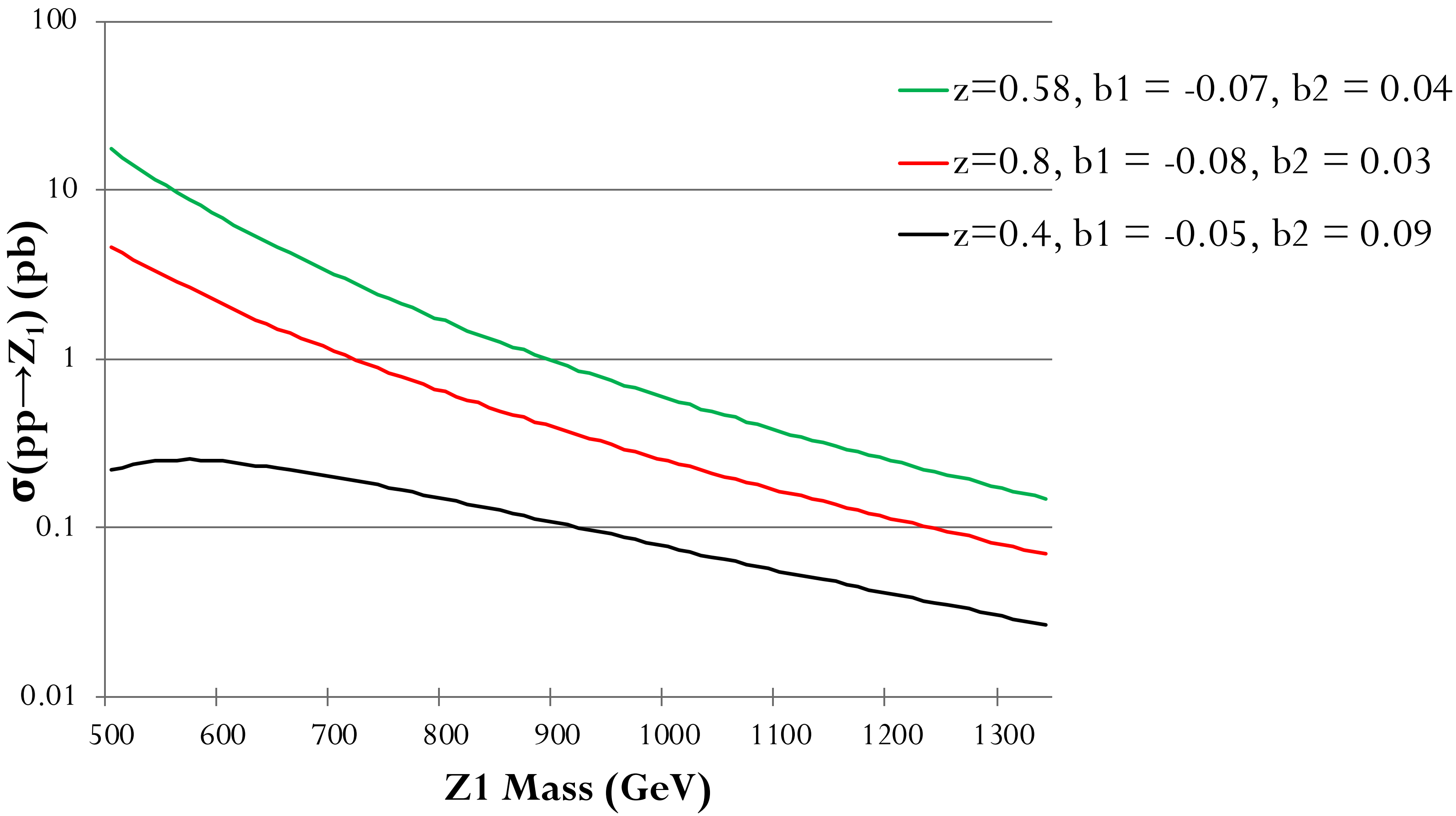
$$= i\, a_{Li}^n\, \gamma^\mu \frac{(1-\gamma^5)}{2} + i\, a_{Ri}^n\, \gamma^\mu \frac{(1+\gamma^5)}{2} \;;\ \text{neutral}$$

- Tri-gauge boson coupling



$$= i a_{RPQ}\left(g^{\mu\upsilon}(k_3 - k_1)^\lambda + g^{\mu\lambda}(k_1 - k_2)^\nu + g^{\lambda\upsilon}(k_2 - k_3)^\mu\right)$$

Drell-Yan Z_1 production (14TeV LHC)



Decays

- Because of the weak boson copy structure, signatures can be similar to SM, but Z_1/Z_2 decay preferentially to bosons.
- Widths can be from a few GeV to hundreds
- Z_2 to WW and W_1W_1 highly suppressed

1	$\Gamma_{Z_1}^{WW} = \frac{1}{3\pi}(\frac{\tilde{g}}{16})^2 \, (1-z^4)(1+z^2)\frac{M_{Z_1}^3}{M_W^2}$
2	$\Gamma_{Z_2}^{W_1W} = \frac{1}{3\pi}(\frac{\tilde{g}}{16})^2 \, z^4(1-z^2)^3(1+10z^2+z^4)\frac{M_{Z_2}^3}{M_W^2}$
3	$\Gamma_{Z_1}^{f\bar{f}} = \frac{N_c}{96\pi} \, (a_{1L}^2 + a_{1R}^2)M_{Z_1}$

(Widths to W's from Accomando, De Curtis, Dominici and Fedeli - **Phys. Rev. D 83, 015012 (2011)**)

Gauge Boson Trilinear Couplings (1)

$$a_{WW\gamma} = a_{W_1W_1\gamma} = a_{W_2W_2\gamma} = e$$

$$a_{WWZ} = \tilde{g} c_{\tilde{\theta}} \left[1 - \frac{x^2}{2c_{\tilde{\theta}}^2} \left(1 - 2s_{\tilde{\theta}}^4\right) \right]$$

$$a_{WWZ_1} = -\frac{\tilde{g} x (1 - z^4)}{2\sqrt{2}}$$

$$a_{WW_1Z} = -\frac{\tilde{g} x (1 - z^4)}{2\sqrt{2} c_{\tilde{\theta}}}$$

$$a_{WW_1Z_1} = -\frac{\tilde{g}}{2} \left[1 - \frac{x^2}{4c_{\tilde{\theta}}^2} \left(1 - (4 - z^2) + \frac{z^2}{1 - z^2} + \frac{z^2 (1 + 2z^2) c_{2\tilde{\theta}}}{1 - z^2} \right) \right]$$

$$a_{WW_1Z_2} = \frac{\tilde{g} z^2}{2} \left[1 + \frac{x^2 z^2}{4c_{\tilde{\theta}}^2} \left(2c_{2\tilde{\theta}} - (4 - s_{\tilde{\theta}}^2) z^2 - \frac{2z^2 s_{\tilde{\theta}}^2}{1 - z^2} \right) \right]$$

$$a_{WW_2Z_1} = -\frac{z^2 \tilde{g}}{2} \left[1 + \frac{x^2}{4c_{\tilde{\theta}}^2} \left(2z^2 - 4z^4 c_{\tilde{\theta}}^2 + \left(1 - \frac{2z^4}{1 - z^2} s_{\tilde{\theta}}^2 \right) \right) \right]$$

$$a_{WW_2Z_2} = -\frac{\tilde{g}}{2} \left[1 + \frac{x^2}{4c_{\tilde{\theta}}^2} \left(\frac{1 + 3z^2 (z^2 - 1 + z^4) - s_{\tilde{\theta}}^2 (1 - 3z^2 + 4z^4 + 4z^6)}{1 - z^2} \right) \right]$$

Accomando, De Curtis, Dominici, Fedeli, hep-ph/1010.0171v1

Gauge Boson Trilinear Couplings (2)

$$a_{W_1W_1Z} = -\frac{\tilde{g}c_{2\tilde{\theta}}}{2c_{\tilde{\theta}}}\left[1+\frac{x^2}{4c_{\tilde{\theta}}^2c_{2\tilde{\theta}}}\left(\frac{3-5z^2-3z^4+z^6}{1-z^2}+\right.\right.$$
$$\left.\left.+s_{\tilde{\theta}}^2\left(2z^4+\frac{4z^2}{1-z^2}-5-2c_{2\tilde{\theta}}-c_{4\tilde{\theta}}\right)\right)\right]$$

$$a_{W_1W_1Z_1} = -\frac{\tilde{g}}{x\sqrt{2}}\left[1-\frac{x^2}{4c_{\tilde{\theta}}}\left(2c_{\tilde{\theta}}^2+1\right)\right]$$

$$a_{W_1W_1Z_2} = -\frac{\tilde{g}xz^2(2-z^2+z^2t_{\tilde{\theta}}^2)}{2\sqrt{2}(1-z^2)}$$

$$a_{W_1W_2Z_2} = \frac{\tilde{g}}{\sqrt{2}x}\left[1-\frac{x^2}{4c_{\tilde{\theta}}^2}\left(z^4+(1+z^4)c_{\tilde{\theta}}^2\right)\right]$$

$$a_{W_1W_2Z_1} = \frac{\tilde{g}xz^2\left(z^2-3+\frac{1}{c_{\tilde{\theta}}^2}\right)}{2\sqrt{2}(1-z^2)}$$

Accomando, De Curtis, Dominici, Fedeli, hep-ph/1010.0171v1

Gauge Boson Trilinear Couplings (3)

$$a_{W_1W_2Z} = \frac{z^2\tilde{g}}{2c_{\tilde{\theta}}}\left[1 + \frac{x^2}{4c_{\tilde{\theta}}^2}\left(2z^2(1-2z^2) + s_{\tilde{\theta}}^2(1+z^4+2c_{2\tilde{\theta}})\right)\right]$$

$$a_{W_2W_2Z} = \frac{\tilde{g}c_{2\tilde{\theta}}}{2c_{\tilde{\theta}}^2}\left[1 + \frac{x^2}{4g_1^2c_{\tilde{\theta}}^2c_{2\tilde{\theta}}}\left(4z^2 - 3 - \frac{4z^6c_{\tilde{\theta}}^2}{1-z^2} + (1-z^2)^2s_{\tilde{\theta}}^2 - (2c_{2\tilde{\theta}} + c_{4\tilde{\theta}})s_{\tilde{\theta}}^2\right)\right]$$

$$a_{W_2W_2Z_1} = \frac{\tilde{g}}{\sqrt{2}x}\left[1 - \frac{x^2}{4c_{\tilde{\theta}}^2}\left(1 + 2z^4c_{\tilde{\theta}}^2\right)\right]$$

$$a_{W_2W_2Z_2} = \frac{\tilde{g}xz^4(1+2c_{2\tilde{\theta}})}{2\sqrt{2}(1-z^2)c_{\tilde{\theta}}^2}$$

Accomando, De Curtis, Dominici, Fedeli, hep-ph/1010.0171v1

Covariant Derivatives

$$D_\mu \Sigma_1 = \partial_\mu \Sigma_1 - i\tilde{g}\Sigma_1 \widetilde{W}_\mu + i g_1 \Sigma_1 \tilde{A}^1_\mu,$$

$$D_\mu \Sigma_2 = \partial_\mu \Sigma_2 - i g_1 \Sigma_2 \tilde{A}^1_\mu + i g_1 \Sigma_2 \tilde{A}^2_\mu$$

$$D_\mu \Sigma_3 = \partial_\mu \Sigma_3 - i g_1 \Sigma_3 \tilde{A}^2_\mu + i\tilde{g}' \Sigma_3 \tilde{Y}_\mu$$