$X^{\pm}$-Gauge Boson Production in Simplest Higgs

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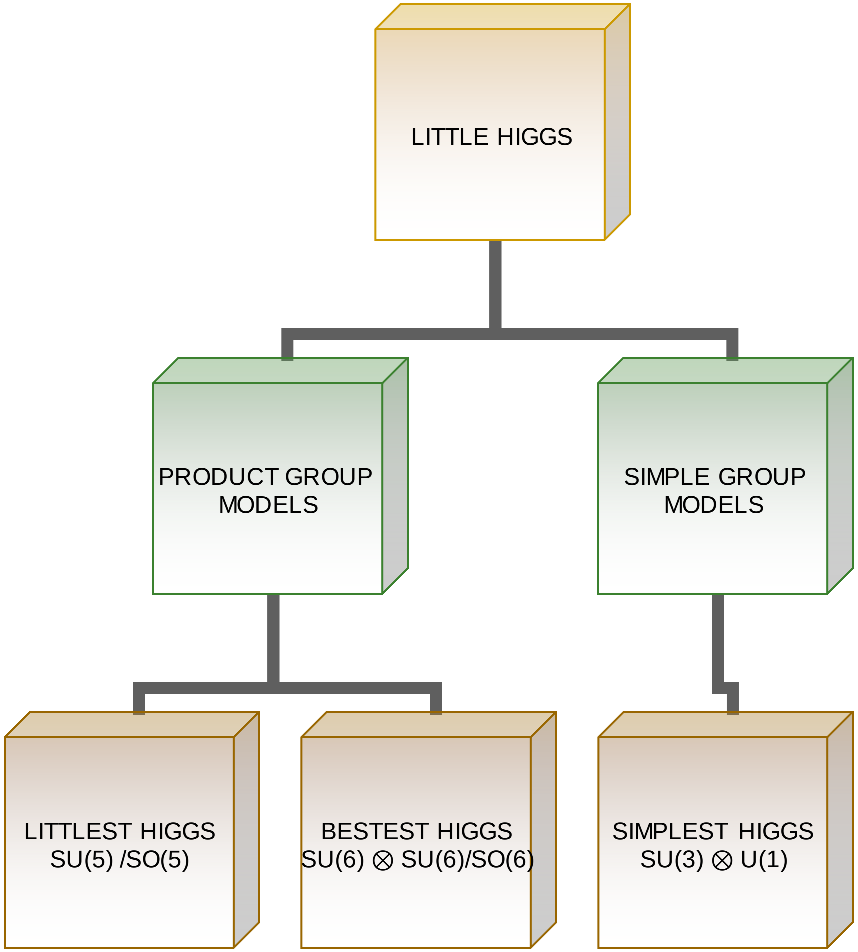
- Simplest Higgs Overview
- $X^{\pm}$ Production
- Results and Conclusions

Little Higgs Models

$$SU(3)_C \otimes ? \otimes U(1)_Y$$

- Little Higgs extensions of SM are characterized by expanded weak sectors and breaking scale f
  - Product groups provide several groups within a larger group
  - Simple groups break a larger group down to SM electroweak sector
    - Simplest Higgs is the minimal expansion of the simple groups



Simplest Higgs

(David Kaplan, Martin Schmaltz)

- Group Structure: $SU(3)_C x SU(3)_W x U(1)_Y$
  - $SU(3)_W \rightarrow SU(2)_W$ at scale **f**
- Differences from the Standard Model
  - Isospin doublets become triplets of SU(3) weak generators
  - New electroweak gauge bosons Y^o, Z', $X^{\pm}$ generated by broken SU(3) generators
  - Other new particles (η, n, T, U, C; T, D, S)
  - $X^{\pm}$,Z',T loops cancel corresponding $W^{\pm}$,Z,t loop corrections to the Higgs mass
  - Higgs quartic self-coupling mass corrections are not large below $SU(3)_W$ breaking scale f

Embeddings/Group Representations

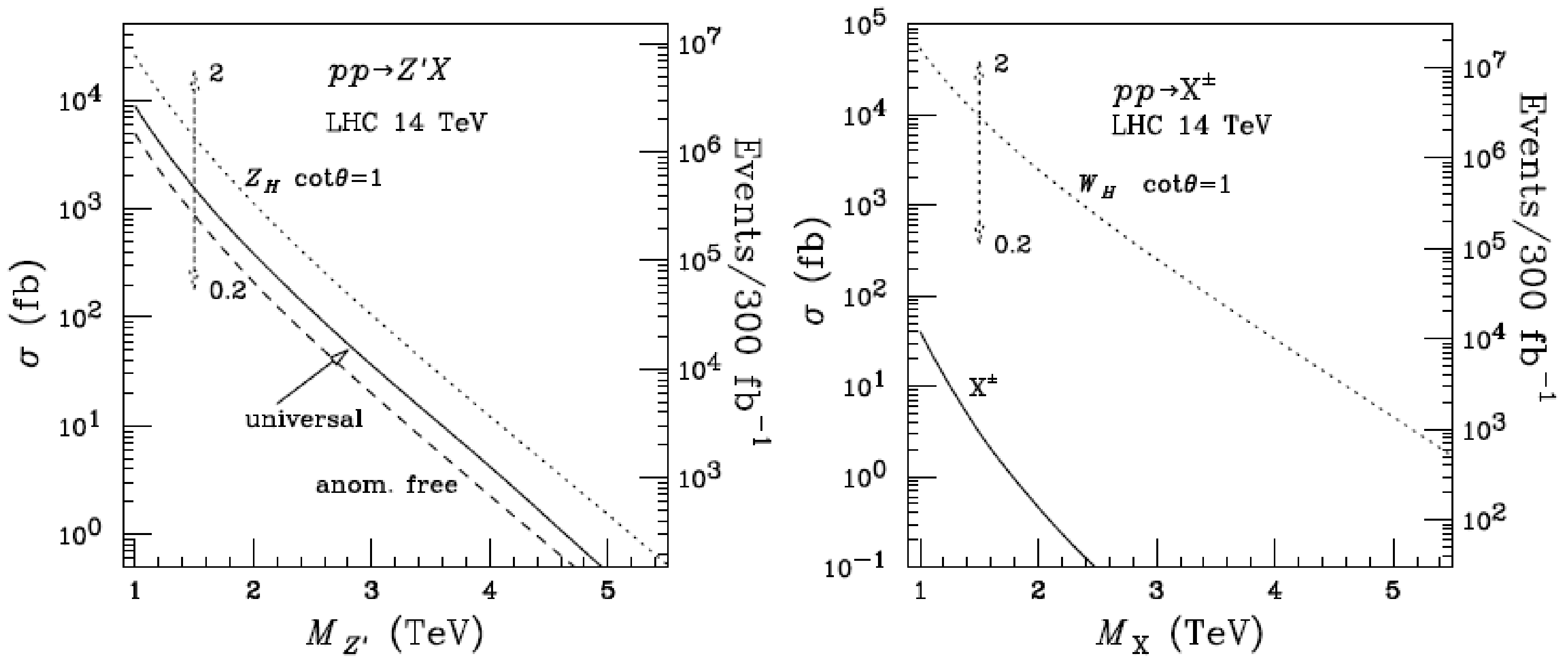
- Universal Embedding
  - Like SM fundamental representation, but expanded to SU(3) version in weak sector
  - Contains gauge anomalies which are assumed to be cancelled in UV completion of model above scale f
- Anomaly Free Embedding
  - Conjugate quark representation in first two generations
  - Free of gauge anomalies
- The embedding has little effect on $X^{\pm}$ production as relevant couplings remain independent of embedding

What Signatures to look for in Simplest Higgs

- New heavy quarks
- New scalar/neutrino interactions
- Gauge bosons
  - Z'
  - $X^{\pm}$
  - Y^{0}

Drell-Yan Production of X± vs. Z'

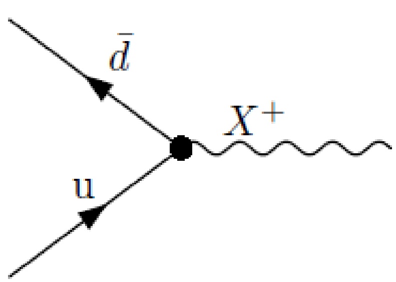
- Drell-Yan production of X± is roughly two orders of magnitude lower than Z' cross-section

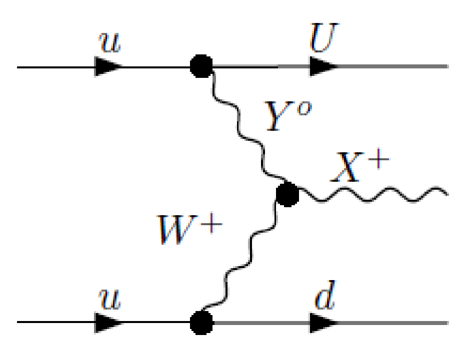


(See Tao Han, Heather E. Logan and Lian-Tao Wang JHEP0601:099,2006)

Production modes

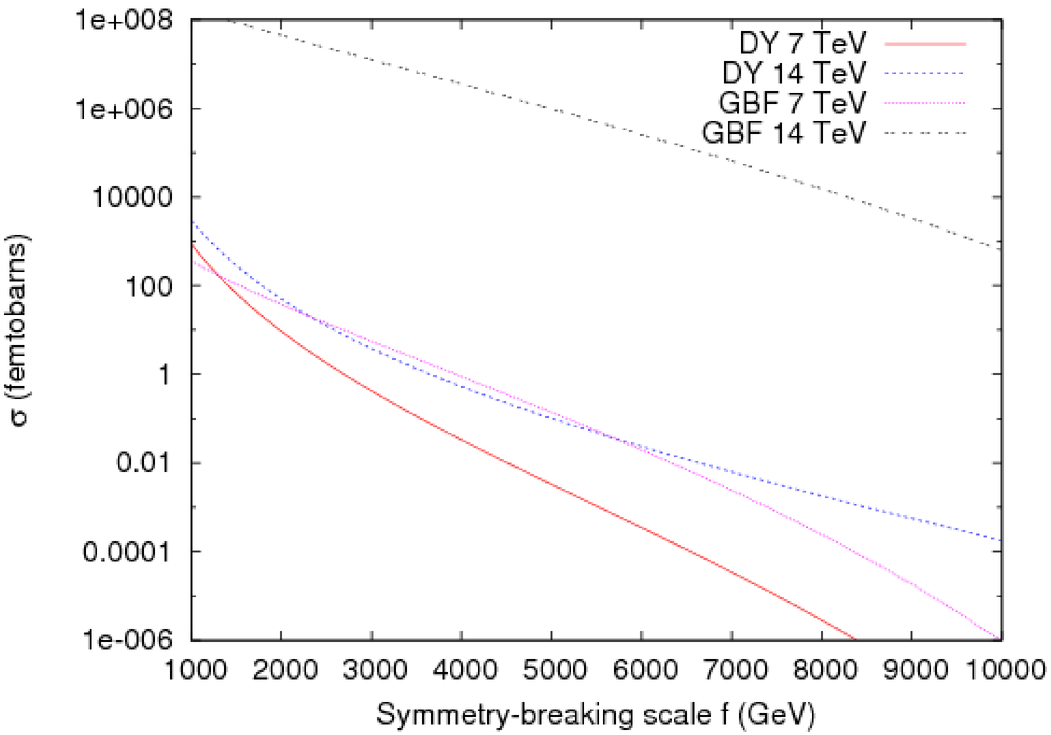
- $X^{\pm}$ production
  - Study focused on neglected gauge boson fusion production mode
  - Gauge boson fusion is larger than Z’ production and $X^{\pm}$ production via Drell-Yan Mode
    - Gauge boson fusion is coupling suppressed, but Drell-Yan is flux suppressed by pdfs especially at pp collider





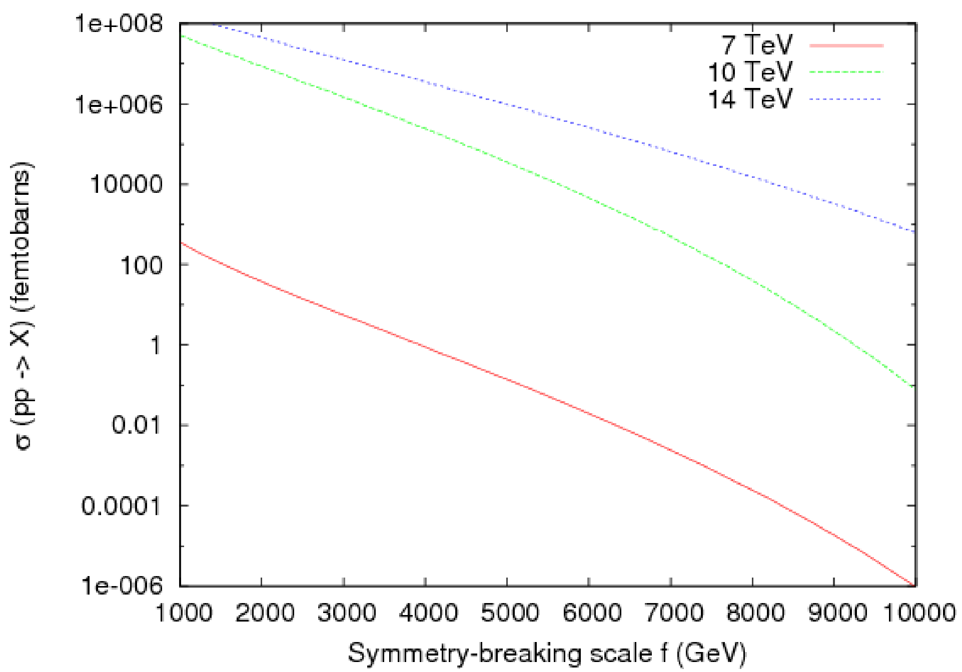
Drell-Yan vs. Gauge Boson Fusion

- Gauge boson fusion cross-section is roughly 3 orders above Z' cross-section
- Fixed values of mixing parameters at $\sin\beta=0.438$ and $\lambda_U=0.5$



Energy Dependence at the LHC

- Gauge boson fusion benefits from pp flux at LHC vs. Tevatron
- Lower energy production largely suppressed by high mass particles



Parameter Dependence

- Sinβ and λ_U have large effect on cross-sections

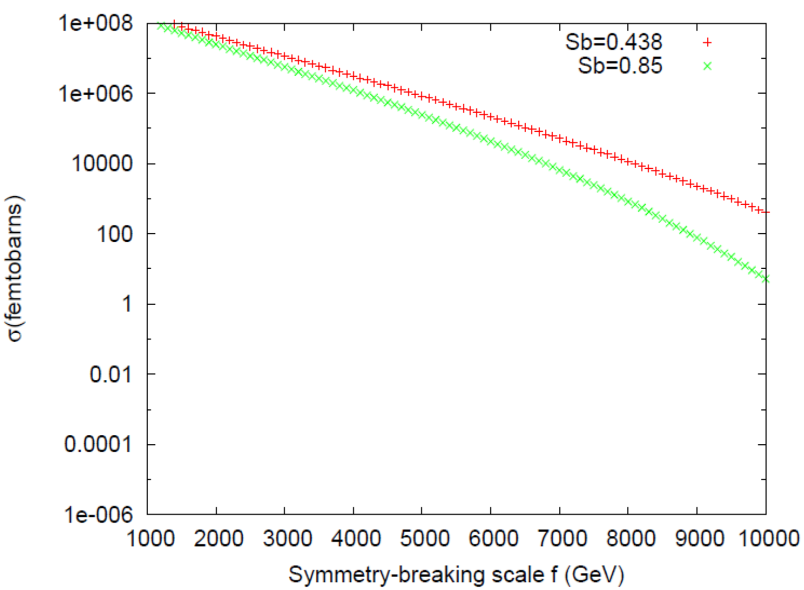


FIG. 3: Scaling of cross-section at 14 TeV center of mass energy where $\lambda = 0.5$

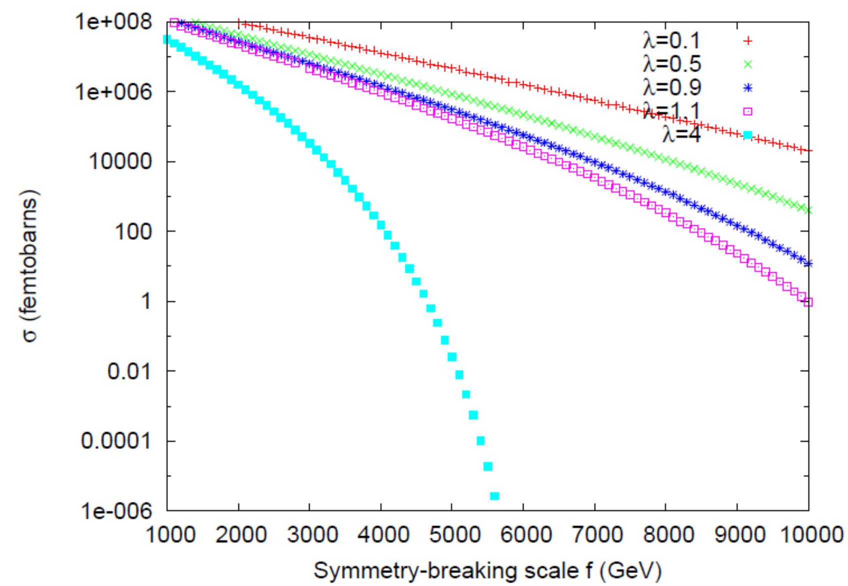


FIG. 4: Scaling of cross-section with λ at 14 Tev center of mass energy with $s_\beta = 0.438$

$X^{\pm}$ Decays

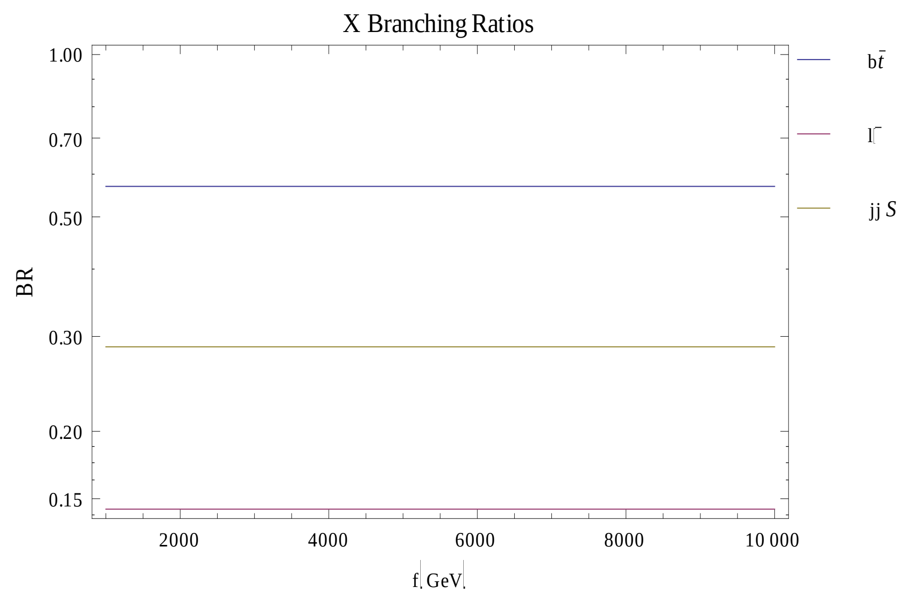
$$\Gamma(X^- \to b\bar{t}) = \frac{3g^2}{48\pi}\delta_t^2 M_Y$$

$$\Gamma(X^- \to jj) = 2\frac{3g^2}{48\pi}\delta_\nu^2 M_Y$$

$$\Gamma(X^- \to l\bar{\nu}) = 3\frac{g^2}{48\pi}\delta_\nu^2 M_Y$$

$$\Gamma(X^- \to Q\bar{q}) = \frac{N_c g^2}{32\pi}\beta^2 M_X[1 - \frac{\beta}{3}]$$

- What would we likely see?
- Partial widths
  - First three partial widths are suppressed by coupling factors δ_t^2 , δ_ν^2
- Most likely decay to 3rd generation quarks



Conclusions

- Cross sections for gauge boson fusion production of $X^{\pm}$ vary from 10^{-1} fb to 100 nb with up to 10^9 events for 10 fb^{-1} of data at 14 TeV
- Z' decays to leptons more than $X^{\pm}$, but larger $X^{\pm}$ production could compensate
- $X^{\pm}$ is potentially viable Simplest Higgs signal at LHC along with the Z'

Nonlinear Sigma Fields

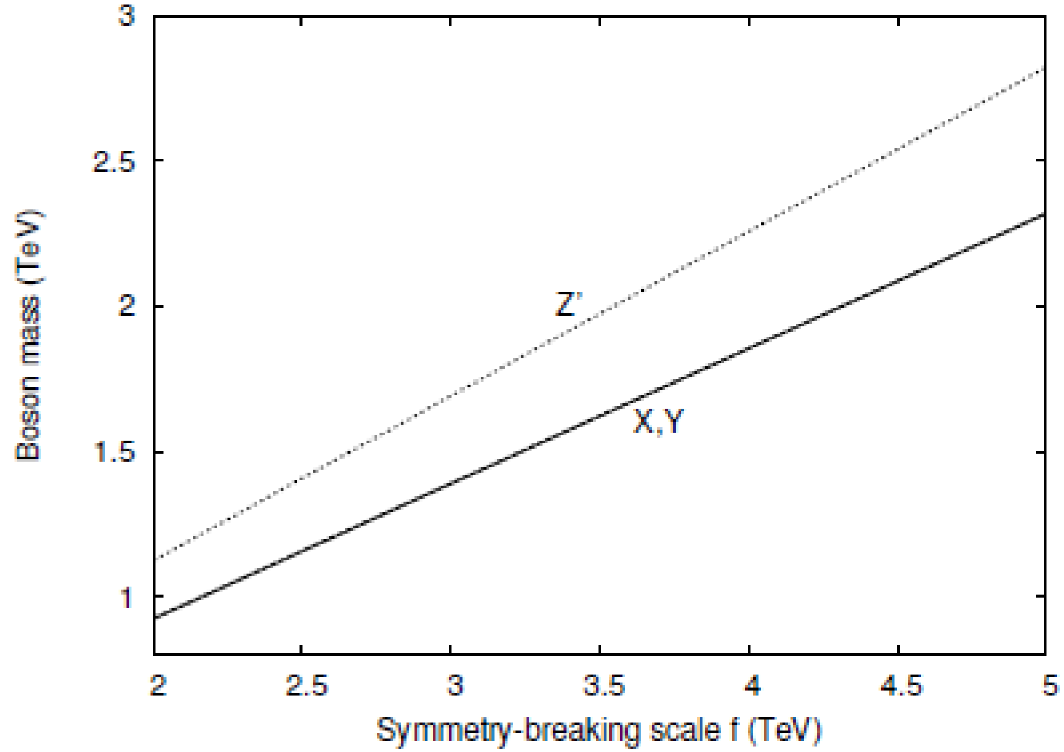
- This construction breaks EWS via two scalar fields resulting in a nondivergent quartic Higgs loop
- Naturally implants higher order scalar terms into model
- Broken generator becomes new scalar η
- Scalar fields are produced via a shared field generator with separate breaking scales f_1 and f_2 for each field where $f_1^2 + f_2^2 = f^2$

$$\Theta = \frac{1}{f}\begin{pmatrix} \frac{\eta}{\sqrt{2}} & 0 & \\ & & h \\ 0 & \frac{\eta}{\sqrt{2}} & \\ & h^\dagger & \frac{\eta}{\sqrt{2}} \end{pmatrix},$$

$$\Phi_1 = e^{i\Theta\frac{f_2}{f_1}}\begin{pmatrix} 0 \\ 0 \\ f_1 \end{pmatrix}, \qquad \Phi_2 = e^{-i\Theta\frac{f_1}{f_2}}\begin{pmatrix} 0 \\ 0 \\ f_2 \end{pmatrix}$$

Gauge Boson Masses

- The $X^{\pm}$ and Y masses vary slightly, but are indistinguishable on this graph



Parameters

- We've seen the two new breaking scales f_1 and f_2 for the Φ fields, and β is a mixing parameter between the fields
- There are also new Yukawa couplings λ_i for the TeV scale fermions. We are interested in the U Yukawa coupling λ
- Production mode comparisons done at "golden point" defined in Schmaltz's original paper sinβ = 0.438, λ = 0.5
- New parameters have large effects on masses, event rates

$$\sin\beta = \frac{f_1}{f}$$

$$\cos\beta = \frac{f_2}{f}$$

$$f_1^{\,2} + f_2^{\,2} = f^{\,2}$$

$$\lambda_U = \lambda_2^{u1}$$

Effect of Embedding on $X^{\pm}$ Production

- Slight difference due to flux of up over down quarks
- Effect is large on Y and Z because they have stronger couplings to vertices that mix heavy and light quarks

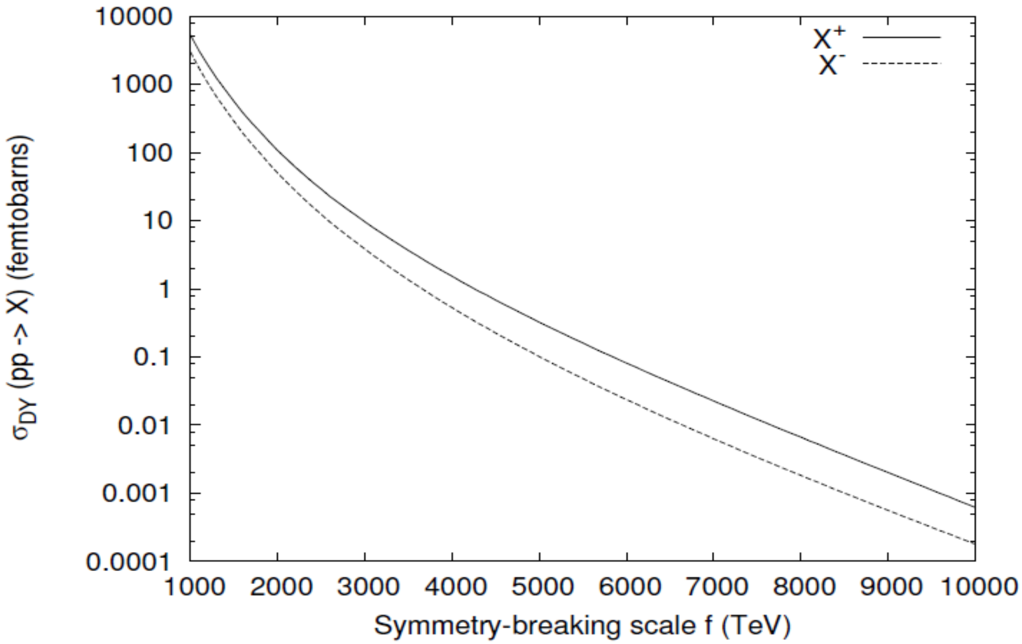


Figure 6.6: The Drell-Yan production cross-section $\sigma(pp \to X)$ at the LHC, with $c_\beta = 0.5$. The cross-section scales as t_β^{-2}.

Higgs Couplings

$W^+_\mu W^-_\nu H$	$\frac{ig^2 v}{2}$	$\left[1 - \frac{v^2}{3f^2}\left(\frac{s^4_\beta}{c^2_\beta} + \frac{c^4_\beta}{s^2_\beta}\right)\right]$	$g^{\mu\nu}$
$W^+_\mu W^-_\nu HH$	$\frac{ig^2}{2}$	$\left[1 - \frac{v^2}{f^2}\left(\frac{s^4_\beta}{c^2_\beta} + \frac{c^4_\beta}{s^2_\beta}\right)\right]$	$g^{\mu\nu}$
$Z^0_\mu Z^0_\nu H$	$\frac{ig^2 v}{2c^2_W}$	$\left[1 - \frac{v^2}{3f^2}\left(\frac{s^4_\beta}{c^2_\beta} + \frac{c^4_\beta}{s^2_\beta}\right)\right]$	$g^{\mu\nu}$
$Z^0_\mu Z^0_\nu HH$	$\frac{ig^2}{2c^2_W}$	$\left[1 - \frac{v^2}{f^2}\left(\frac{s^4_\beta}{c^2_\beta} + \frac{c^4_\beta}{s^2_\beta}\right)\right]$	$g^{\mu\nu}$
$X^+_\mu X^-_\nu H$	$-\frac{ig^2 v}{2}$	$\left[1 - \frac{v^2}{3f^2}\left(\frac{s^4_\beta}{c^2_\beta} + \frac{c^4_\beta}{s^2_\beta}\right)\right]$	$g^{\mu\nu}$
$X^+_\mu X^-_\nu HH$	$-\frac{ig^2}{2}$	$\left[1 - \frac{v^2}{f^2}\left(\frac{s^4_\beta}{c^2_\beta} + \frac{c^4_\beta}{s^2_\beta}\right)\right]$	$g^{\mu\nu}$
$Z'_\mu Z'_\nu H$	$-\frac{ig^2 v}{2c^2_W}$	$\left[1 - \frac{v^2}{3f^2}\left(\frac{s^4_\beta}{c^2_\beta} + \frac{c^4_\beta}{s^2_\beta}\right)\right]$	$g^{\mu\nu}$
$Z'_\mu Z'_\nu HH$	$-\frac{ig^2}{2c^2_W}$	$\left[1 - \frac{v^2}{f^2}\left(\frac{s^4_\beta}{c^2_\beta} + \frac{c^4_\beta}{s^2_\beta}\right)\right]$	$g^{\mu\nu}$

TABLE III: Nonderivative couplings of gauge bosons to scalars in the Simplest Higgs model, to $\mathcal{O}(\frac{v}{f})^2$, with corrections due to complete Z^0, Z' diagonalization ($\approx$ 2 percent for $f = 2$ TeV) neglected except in leading terms. There are no Higgs couplings to the photon or Y^o bosons. [3]

Gauge Boson Couplings

$W^+_\mu(k_1)W^-_\kappa(k_2)A_\nu(k_3)$	$igs_W\left(g^{\mu\nu}(k_3-k_1)^\kappa+g^{\mu\kappa}(k_1-k_2)^\nu+g^{\kappa\nu}(k_2-k_3)^\mu\right)$
$W^+_\mu(k_1)W^-_\kappa(k_2)Z^0_\nu(k_3)$	$igc_W\left(g^{\mu\nu}(k_3-k_1)^\kappa+g^{\mu\kappa}(k_1-k_2)^\nu+g^{\kappa\nu}(k_2-k_3)^\mu\right)$
$W^+_\mu(k_1)W^-_\kappa(k_2){Z'}_\nu(k_3)$	$-igc_W\delta_Z\left(g^{\mu\nu}(k_3-k_1)^\kappa+g^{\mu\kappa}(k_1-k_2)^\nu+g^{\kappa\nu}(k_2-k_3)^\mu\right)$
$W^+_\mu(k_1)W^-_\kappa(k_2)Y^0_\nu(k_3)$	0
$X^+_\mu(k_1)X^-_\kappa(k_2){Z'}_\nu(k_3)$	$\frac{ig}{2}\sqrt{3-t_W^2}\left(g^{\mu\nu}(k_3-k_1)^\kappa+g^{\mu\kappa}(k_1-k_2)^\nu+g^{\kappa\nu}(k_2-k_3)^\mu\right)$
$A_\mu(k_1)A_\kappa(k_2){Y^0}_\nu(k_3)$	0
$A_\mu(k_1)Z^0_\kappa(k_2){Y^0}_\nu(k_3)$	0
$A_\mu(k_1){Z'}_\kappa(k_2){Y^0}_\nu(k_3)$	0
${Z^0}_\mu(k_1)Z^0_\kappa(k_2){Y^0}_\nu(k_3)$	0
${Z^0}_\mu(k_1){Z'}_\kappa(k_2){Y^0}_\nu(k_3)$	0
${Z'}_\mu(k_1){Z'}_\kappa(k_2){Y^0}_\nu(k_3)$	0
$X^+_\mu(k_1)W^-_\kappa(k_2)A_\nu(k_3)$	0
$X^+_\mu(k_1)W^-_\kappa(k_2){Z^0}_\nu(k_3)$	0
$X^+_\mu(k_1)W^-_\kappa(k_2){Z'}_\nu(k_3)$	0
$X^+_\mu(k_1)X^-_\kappa(k_2){Y^0}_\nu(k_3)$	0
$X^+_\mu(k_1)W^-_\kappa(k_2){Y^0}_\nu(k_3)$	$-\frac{g}{\sqrt{2}}\left(g^{\mu\nu}(k_3-k_1)^\kappa+g^{\mu\kappa}(k_1-k_2)^\nu+g^{\kappa\nu}(k_2-k_3)^\mu\right)$

TABLE IV: Some trilinear gauge boson vertex factors of the Simplest Higgs model. All momenta are inward. The mixing factor $\delta_Z=-\frac{\frac{1}{8}\sqrt{3-t_W^2}(1-t_W^2)\frac{v^2}{f^2}}{C_W}$. For couplings including the Z^0 or Z' bosons, the results are to leading order, and are otherwise exact.

Gauge Boson Fermion Couplings

	g_V (Univ.)	g_A (Univ.)	g_V (A.F.)	g_A (A.F.)
$X_\mu^+ \bar{t} b$	$\frac{g\delta_t}{2\sqrt{2}}$	$\frac{-g\delta_t}{2\sqrt{2}}$	$\frac{g\delta_t}{2\sqrt{2}}$	$\frac{-g\delta_t}{2\sqrt{2}}$
$X_\mu^+ \bar{u} d$	$\frac{g\delta_\nu}{2\sqrt{2}}$	$\frac{-g\delta_\nu}{2\sqrt{2}}$	$\frac{-g\delta_\nu}{2\sqrt{2}}$	$\frac{g\delta_\nu}{2\sqrt{2}}$
$X_\mu^+ \bar{T} b$	$\frac{-g}{2\sqrt{2}}$	$\frac{g}{2\sqrt{2}}$	$\frac{-g}{2\sqrt{2}}$	$\frac{g}{2\sqrt{2}}$
$X_\mu^+ \bar{U} d$	$\frac{-g}{2\sqrt{2}}$	$\frac{g}{2\sqrt{2}}$	$---$	$---$
$X_\mu^+ \bar{u} D$	$---$	$---$	$\frac{g}{2\sqrt{2}}$	$\frac{-g}{2\sqrt{2}}$
$Y_\mu^0 \bar{t} t$	$\frac{g}{2\sqrt{2}}\delta_t$	$-\frac{g}{2\sqrt{2}}\delta_t$	$\frac{g}{2\sqrt{2}}\delta_t$	$-\frac{g}{2\sqrt{2}}\delta_t$
$Y_\mu^0 \bar{b} b$	0	0	0	0
$Y_\mu^0 \bar{u} u$	$\frac{g}{2\sqrt{2}}\delta_\nu$	$-\frac{g}{2\sqrt{2}}\delta_\nu$	0	0
$Y_\mu^0 \bar{d} d$	0	0	$\frac{g}{2\sqrt{2}}\delta_\nu$	$-\frac{g}{2\sqrt{2}}\delta_\nu$
$Y_\mu^0 \bar{u} U$	$\frac{g}{2\sqrt{2}}$	$-\frac{g}{2\sqrt{2}}$	$---$	$---$
$Y_\mu^0 \bar{D} d$	$---$	$---$	$\frac{g}{2\sqrt{2}}$	$-\frac{g}{2\sqrt{2}}$
$Z'_\mu \bar{t} t$	$\frac{-ig}{2\sqrt{3-t_W^2}}\left(\frac{1}{2}+\frac{5}{6}t_W^2\right)$	$\frac{ig}{2\sqrt{3-t_W^2}}\left(\frac{1}{2}-\frac{1}{2}t_W^2\right)$	$\frac{-ig}{2\sqrt{3-t_W^2}}\left(\frac{1}{2}+\frac{5}{6}t_W^2\right)$	$\frac{ig}{2\sqrt{3-t_W^2}}\left(\frac{1}{2}-\frac{1}{2}t_W^2\right)$
$Z'_\mu \bar{b} b$	$\frac{-ig}{2\sqrt{3-t_W^2}}\left(\frac{1}{2}-\frac{1}{6}t_W^2\right)$	$\frac{ig}{2\sqrt{3-t_W^2}}\left(\frac{1}{2}+\frac{1}{2}t_W^2\right)$	$\frac{-ig}{2\sqrt{3-t_W^2}}\left(\frac{1}{2}-\frac{1}{6}t_W^2\right)$	$\frac{ig}{2\sqrt{3-t_W^2}}\left(\frac{1}{2}+\frac{1}{2}t_W^2\right)$
$Z'_\mu \bar{u} u$	$\frac{-ig}{2\sqrt{3-t_W^2}}\left(\frac{1}{2}+\frac{5}{6}t_W^2\right)$	$\frac{ig}{2\sqrt{3-t_W^2}}\left(\frac{1}{2}-\frac{1}{2}t_W^2\right)$	$\frac{-ig}{2\sqrt{3-t_W^2}}\left(\frac{1}{2}+\frac{1}{2}t_W^2\right)$	$\frac{-ig}{2\sqrt{3-t_W^2}}\left(-\frac{1}{2}+\frac{5}{6}t_W^2\right)$
$Z'_\mu \bar{d} d$	$\frac{-ig}{2\sqrt{3-t_W^2}}\left(\frac{1}{2}-\frac{1}{6}t_W^2\right)$	$\frac{ig}{2\sqrt{3-t_W^2}}\left(\frac{1}{2}+\frac{1}{2}t_W^2\right)$	$\frac{-ig}{2\sqrt{3-t_W^2}}\left(\frac{1}{2}-\frac{1}{2}t_W^2\right)$	$\frac{-ig}{2\sqrt{3-t_W^2}}\left(-\frac{1}{2}-\frac{1}{6}t_W^2\right)$
$Z'_\mu \bar{T} T$	$\frac{ig}{2\sqrt{3-t_W^2}}\left(1-\frac{4}{3}t_W^2\right)$	$-\frac{ig}{2\sqrt{3-t_W^2}}$	$\frac{ig}{2\sqrt{3-t_W^2}}\left(1-\frac{4}{3}t_W^2\right)$	$-\frac{ig}{2\sqrt{3-t_W^2}}$

Table 5.7: Gauge boson couplings to quarks in the Simplest Higgs model, in the Universal and Anomaly-Free embeddings, in the form $g_V\gamma^\mu + g_A\gamma^\mu\gamma_5$. Crossings of the massive quarks U, D, C, S, B, T require a minus sign, as explained in the text. In all cases the second generation couplings are identical to those of the first generation. Some entries are dashed because some quarks exist in only one embedding.

Continued

	SU(3) simple group
$Z'\bar{t}t$: $Z'\bar{b}b$:	$-\frac{ig}{c_W\sqrt{3-4s_W^2}}[(\frac{1}{2}-\frac{1}{3}s_W^2)P_L+\frac{2}{3}s_W^2P_R]$ $-\frac{ig}{c_W\sqrt{3-4s_W^2}}[(\frac{1}{2}-\frac{1}{3}s_W^2)P_L-\frac{1}{3}s_W^2P_R]$
$Z'\bar{u}u$:	$-\frac{ig}{c_W\sqrt{3-4s_W^2}}[(-\frac{1}{2}+\frac{2}{3}s_W^2)P_L+\frac{2}{3}s_W^2P_R]$ (anomaly free) $-\frac{ig}{c_W\sqrt{3-4s_W^2}}[(\frac{1}{2}-\frac{1}{3}s_W^2)P_L+\frac{2}{3}s_W^2P_R]$ (universal)
$Z'\bar{d}d$:	$-\frac{ig}{c_W\sqrt{3-4s_W^2}}[(-\frac{1}{2}+\frac{2}{3}s_W^2)P_L-\frac{1}{3}s_W^2P_R]$ (anomaly free) $-\frac{ig}{c_W\sqrt{3-4s_W^2}}[(\frac{1}{2}-\frac{1}{3}s_W^2)P_L-\frac{1}{3}s_W^2P_R]$ (universal)
$Z'\bar{e}e$: $Z'\bar{\nu}\nu$:	$-\frac{ig}{c_W\sqrt{3-4s_W^2}}[(\frac{1}{2}-s_W^2)P_L-s_W^2P_R]$ $-\frac{ig}{c_W\sqrt{3-4s_W^2}}(\frac{1}{2}-s_W^2)P_L$
$X_\mu^-\bar{b}t$: $X_\mu^-\bar{d}u$: $X_\mu^-\bar{e}\nu$: $Y_\mu^0\bar{t}t$:	$\frac{g}{\sqrt{2}}\delta_t\gamma_\mu P_L$ $\frac{g}{\sqrt{2}}\delta_\nu\gamma_\mu P_L$ $\frac{g}{\sqrt{2}}\delta_\nu\gamma_\mu P_L$ $\frac{g}{\sqrt{2}}\delta_t\gamma_\mu P_L$
$Y_\mu^0\bar{u}u$:	0 (anomaly free) $\frac{g}{\sqrt{2}}\delta_\nu\gamma_\mu P_L$ (universal)
$Y_\mu^0\bar{d}d$:	$\frac{g}{\sqrt{2}}\delta_\nu\gamma_\mu P_L$ (anomaly free) 0 (universal)
$Y_\mu^0\bar{e}e$: $Y_\mu^0\bar{\nu}\nu$:	0 $\frac{g}{\sqrt{2}}\delta_\nu\gamma_\mu P_L$
$Y_\mu^0 H\eta$:	$\frac{ig}{2\sqrt{2}}(p_\eta-p_H)_\mu$

Table 4: Heavy gauge boson couplings in the SU(3) simple group model. We neglect flavor misalignments. The momenta $p_{\eta,H}$ of the scalars are outgoing.

Gauge Boson Masses

A	0
$W^{\pm}$	$\frac{gv}{2}\left[1-\frac{v^2}{12f^2}\left(\frac{s_\beta^4}{c_\beta^2}+\frac{c_\beta^4}{s_\beta^2}\right)\right]$
Z^0	$\frac{gv}{2c_W}\left[1-\frac{v^2}{12f^2}\left(\frac{s_\beta^4}{c_\beta^2}+\frac{c_\beta^4}{s_\beta^2}\right)-\frac{v^2}{16f^2}(1-t_W^2)^2\right]$
$X^{\pm}$	$\frac{gf}{\sqrt{2}}\left(1-\frac{v^2}{4f^2}\right)$
Z'	$\frac{\sqrt{2}gf}{\sqrt{3-t_W^2}}\left[1-\frac{v^2(3-t_W^2)}{16f^2c_W^2}\right]$
$Y^0,\bar{Y}^0$	$\frac{gf}{\sqrt{2}}$

TABLE I: The masses of the gauge bosons in the Simplest Higgs model, with corrections to $\mathcal{O}(\frac{v}{f})^2$. Particle A is the photon.[3]

Branching Ratios of $X^{\pm}$

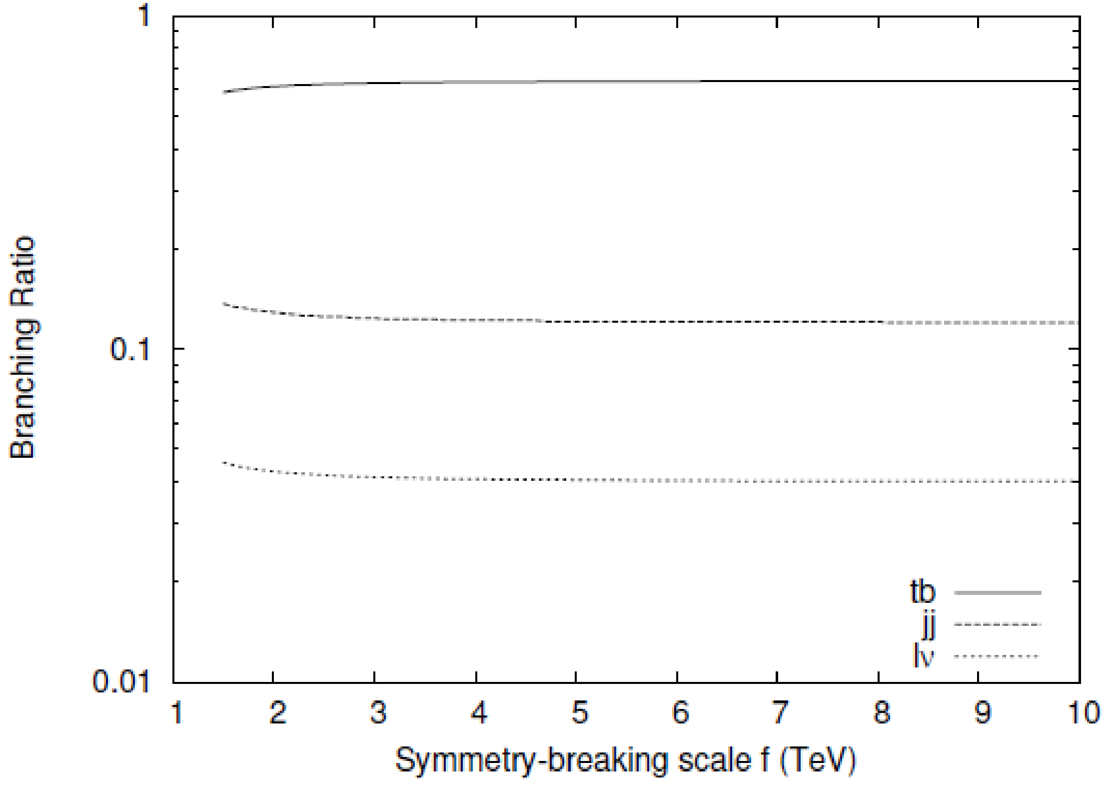


Figure 6.14: The tree-level branching ratios for the $X^{\pm}$ gauge boson of the Simplest Higgs model, for $c_{\beta} = 0.5$.

Appendix D (Z,Y Branching Ratios)

	Universal	Anomaly-Free
l^+l^-	3.0%	3.7%
$\bar{\nu}\nu$	1.7%	2.1%
$\bar{t}t$	14.6%	17.6%
$\bar{b}b$	13.3%	16.1%
$\bar{u}u$	14.7%	12.5%
$\bar{d}d$	13.3%	10.9%
W^+W^-	0.9%	1.1%
Z^0H	0.9%	1.1%
$\Gamma/Mass$	0.015	0.012

Table 6.1: The branching ratios and total width-to-mass ratio of the Simplest Higgs Z', in the limit of massless final state particles. For all fermion pairs the branching ratios are per flavor. Any possible decays involving Simplest Higgs particles beyond those in the Standard Model are omitted.

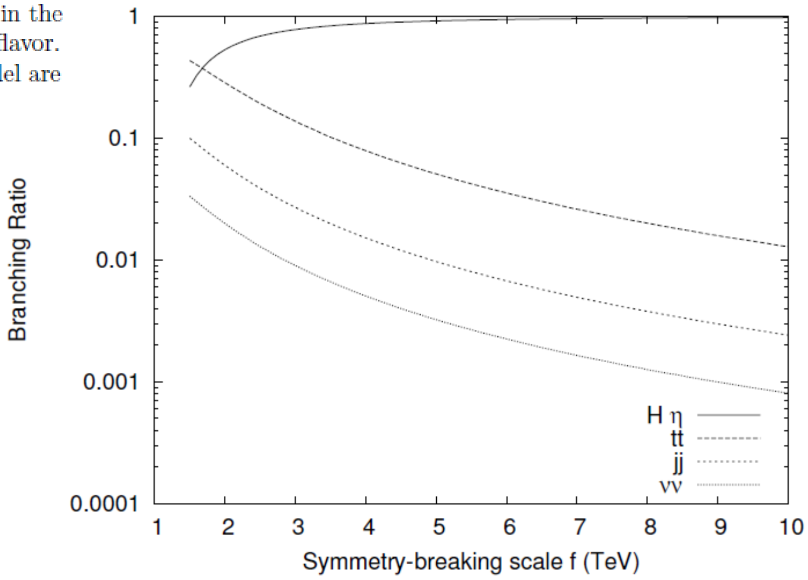


Figure 6.10: The tree-level branching ratios for the Y^0 gauge boson of the Simplest Higgs model, for $c_\beta = 0.5$.

Scalar Field Expansion

$$\Theta = \frac{1}{f}\left[\begin{pmatrix} \begin{matrix} 0 & 0 \\ 0 & 0 \end{matrix} & h \\ h^\dagger & 0 \end{pmatrix} + \frac{\eta}{\sqrt{2}}\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}\right], \qquad h = \begin{pmatrix} h^0 \\ h^- \end{pmatrix}$$

$$\Phi_1 = e^{i\Theta f_2/f_1}\begin{pmatrix} 0 \\ 0 \\ f_1 \end{pmatrix} = f c_\beta \left[\begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} + \frac{i t_\beta}{f}\begin{pmatrix} h \\ \eta/\sqrt{2} \end{pmatrix} - \frac{t_\beta^2}{2f^2}\begin{pmatrix} \sqrt{2}\eta h \\ h^\dagger h + \eta^2/2 \end{pmatrix} + \cdots\right]$$

$$\Phi_2 = e^{-i\Theta f_1/f_2}\begin{pmatrix} 0 \\ 0 \\ f_2 \end{pmatrix} = f s_\beta \left[\begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} - \frac{i}{t_\beta f}\begin{pmatrix} h \\ \eta/\sqrt{2} \end{pmatrix} - \frac{1}{2t_\beta^2 f^2}\begin{pmatrix} \sqrt{2}\eta h \\ h^\dagger h + \eta^2/2 \end{pmatrix} + \cdots\right]$$

Sign of W and Z coupling

$$A^a T^a = \frac{A^3}{2}\begin{pmatrix} 1 & & \\ & -1 & \\ & & 0 \end{pmatrix} + \frac{A^8}{2\sqrt{3}}\begin{pmatrix} 1 & & \\ & 1 & \\ & & -2 \end{pmatrix} + \frac{1}{\sqrt{2}}\begin{pmatrix} & W^+ & Y^0 \\ W^- & & X^- \\ \overline{Y}^0 & X^+ & \end{pmatrix}$$

$$\begin{aligned} \mathsf{D}_1 &= \overleftarrow{\partial}^{\mu}\partial_{\mu} \\ \mathsf{D}_2 &= g^2 A_a^{\mu} A_{b\mu} T_a T_b \\ \mathsf{D}_3 &= -\frac{2gg_x}{3} A_a^{\mu} B_{x\mu} T_a \\ \mathsf{D}_4 &= \frac{g_x^2}{9} B_x^{\mu} B_{x\mu} \end{aligned}$$

$$\mathcal{L}_{\Phi} = \left(\mathcal{D}^{\mu}\Phi_1\right)^{\dagger}\left(\mathcal{D}_{\mu}\Phi_1\right) + \left(\mathcal{D}^{\mu}\Phi_2\right)^{\dagger}\left(\mathcal{D}_{\mu}\Phi_2\right)$$

$$\begin{aligned} \Phi_i^{\dagger}\mathsf{D}_2\Phi_i = \; & g^2\left[\frac{1}{2}W^+W^- + (\frac{1}{2}A_3 + \frac{1}{2\sqrt{3}}A_8)^2 + \frac{1}{2}Y^0\overline{Y}^0\right]\left[\frac{(v+H)^2}{2} - \frac{1}{12f^2}\left(\frac{s_\beta^4}{c_\beta^2} + \frac{c_\beta^4}{s_\beta^2}\right)(v+H)^4\right] \\ & + g^2\left[\frac{1}{2}Y^0\overline{Y}^0 + \frac{1}{2}X^+X^- + \frac{1}{3}A_8A_8\right]\left[f^2 - \frac{(v+H)^2}{2} + \frac{1}{12f^2}\left(\frac{s_\beta^4}{c_\beta^2} + \frac{c_\beta^4}{s_\beta^2}\right)(v+H)^4\right] \end{aligned}$$

$$\begin{aligned} \Phi_i^{\dagger}\mathsf{D}_3\Phi_i = \; & -\frac{2gg_x}{3}B_x\left[\frac{1}{2}A_3 + \frac{1}{2\sqrt{3}}A_8\right]\left[\frac{(v+H)^2}{2} - \frac{1}{12f^2}\left(\frac{s_\beta^4}{c_\beta^2} + \frac{c_\beta^4}{s_\beta^2}\right)(v+H)^4\right] \\ & -\frac{2gg_x}{3}B_x\left[-\frac{1}{\sqrt{3}}A_8\right]\left[f^2 - \frac{(v+H)^2}{2} + \frac{1}{12f^2}\left(\frac{s_\beta^4}{c_\beta^2} + \frac{c_\beta^4}{s_\beta^2}\right)(v+H)^4\right] \end{aligned}$$

$$\Phi_i^{\dagger}\mathsf{D}_4\Phi_i = \frac{g_x^2}{9}B_xB_xf^2$$

Yukawa Sector

$$\mathcal{L} = \lambda_1^{un} i u_1^{nc} \Phi_1^\dagger Q_n + \lambda_2^{un} i u_2^{nc} \Phi_2^\dagger Q_n + \frac{\lambda_d^{mn}}{\Lambda} i d_m^c \epsilon_{ijk} \Phi_1^i \Phi_2^j Q_n^k + \text{h.c.}$$

- This is for the fundamental representation. There is a mixing between the SM and new heavy quark copies. There are separate coupling to each scalar field that get combined when you diagonalize the mass matrix. Both quark become linear combinations of the two quark states shown above.

$$U_n^c = \frac{\lambda_1^{un} c_\beta u_1^{nc} + \lambda_2^{un} s_\beta u_2^{nc}}{\sqrt{(\lambda_1^{un})^2 c_\beta^2 + (\lambda_2^{un})^2 s_\beta^2}} \qquad u_n^c = \frac{-\lambda_2^{un} s_\beta u_1^{nc} + \lambda_1^{un} c_\beta u_2^{nc}}{\sqrt{(\lambda_1^{un})^2 c_\beta^2 + (\lambda_2^{un})^2 s_\beta^2}}.$$

$$M_{U_n} = f\sqrt{(\lambda_1^{un})^2 c_\beta^2 + (\lambda_2^{un})^2 s_\beta^2}$$

$$\mathcal{L}_{\text{up mass}} = -M_{U_n} U_n^c U_n + \frac{v}{\sqrt{2}} \frac{s_\beta c_\beta [(\lambda_1^{un})^2 - (\lambda_2^{un})^2]}{\sqrt{(\lambda_1^{un})^2 c_\beta^2 + (\lambda_2^{un})^2 s_\beta^2}} U_n^c u_n - \frac{v}{\sqrt{2}} \frac{\lambda_1^{un} \lambda_2^{un}}{\sqrt{(\lambda_1^{un})^2 c_\beta^2 + (\lambda_2^{un})^2 s_\beta^2}} u_n^c u_n + \text{h.c.}$$

Yukawa Continued

- To leading order: $$\frac{\lambda_1^{um}\lambda_2^{um} f}{\sqrt{2} M_{U_m}} = \frac{m_{u_m}}{v}.$$

- Since u mass is relatively small one of the Yukawa coupling must be small leading to the simplified masses

$$M_U = f\lambda_U s_\beta, \qquad M_C = f\lambda_C s_\beta, \qquad M_T = f\sqrt{\lambda_1^2 c_\beta^2 + \lambda_2^2 s_\beta^2}$$

Littlest Higgs/Bestest Higgs

- Littlest Higgs SU(5)/SO(5)
  - Different multiplet representation
  - Product group model similar to Simplest Higgs
- Bestest Higgs SO(6)xSO(6)/SO(6)
  - Larger parameter space to agree with electroweak precision measurements
  - Allows lighter heavy top partner
  - Higgs quartic coupling is smaller

Radiative Corrections in Simplest Higgs

- SU(3) symmetric term above breaking scale

$$|\Phi_1^\dagger \Phi_2|^2 = f^4 s_\beta^2 c_\beta^2 - f^2 h^\dagger h + \frac{1}{3 s_\beta^2 c_\beta^2}(h^\dagger h)^2 + \frac{3}{32 s_\beta^2 c_\beta^2} h^\dagger h \eta^2 + \mathcal{O}(\phi^6)$$

$$V_2 = \frac{3}{64\pi^2} g^4 \log(\Lambda^2/M_X^2) f^2 (h^\dagger h)$$

$$V_4 = \frac{3}{64\pi^2} g^4 \log(\Lambda^2/M_X^2) \left[-\frac{1}{3 s_\beta^2 c_\beta^2}(h^\dagger h)^2 - \frac{3}{32 s_\beta^2 c_\beta^2}(h^\dagger h)\eta^2 \right] - \frac{3}{128\pi^2} g^4 \log(M_X^2/M_W^2)(h^\dagger h)^2.$$

$$V_2 = \frac{3}{32\pi^2} g^4 \frac{1+t_W^2}{3-t_W^2} \log(\Lambda^2/M_{Z'}^2) f^2 (h^\dagger h)$$

$$V_4 = \frac{3}{32\pi^2} g^4 \frac{1+t_W^2}{3-t_W^2} \log(\Lambda^2/M_{Z'}^2) \left[-\frac{1}{3 s_\beta^2 c_\beta^2}(h^\dagger h)^2 - \frac{3}{32 s_\beta^2 c_\beta^2}(h^\dagger h)\eta^2 \right] - \frac{3}{256\pi^2} g^4 (1+t_W^2)^2 \log(M_{Z'}^2/M_Z^2)(h^\dagger h)^2.$$

Radiative Corrections Continued

$$V_2 = -\frac{3}{8\pi^2}\lambda_t^2 M_T^2 \log(\Lambda^2/M_T^2)(h^\dagger h)$$

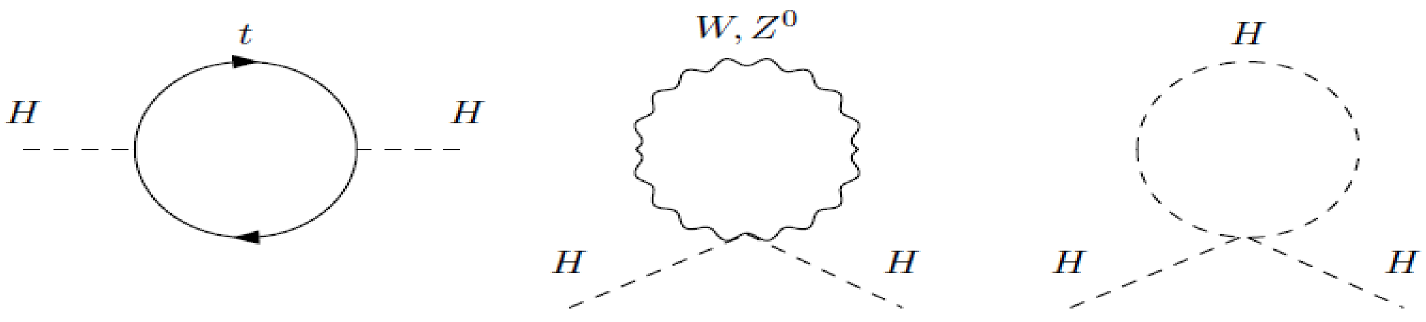
$$V_4 = -\frac{3}{8\pi^2}\lambda_t^2 \frac{M_T^2}{f^2}\log(\Lambda^2/M_T^2)\left[-\frac{1}{3s_\beta^2 c_\beta^2}(h^\dagger h)^2 - \frac{3}{32 s_\beta^2 c_\beta^2}(h^\dagger h)\eta^2\right]$$

$$+\frac{3}{16\pi^2}\lambda_t^4 \log(M_T^2/m_t^2)(h^\dagger h)^2,$$

Little Higgs Models

(Nima Arkani-Hamed, Andy Cohen, Howard Georgi, Thomas Gregoire, Jay Wacker Emmanuel Katz, and Ann Nelson)

- The Little Higgs addresses the hierarchy problem by providing new particles to cancel with divergent Higgs mass contributions



- Weakly coupled new physics up to TeV scale for consistency with precision electroweak measurements
- These models produce light Higgs of 114 GeV up to around 500 GeV

Representation

$$\Psi_{qL} = (3,3)_{\frac{1}{3}}$$
$$u_R = (3,1)_{\frac{2}{3}}$$
$$d_R = (3,1)_{-\frac{1}{3}}$$
$$U_R = (3,1)_{\frac{2}{3}}$$
$$\Psi_L = (1,3)_{-\frac{1}{3}}$$
$$e_R = (1,1)_{-1}$$
$$n_R = (1,1)_0$$

- Fundamental representation is used in the Universal Embedding

$$\Psi_L = \begin{pmatrix} \nu_e \\ e \\ i n_e \end{pmatrix}_L \qquad \Psi_{qL} = \begin{pmatrix} u \\ d \\ iU \end{pmatrix}_L$$

- Conjugate representation is used in Anomaly Free Embedding

$$\Psi_{qL} = \begin{pmatrix} u \\ d \\ iD \end{pmatrix}_L$$

$$\Psi_{qL} = (3,\bar{3})_0$$
$$u_R = (3,1)_{\frac{2}{3}}$$
$$d_R = (3,1)_{-\frac{1}{3}}$$
$$D_R = (3,1)_{-\frac{1}{3}}$$