Little Higgs models and their phenomenology

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Main talk about chapter 6: Collider phenomenology
6.1 Heavy gauge boson
6.2 Heavy top

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Little Higgs model

1. Littlest Higgs (LH² model)
   - most economical and attractive model
   - gauge symmetry breaking: 2 stages

\[ [\text{SU}(2) \times \text{U}(1)]^2 \rightarrow \text{SU}(2)_L \times \text{U}(1)_Y \rightarrow \text{U}(1)_{\text{em}} \]

\[ f \sim 1 \text{TeV} \quad \text{v} = 246 \text{GeV} \]

\[ \text{vev(Vacuum Expectation Value)} \]

\[ \begin{cases} \tan \psi = \frac{g_2}{g_1} \\ W_H^a = -\cos \psi W_1^a + \sin \psi W_2^a \end{cases} \]

\begin{align*}
g & : \text{gauge coupling constant} \\
\Psi & : \text{mixing angle} \\
W_H^\pm, W_H^3, (B_H) & : \text{top quark} T
\end{align*}
2. Littlest Higgs with T parity (LH$^2$T model)

- **T parity**: similar to R parity in MSSM of SUSY
- lightest T-odd particle (LTP): dark matter candidate

Heavy gauge boson (T-odd) → SM particle (T-even)

- new particle: (gauge boson) $W_H^{\pm}$, $W_H^3$, $B_H$
- (top quark) $T$, $T_\pm$

3. Little Higgs from a simple group (SU(3) model)

- new particle: (gauge boson) $X^\pm$, $Y$, $Z$
- (top quark) $T$, $U_H$, $N_H$
gauge sector

\[ L_{\text{kinetic}} = \frac{1}{4} H^\dagger H (g^2 W^a_{L\mu} W^{\mu a}_L - W^a_{H\mu} W^{\mu a}_H - 2 \cot 2\psi W^a_{H\mu} W^{\mu a}_L) \]

\[ + g'^2 (B_{L\mu} B^{\mu}_L - B_{H\mu} B^{\mu}_H - 2 \cot 2\psi' B_{H\mu} B^{\mu}_L) \]

Eq.(27)

\[ a = 1, 2, 3 \rightarrow W^a = W^\pm, Z \]

L : light = SM particle

H : heavy = LH particle

<One-loop contribution to Higgs>
1. Heavy gauge boson of $L^2H$ model

$<W_H^\pm, W_H^3>$

Mass: $M(W_H) = \frac{g}{\sin 2\psi} f$, Eq.(22)

$L_{\text{heavy gauge}} = g \cot \psi W_{H \mu}^a \left( \tilde{L}_\mu \frac{\sigma^a}{2} L + \tilde{Q}_\mu \frac{\sigma^a}{2} Q \right)$, Eq.(78)

- $L$ : SM left-handed lepton doublet
- $Q$ : SM left-handed quark doublet

$<B_H>$

- coupling to SM fermions depends on $U(1)_1$ and $U(1)_2$
- quite model independent
- eliminating $B_H$ may reduce the amount of fine tuning

$\rightarrow$ Analysis focuses on production and decay of $W_H$ bosons.
1. Heavy gauge boson of $L^2H$ model

Tevatron collider (pp-bar 1.96TeV)

→ $W_H$ bosons: out of kinematic reach

LHC (pp 14TeV)

→ $W_H$ bosons: discover reach is quite high.

![Production cross section diagram](Fig.10)

\[ \psi = \pi/4 \quad \text{...} \quad \cot \psi = 1 \]

→ General case: $\times \cot^2 \psi$

\[ \Gamma_{\text{tot}} = \frac{g^2}{96\pi} (\cot^2 2\psi + 24 \cot^2 \psi) M \]

\[ \Gamma(W_H^3 \to \ell^+ \ell^-) = \frac{g^2 \cot^2 \psi}{96\pi} M, \quad \Gamma(W_H^3 \to \bar{q}q) = \frac{g^2 \cot^2 \psi}{32\pi} M, \]

\[ \Gamma(W_H^3 \to Zh) = \frac{g^2 \cot^2 2\psi}{192\pi} M, \quad \Gamma(W_H^3 \to W^+W^-) = \frac{g^2 \cot^2 2\psi}{192\pi} M \]

\[ \begin{cases} l = e, \mu, \tau \\ q = u, d, c, s, t, b \end{cases} \]
1. Heavy gauge boson of $L^2H$ model

$W_H^3 \rightarrow l^+l^- \ (l=e \ or \ \mu)$

- cleanest mode: virtually free of background (by $Z$ discovery)

\[
\begin{aligned}
10 \text{ events} & \quad \sigma = 10^{-1} \text{ fb} \\
100 \text{ fb}^{-1} & \quad = 10^{-4} \text{ pb}
\end{aligned}
\]

? \quad \text{M}(W_H) = 5(\cot \psi)^{1/3} \text{ TeV} \quad = 5 \text{ TeV} \quad (\text{for } \psi = \pi/4)

(Fig.10)

<production cross section>

However, discovering $W_H$ does not by itself provide a striking signature for LH model …
1. Heavy gauge boson of $L^2H$ model

- $<W_H Zh$ coupling$>$
  - a clean way to verify $L^2H$ origin of $W_H$
  - $W_H W_L H^*H$ term in Eq.(27)
  - coefficient $(g, \cot^2\psi)$: direct consequence of LH$^2$ symmetry breaking

$$L_{\text{kinetic}} = \frac{1}{4} H^+ H \frac{\sqrt{2}}{2} W_L^a W_L^{a*} - W_H^a W_H^{a*} - 2\cot 2\psi W_H^a W_L^{a*} + g^2 (B_L H^*B_L - B_H H^*B_H - 2\cot 2\psi'B_H B_L^*)$$

Eq.(27)

- independent determination of $\{ \text{mixing angle } \psi, W_H$ partial width $(g, \psi) \}$ test of $L^2H$

- $l^+l^-$ and Zh channel$>$
  - number of events provides difference between $L^2H$ and Big Higgs models

$$N(l^+l^-) = \mathcal{L} \sigma_{\text{prod}}^{(0)} f(\tan^2\psi) \quad \rightarrow \quad \text{mixing angle } \psi$$

different $\{ N(Zh) = \mathcal{L} \sigma_{\text{prod}}^{(0)} g(\tan^2\psi) \ldots L^2H$ 

$$N(Zh) = 0.5N(l^+l^-) \quad \ldots \quad \text{Big Higgs}$$

- recent analysis has confirmed this conclusion
1. Heavy gauge boson of $L^2H$ model

more detailed analysis...

$W_H^3$
\[
\begin{align*}
\rightarrow & \ l^+l^- \\
\rightarrow & \ Zh \rightarrow l^+l^- \ bb(\text{bar}) / jj\gamma\gamma
\end{align*}
\]

$W_H^\pm$
\[
\begin{align*}
\rightarrow & \ l^\pm\nu \\
\rightarrow & \ W^\pm h \rightarrow l^\pm\nu \ bb(\text{bar}) / jj\gamma\gamma
\end{align*}
\]

Regions to the left of lines are accessible.

\[
\begin{align*}
Z_H = W_H^3 \\
V_H = W_H^3, W_H^\pm
\end{align*}
\]
2. Heavy gauge boson of SU(3) model

\(<X^\pm \text{ and } Y \text{ bosons}>\)
- do not couple to SM fermions
- production cross section: suppressed by \(v^2/f^2\)
  \[ L \propto v/f \Rightarrow \sigma \propto v^2/f^2 \]

\[ M_X = M_Y = \frac{gf}{\sqrt{2}} \approx 0.46f, \quad M_{Z'} = \frac{\sqrt{2}gf}{\sqrt{3-t_W^2}} \approx 0.56f. \]

\(<Z' \text{ boson}>
- production cross section: unsuppressed
- \(l^+ l^-\) and \(Zh\) event rate \(\Rightarrow\) non-LH \(Z'\) or \(LH^2\)
3. Heavy gauge boson of $L^2HT$ model

- spectrum: same as original LH
- phenomenology: different from LH

\[ \text{TeV-scale gauge bosons} = T\text{-odd} \]

\[ \text{resemble SUSY with R parity} \]

\[ \langle B_H \text{ boson} \rangle \]

\[ \tilde{M}(B_H) = g' f/\sqrt{5} \approx 0.16 f \]

- obligatory in this model
- lightest T-odd particle (LTP)
- $W_H$ or $B_H$ pair-production: characterized by large missing $p_t$
top quark sector

\[ L_{\text{top-Higgs}} = \lambda_i q_L^\dagger \tilde{H} T_R + \lambda_T q_L^\dagger \tilde{H} T_R - \frac{1}{\sqrt{2} f} (H^\dagger H) T_L^\dagger (\lambda_T T_R + \lambda_t T_R) + \text{h.c.} \]  
Eq. (32)

\[ \langle \text{One-loop contribution to Higgs} \rangle \]

(a) \( -6\lambda_i^2 \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2} \)  
(b) \( -6\lambda_T^2 \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 - M_T^2} \)  
(c) \( +6 \frac{\sqrt{2} \lambda_T}{f} \int \frac{d^4k}{(2\pi)^4} \frac{M_T}{k^2 - M_T^2} \)

\( (a) + (b) + (c) \sim 0 \rightarrow \text{quadratic divergences nearly cancel} \)

necessary condition :  
\[ \frac{M_T}{f} = \frac{\lambda_i^2 + \lambda_T^2}{\sqrt{2} \lambda_T} \]  
Eq. (35)
1. Heavy top quark of $L^2H$ model

<pair production>

$gg \rightarrow TT(\bar{\text{bar}}) \ , \ qq(\bar{\text{bar}}) \rightarrow TT(\bar{\text{bar}})$

- strong interaction: dominate for low T mass
- not dominant for $M_T \gg 1\text{TeV}$

<single production>

$bq \rightarrow Tq'$

- W exchange process
- becomes dominant

$(\text{decay of } T)$

$$\Gamma(T \rightarrow th) = \Gamma(T \rightarrow tZ^0) = \frac{1}{2} \Gamma(T \rightarrow bW^+) = \frac{\lambda_T^2 M_T}{64\pi}$$
1. Heavy top quark of $L^2H$ model

\[ \Gamma(T \rightarrow th) = \frac{1}{2} \Gamma(T \rightarrow bW^+) = \frac{\lambda_T^2 M_T}{64\pi} \]

- $<T \rightarrow \text{Wb}>$

- final state : $\text{Wb} \rightarrow l\nu b$
  - 2000 GeV for $\lambda_1/\lambda_2 = 1$ (5$\sigma$ discovery)
  - 2500 GeV for $\lambda_1/\lambda_2 = 2$ (300fb$^{-1}$)

- $<T \rightarrow \text{Zt}>$

- final state : $Z \rightarrow l^+l^-$, $t \rightarrow \text{Wb} \rightarrow l\nu b$
- small background ($t\nu Z$)
- lower statistics than Wb
  - 1050 GeV for $\lambda_1/\lambda_2 = 1$ (5$\sigma$ discovery)
  - 1400 GeV for $\lambda_1/\lambda_2 = 2$ (300fb$^{-1}$)

- $<T \rightarrow \text{th}>$

- more challenging mode
- $M_T$ in other channel
  - can separate signal from background
1. Heavy top quark of $L^2H$ model

discovery of T quark: not smoking gun signal for LH model

canceling one-loop quadratic divergence

$$\frac{M_T}{f} = \frac{\lambda_t^2 + \lambda_T^2}{\sqrt{2}\lambda_T}$$

Eq.(35)

\[
\begin{align*}
\lambda_t & : \text{top Yukawa} \\
M_T & : \text{directly measured} \\
f & : W_H \text{ boson (mass, cross section)} \\
\lambda_T & : \text{more difficult} \\
M(W_H) & = \frac{\sqrt{g}}{\sin 2\psi} f \\
\sigma_W & \rightarrow \psi, g \\
- & \text{single T production cross section: final state has } b \\
- & \text{large uncertainty in } b \text{ quark pdf (Probability Density Function)} \\
- & \text{total cross section: all T decay channel} \\
\end{align*}
\]
2. Heavy top quark of SU(3) model

- similar to LH$^2$

\[ \Gamma(T \to th) = \Gamma(T \to tZ^0) = \frac{1}{2} \Gamma(T \to bW^+) = \frac{\lambda_T^2 M_T}{64\pi} \]

- new T decay: $t\eta$, $tY^0$, $bX^+$
- same search strategies as LH$^2$
- $U_H$, $N_H$ in addition to T: TeV-scale quarks
3. Heavy top quark of $L^2$HT model

$<T_+ \text{ and } T_->$

\[
M_T = \sqrt{\lambda_1^2 + \lambda_2^2} f. (=M_{T_+}) \quad \left\{ \begin{array}{l} M_{T_-} < M_{T_+} \\
M_{T_-} = \lambda_2 f. \end{array} \right.
\]

$<T_+>$
- phenomenology: similar to no T parity
- same decay: $Wb$, $tZ$, $th$

\[
\Gamma(T \to th) = \Gamma(T \to tZ^0) = \frac{1}{2} \Gamma(T \to bW^+) = \frac{\lambda_2^2 M_T}{64\pi}
\]
- new decay: $T_+ \to T_- B_H$

$<T_->$
- pair-production: $qq(\bar{q}) \to T_- T_-(\bar{q})$
- decay: $tB_H$
- large amount of missing $p_t$ ($B_H$)
- vector-like TeV-scale T-odd fermions $\to$ LTP $B_H$