- 論文講読 -

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 (LH^2 model)

   - most economical and attractive model
   - gauge symmetry breaking : 2 stages

EWSB (ElectroWeak Symmetry Breaking)

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

f~1TeV v=246GeV

vev(Vacuum Expectation Value)

$$\begin{cases} g = \dfrac{g_1 g_2}{\sqrt{g_1^2 + g_2^2}} \\ \tan\psi = \dfrac{g_2}{g_1} \\ W_H^a = -\cos\psi\, W_1^a + \sin\psi\, W_2^a \end{cases}$$

g : gauge coupling constant

Ψ : mixing angle

new particle : (gauge boson) $W_H^{\pm}$, W_H^3 , (B_H)

(top quark) T

Alternative Little Higgs models

2. Littlest Higgs with T parity (LH^2T model)

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

heavy gauge boson (T-odd) $\not\longrightarrow$ 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)

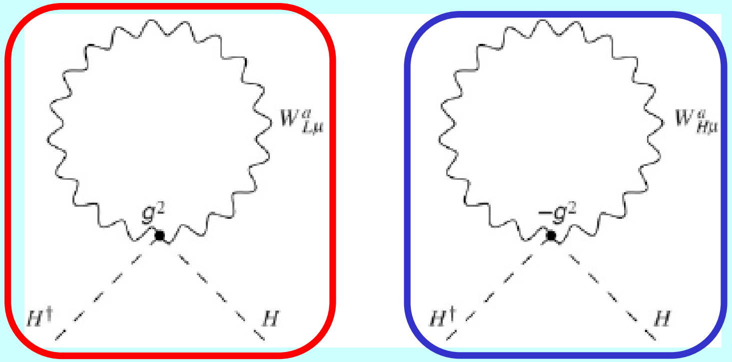
new particle : (gauge boson) $X^{\pm}$, Y, Z'
(top quark) T, U_H, N_H

gauge sector

$$L_{kinetic} = \frac{1}{4} H^\dagger H \left(g^2 \left(W^a_{L\mu} W_L^{\mu a} - W^a_{H\mu} W_H^{\mu a} - 2\cot 2\psi \, W^a_{H\mu} W_L^{\mu a}\right) + g'^2 \left(B_{L\mu} B_L^\mu - B_{H\mu} B_H^\mu - 2\cot 2\psi' \, B_{H\mu} B_L^\mu\right)\right). \quad \text{Eq.(27)}$$

a = 1,2,3 → 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)

$$L_{\text{heavy gauge}} = g \cot\psi \, W^a_{H\mu} \left(\bar{L}\gamma^\mu \frac{\sigma^a}{2} L + \bar{Q}\gamma^\mu \frac{\sigma^a}{2} Q \right)$$ 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

→ Analysis focuses on production and decay of W_H bosons.

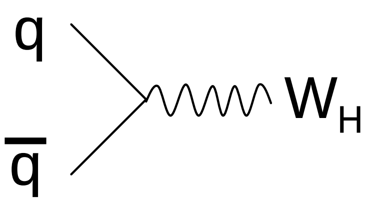
1. Heavy gauge boson of L^2H model

Tevatron collider (pp-bar 1.96TeV)

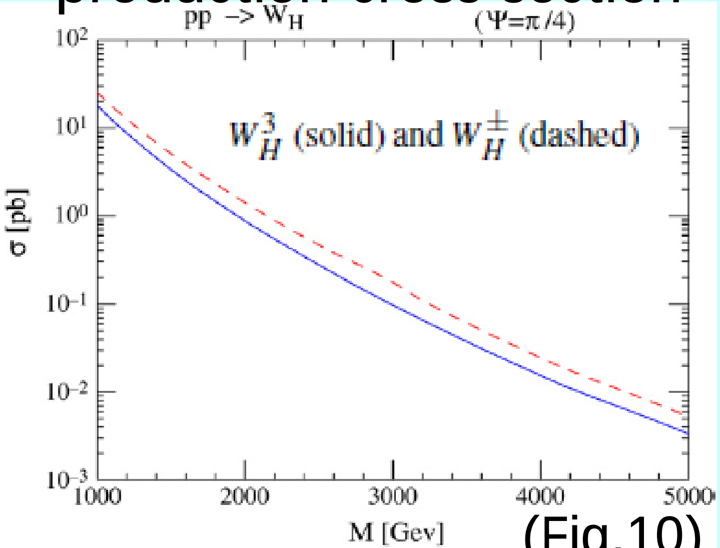
→ W_H bosons : out of kinematic reach

LHC (pp 14TeV)

→ W_H bosons : discover reach is quite high.



<production cross section>



(Fig.10)

$\psi=\pi/4$ ... $\cot\psi=1$

→ General case : $\times\cot^2\psi$

<total width>

$$\Gamma_{\rm tot} = \frac{g^2}{96\pi}(\cot^2 2\psi + 24\cot^2\psi)\,M$$

$$\left(M \equiv M(W_H) \right)$$

<partial width>

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

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

l = e, μ, τ

q= u, d, c, s, t, b

1. Heavy gauge boson of L^{2}H model

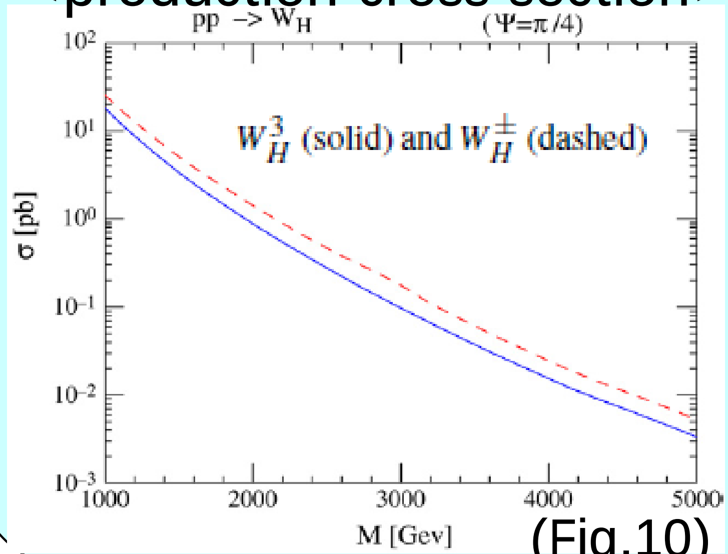
$W_H^3 \rightarrow l^+l^-$ (l=e or μ)

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

$\left\{ \begin{array}{l} \text{10 events} \\ \text{100 fb}^{-1} \end{array} \right. \rightarrow \sigma = 10^{-1}$ fb $= 10^{-4}$ pb $\overset{?}{\Longleftrightarrow}$ $M(W_H) = 5(\cot\psi)^{1/3}$ TeV $= 5$ TeV (for $\psi = \pi/4$)

(Fig.10)

<production cross section>



(Fig.10)

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

$$L_{kinetic} = \frac{1}{4} H^\dagger H \left(g^2 (W^a_{L\mu} W^{\mu a}_L - W^a_{H\mu} W^{\mu a}_H - 2 \cot 2\psi \, W^a_{H\mu} W^{\mu a}_L) + g'^2 (B_{L\mu} B^\mu_L - B_{H\mu} B^\mu_H - 2 \cot 2\psi' \, B_{H\mu} B^\mu_L) \right). \quad \text{Eq.(27)}$$

independent determination of { mixing angle ψ ; W_H^3 partial width (g, ψ) } ➡ test of L^2H

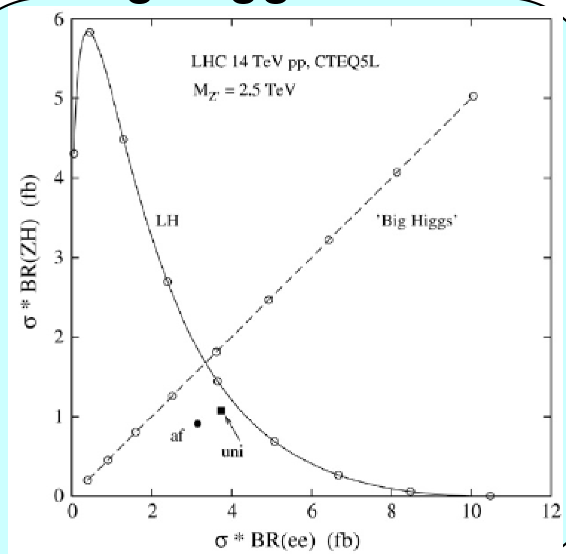
<$l^+ l^-$ and Zh channel>

- number of events provides difference between L^2H and Big Higgs models

$$N(\ell^+\ell^-) = \mathcal{L}\, \sigma^{(0)}_{\rm prod}\, f(\tan^2\psi) \longrightarrow \text{mixing angle } \psi$$

different
$$\begin{cases} N(Zh) = \mathcal{L}\, \sigma^{(0)}_{\rm prod}\, g(\tan^2\psi), & \ldots\ L^2H \\ N(Zh) = 0.5 N(l^+ l^-) & \ldots\ \text{Big Higgs} \end{cases}$$

- recent analysis has confirmed this conclusion ⟶

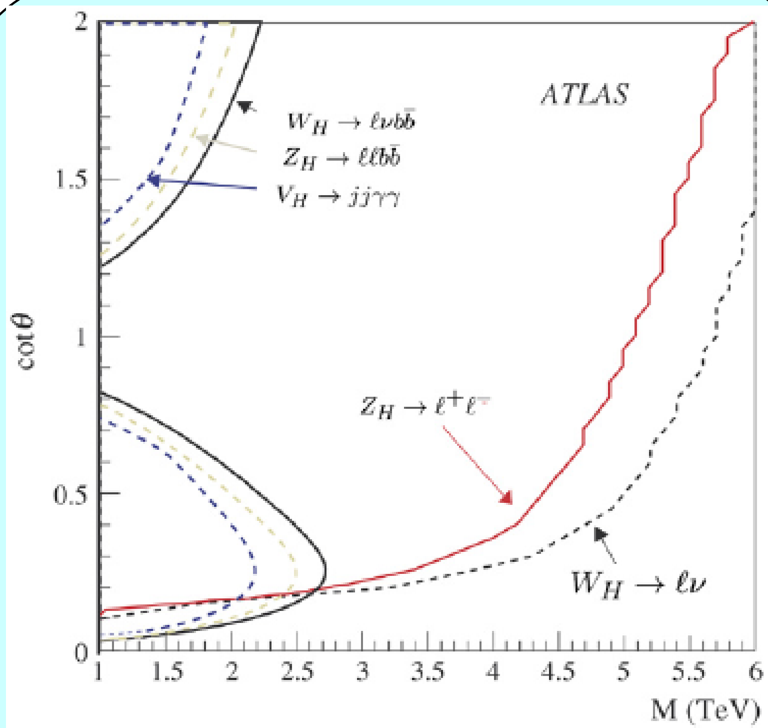


1. Heavy gauge boson of L^2H model

more detailed analysis…

W_H^3 { → l^+l^-
→ Zh → l^+l^- bb(bar) / jj$\gamma\gamma$

$W_H^\pm$ { → $l^\pm\nu$
→ $W^\pm$h → $l^\pm\nu$ bb(bar) / jj$\gamma\gamma$



5σ discovery at the LHC with 300 fb^{-1}

Regions to the left of lines are accessible.

$Z_H = W_H^3$
$V_H = W_H^3, W_H^\pm$

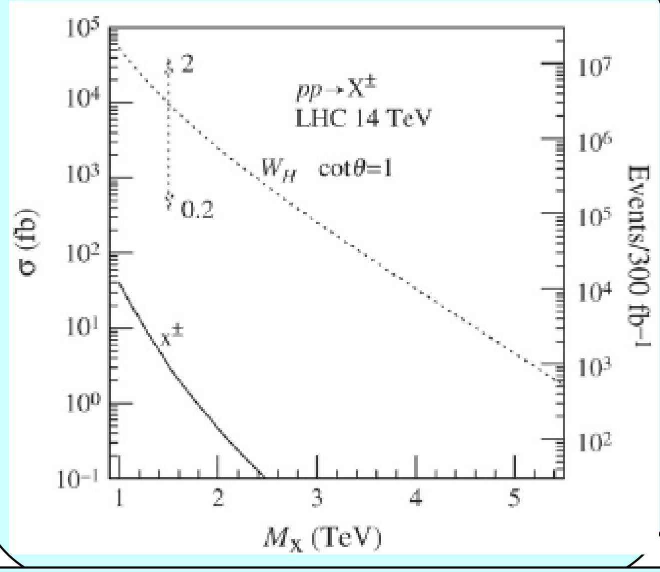
2. Heavy gauge boson of SU(3) model

<$X^{\pm}$ and Y bosons>

- do not couple to SM fermions
- production cross section : suppressed by v^2/f^2

$L \propto v/f \rightarrow \sigma \propto v^2/f^2$

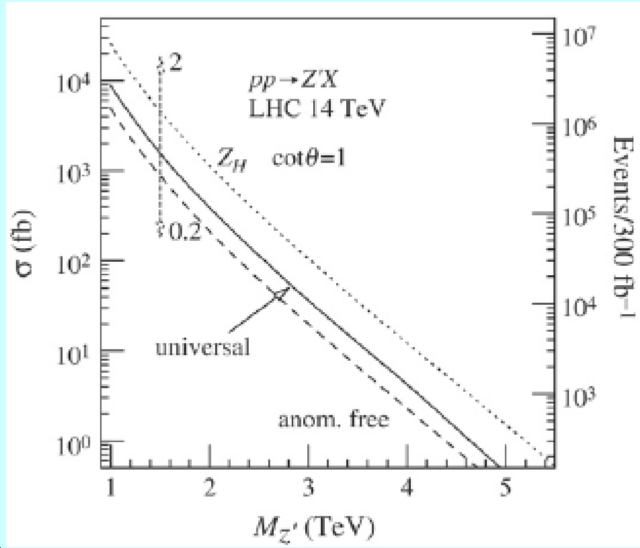
$$M_X = M_Y = \frac{gf}{\sqrt{2}} \approx 0.46 f, \quad M_{Z'} = \frac{\sqrt{2} g f}{\sqrt{3 - t_w^2}} \approx 0.56 f.$$



Solid lines correspond to the $SU(3)$ simple group model
Dotted lines represent the Littlest Higgs model with $\psi = \pi/4$,
dotted arrows show the variation when cot ψ is varied between 0.2 and 2

<Z' boson>

- production cross section : unsuppressed
- l^+l^- and Zh event rate → non-LH Z' or LH^2



3. Heavy gauge boson of L^2HT model

spectrum : same as original LH
phenomenology : different from LH

↑

TeV-scale gauge bosons = T-odd

↓

resemble SUSY with R parity

<B_H boson>

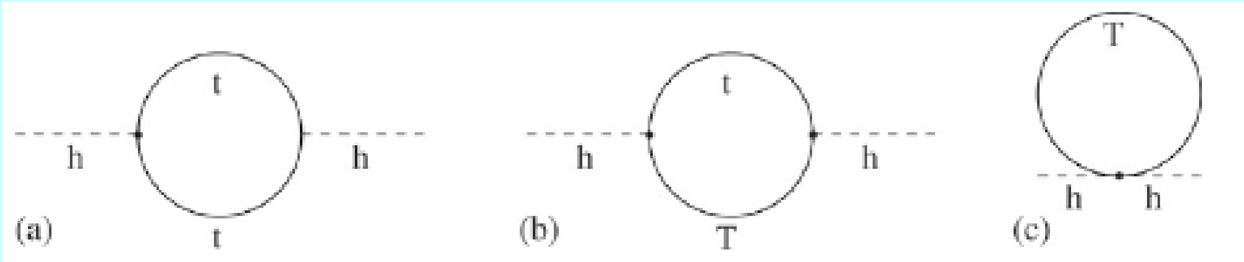
$$M(B_H) = g' f/\sqrt{5} \approx 0.16 f$$

- 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

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

<One-loop contribution to Higgs>



$$-6\lambda_t^2 \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2} \qquad -6\lambda_T^2 \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 - M_T^2} \qquad +6\frac{\sqrt{2}\lambda_T}{f} \int \frac{d^4k}{(2\pi)^4} \frac{M_T}{k^2 - M_T^2}$$

(a)+(b)+(c)~0 → quadratic divergences nearly cancel

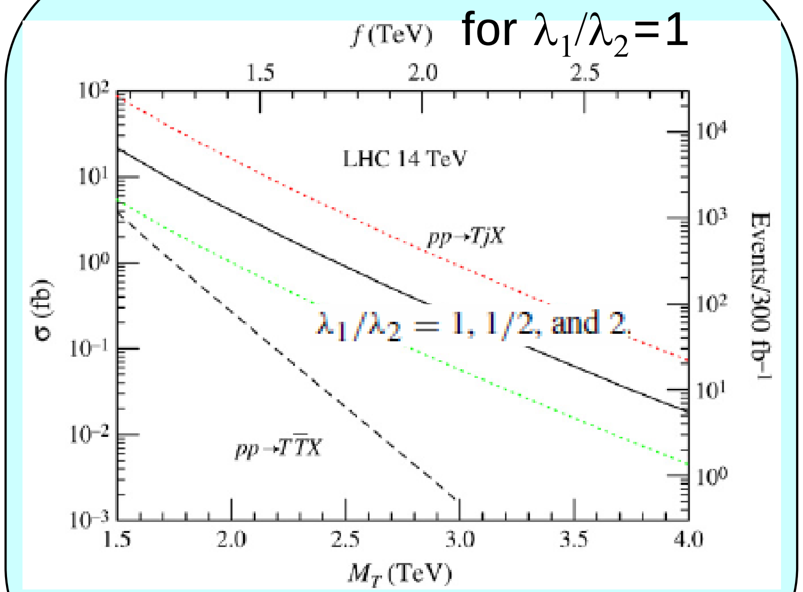
necessary condition : $\frac{M_T}{f} = \frac{\lambda_t^2 + \lambda_T^2}{\sqrt{2}\lambda_T}$ Eq.(35)

1. Heavy top quark of L^{2}H model

<pair production>

gg → TT(bar) , qq(bar) → TT(bar)

- strong interaction : dominate fo low T mass
- not dominant for M_T >> 1TeV

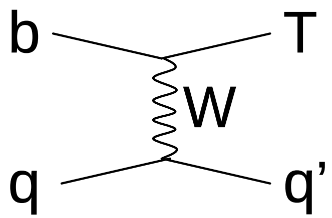


dashed line corresponds to the $T\bar{T}$ pair production

<single production>

bq → Tq'

- W exchange process
- becomes dominant



(decay of T)

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

1. Heavy top quark of L^2H model

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

<T → Wb>

- final state : Wb → lνb

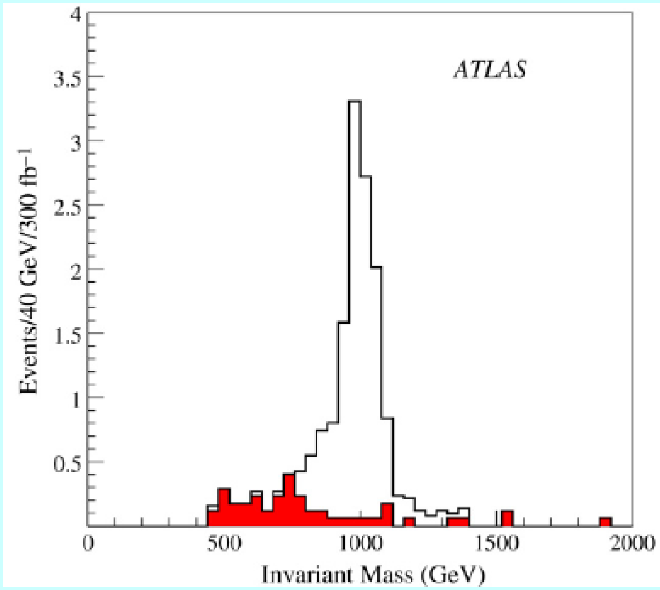
2000 GeV for $\lambda_1/\lambda_2=1$
2500 GeV for $\lambda_1/\lambda_2=2$
(5σ discovery, 300fb^{-1})

<T → Zt>

- final state : Z → l^+l^- , t → Wb → lνb
- small background (tbZ)
- lower statistics than Wb

1050 GeV for $\lambda_1/\lambda_2=1$
1400 GeV for $\lambda_1/\lambda_2=2$
(5σ discovery, 300fb^{-1})

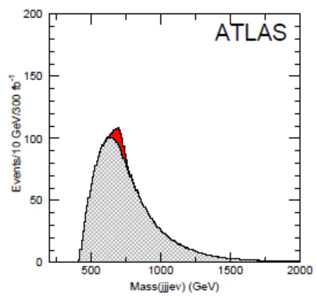
Invariant mass of the Zt pair



$M_T = 1$ TeV, $\lambda_1/\lambda_2 = 1$, and Br$(T \to Zt) = 25\%$.

<T → 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

$$\frac{M_T}{f} = \frac{\lambda_t^2 + \lambda_T^2}{\sqrt{2}\lambda_T} \quad \text{Eq.(35)}$$

- λ_t : top Yukawa
- M_T : directly measured
- f : W_H boson (mass, cross section)
  - $M(W_H) = \frac{g}{\sin 2\psi} f,$
  - $\sigma_W \rightarrow \psi$, g
- λ_T : more difficult ...

  - single T production cross section : final state has b
  - large uncertainty in b quark pdf (Probability Density Function)
  - total cross section : all T decay channel …

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^2HT model

<T_+ and T_->

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

<T_+>

- phenomenology : similar to no T parity
- same decay : Wb, tZ, th

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

- new decay : $T_+ \rightarrow T_- B_H$

<T_->

- pair-production : $qq(bar) \rightarrow T_- T_-(bar)$
  $gg \rightarrow T_- T_-(bar)$
- decay : tB_H
- large amount of missing p_t (B_H)
- vector-like TeV-scale T-odd fermions → LTP B_H