Little Higgs Model and its phenomenology

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@ KEK

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§1. Introduction

◎ New Physics $\longrightarrow$ Higgs sector, etc.

Higgs mass self-coupling, yukawa, etc.

★ Various models estimate m_H:

○	MSSM	$m_H \lesssim$ 130 GeV	$\Longleftarrow$	symmetry
○	Little Higgs	$m_H \sim \mathcal{O}$(200GeV)	$\Longleftarrow$	symmetry
○	Top-condensate	$m_H \sim \sqrt{2} m_t$	$\Longleftarrow$	quasi-IR fixed point of RGE
	⋮			

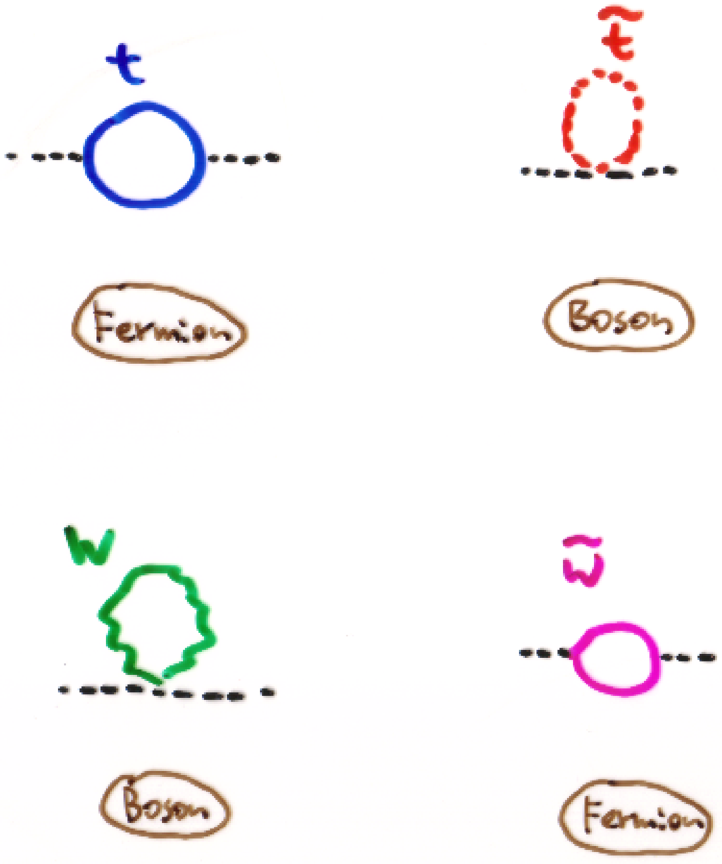
• Little Higgs models are based on the idea,

Higgs as the pseudo Nambu-Goldstone boson.

Cancellation of quadratic divergence

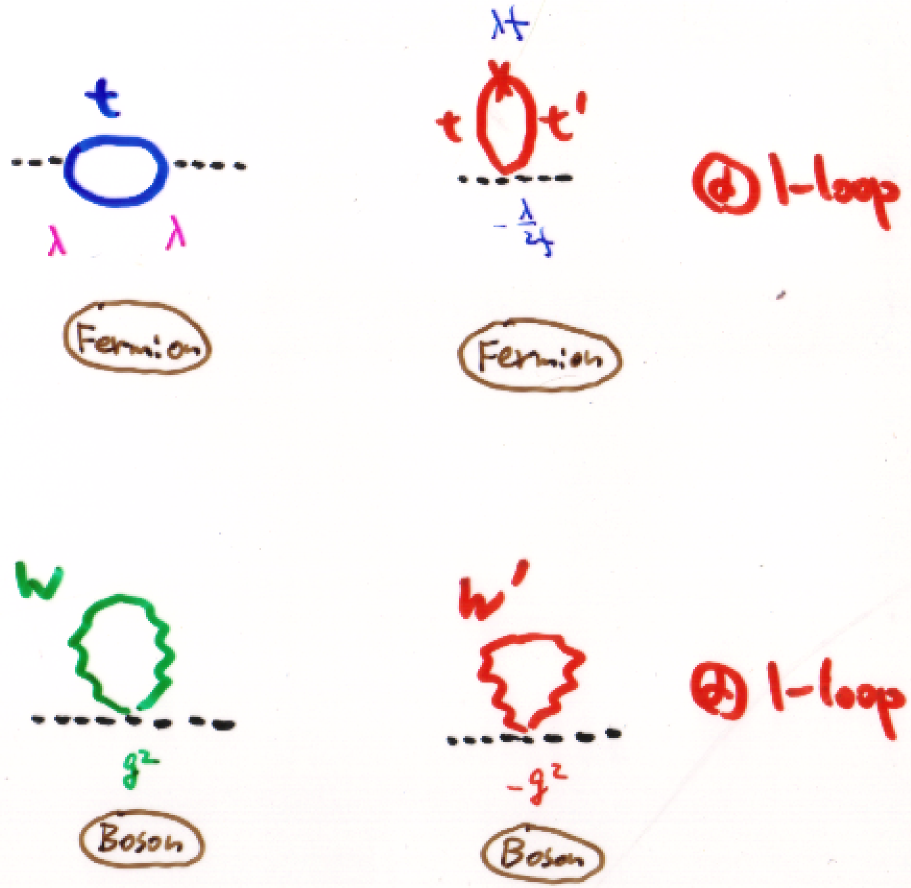
SUSY

Fermion-loops cancel Λ^2 of boson-loops thanks to the opposite spin statistics.

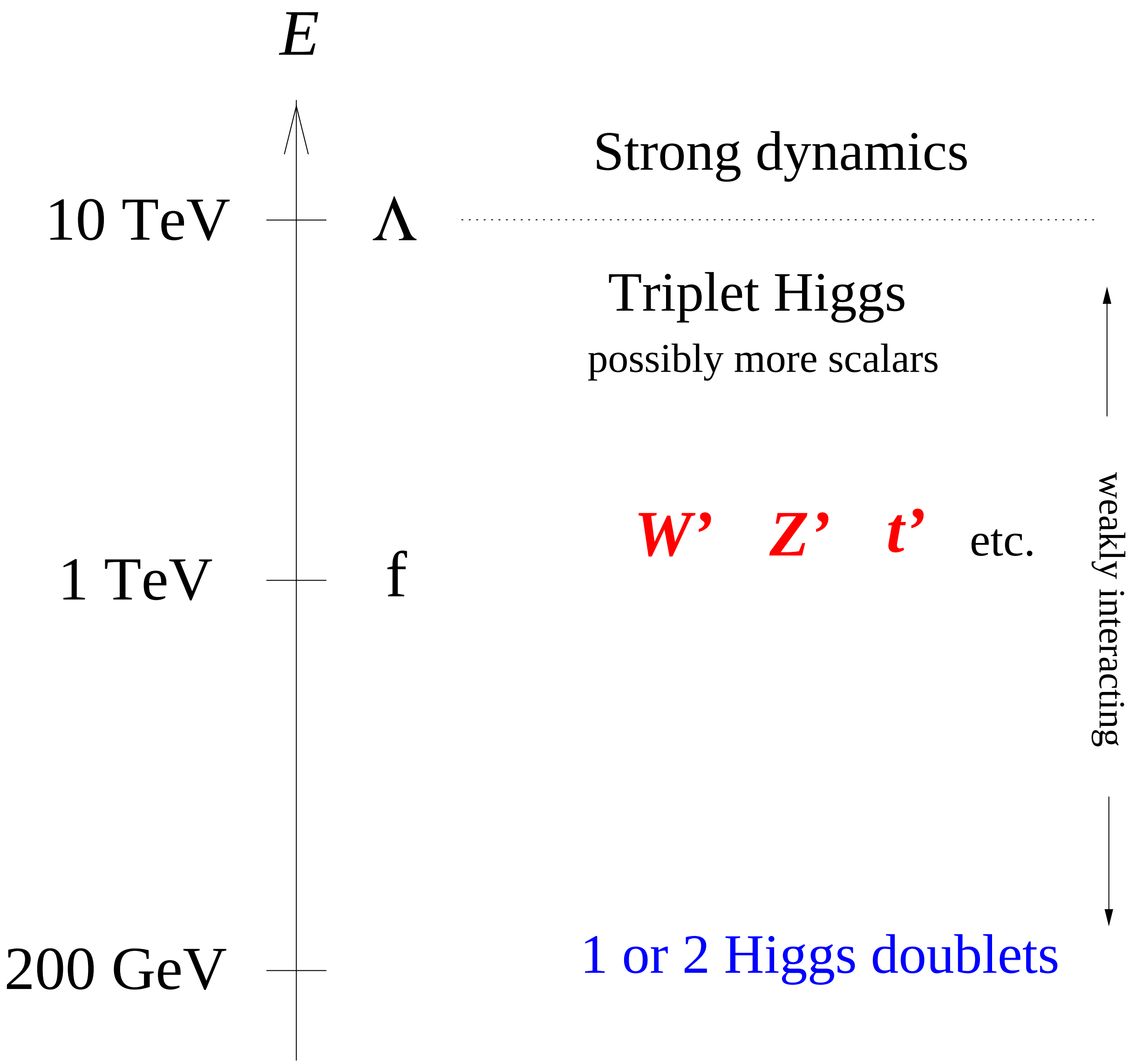


Little Higgs

The same-spin particles cancel Λ^2 thanks to a symmetry built in.



Mass spectrum for Little Higgs models



§2. The Littlest Higgs model

N.Arkani-Hamed, A.G.Cohen, E.Katz, and A.E.Nelson, JHEP **0207**, 034 (2002).

- For the little higgs mechanism, we need $W^a, W'^a, B, B', \cdots$, i.e., our global symmetry group G must contain

$$G \supset G_1 \times G_2 \equiv [SU(2) \times U(1)]^2. \qquad \cdots \qquad \text{rank 4}$$

- We may take $G = SU(5)$ and consider the symmetry breaking pattern:

$$SU(5) \to SO(5)$$

- A convenient basis for the breaking is characterized by the direction Σ_0,

$$\Sigma_0 = \begin{pmatrix} & & \mathbb{1} \\ & 1 & \\ \mathbb{1} & & \end{pmatrix}.$$

- We embed the gauge generators of G_1 and G_2 into the global $SU(5)$:

$$Q_1^a = \begin{pmatrix} \sigma^a/2 & & \\ & & \\ & & \end{pmatrix}, \qquad Q_2^a = \begin{pmatrix} & & \\ & & \\ & & -\sigma^{a*}/2 \end{pmatrix},$$

$$Y_1 = \mathrm{diag}(-3,-3,2,2,2)/10, \qquad Y_2 = \mathrm{diag}(-2,-2,-2,3,3)/10.$$

★ We will find

$$[SU(2)\times U(1)]^2 \xrightarrow{\Sigma_0} SU(2)_L \times U(1)_Y \quad \text{(SM gauge group)}$$

- The non-linear sigma model based on $SU(5)/SO(5)$ has 14 NG bosons:

$$\underbrace{\mathbf{1}_0 \oplus \mathbf{3}_0}_{\text{eaten by } W'^a, B'} \quad \oplus \quad \underbrace{\mathbf{2}_{\pm 1/2} \oplus \mathbf{3}_{\pm 1}}_{\text{10 NG bosons}}$$

Non-linear sigma field

$$\Sigma = e^{2i\Pi/f}\Sigma_0, \quad \Pi = \begin{pmatrix} \mathbf{0}_{2\times 2} & h^\dagger/\sqrt{2} & \phi^\dagger \\ h/\sqrt{2} & \mathbf{0}_{1\times 1} & h^*/\sqrt{2} \\ \phi & h^{\mathrm{T}}/\sqrt{2} & \mathbf{0}_{2\times 2} \end{pmatrix},$$

$$h = (h^+,\ h^0), \quad \phi = \begin{pmatrix} \phi^{++} & \phi^+/\sqrt{2} \\ \phi^+/\sqrt{2} & \phi^0 \end{pmatrix}.$$

Under the global $SU(5)$, Σ transforms as $\Sigma \to \Sigma' = g\Sigma g^T$, $\qquad g \in SU(5)$.

The Littlest Higgs model @tree

$$\boxed{\mathcal{L}_0 = \mathcal{L}_K + \mathcal{L}_t + \mathcal{L}_\psi}$$

- $\mathcal{L}_K$: kinetic term

$$\mathcal{L}_K = \frac{f^2}{4}\text{tr}|D_\mu\Sigma|^2 + (\text{fermion}) + (\text{gauge}) + \cdots ,$$

$$D\Sigma = \partial\Sigma - \sum_{j=1}^{2}\left\{ig_j W_j^a(Q_j^a\Sigma + \Sigma Q_j^{aT}) + ig'_j B_j(Y_j\Sigma + \Sigma Y_j^T)\right\} .$$

- $\mathcal{L}_t$: yukawa sector for t and t'

$$\mathcal{L}_t = \frac{\lambda_1}{2} f\epsilon_{ijk}\epsilon_{xy}\chi_i\Sigma_{jx}\Sigma_{ky}t^c + \lambda_2 f t' t'^c + (\text{h.c.}) ,$$

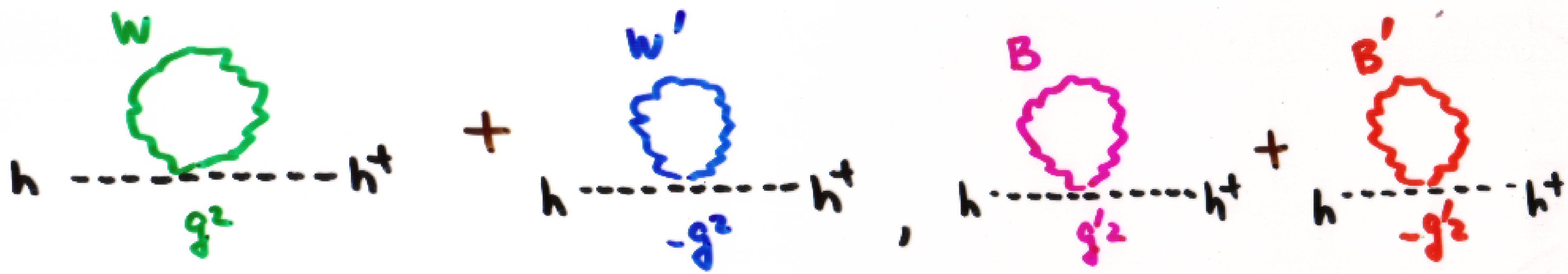
$$\chi_i = (b\ t\ t'), \quad i,j,k = 1,2,3, \quad x,y = 4,5$$

- $\mathcal{L}_\psi$: yukawa sector for other fermions

Gauge-Higgs coupling

$$\mathcal{L}_{h2} = \frac{1}{4} h \left(g_1 g_2 W_1^a W_2^a + g_1' g_2' B_1 B_2 \right) h^\dagger$$
$$= \frac{1}{4} h \left[g^2 \left(W^a W^a - W'^a W'^a \right) + g'^2 \left(B B - B' B' \right) \right] h^\dagger$$

$\Rightarrow$ **No quadratic divergence!!**

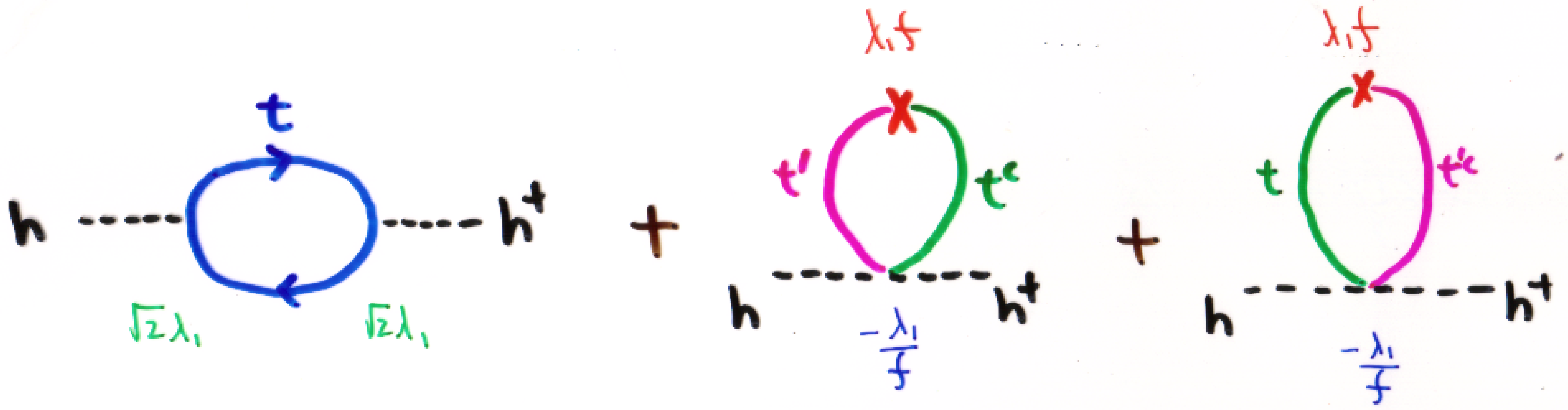


★ No cancellation mechanism for ϕ-part

yukawa sector

$$\mathcal{L}_t = \sqrt{2}\lambda_1 q_3 h t^c + \lambda_1 f t' t^c - \frac{\lambda_1}{f} h h^\dagger t' t^c + \cdots$$

$\Rightarrow$ **No quadratic divergence!!**



Mass spectrum @tree

$$M_{W'} = \frac{f}{2}\sqrt{g_1^2 + g_2^2}, \quad M_{B'} = \frac{f}{2\sqrt{5}}\sqrt{{g'_1}^2 + {g'_2}^2}, \quad M_{t'} = f\sqrt{\lambda_1^2 + \lambda_2^2}$$

- By using SM couplings, we obtain the relations

$$\frac{1}{g_1^2} + \frac{1}{g_2^2} = \frac{1}{g_{\mathsf{SM}}^2} \simeq \frac{1}{0.43}, \quad \frac{1}{{g'_1}^2} + \frac{1}{{g'_2}^2} = \frac{1}{{g'}_{\mathsf{SM}}^2} \simeq \frac{1}{0.12}, \quad \frac{1}{\lambda_1^2} + \frac{1}{\lambda_2^2} \simeq \frac{v^2}{m_t^2},$$

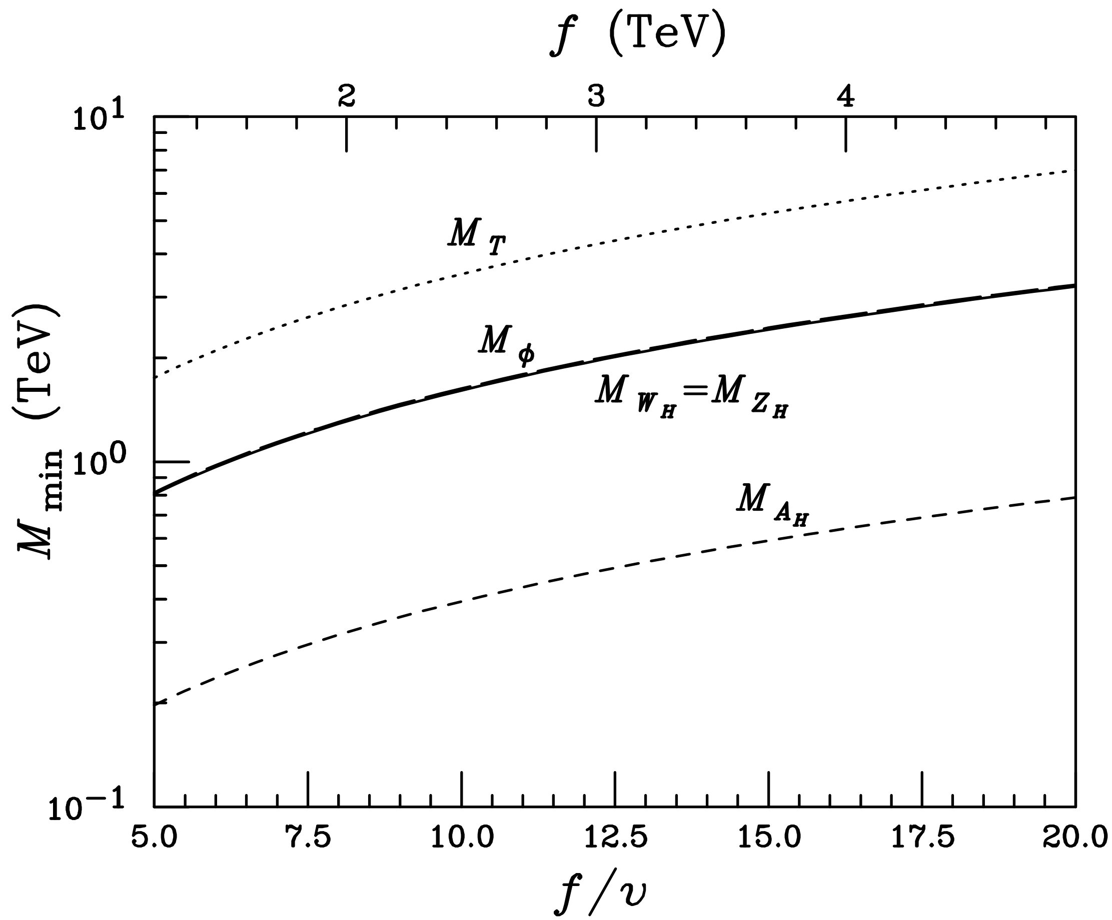
★ Combining the perturbative bound, $g_1^2 < 4\pi, \cdots$, we find approximately

$$0.7 \lesssim M_{W'}/f \lesssim 1.8,$$
$$0.2 \lesssim M_{B'}/f \lesssim 0.8,$$
$$1.4 \lesssim M_{t'}/f \lesssim 3.5.$$

◎ Naturalness requires $f \sim \mathcal{O}(1\mathsf{TeV})$.

Theoretical lower bounds for the heavy state masses

T.Han, et.al, PRD67(2003)095004.



$1/10 < g_2/g_1 < 2, \quad 1/10 < g_1'/g_2' < 2$

Higgs potential @1-loop

- The Higgs potential is obtained from the Coleman-Weinberg potential:

$$V_1 = \frac{\Lambda^2}{(4\pi)^2} M_V^2 + \frac{3}{64\pi^2} M_V^4 \log M_V^2/\Lambda^2 - \frac{3}{64\pi^2} M_f^4 \log M_f^2/\Lambda^2$$

$\longrightarrow$ The quartic coupling for the higgs is determined by the gauge couplings.

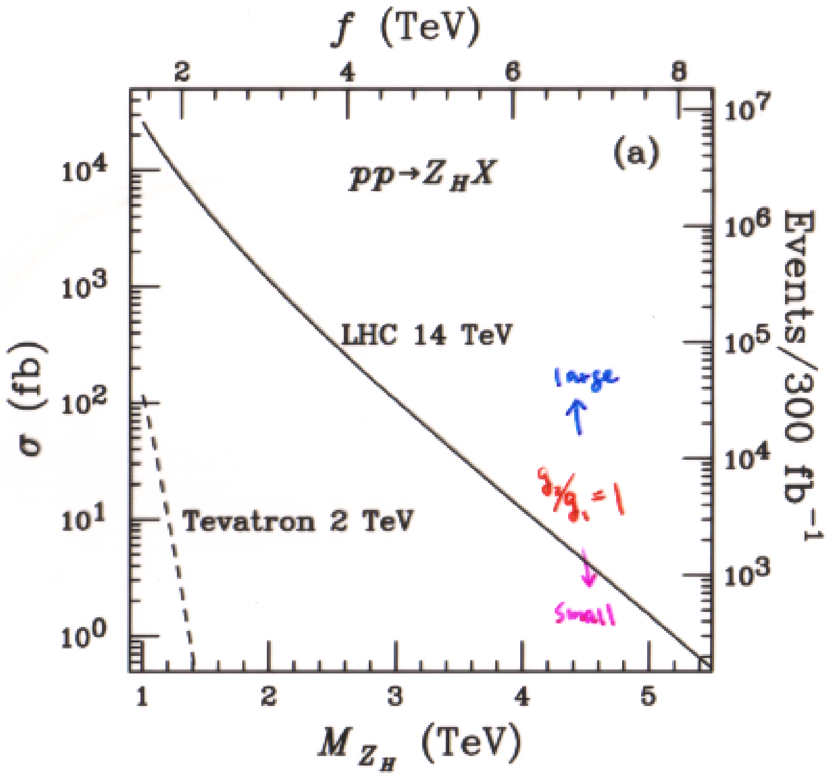
$\longrightarrow$ The negative mass squared of the higgs comes from the fermion loop.

$\longrightarrow$ The triplet higgs also has the VEV proportional to v^2/f^2.

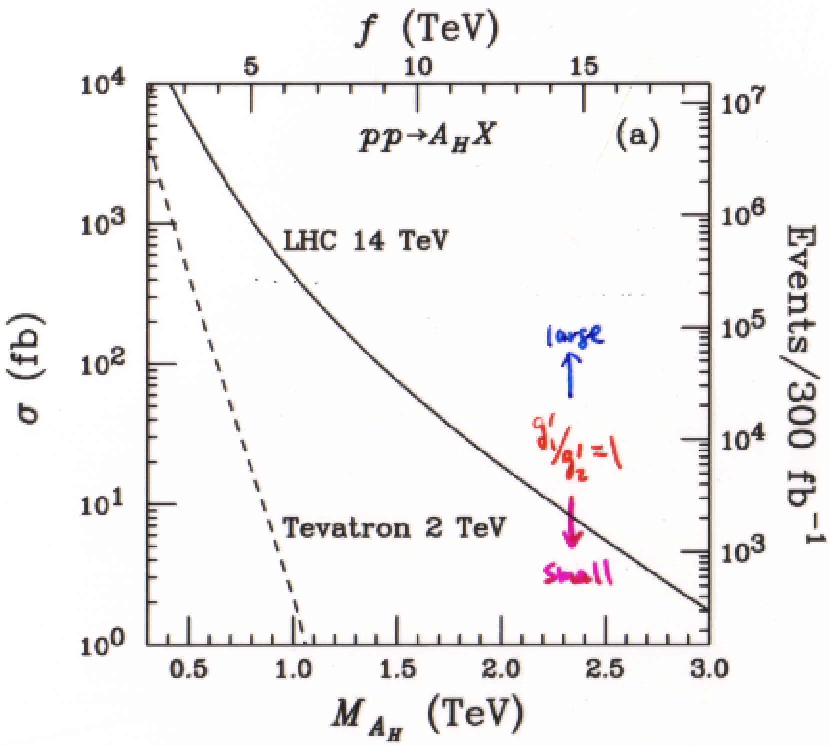
§3. Search for $W', Z', t', \cdots$ at LHC

- Production via the Drell-Yan process, $q\bar{q}' \to Z', A'$

T.Han, et.al, PRD67(2003)095004.



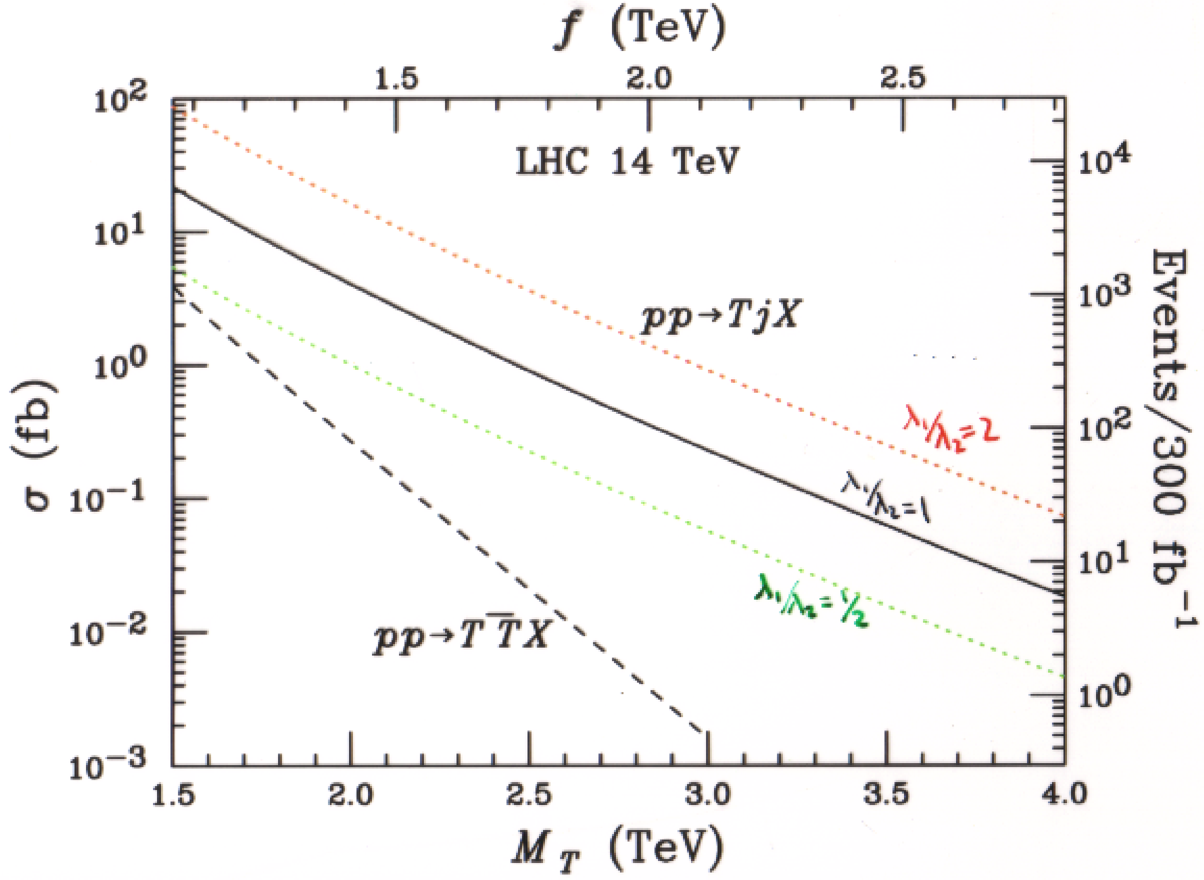
$\mathrm{Br}(Z' \to \ell^+\ell^-) \sim 0.1$



$\mathrm{Br}(A' \to \ell^+\ell^-) \sim 0.4$

- Single t' production via $qb \to q't'$

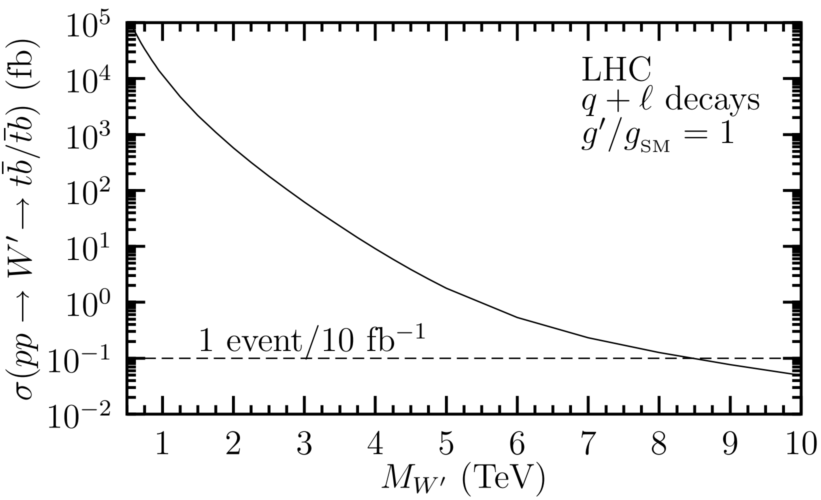
T.Han, et.al, PRD67(2003)095004.

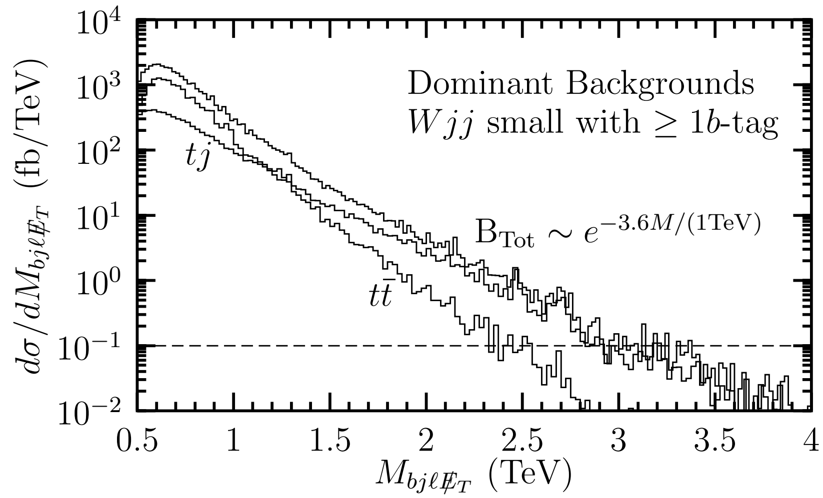


$V_{t'b} = \lambda_1/\lambda_2 \cdot m_t/m_{t'} \cdot V_{tb}^{SM}$

- Search for W' via $pp \to W' \to t\bar{b}/\bar{t}b$

Z. Sullivan, hep-ph/0306266.

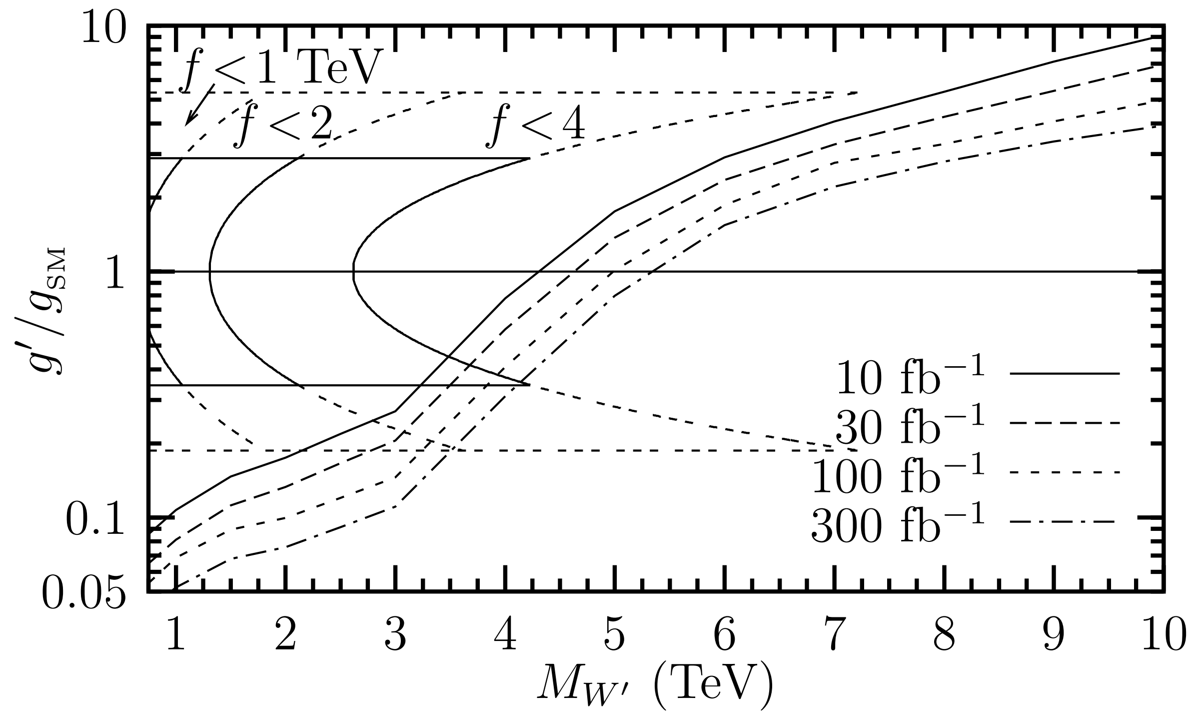




$$\mathcal{L}_{\rm int} = \frac{g'}{2\sqrt{2}} V_{ij} W'_\mu \bar{q}^i_L \gamma^\mu q^j, \qquad g' = g_1/g_2 \quad \text{for LH}$$

★ 95 % C.L. exclusion reach at LHC and predictions of M_W' in the LH model

Z. Sullivan, hep-ph/0306266.



- dot-dashed contours: maximally allowed parameter space,

$$0.187 < g'/g_{\mathsf{SM}} < 5.34$$

- solid contours: perturbative parameter space, $\alpha_i \equiv g_i^2/(4\pi) < 1/\pi$

§4. EW precision tests for the littlest higgs

• The littlest higgs model leads to dangerous operators such as

$$
\begin{aligned}
&W - W',\ Z - W'^3, B' \text{ mixing} && \rightarrow && S, T \\
&t_L - t'_L \text{ mixing} && \rightarrow && T \\
&\langle \phi \rangle \neq 0 && \rightarrow && T
\end{aligned}
$$

★ The symmetry breaking scale is bounded by

$$f > 4\text{TeV} \qquad 95\ \%\ \text{C.L.}$$

C.Csaki, J.Hubisz, G.D.Kribs, P.Meade, J.Terning, PRD67, 115002 (2003).

★ In a similar analysis, the constraints are found as

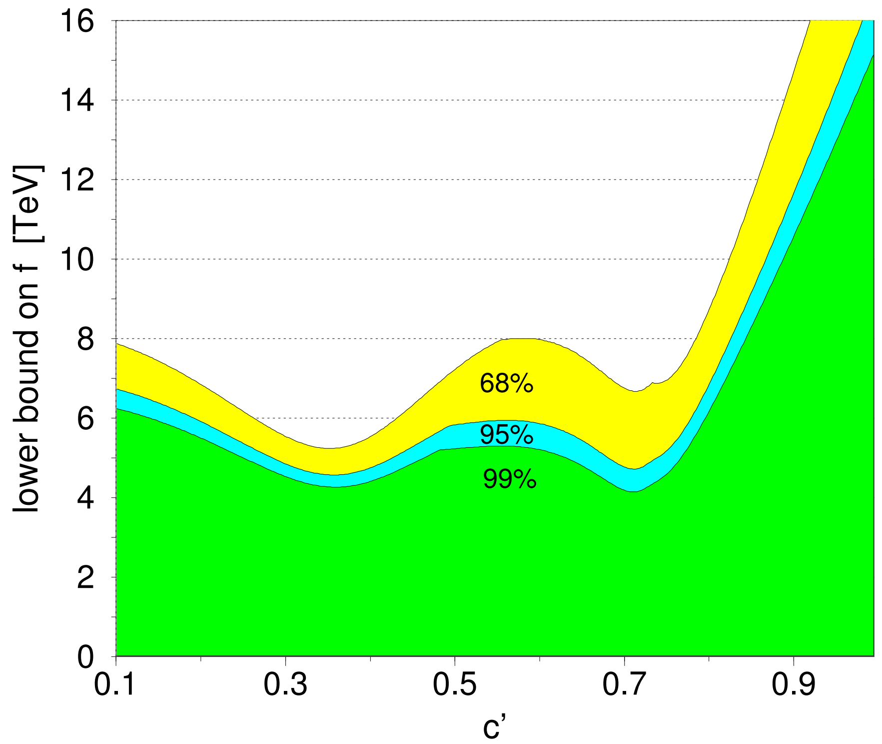
$$f \gtrsim 3.5\text{TeV} \qquad m_{t'} \gtrsim 10\text{TeV}.$$

J.L.Hewett, F.J.Petriello, T.G.Rizzoet, hep-ph/0211218.

⟶ These bounds imply that one would need significantly fine tuning to get m_H as light as 200 GeV.

Excluded parameter region for f

C.Csaki, et. al, PRD67, 115002 (2003).



$$c = g_{\mathsf{SM}}/g_2, \quad c' = g'_{\mathsf{SM}}/g'_2$$

★ The parameter c was allowed to vary between $0.1 < c < 0.995$.

§5. Summary

★ Little Higgs Mechanism: New idea for stabilizing m_H around the weak scale

Particles of the same spin cancel the quadratic divergence at 1-loop.

★ The Littlest Higgs Model: $SU(5)/SO(5)$

$\rightarrow$ The heavy particles such as W', t' should lie around the TeV scale.

$\rightarrow$ We can study them at LHC.

$\rightarrow$ However, this model is constrained by the precision data.

★ Various little higgs models unconstrained by the current data have been proposed by several authors:

$$SU(6)/Sp(6), \quad SU(4)^4/SU(3)^4, \quad SU(9)/SU(8), \cdots$$

$\rightarrow$ Their models contain 2 Higgs doublets and so on.