Little Higgs Phenomenology

Tao Han
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ICFP, KIAS (Oct.6, 2003)

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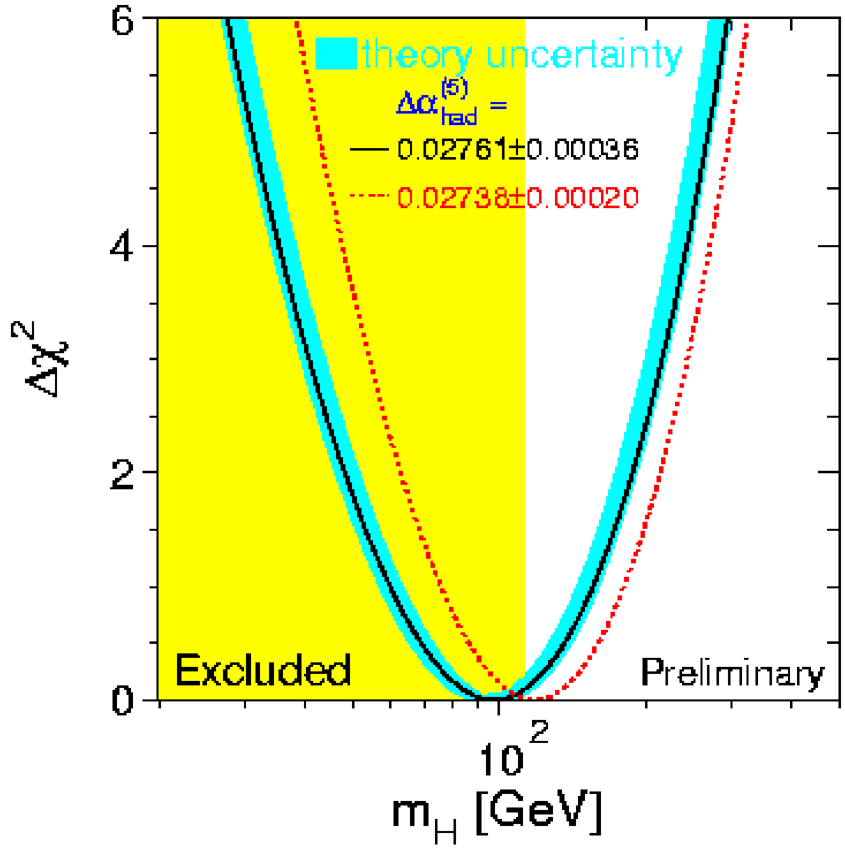
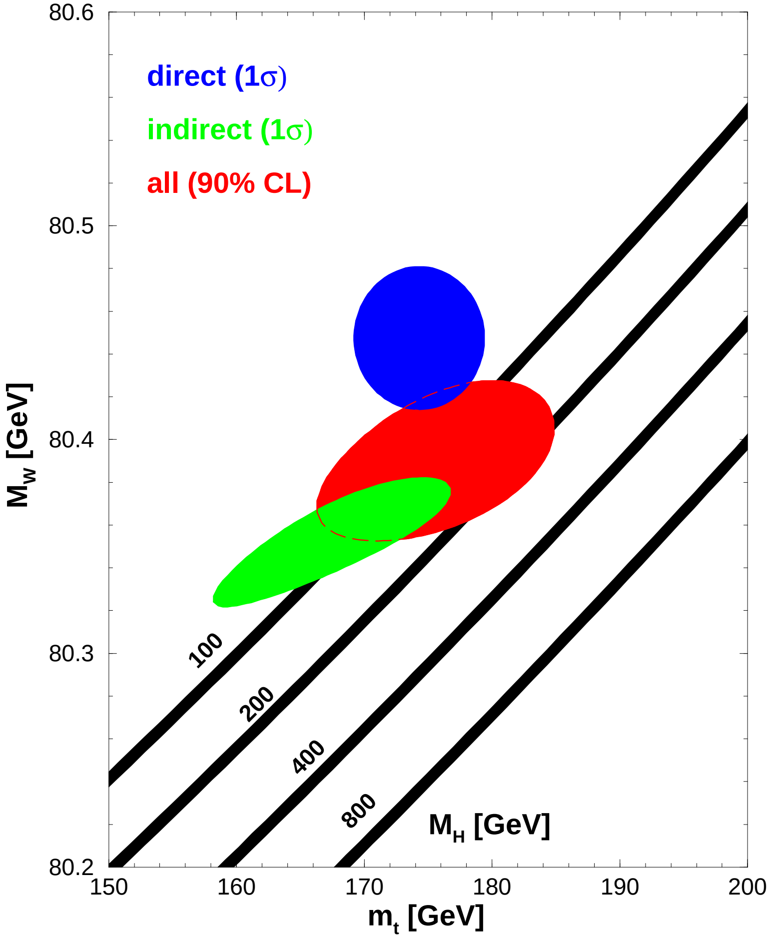
- Introduction and Motivation
- The Littlest Higgs Model *
- The Quark Flavor Sector †
- Collider Phenomenology *
- Summary

*TH, H. Logan, B. McElrath, and L. Wang: hep-ph/0301040 (PRD), hep-ph/0302188 (PLB)
†T.M. Aliev, D.A. Demir, TH, and L. Wang, to appear.

Introduction and Motivation

Precision EW data: SM with a light Higgs ?





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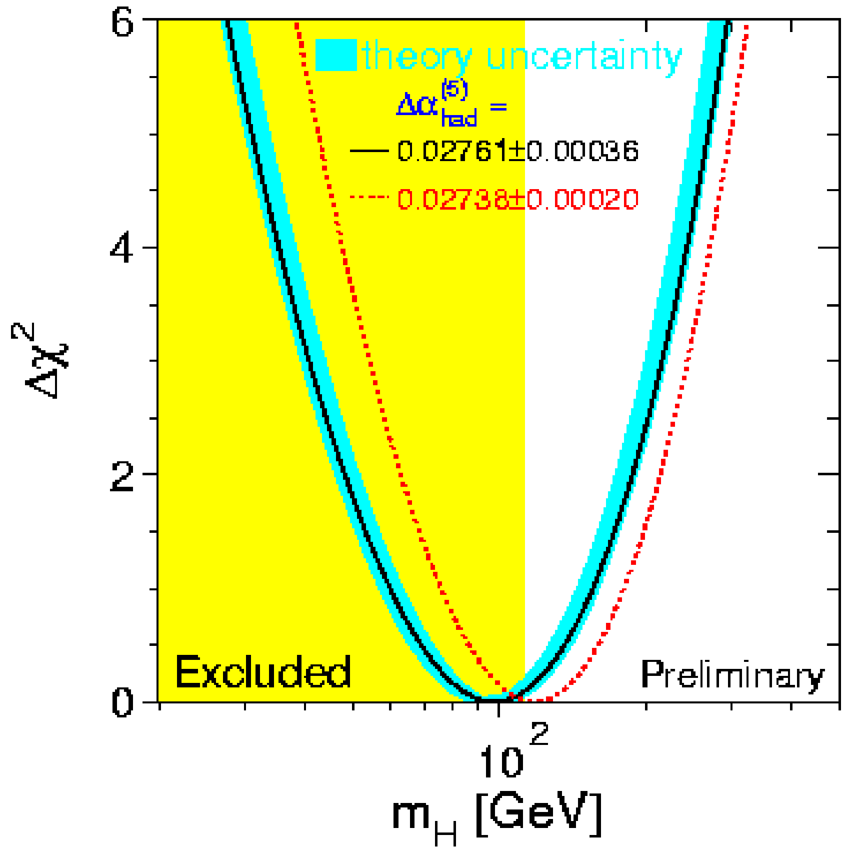
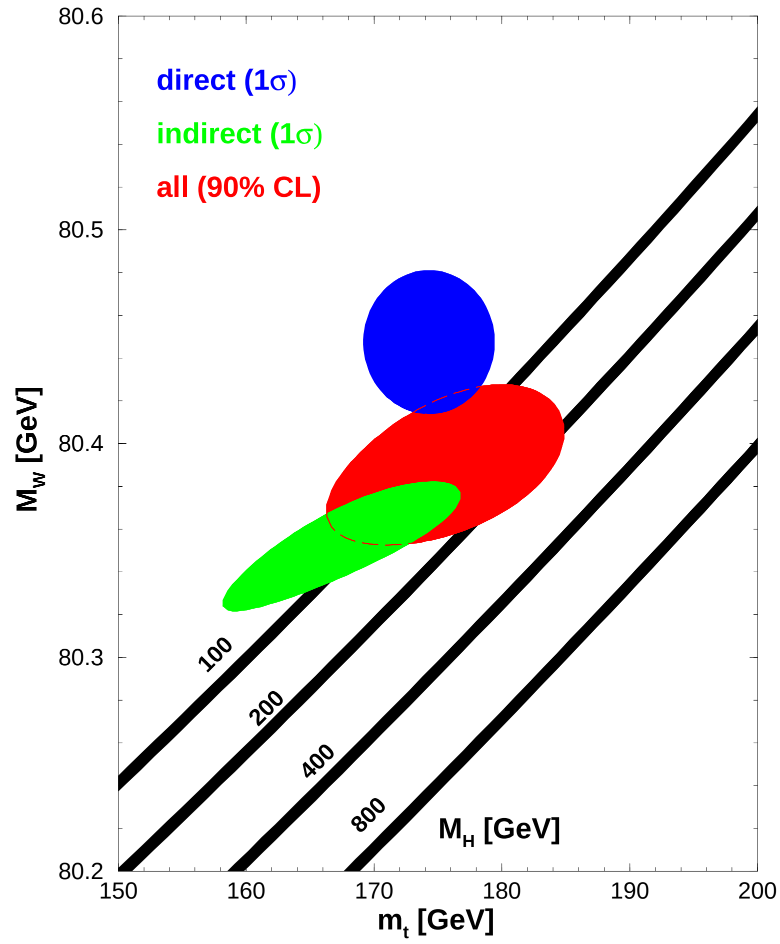




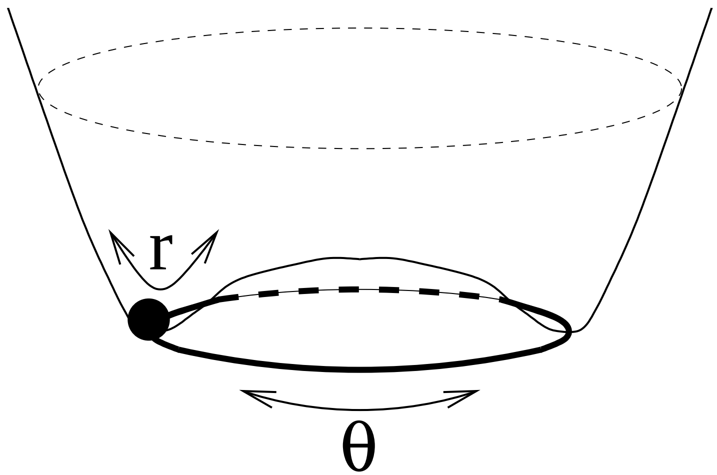
EW precision data: $m_H < 204$ GeV at 95% CL;*

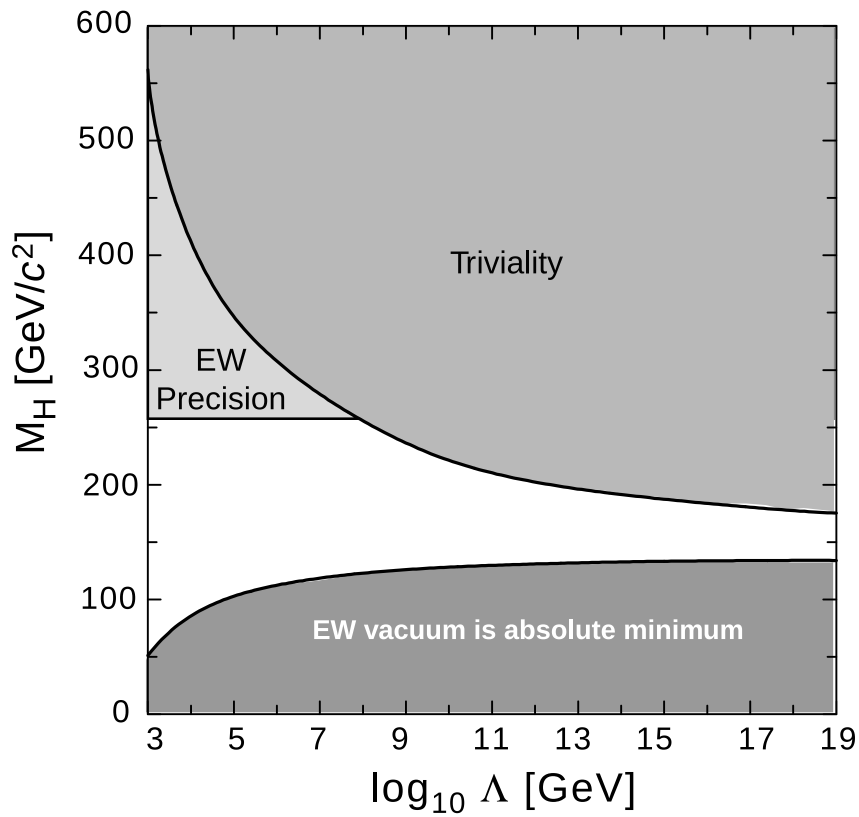
*LEP-EW; Hagiwara et al., PDG, 2002; J.Erler hep-ph/0212272.

SM as an effective theory ?

$$V = -\mu^2\Phi^2 + \lambda\Phi^4, \quad <\Phi> = \frac{v}{\sqrt{2}} = \sqrt{\frac{\mu^2}{2\lambda}}, \quad v^{-2} = \sqrt{2}\, G_F$$

$$m_H = \sqrt{2\lambda}\; v$$





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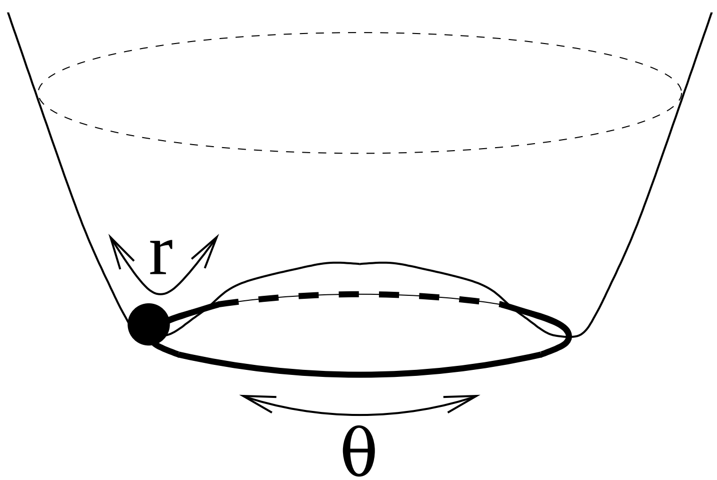
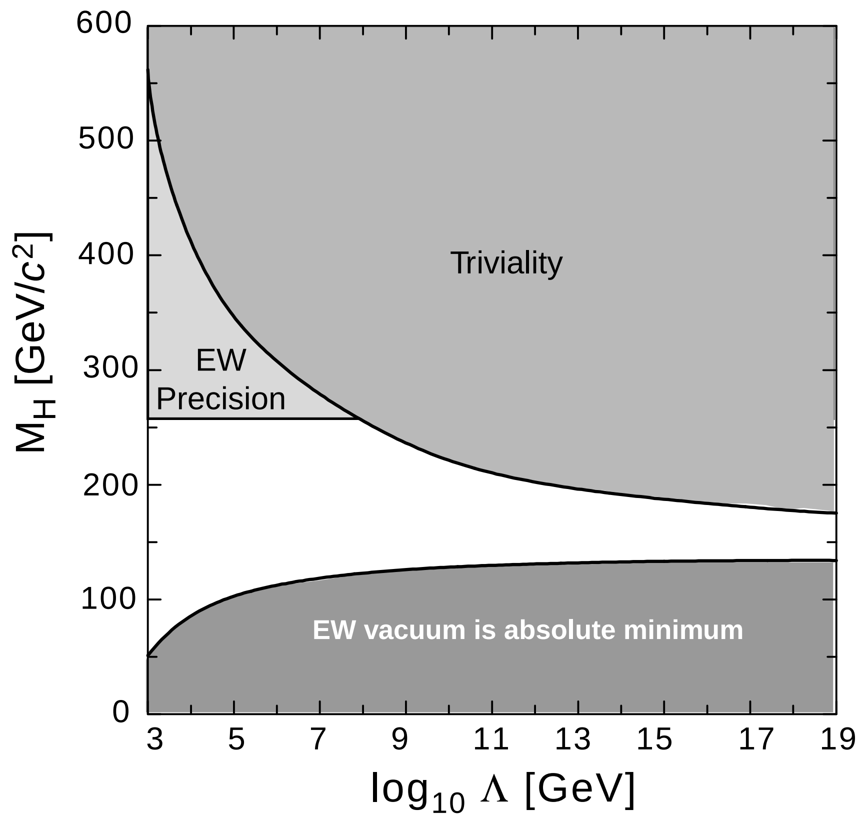


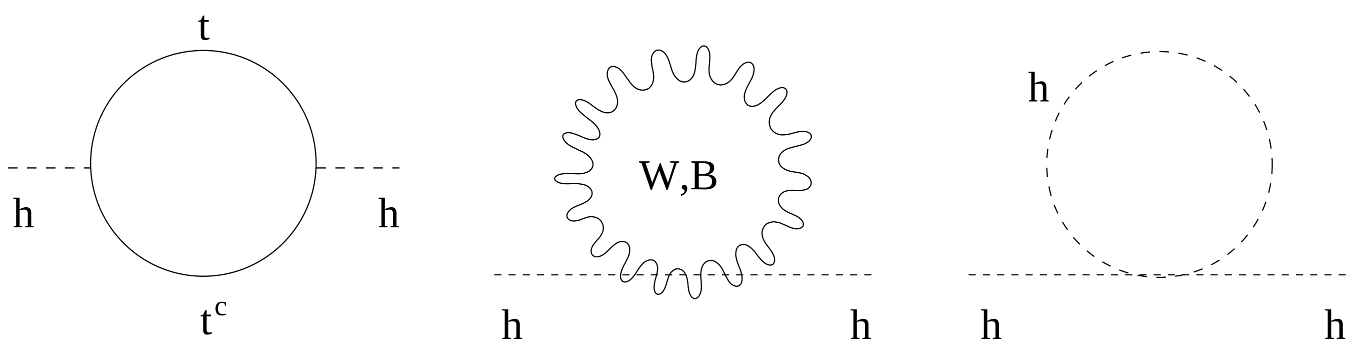


SM with a light H could be an effective theory to $\Lambda \sim M_{pl}$.

a stable vacuum; non-trivial interactions; renormalizability ...

Unnatural ?

Due to quantum corrections, the Higgs mass is quadratically sensitive to the cutoff scale: $\sim \Lambda^2$.



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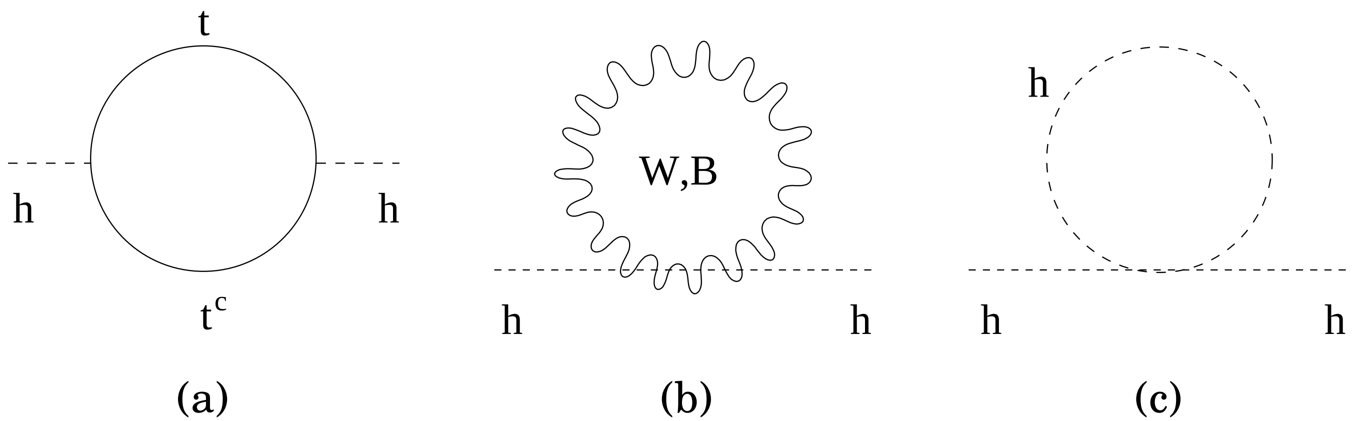

$$m_H^2 = m_{H0}^2 \quad - \frac{3}{8\pi^2} y_t^2 \Lambda^2 \quad + \frac{1}{16\pi^2} g^2 \Lambda^2 \quad + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

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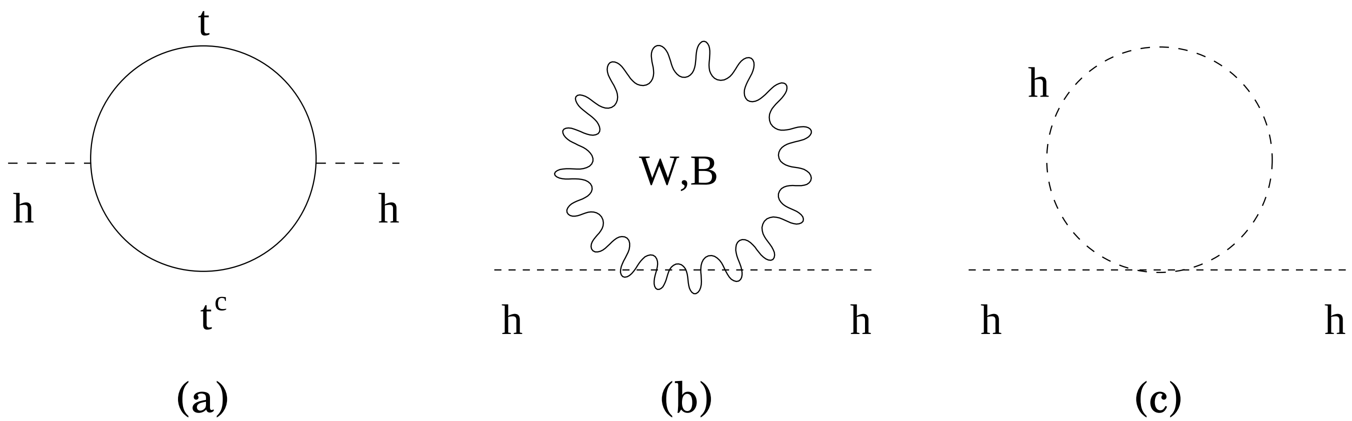

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$$(200 \text{ GeV})^2 = m_{H0}^2 + \left[-(2 \text{ TeV})^2 + (700 \text{ GeV})^2 + (500 \text{ GeV})^2 \right] \left(\frac{\Lambda}{10 \text{ TeV}} \right)^2$$

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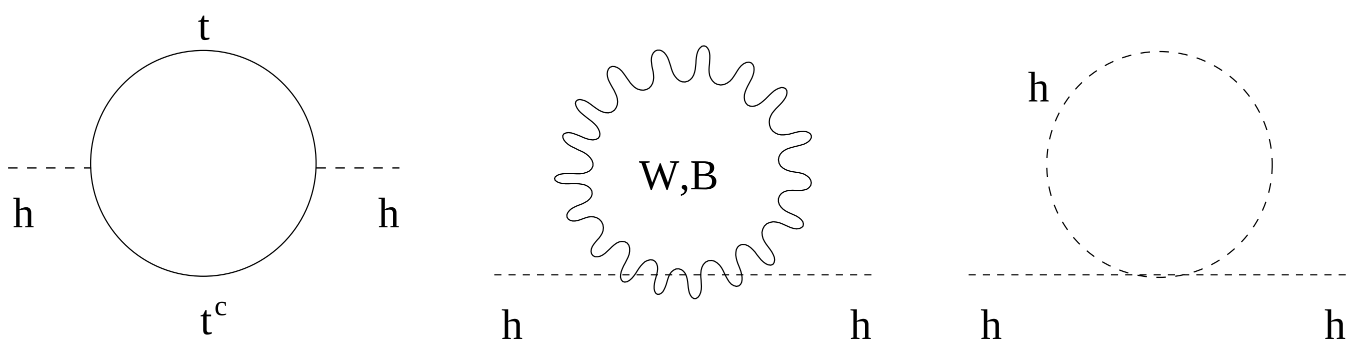

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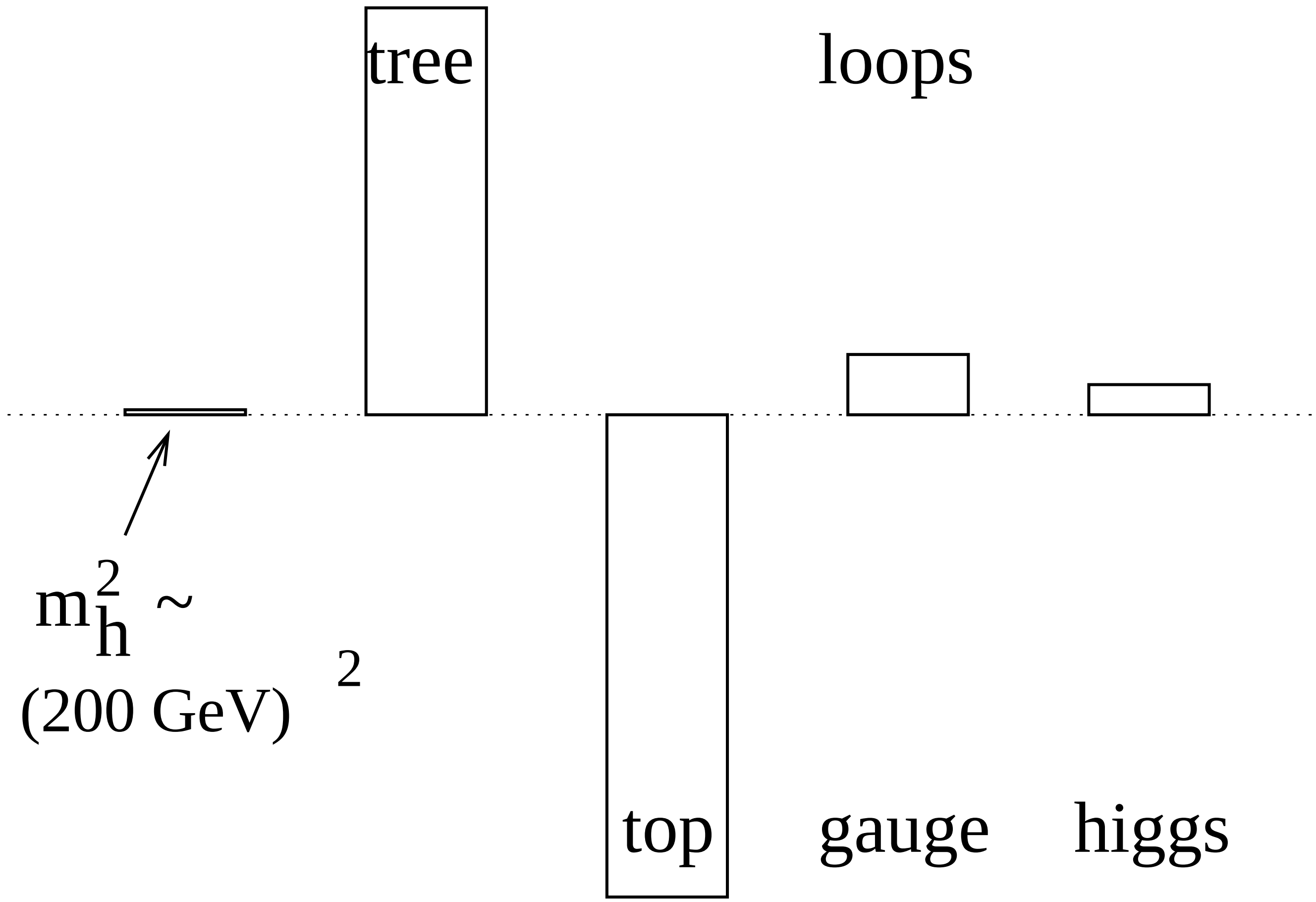
If $\Lambda \sim M_{pl}$, it would need a 10^{-30}-level cancellation!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loops
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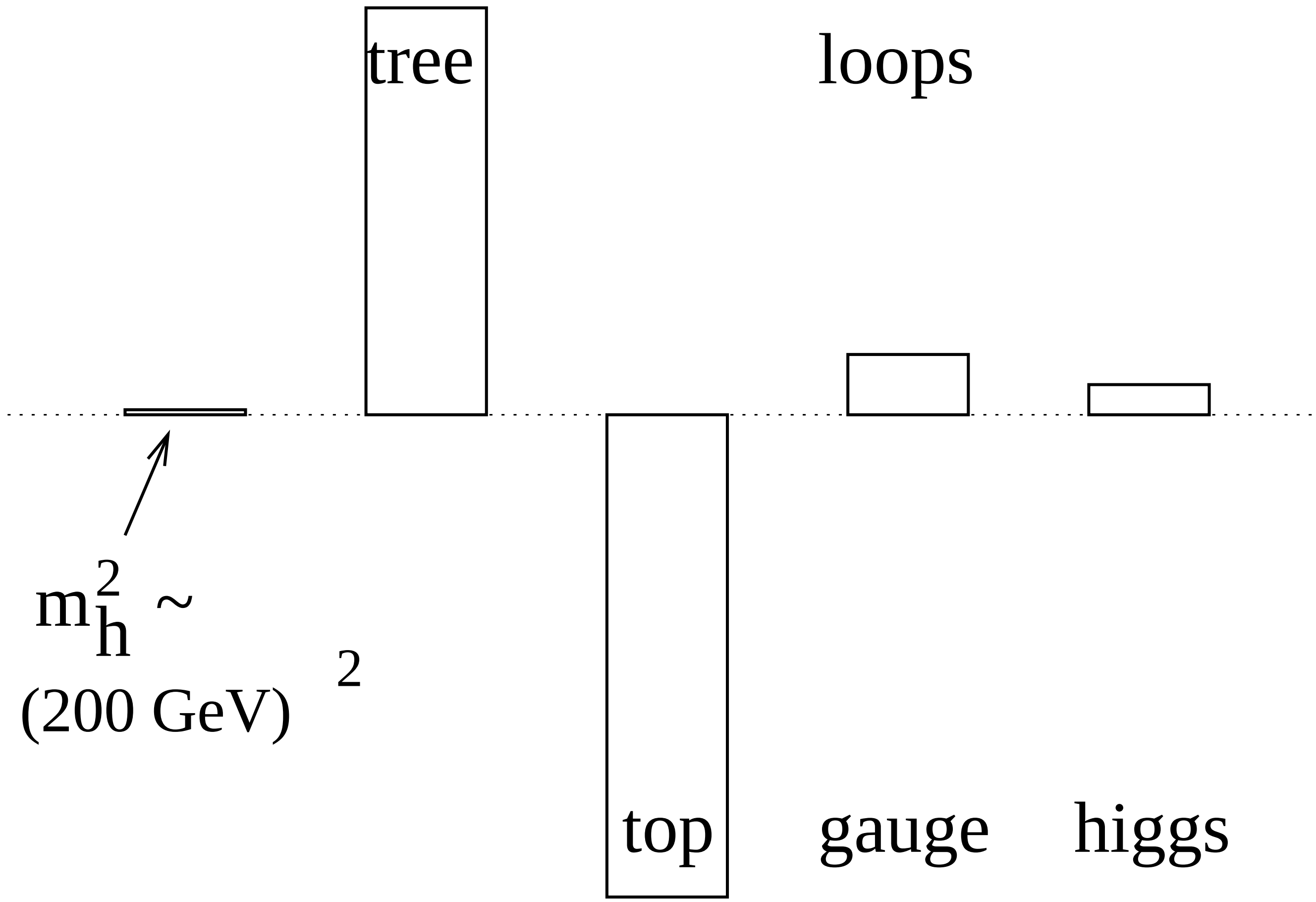

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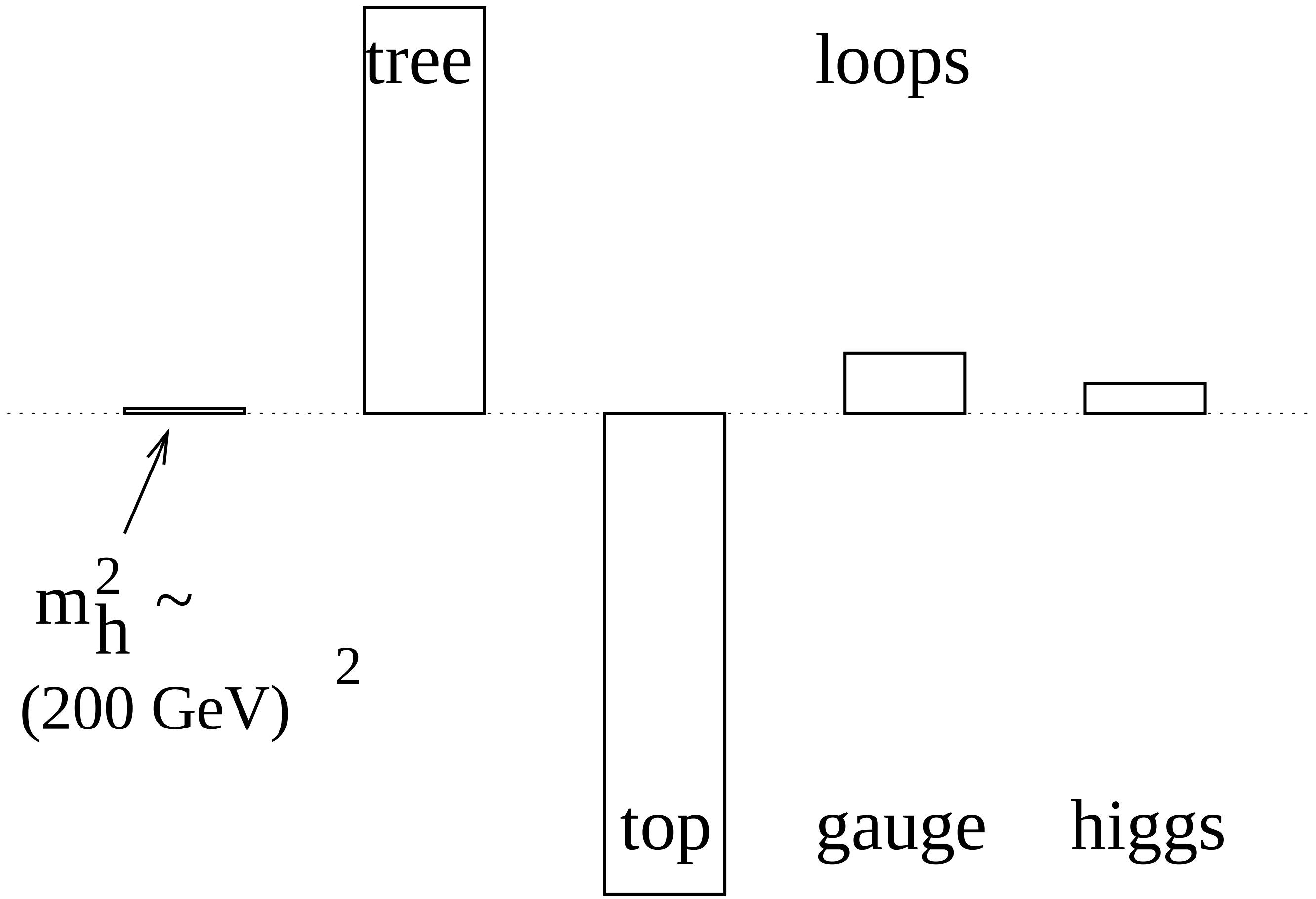

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Naturalness requirement: less than 90% cancellation on m_H^2

$$\Lambda_t \lesssim 3\ \text{TeV} \quad \Lambda_W \lesssim 9\ \text{TeV} \quad \Lambda_H \lesssim 12\ \text{TeV}$$

Cancellation Mechanisms ?

- SUSY (symmetry between *opposite* spin & statistics)

  Natural cancellations: $\tilde{t}$ versus t

  $\tilde{W}$ versus W

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  H_d versus H_u,

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  H_d versus H_u,

lead to

$$\Delta m_H^2 \sim (M_{SUSY}^2 - M_{SM}^2)\frac{\lambda_f^2}{16\pi^2}\ln\left(\frac{\Lambda}{M_{SUSY}}\right)$$

Weak scale SUSY is natural if $M_{SUSY} \sim \mathcal{O}(1)$ TeV.

$\Rightarrow$ predict TeV scale new physics.

The Little Higgs idea

- Higgs is a pseudo-Goldstone boson from global symmetry breaking (at scale $4\pi f$)[‡]
- Higgs acquires a mass radiatively at the EW scale v (by collective breaking)
- Quadratic divergences cancelled at one-loop level by new states:[*]

$$W, Z, B \leftrightarrow W_H, Z_H, B_H; \quad t \leftrightarrow T; \quad H \leftrightarrow \Phi.$$

(cancellation among same spin states!)

An alternative way to keep H light (naturally)

[‡]Dimopoulos, Preskill, 1982; H.Georgi, D.B.Kaplan, 1984; T. Banks, 1984.

[*]Arkani-Hamed, Cohen, Georgi, hep-ph/0105239.

The Littlest Higgs Model

A specific realization: $SU(5)$ Non-linear σ-model*

The gauged non-linear σ-model:

$$\mathcal{L}_\Sigma = \frac{1}{2}\frac{f^2}{4}\text{Tr}|\mathcal{D}_\mu\Sigma|^2, \qquad \Sigma = e^{2i\Pi/f}\Sigma_0,$$

where f is the condensate scale (the Goldstone-boson decay constant);
Σ, Σ_0, Π are 5×5 matrices.

*Arkani-Hamed, Cohen, Katz, Nelson, hep-ph/0206021.

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A subgroup is gauged:

$$G_1 \otimes G_2 = [SU(2)\otimes U(1)]_1 \otimes [SU(2)\otimes U(1)]_2$$

with the co-variant derivative

$$\mathcal{D}_\mu\Sigma = \partial_\mu\Sigma - i\sum_{j=1}^{2}\left[g_j W_j^a(Q_j^a\Sigma + \Sigma Q_j^{a\mathsf{T}}) + g_j' B_j(Y_j\Sigma + \Sigma Y_j^{\mathsf{T}})\right]$$

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The Goldstone bosons:

The spontaneous symmetry breaking by

$$\langle \Sigma \rangle = \Sigma_0 = \begin{pmatrix} & & \mathbb{1} \\ & 1 & \\ \mathbb{1} & & \end{pmatrix}$$

Global: $SU(5) \Rightarrow SO(5)$, leading to 14 Goldstone bosons;

Gauged: $[SU(2) \otimes U(1)]_1 \otimes [SU(2) \otimes U(1)]_2 \Rightarrow SU(2)_L \otimes U(1)_Y$

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The fate of the Goldstone bosons

$1_0 \oplus 3_0$	Longitudinal modes of $Z_H, W_H^{\pm}, A_H$
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The h, ϕ are parameterized by

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

Gauge Cancellation

Coupling of gauge bosons to Higgs is:

$$\mathcal{L}_\Sigma(W \cdot W) = \frac{g^2}{4}\left[W_\mu^a W^{b\mu} - \frac{(c^2 - s^2)}{sc} W_\mu^a W'^{b\mu}\right] \text{Tr}\left[h^\dagger h \delta^{ab}\right] - \frac{g^2}{4}\left[W'^a_\mu W'^{a\mu}\right] \text{Tr}\left[h^\dagger h\right]$$

$$\mathcal{L}_\Sigma(B \cdot B) = \frac{g'^2}{4}\left[B_\mu B^\mu - \frac{(c'^2 - s'^2)}{s'c'} B_\mu B'^\mu\right] \text{Tr}\left[h^\dagger h\right] - \frac{g'^2}{4}\left[B'_\mu B'^\mu\right] \text{Tr}\left[h^\dagger h\right]$$

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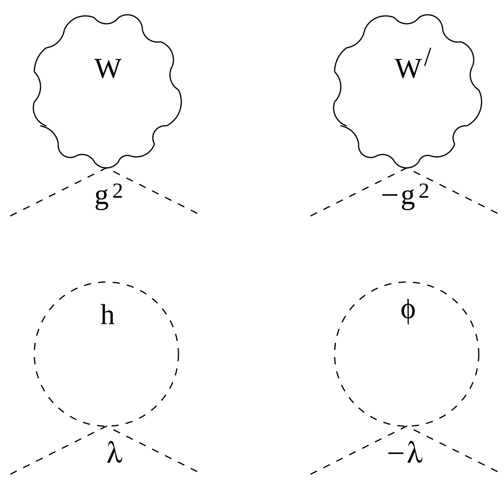
The global symmetry ensures the new gauge bosons couple with $-g_i^2$!



New heavy quark and the $t - T$ Cancellation

Introduce a vector-like pair of colored fermions

$$\tilde{t}:\ (3_c, 1_L)_{Y_i} \quad \text{and} \quad \tilde{t}'^c:\ (3_c, 1_L)_{-Y_i}.$$

The Lagrangian is:

$$\mathcal{L}_Y = \frac{1}{2}\lambda_1 f \epsilon_{ijk}\epsilon_{xy}\chi_i\Sigma_{jx}\Sigma_{ky}u_3'^c + \lambda_2 f\tilde{t}\tilde{t}'^c + \text{h.c.}$$

where $\chi_i = (b_3, t_3, \tilde{t})$, i, j, k run over 1...3, and x, y run over 4...5.

Basically,

$$t_3 \to t_L,\ \tilde{t} \to T_L,\ u_3'^c \to t_R,\ \tilde{t}'^c \to T_R.$$

- The λ_2 term gives the mixing and the top-quark mass

$$m_t = \frac{\lambda_1\lambda_2}{\sqrt{\lambda_1^2 + \lambda_2^2}}\ v; \quad M_T = \sqrt{\lambda_1^2 + \lambda_2^2}\ f.$$

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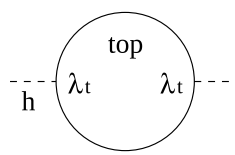
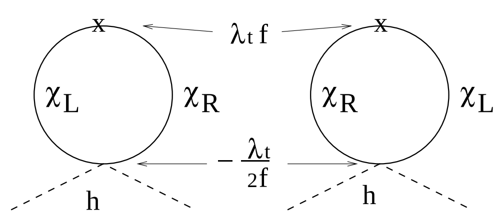
- Due to the $SU(3)_1$ flavor symmetry, the λ_1 term guarantees the cancellation for the quadratic divergence:

$$-i\lambda_1(\sqrt{2}h^0 t_3 + if\tilde{t} - ih^0 h^{0*}\tilde{t}/f) \ u_3'^c + \text{h.c.}$$





Higgs Potential and EWSB

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△ Radiatively, intergrating out the heavy gauge bosons and T:

$$V = \lambda_{\phi^2} f^2 \mathrm{Tr}(\phi^\dagger \phi) + i\lambda_{h\phi h} f \left(h\phi^\dagger h^T - h^* \phi h^\dagger \right) - \mu^2 hh^\dagger + \lambda_{h^4} (hh^\dagger)^2,$$

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- EWSB: for $\mu^2 > 0$

$$v^2 = \frac{\mu^2}{\lambda_{h^4} - \lambda^2_{h\phi h}/\lambda_{\phi^2}}, \qquad v' = \frac{\lambda_{h\phi h}}{2\lambda_{\phi^2}} \frac{v^2}{f}.$$

- Higgs masses:

$$M^2_\Phi \lesssim \lambda_{\phi^2} f^2, \quad m^2_H = 2\mu^2 \sim v^2 \lesssim a_{1-\mathrm{loop}} \frac{f^2}{16\pi^2} + a_{2-\mathrm{loop}} \frac{f^2}{16\pi^2}$$

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Naturalness

If we require no more than 10% fine-tuning, then

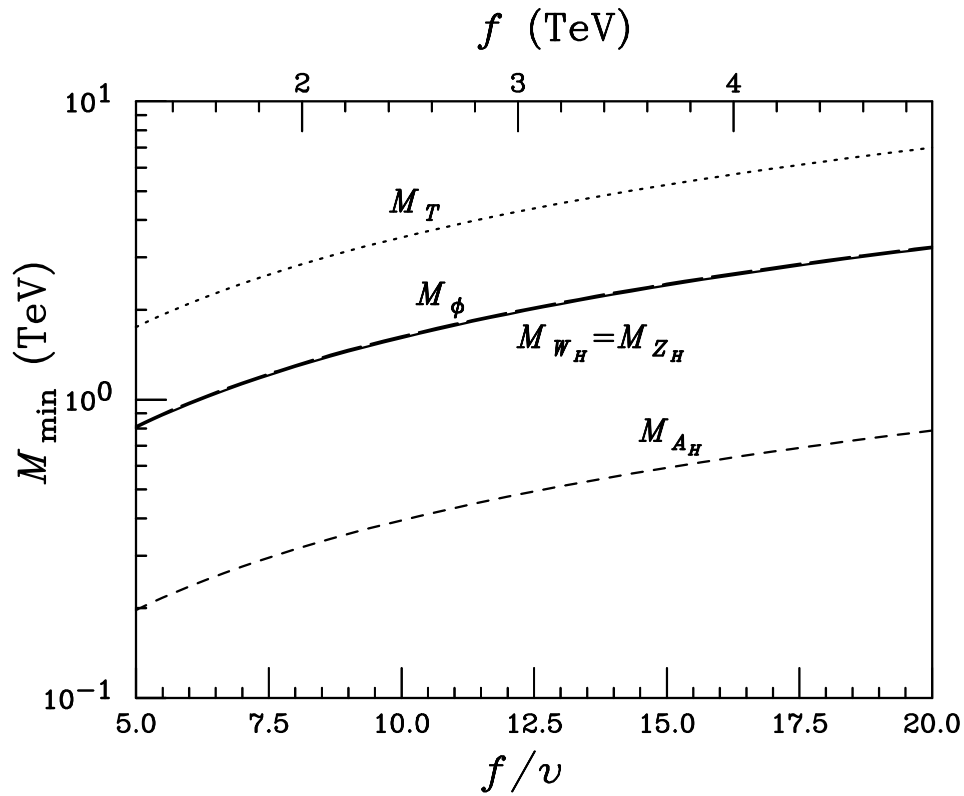
$$f \leq \frac{4\pi m_h}{\sqrt{0.1 a_{\mathrm{max}}}} \simeq \frac{8\ \mathrm{TeV}}{\sqrt{a_{\mathrm{max}}}} \left(\frac{m_h}{200\ \mathrm{GeV}} \right),$$

where a_{max} is the larger of the 1-loop and 2-loop contributions.

Independent model parameters

$\tan\theta = \frac{s}{c} = \frac{g_2}{g_1}$	New $SU(2)$ gauge coupling (or equivalently mixing angle θ)
$\tan\theta' = \frac{s'}{c'} = \frac{g'_2}{g'_1}$	New $U(1)$ gauge coupling (or equivalently mixing angle θ')
f	Symmetry breaking scale $\mathcal{O}$ (TeV)
v'	Triplet ϕ vacuum expectation value, $v'/v \lesssim v/4f$
m_H	Regular SM Higgs mass
M_T	Heavy vector top mass, we trade λ_2 for M_T

New heavy masses in LH:



Heavy particles	Mass
A_H	$m_z^2 s_W^2 \ \frac{f^2}{5 s'^2 c'^2 v^2}$
Z_H	$m_W^2 \ \frac{f^2}{s^2 c^2 v^2}$
W_H	$m_W^2 \ \frac{f^2}{s^2 c^2 v^2}$
$\phi^{0,\ \pm,\ \pm\pm}$	$\frac{2 m_H^2 f^2}{v^2} \ \frac{1}{1-(4v'f/v^2)^2}$
T	$\sqrt{\lambda_1^2 + \lambda_2^2}\ f$

where $m_W = gv/2$.

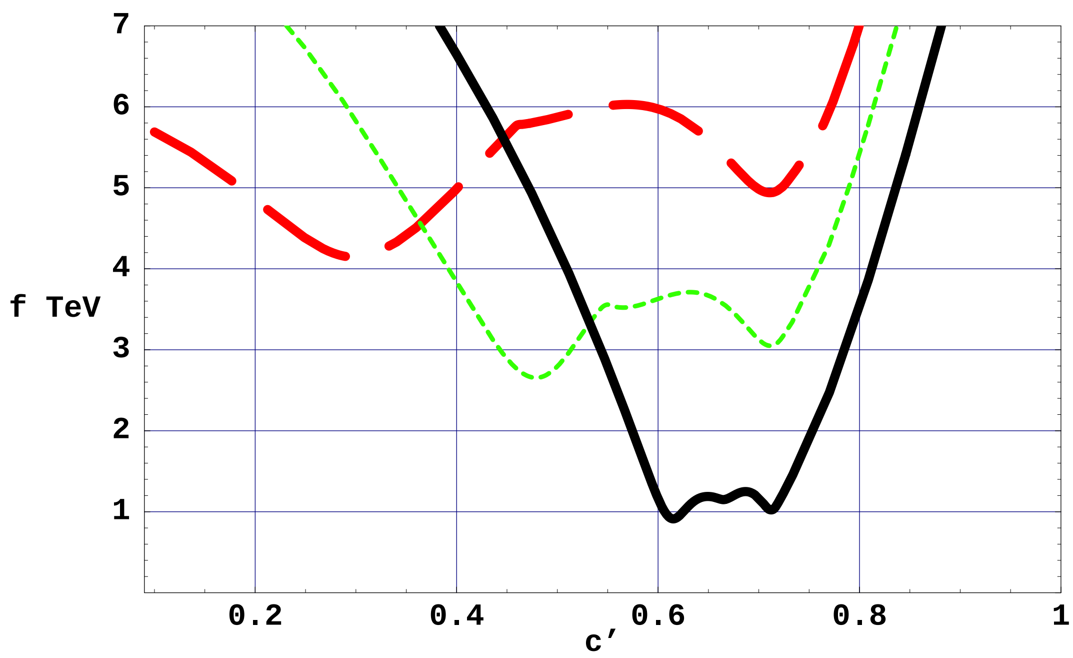
Electroweak Precision Constraints

- Both $U(1)$'s violate the custodial $SU(2)$ symmetry

$$\frac{M^2_{W_L^\pm}}{M^2_{Z_L}} = c_W^2 \left[1 + \frac{v^2}{f^2}\frac{5}{4}(c'^2 - s'^2)^2 - 4\frac{v'^2}{v^2}\right].$$

- Csaki *et al.*, [hep-ph/0211124, 0303236]; Hewett *et al.*, [hep-ph/0211218]. They found, generically, $f > 3 - 4$ TeV at 95% CL.

- For certain choices of parameters: $c'^2 \approx s'^2$, $v' \ll v$ ...



Minimal Flavor Sector

Quark sector is extended due to the heavy T

- $u, d,\ c, s,$ and b quarks unchanged; mass eigenstates $t - T$ mixing:

$$q_3 = c_L t_L + s_L T_L, \quad \tilde{t} = -s_L t_L + c_L T_L.$$

- The gauge-boson charged currents read:

$$\mathcal{L}_{CC} = g J_\mu^+ \ (Y_L W_L^\mu + Y_H W_H^\mu) + \text{h.c.}\ ,$$

where

$$\sqrt{2} J_\mu^+ = (\bar{u}\ \bar{c}\ \bar{t}\ \bar{T})_L \gamma_\mu \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & c_L \\ 0 & 0 & s_L \end{pmatrix} \begin{pmatrix} SM \\ 3 \times 3 \\ V_{CKM} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L ,$$

$$Y_L = \left(1 - \frac{v^2}{2f^2} c^2 c_{2\theta}^2\right), \quad Y_H = \frac{c}{s}\left(1 + \frac{v^2}{2f^2} s^2 c_{2\theta}^2\right).$$

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$$\mathcal{L}_{CC} = g J^{+}_{\mu} \ (Y_L W^{\mu}_{L} + Y_H W^{\mu}_{H}) + \text{h.c.} \ ,$$

where

$$\sqrt{2} J^{+}_{\mu} = (\bar{u}\ \bar{c}\ \bar{t}\ \bar{T})_L \gamma_\mu \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & c_L \\ 0 & 0 & s_L \end{pmatrix} \begin{pmatrix} SM \\ 3 \times 3 \\ V_{CKM} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L ,$$

$$Y_L = \left(1 - \frac{v^2}{2f^2} c^2 c^2_{2\theta}\right), \quad Y_H = \frac{c}{s} \left(1 + \frac{v^2}{2f^2} s^2 c^2_{2\theta}\right).$$

In this minimal extension:

The 3×3 "CKM" matrix is not unitary anymore: $V_{tb} = c_L V^{\text{SM}}_{tb}$;

The charged current strength is reduced as in Y_L;

New contributions from W_H and T;

No new CP phase.

- The Higgs-boson charged currents read:

$$\mathcal{L}'_{CC} = Y_\Phi (J_L + J_R)\Phi^+ + \text{h.c.}$$

where

$$\sqrt{2} v J_L = (\bar{u},\ \bar{c},\ c_L \bar{t}\ + s_L \overline{T})_L \left(V_{CKM}^{SM}\right) \begin{pmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_R ,$$

$$\sqrt{2} v J_R = (\bar{u},\ \bar{c},\ c_L \bar{t}\ + s_L \overline{T})_R \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix} \left(V_{CKM}^{SM}\right) \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L ,$$

$$Y_\Phi = c_+ v_f + 2 s_+ .$$

with $s_+ = 2v'/\sqrt{v^2 + 4v'^2}$ and $c_+^2 = 1 - s_+^2$.

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$$Y_\Phi = c_+ v_f + 2 s_+ .$$

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- Summary of the charged current modification:

  The SM charged current strength W_L modified at $\mathcal{O}(v^2/f^2)$;

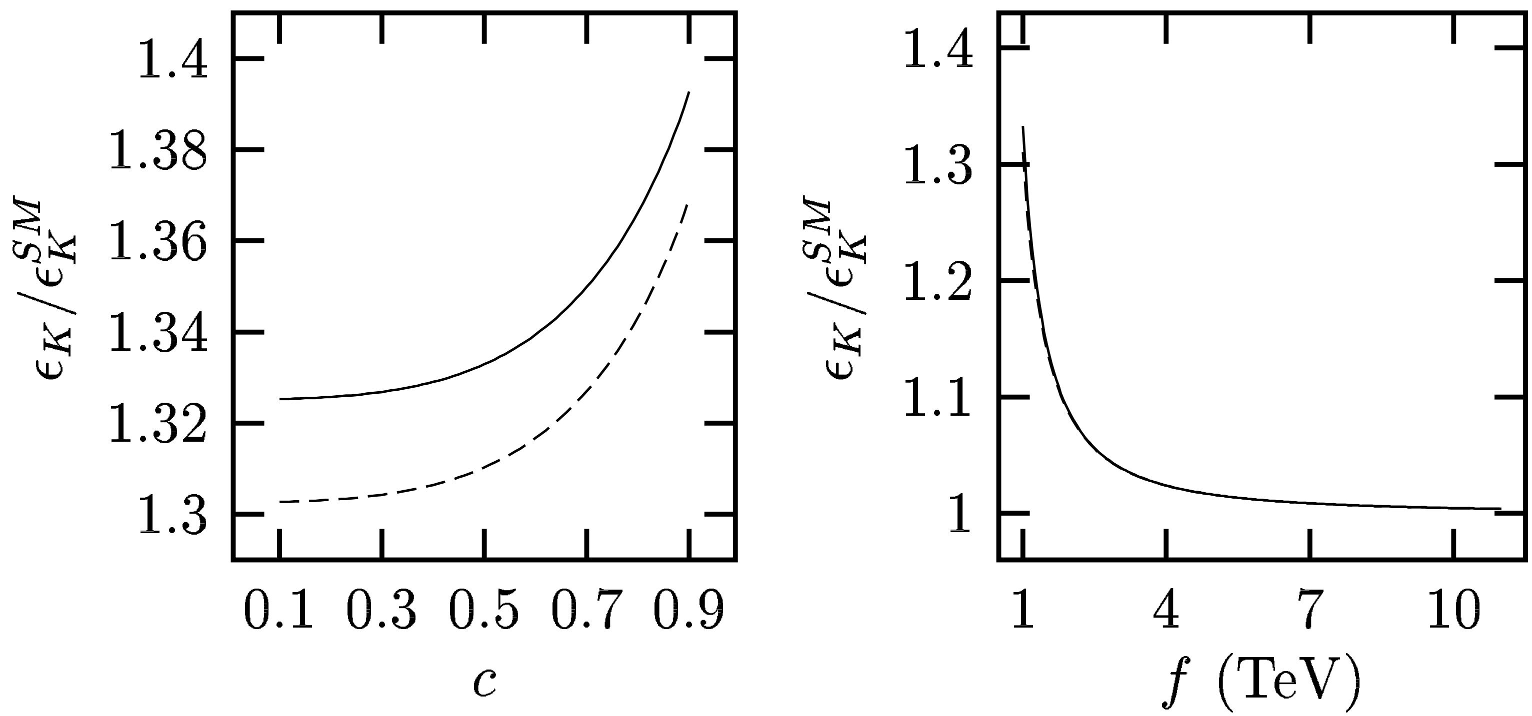
  New contribution from W_H proportional to c;

  New contribution from T at $\mathcal{O}(v^2/f^2)$;

  New contribution from Φ at $\mathcal{O}(v/f,\ v'/v)$.

Oberservable porcesses

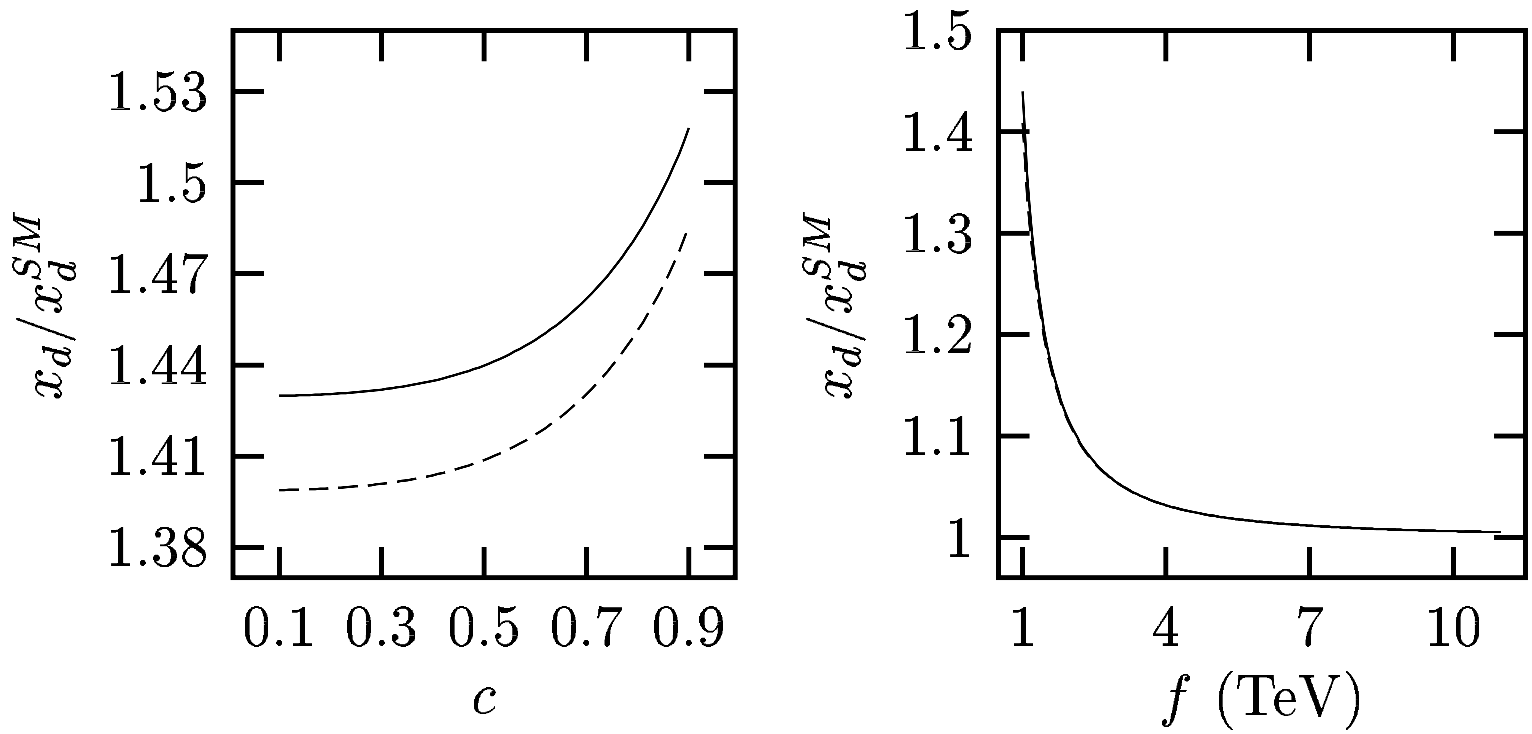
- $K^0 - \overline{K^0}$: T, $W_H^{\pm}$, $\Phi^{\pm}$ all contribute.



- Experimentally $|\epsilon_K| = 2.282 \times 10^{-3} \pm 1\%$;
- left: for $f = 1$ TeV, deviation could be significant, upto $> 30\%$;
- right: for $c = 0.5$, a strong constraint obtained $f > 9$ TeV.

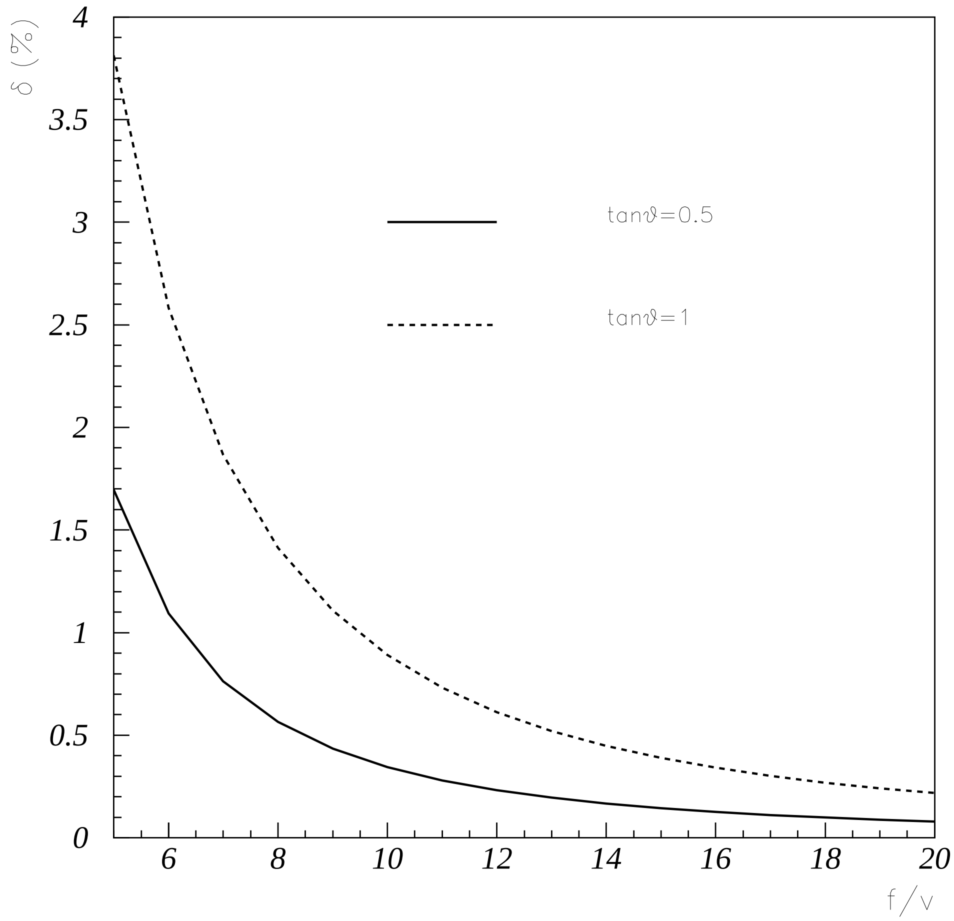
(Solid and dashed curves for $m_h = 115,\ 200$ GeV.)

- $B^0 - \overline{B^0}$: T, $W_H^{\pm}$, $\Phi^{\pm}$ all contribute.



- Experimentally $|\Delta x_d| \approx \pm 2\%$;
- (a) for $f = 1$ TeV, deviation could be significant, upto $> 40\%$;
- (b) for $c = 0.5$, a strong constraint obtained $f > 7$ TeV.

- $b \to s\gamma$: T, $W_H^{\pm}$, $\Phi^{\pm}$ all contribute.

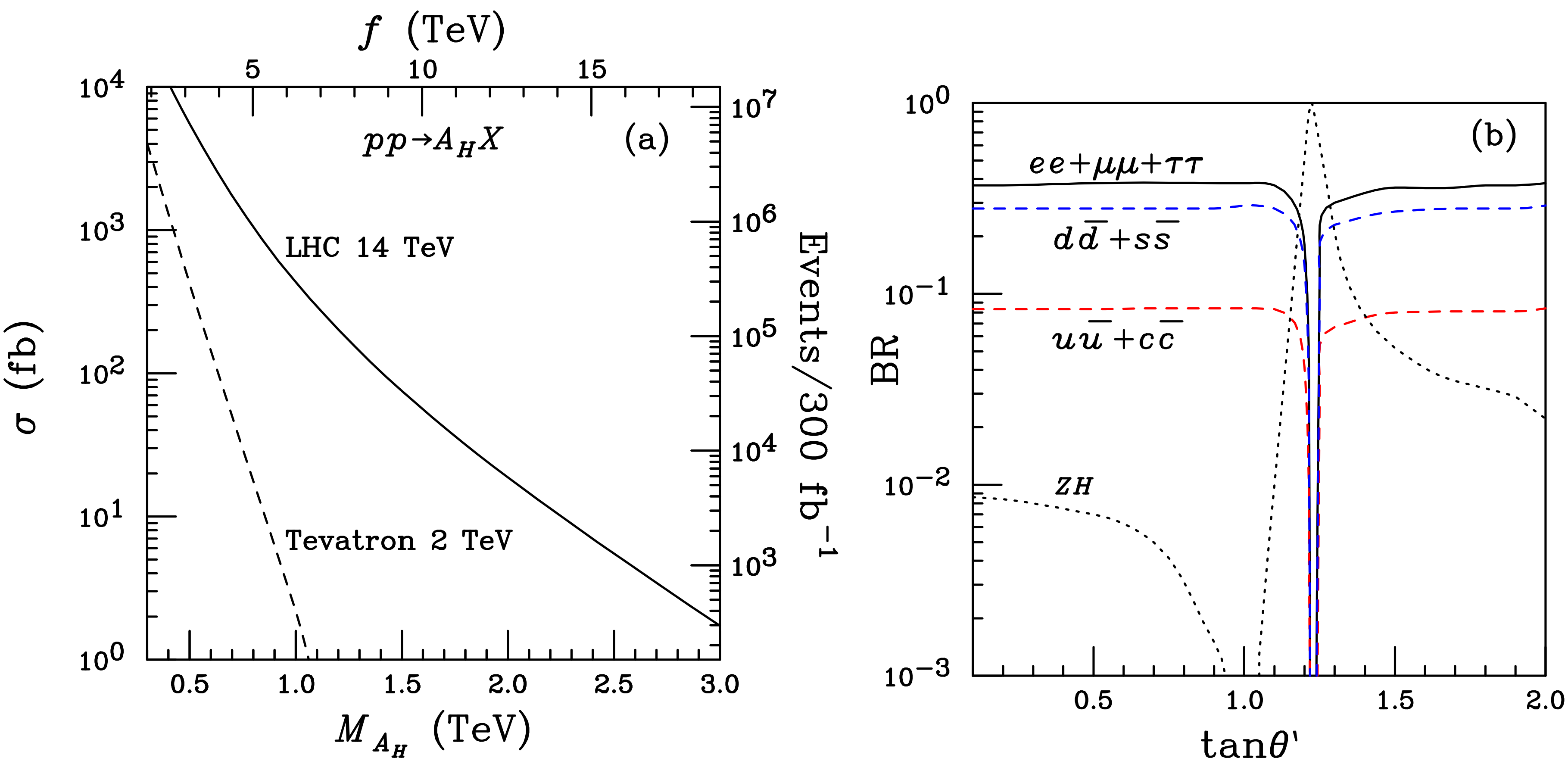


- Theoretically and experimentally $\Delta BR(b \to s\gamma) \approx \pm 10\%$;
- For $f = 1$ TeV, deviation could be upto 4%;
  still too small to put significant constraints.

Collider Phenomenology

The heavy A_H signal at hadron colliders

- A_H should be the lightest new state;
- DY production rate large



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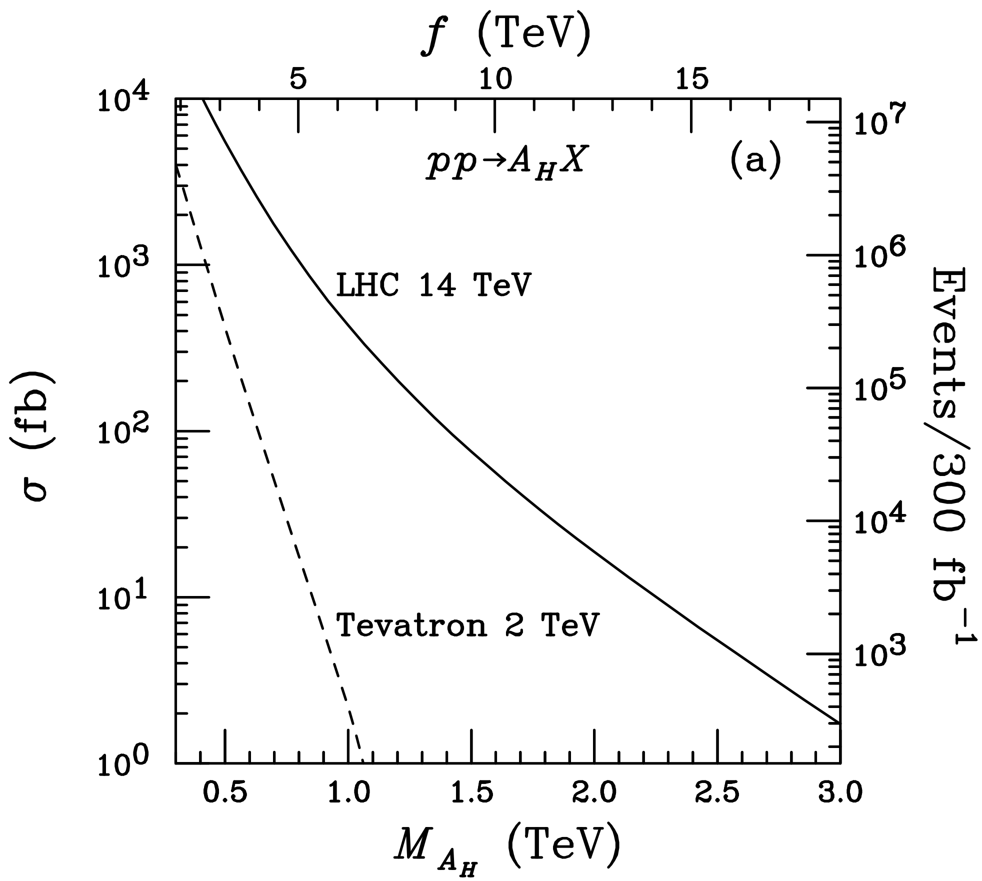
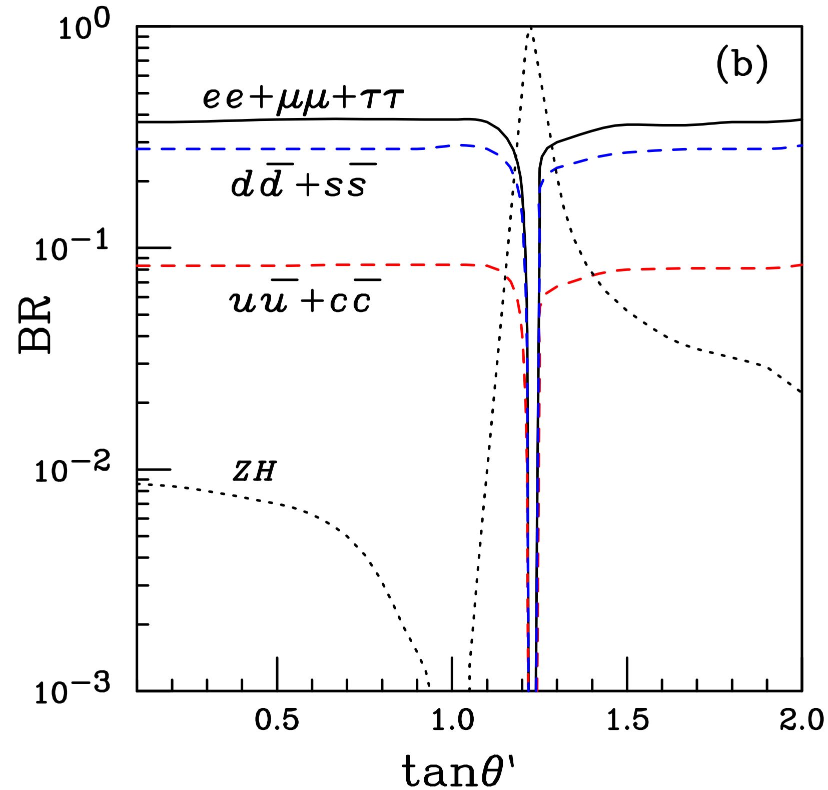


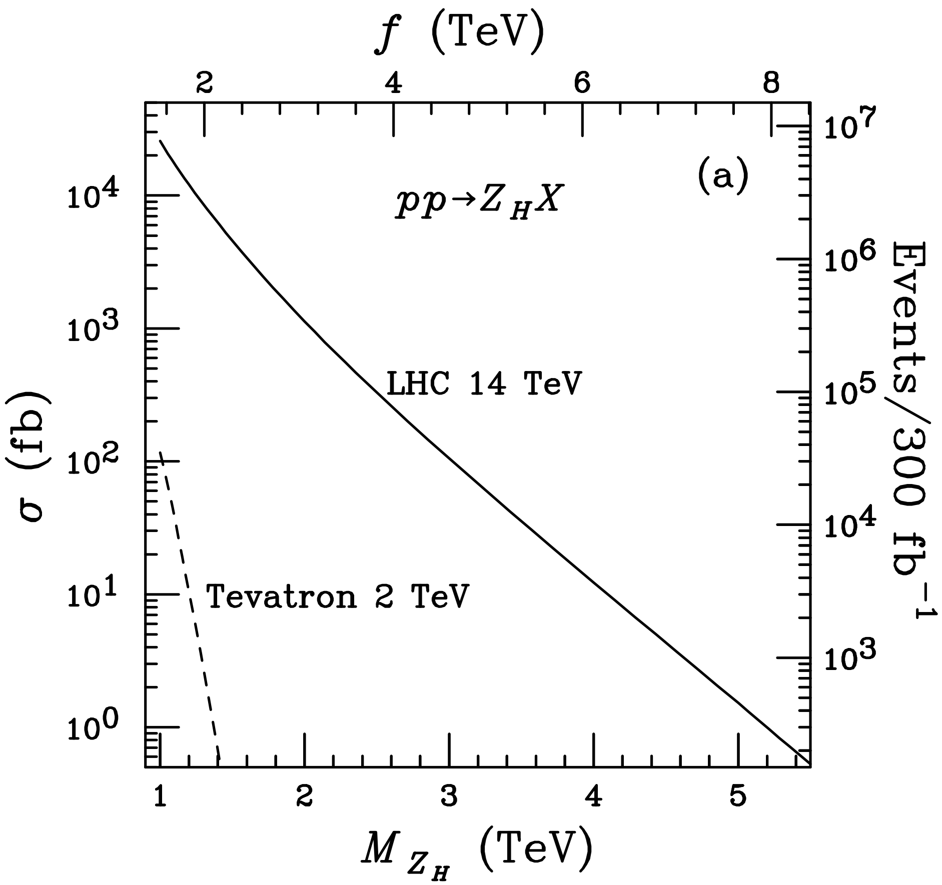


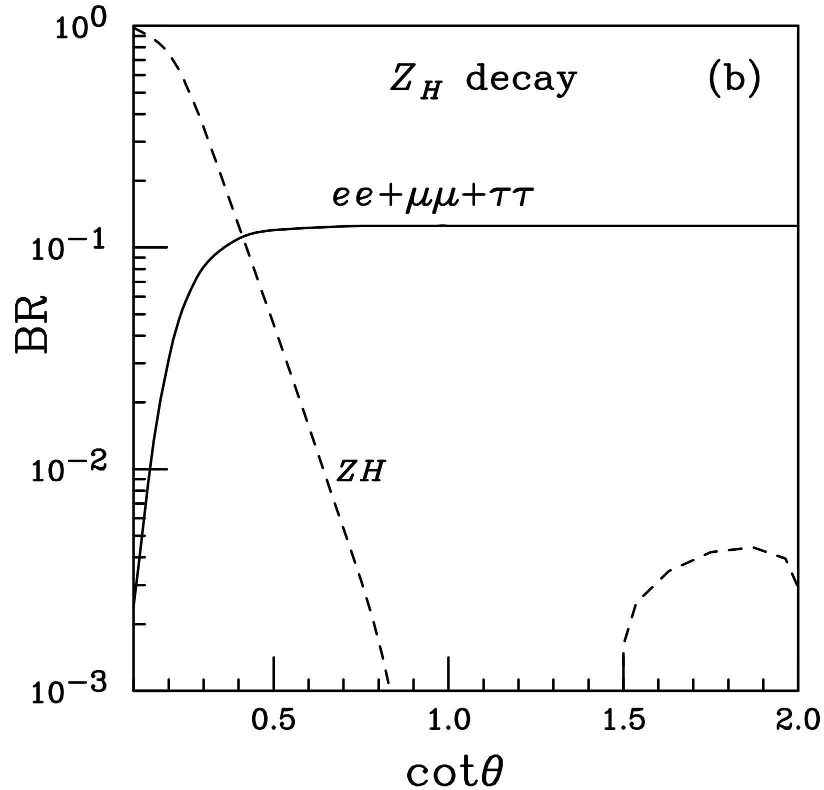
Tevatron: $M_{A_H} > 0.5$ TeV or $f > 3$ TeV;*
LHC: $M_{A_H} \sim 3$ TeV or $f \sim 18$ TeV.

*Hewett, Petriello, Rizzo, `hep-ph/0211218`.

The heavy Z_H signal at hadron colliders

- Z_H/W_H rebust new state
- DY production rate large





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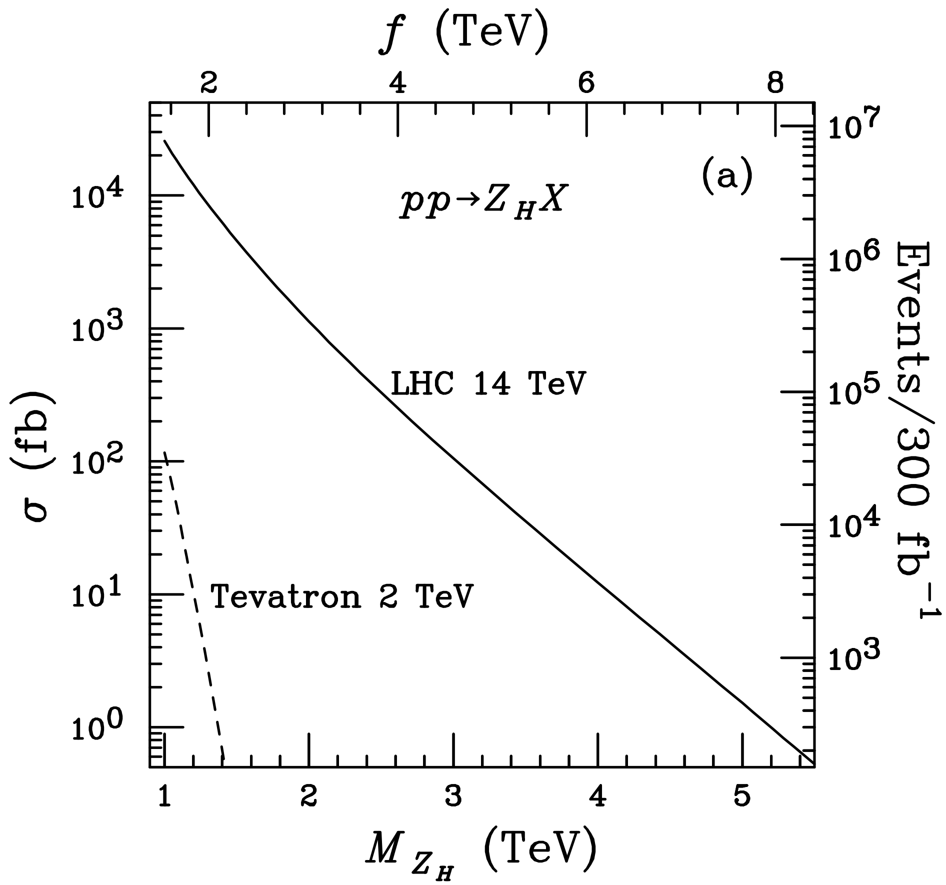
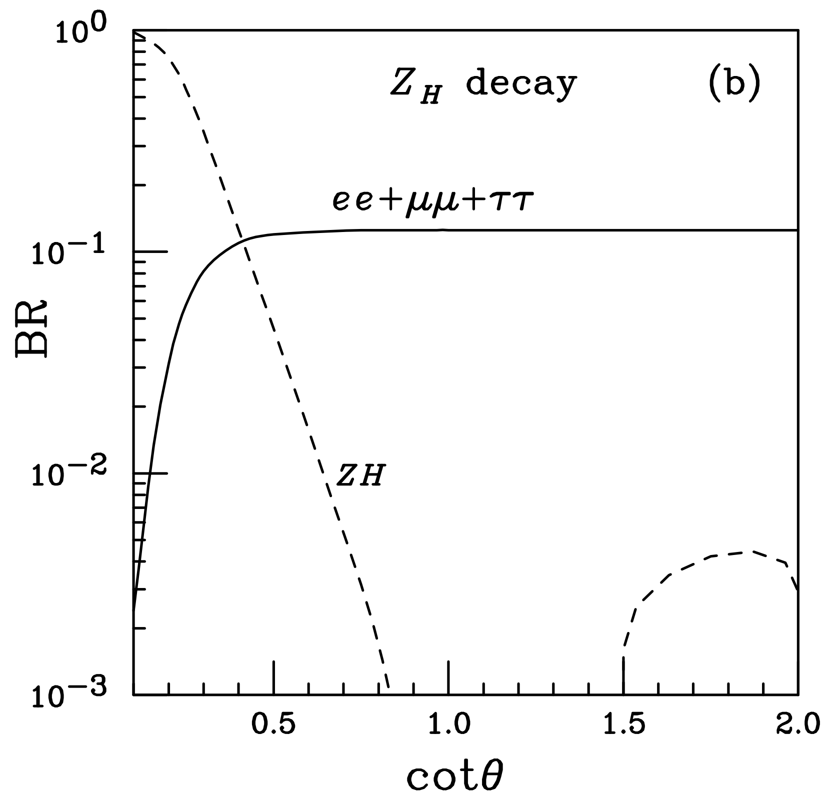


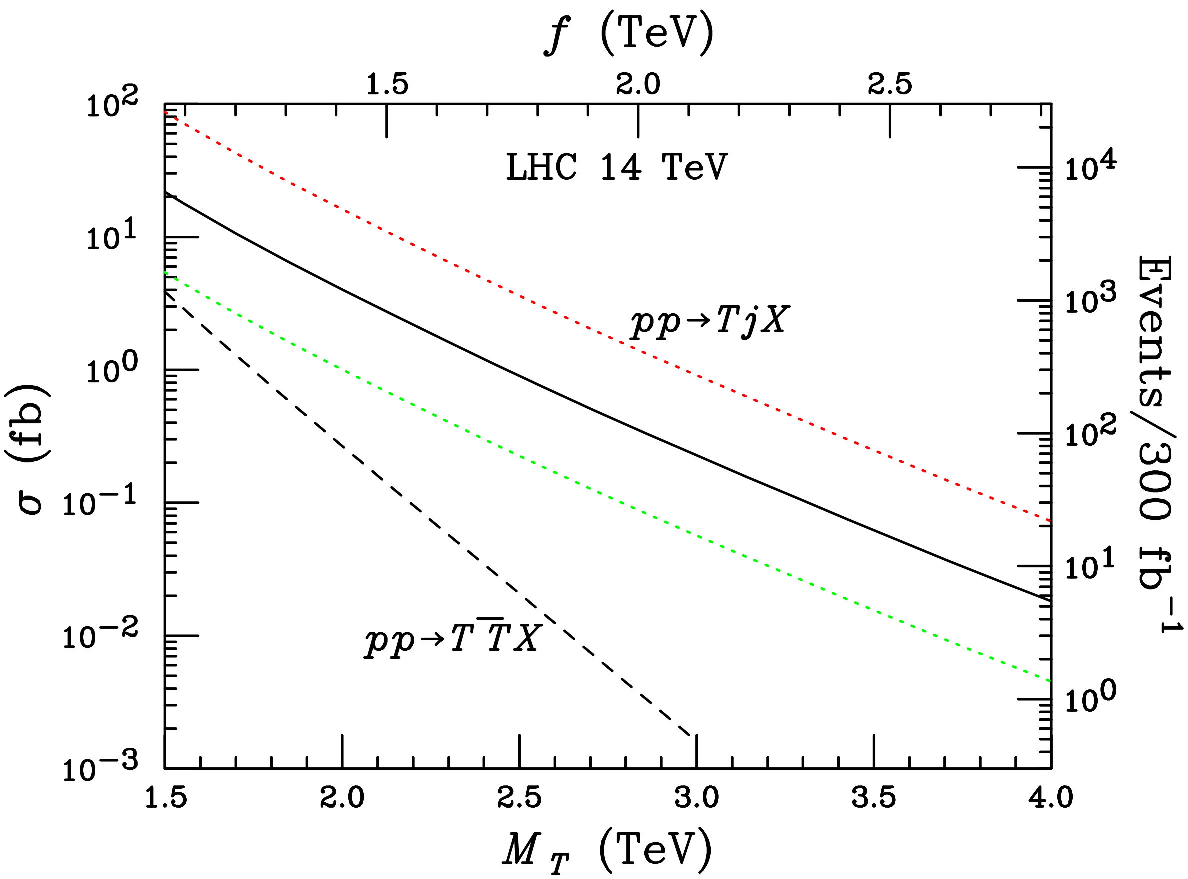


Tevatron: not quite accessible;

LHC: $M_{Z_H} \sim 5$ TeV or $f \sim 8$ TeV;

Quite robust for the LH idea !

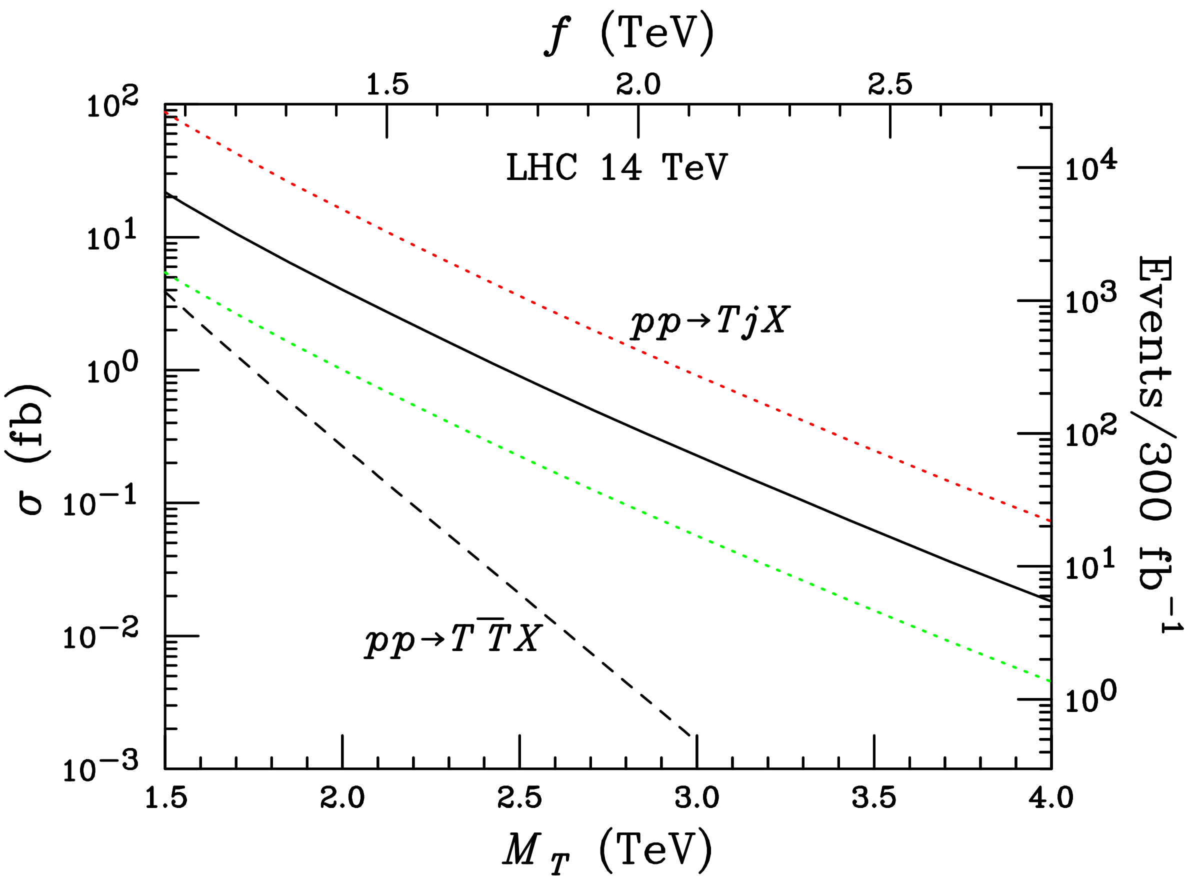
The heavy T signal at LHC



$gg \to T\bar{T}$ phase-space suppression;

$qb \to q'T$ via t-channel W_L exchange!

The heavy T signal at LHC



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Summary

- The Little Higgs idea provides a new way to address the
  (little) Hierarchy/naturalness problem
  by making the Higgs be a pseudo-Goldstone boson;
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- UV completion at 10 TeV scale ?

  higher scale SUSY or new Dynamical Symmetry Breaking?