Little Higgs Phenomenology

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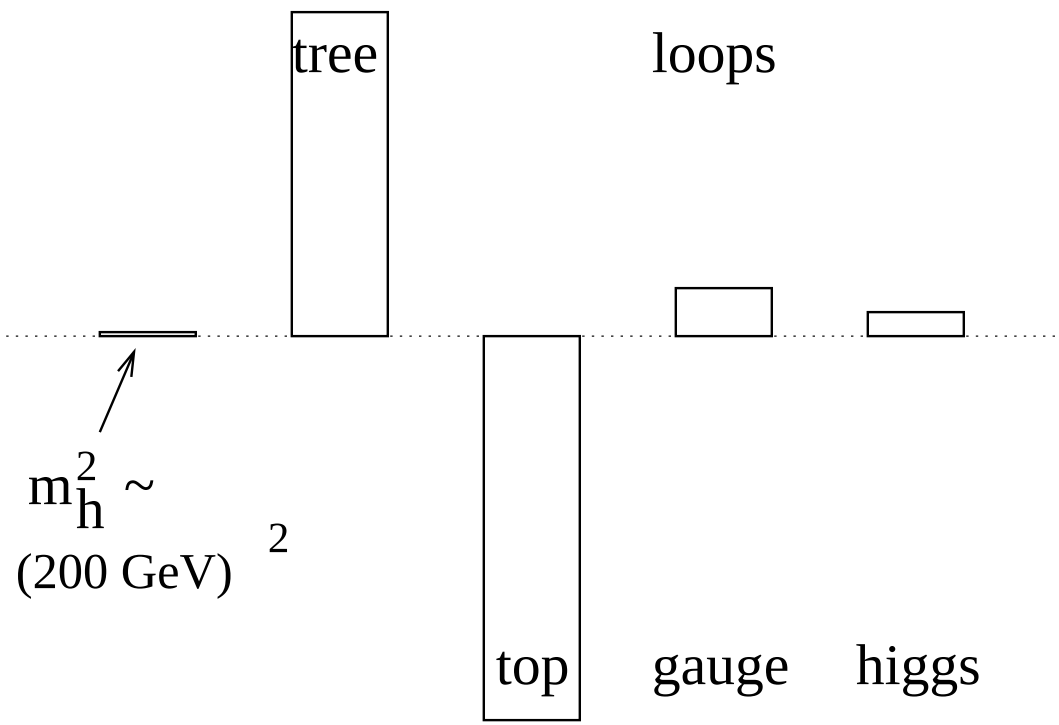
T. Han, H.L., B. McElrath, and L.T. Wang: hep-ph/0301040, hep-ph/0302188

The naturalness problem of the Standard Model

The Standard Model describes excellently all current experimental data – it works fine up to a scale of about 1 TeV.

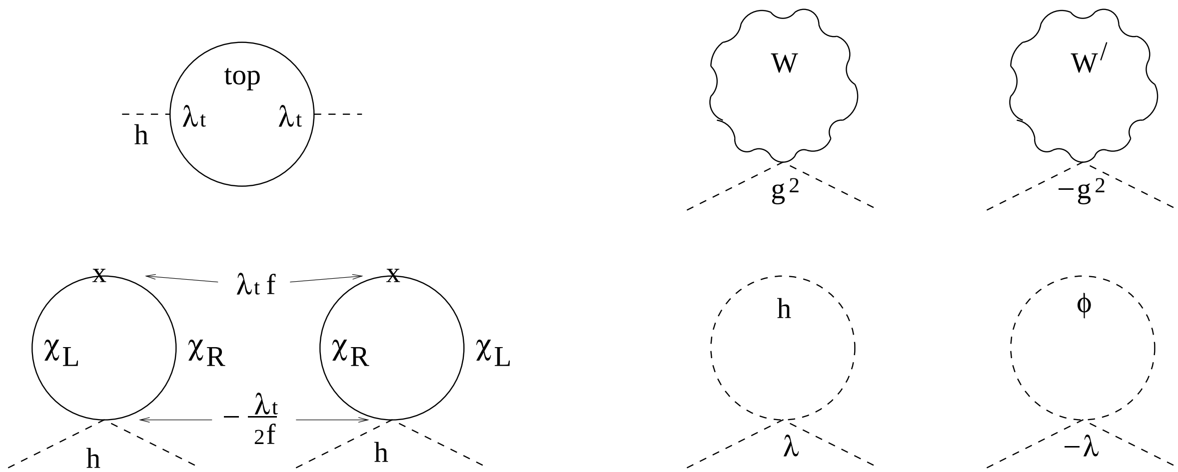
However, the Standard Model Higgs mass is quadratically sensitive to the cutoff scale Λ of the SM effective theory via radiative corrections.



For $\Lambda = 10$ TeV: 1% fine tuning!

How can the quadratically divergent loops be cancelled?

$\longrightarrow$ Introduce "partners" to cancel each loop divergence.



There must be a symmetry relating the couplings of the new particles to the SM, otherwise this is just another fine-tuning. (Classic example is SUSY.)

Naturalness: need new weakly coupled particles related to...

top		2 TeV
W, Z	at or below	5 TeV
Higgs		10 TeV

The Little Higgs Idea

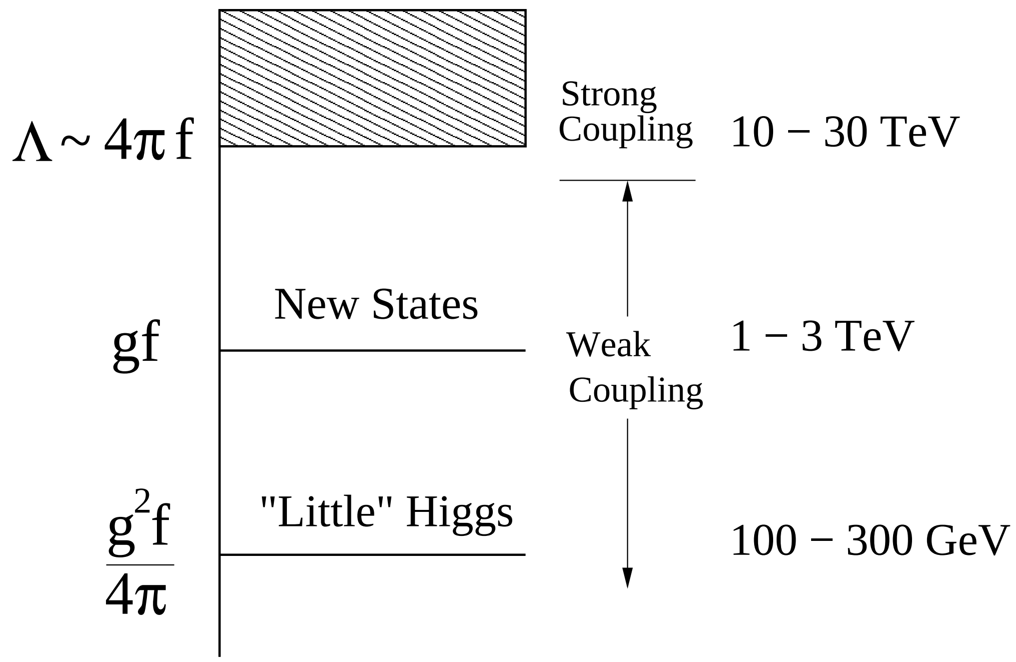
The Higgs is a pseudo-Nambu-Goldstone boson protected by an approximate global symmetry

The Higgs acquires mass only through "collective breaking" of the global symmetry

- Higgs is a pseudo-Goldstone boson from global symmetry breaking at scale
  $\Lambda \sim 4\pi f \sim 10 - 30$ TeV;

- Quadratic divergences cancelled at one-loop level by new states
  $M \sim gf \sim 1 - 3$ TeV;

- Higgs acquires a mass radiatively at the EW scale
  $v \sim g^2 f/4\pi \sim 100 - 300$ GeV.



Many Little Higgs models... and more coming...

Moose Arkani-Hamed et al, hep-ph/0105239

Minimal Moose Arkani-Hamed et al, hep-ph/0206020

Littlest Higgs SU(5)/SO(5) Arkani-Hamed et al, hep-ph/0206021

SU(6)/Sp(6) Low, Skiba, Smith, hep-ph/0207243

SU(4)/SU(3) Simple Group Kaplan, Schmaltz, hep-ph/0302049

Custodial SU(2) Moose Chang, Wacker, hep-ph/0303001

The Littlest Higgs – sketch of the model

SU(5)/SO(5) non-linear sigma model, with gauged subgroup $[SU(2) \otimes U(1)]^2$

$$\Sigma = e^{2i\Pi/f}\Sigma_0, \qquad \Sigma_0 = \begin{pmatrix} & & \mathbb{1} \\ & 1 & \\ \mathbb{1} & & \end{pmatrix} \qquad (5 \times 5 \text{ matrix})$$

Breaks SU(5) $\to$ SO(5) and $[SU(2) \otimes U(1)]^2 \to SU(2)_L \otimes U(1)_Y$.

Goldstone bosons: 4 are eaten, leaving a complex doublet h (which becomes the SM Higgs) and a complex triplet ϕ.

The Littlest Higgs Model – Gauge structure

Gauged $[SU(2) \times U(1)]^2$ subgroup:

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

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

Note new gauge couplings $\{g_1,\ g_2,\ g_1',\ g_2'\}$ and mixing angles $\{c,\ s,\ c',\ s'\}$ to diagonalize to the SM gauge basis (EWSB introduces further mixing):

$$g = g_1 s = g_2 c, \qquad g' = g_1' s' = g_2' c'$$

Global Symmetries: (protect the Higgs mass)

$$SU(3)_1 \to \left(\begin{array}{c|c} 0_{2\times2} & \\ \hline & V_3 \end{array}\right) \qquad SU(3)_2 \to \left(\begin{array}{c|c} V_3 & \\ \hline & 0_{2\times2} \end{array}\right)$$

Top sector

Add a vector-like pair of colored Weyl fermions $\tilde{t}$ and $\tilde{t}'^c$.

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

where $\chi_i = (b_3, t_3, \tilde{t})$, $i, j, k = 1 \ldots 3$ and $x, y = 4 \ldots 5$.
The bare mass term $\lambda_2 f \tilde{t}\tilde{t}'^c$ is *chosen* to be $\mathcal{O}(f)$.

The λ_1 term preserves global $SU(3)_2$, guaranteeing cancellation of the quadratic divergence:

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

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

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

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

New particle content

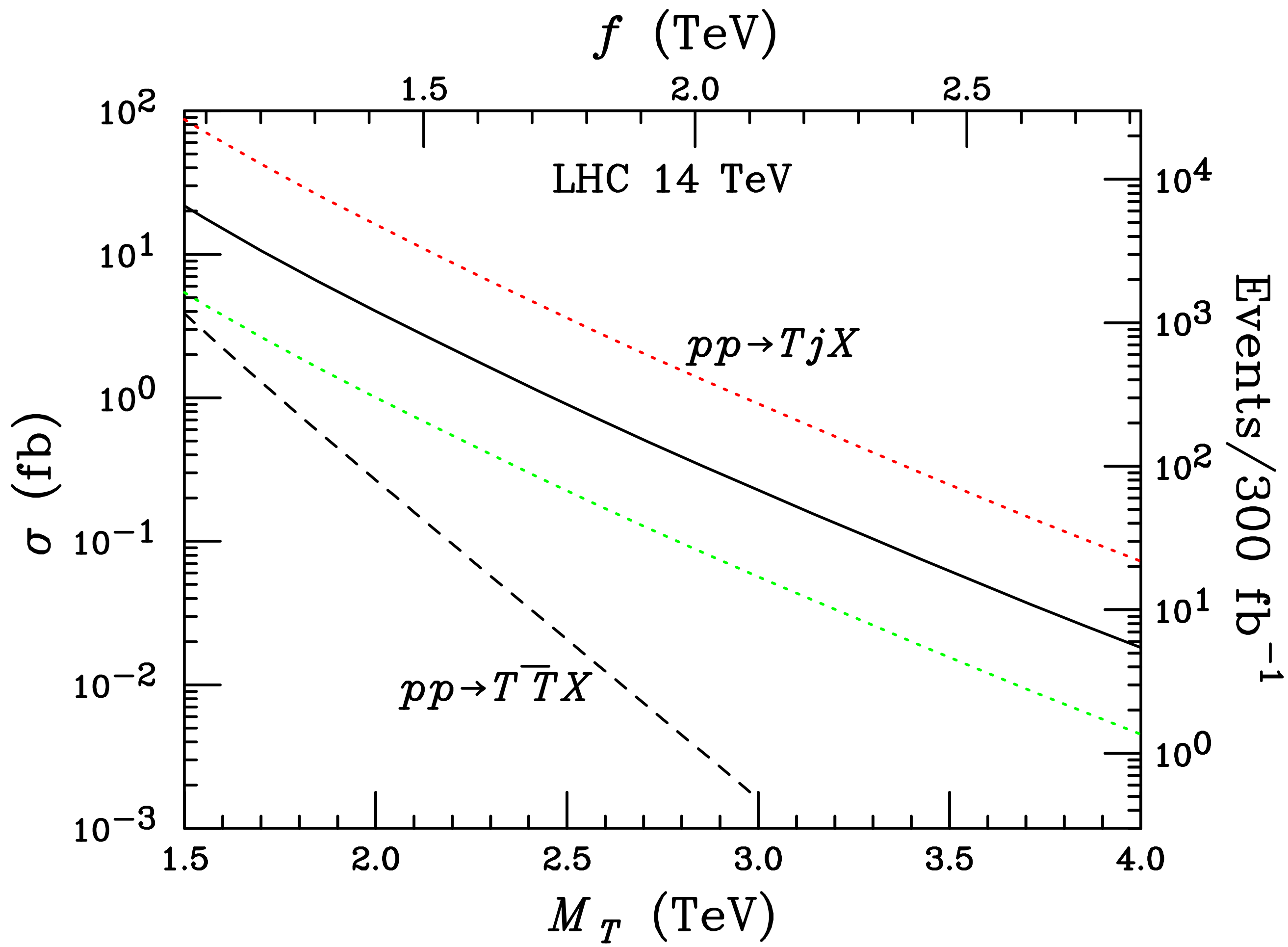
Particle	Mass
A_H	$m_Z^2 s_W^2 \left(\frac{f^2}{5s'^2c'^2v^2} + \mathcal{O}(1)\right)$
$Z_H,\ W_H^\pm$	$m_W^2 \left(\frac{f^2}{s^2c^2v^2} + \mathcal{O}(1)\right)$
$\phi^0,\ \phi^P,\ \phi^\pm,\ \phi^{\pm\pm}$	$\frac{2m_h^2 f^2}{v^2}\frac{1}{1-(4v'f/v^2)^2}$
T	$\sqrt{\lambda_1^2+\lambda_2^2}f + \mathcal{O}(\frac{v^2}{f^2})$

Phenomenology

- Heavy top quark partner
- Heavy gauge partners
- Electroweak precision constraints
- Heavy scalars
- Loop effects

Heavy top quark partner

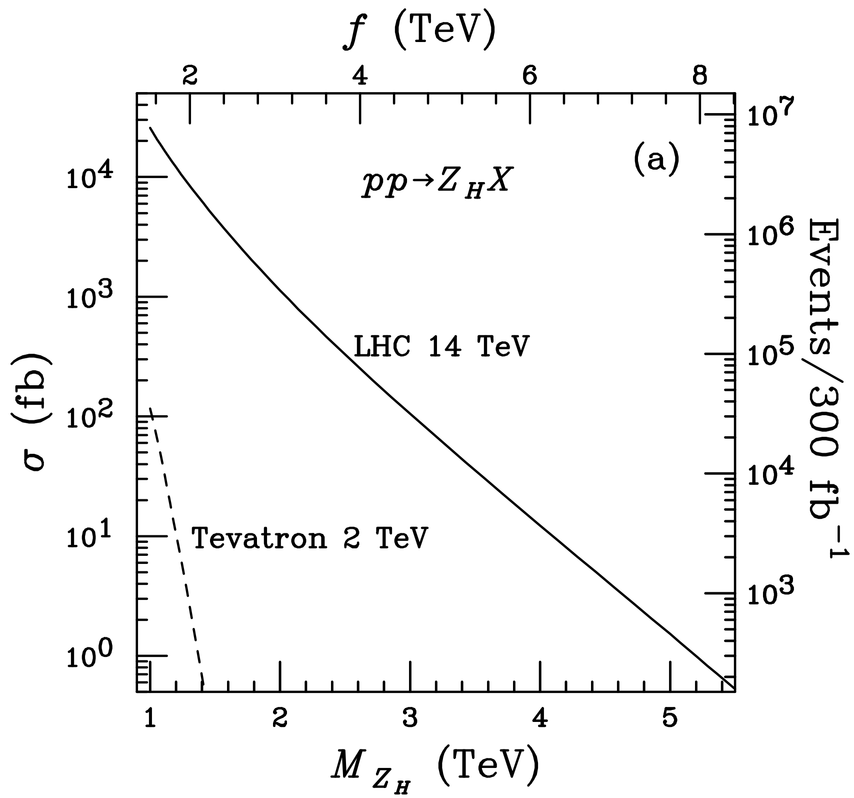
T production cross section $\sim$ 1-10 fb at LHC for $M_T = 2$ TeV.



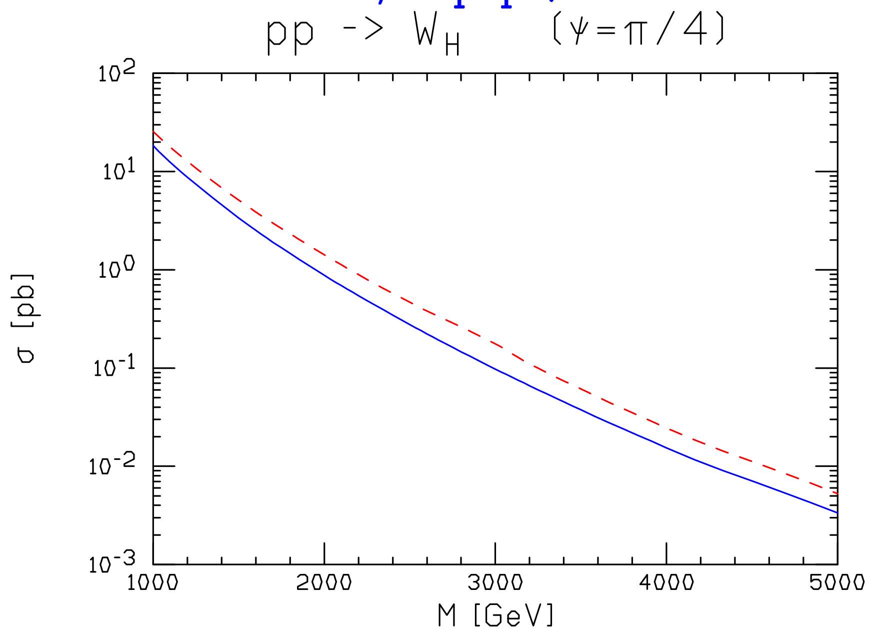
Solid line: $\lambda_1/\lambda_2 = 1$; Dotted: $\lambda_1/\lambda_2 = 2$, $1/2$

T decays: Equipartition $\longrightarrow tH : tZ : bW = 1 : 1 : 2$.

Heavy gauge partners: Z_H and $W_H^{\pm}$

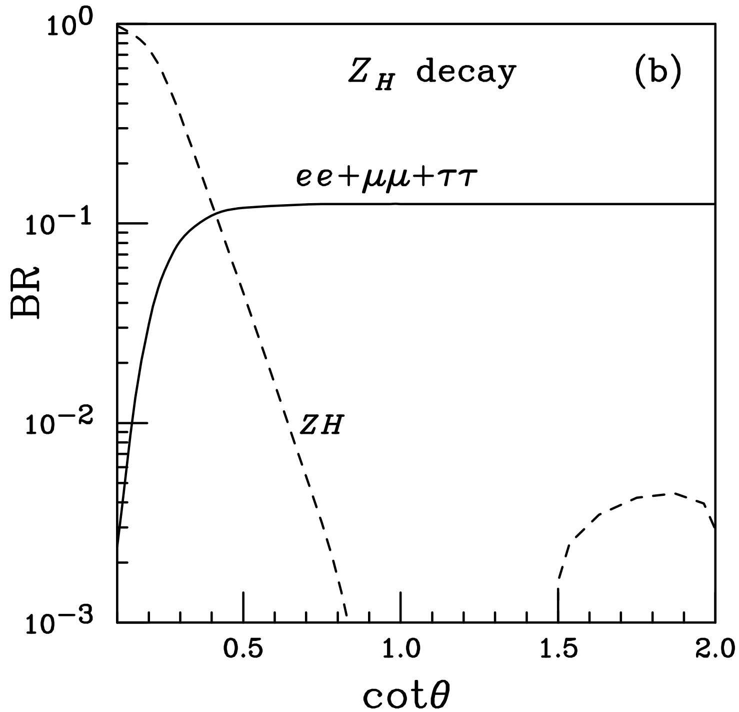


Burdman et al, **hep-ph/0212228**

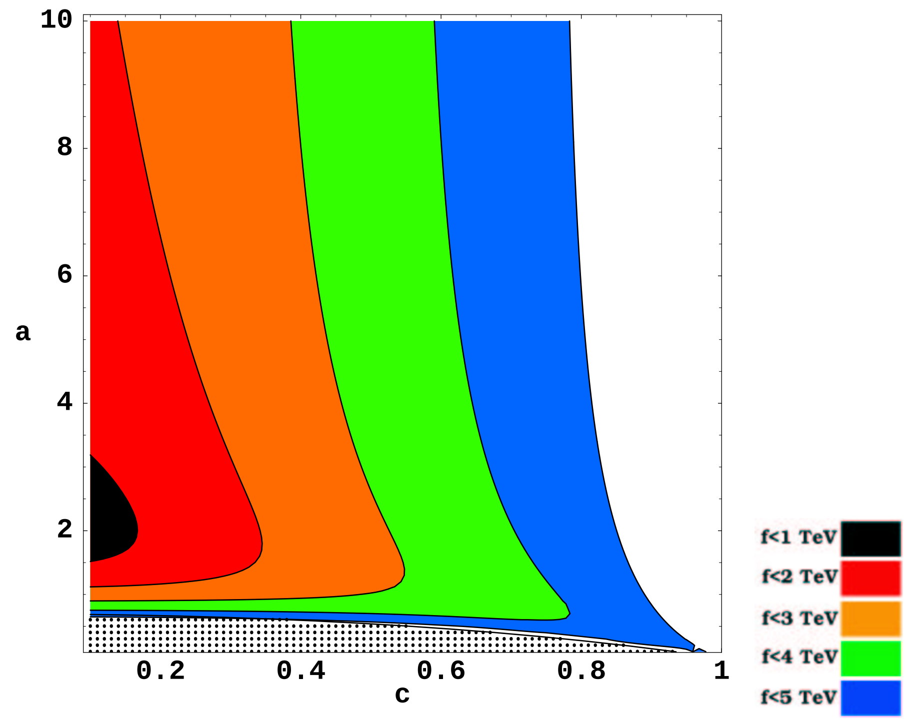


Dashes: $W_H^{\pm}$; solid: Z_H

Cross section $\sim \cot^2\theta$; here $\cot\theta = 1$.



Csaki et al, hep-ph/0303236



Z_H, $W_H^\pm$ couple to SU(2)$_L$ doublets with strength $\sim g\cot\theta$
$\rightarrow$ Equipartition among fermions.

EW precision favors low $\cot\theta \equiv c/s$.

Validity of effective theory: $g_1, g_2 \leq \sqrt{4\pi} \longrightarrow c \geq 0.18$

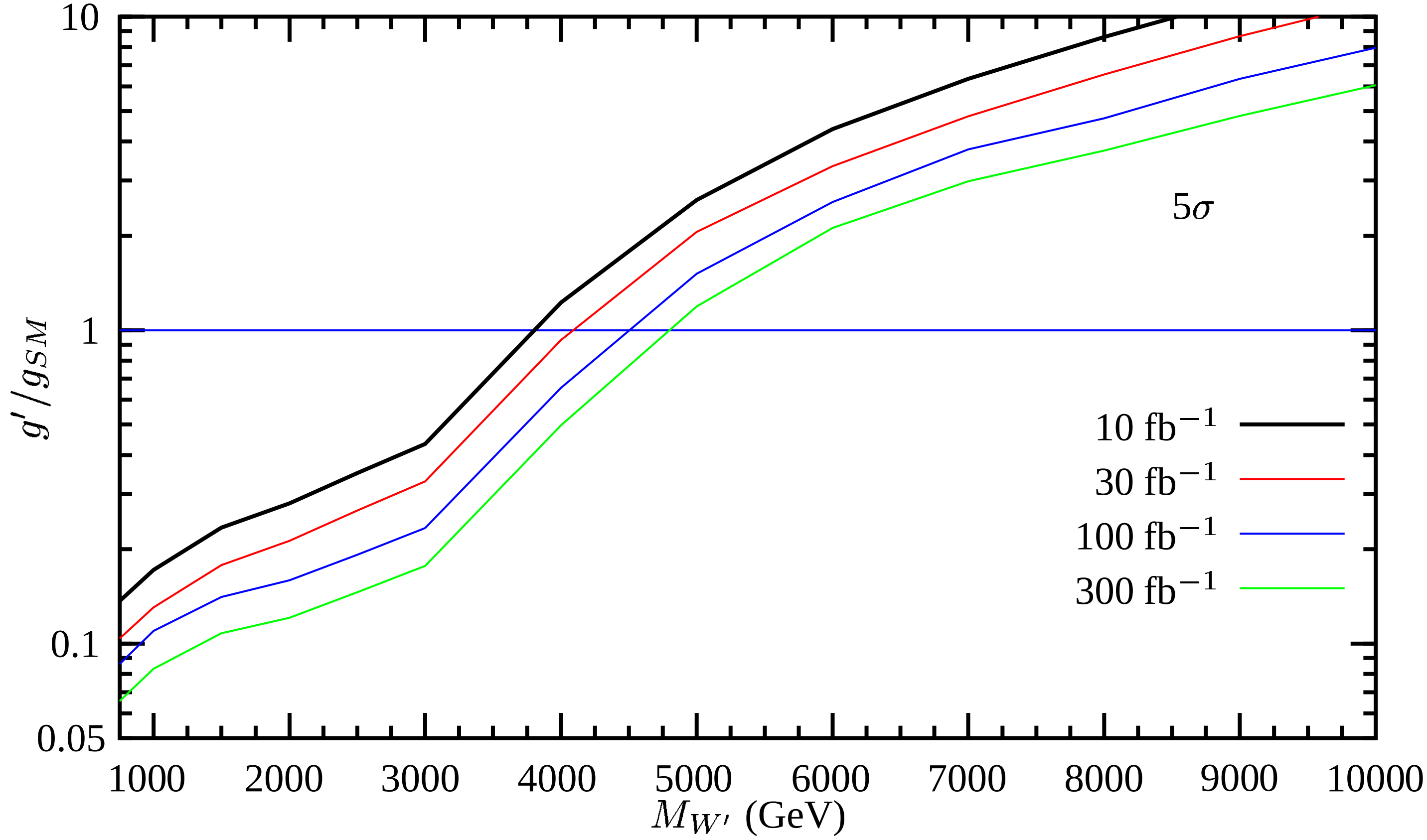
Current Tevatron Run I limit on a sequential Z' is ~ 600 GeV.

Current bounds for W':

CDF: $M_{W'} \gtrsim 540$ GeV (from $W' \to t\bar{b}$) hep-ex/0209030

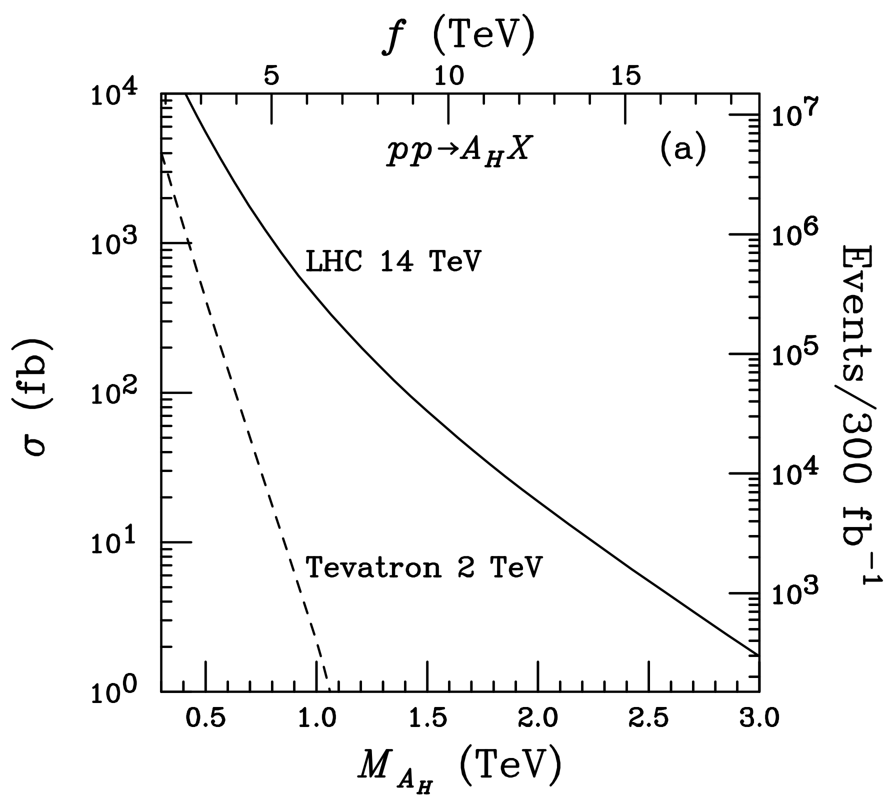
LEP: $M_{W'} \gtrsim 700$ GeV (sequential $W' \to \ell\nu$)

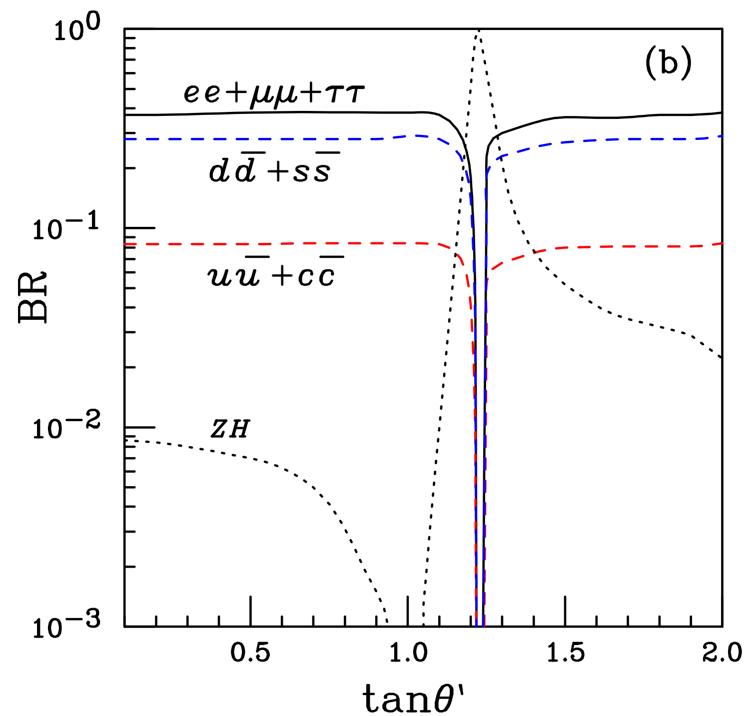
$W' \to t\bar{b}$ at the LHC: Sullivan, talk at PHENO'03



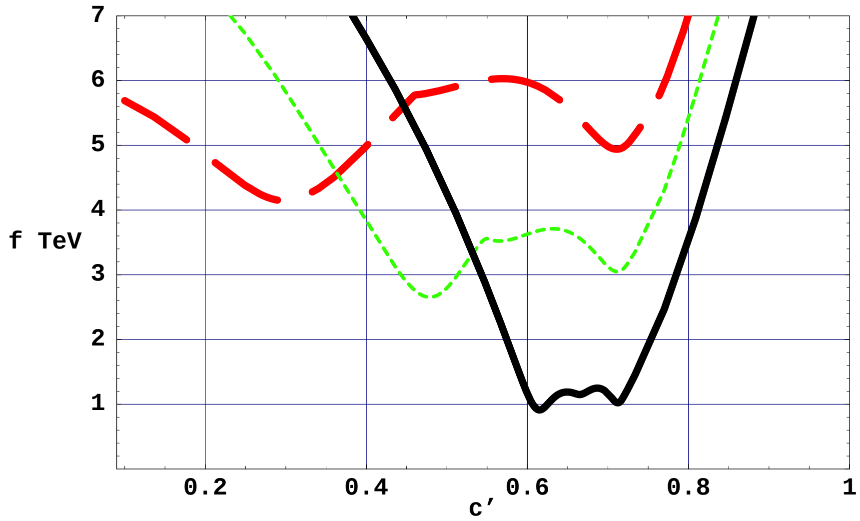
A_H production and decay

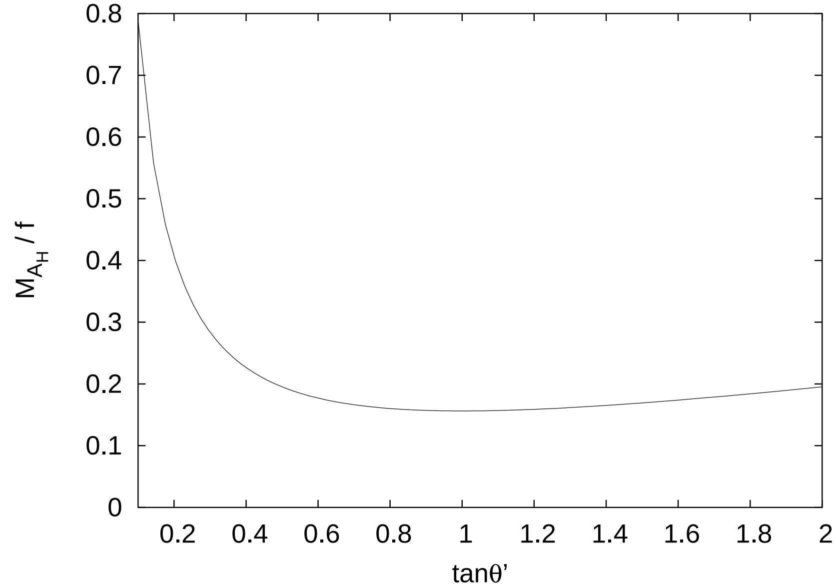
A_H is very light in the Littlest Higgs model – strong constraints from Tevatron Run I.





Csaki et al, hep-ph/0303236



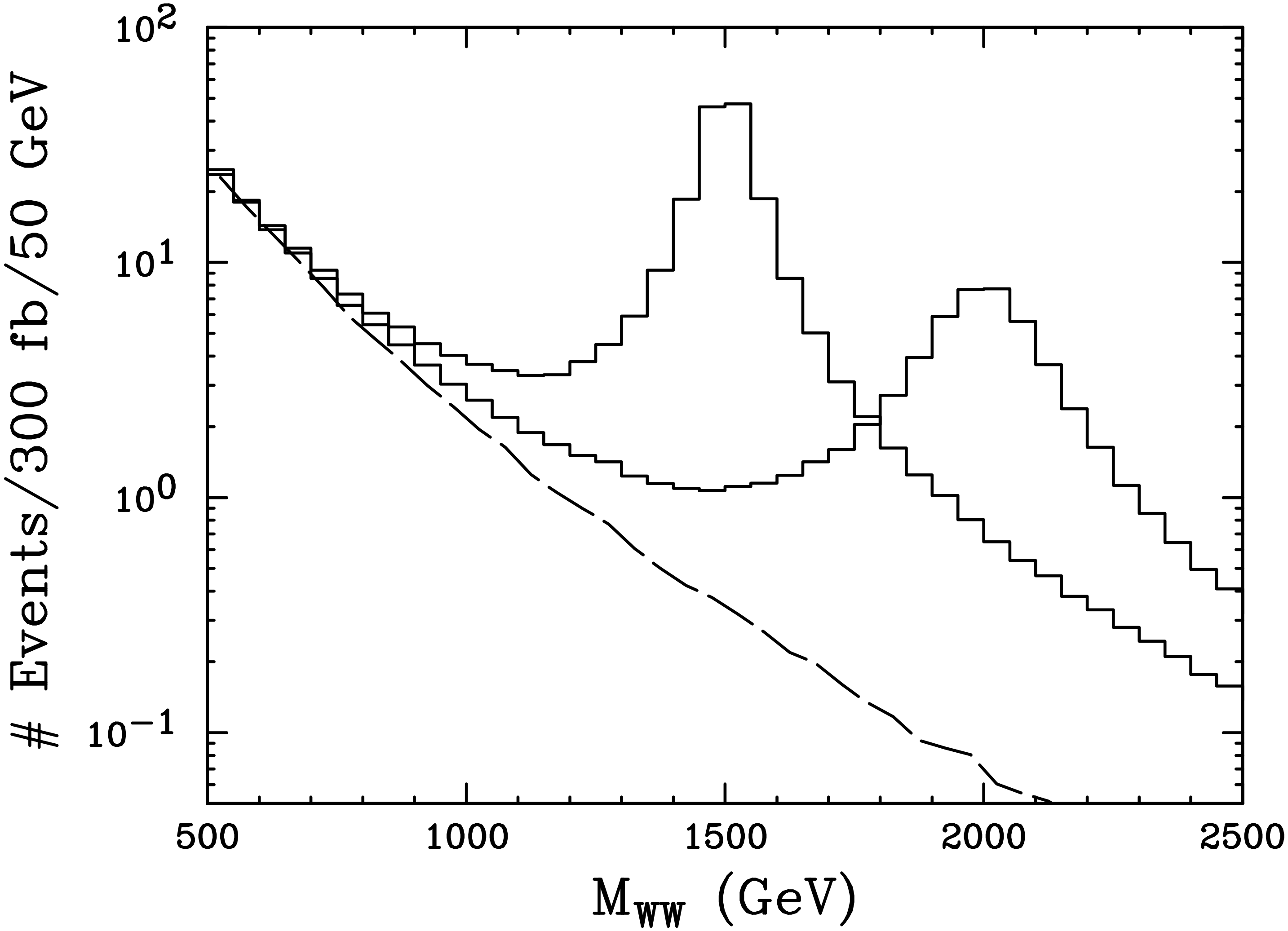


Gauge invariance + anomaly cancellation + naturalness
$\rightarrow c' \sim \sqrt{2}$, $\tan\theta' \sim 1$.
$\rightarrow M_{A_H} \sim g' f/\sqrt{20} \sim 0.2 f$.

Tevatron Run I excludes sequential Z' up to ~ 600 GeV
$\longrightarrow f \gtrsim 3$ TeV!! Also pointed out by Hewett et al, hep-ph/0211218

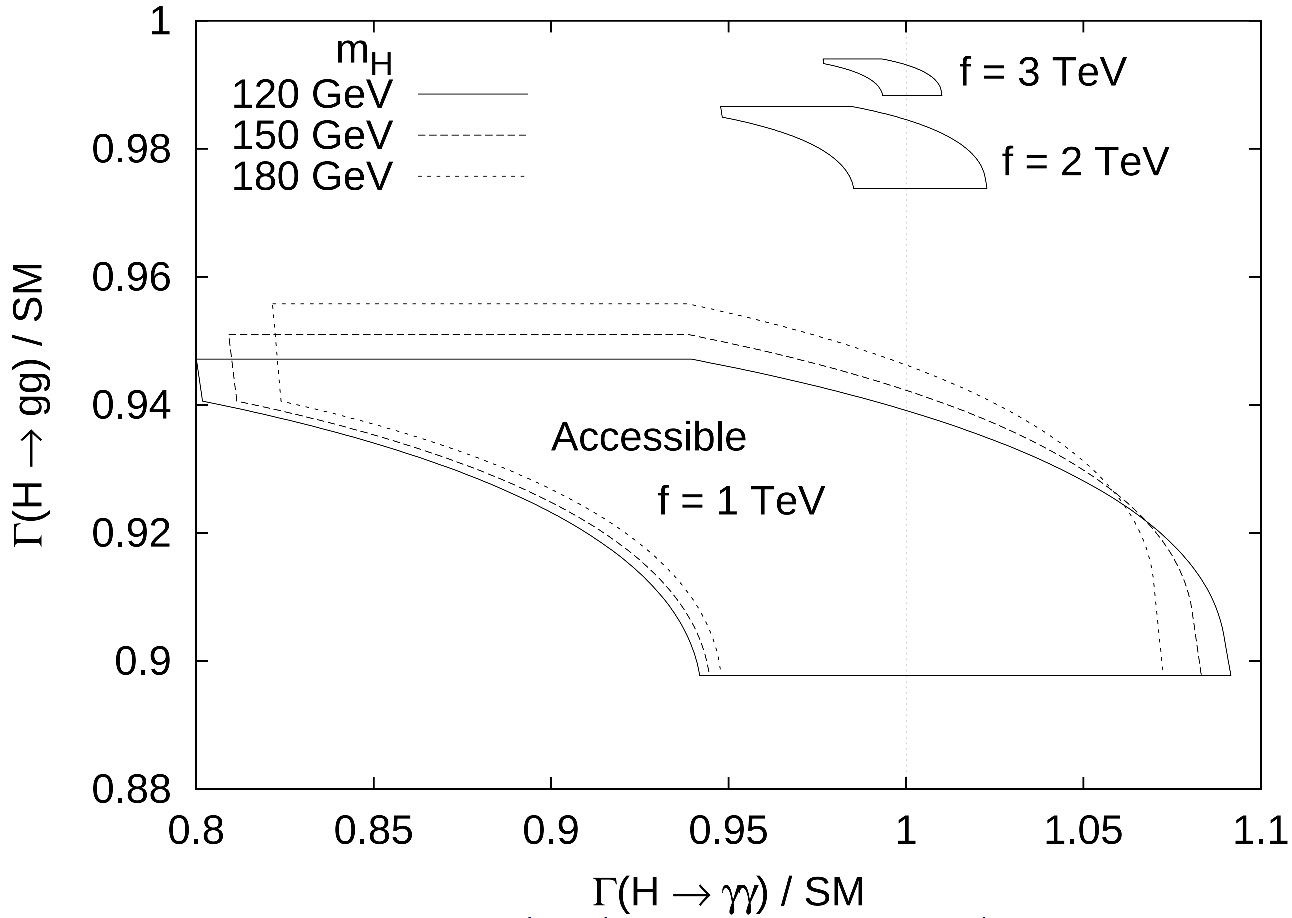
BUT: Model dependent! Viability of the model improves greatly if only $U(1)_Y$ is gauged $\rightarrow$ no A_H particle.

Resonant $W^+W^+ \to \Phi^{++} \to W^+W^+$



Cross section is proportional to $(v'/v)^2 = (0.1)^2$ for this plot

Loop-induced h decays: gg, $\gamma\gamma$



Han, H.L., McElrath, Wang, `hep-ph/0302118`

$\gamma\gamma$ collider: measure $\gamma\gamma \to h$ to $\sim 3\%$. Probe $f \lesssim 1.8$ (1.2) TeV at 2 (5) σ.

Does not depend on U(1) sector.

Conclusions

The Little Higgs idea is a new way to address the naturalness problem by making the Higgs a pseudo-Nambu-Goldstone boson.

Quadratically divergent radiative corrections to the Higgs mass due to top, gauge, and Higgs loops are cancelled by new particles of the same statistics.

There are viable models that satisfy precision electroweak constraints yet have new particles at a low enough scale that there is no fine tuning.

The LHC can discover the new particles or rule them out up to a mass scale at which the idea becomes fine tuned.