Little Higgs Phenomenology

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Based on T. Han, H.L., B. McElrath, and L.T. Wang,
PRD67:095004 (2003) [hep-ph/0301040]; PLB563:191 (2003) [hep-ph/0302188]

The Standard Model's "little hierarchy"

The Standard Model works great – it is in very good agreement with all the precision electroweak data.

However, we know that the SM must be an effective theory since the Higgs mass is quadratically sensitive to the cutoff scale Λ of the SM effective theory via radiative corrections.

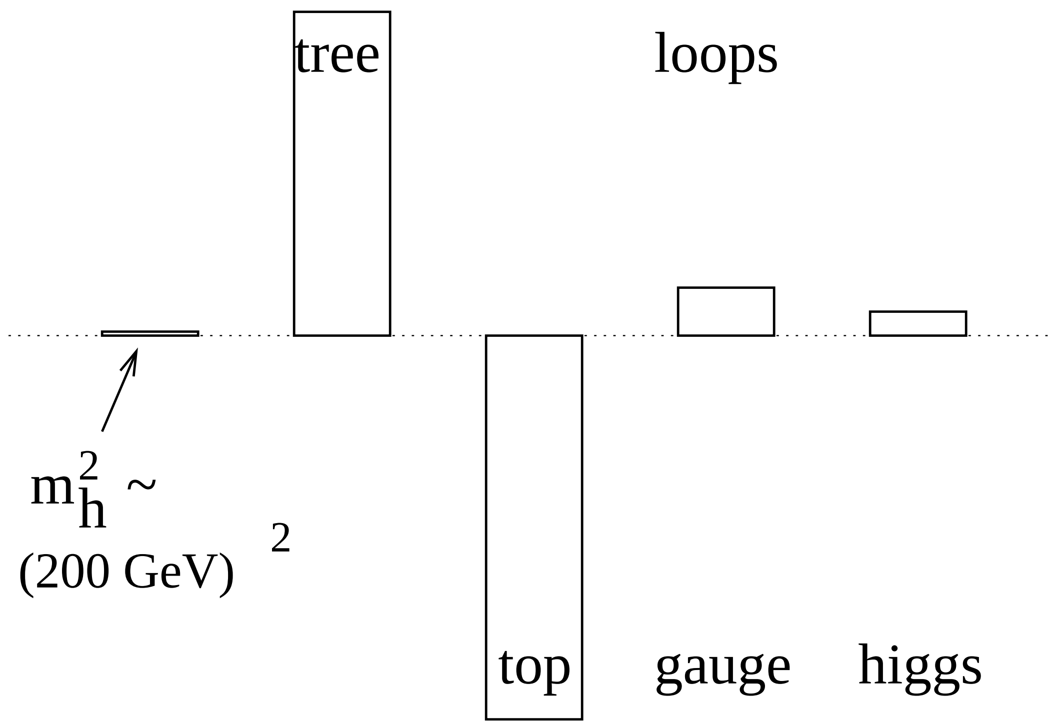
How high should Λ be? In general the new theory at Λ will generate dimension-6 operators in the low-energy theory suppressed by $1/\Lambda^2$.

But we have probed these dimension-6 operators already: electroweak precision data generally constrains them to be suppressed by mass scales of $\sim 1 - 10$ TeV.

This gap between the Higgs mass/vev ~ 200 GeV and the scale pointed to by electroweak precision data $\sim 1 - 10$ TeV is called the "little hierarchy".

Is the little hierarchy a problem? Maybe, if one is worried about fine tuning of the Higgs mass/vev.

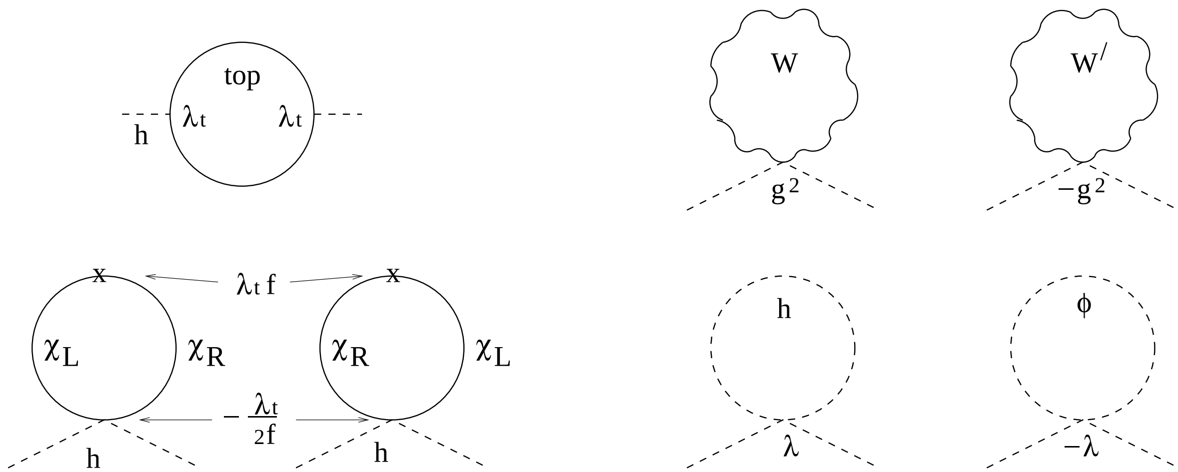
For example, if $\Lambda = 10$ TeV, the cancellation between the tree-level and loop m_h^2 must be fine tuned to 1%!



To avoid fine tuning, need to cancel off the quadratically divergent loops in some natural way.

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. (E.g., SUSY.)

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

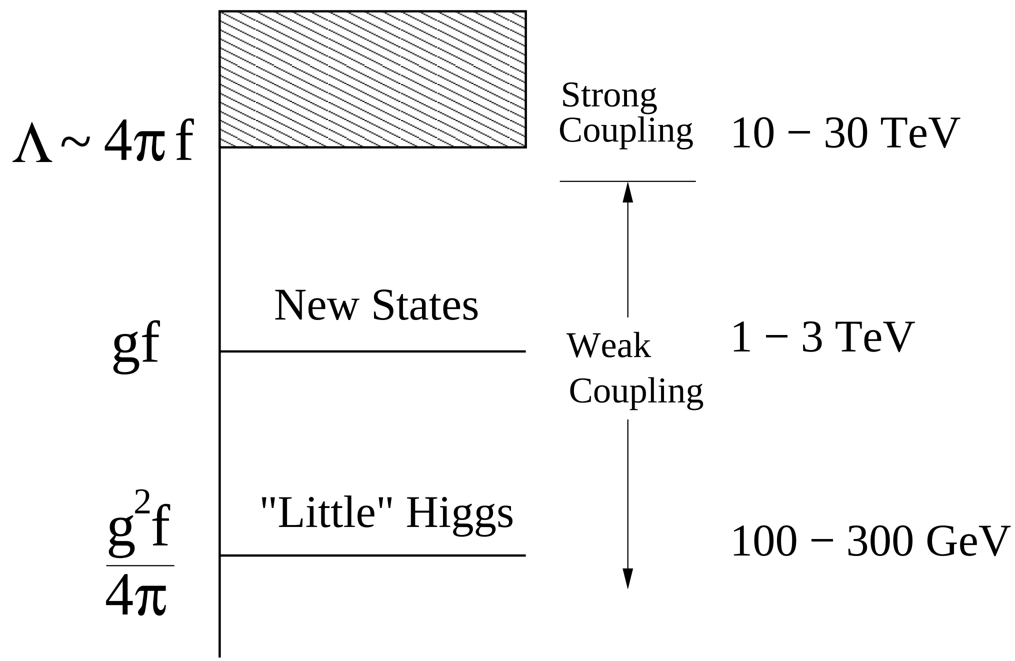
top		2 TeV
W, Z	at or below roughly	5 TeV
Higgs		10 TeV

The Little Higgs Idea

The Higgs is a pseudo-Nambu-Goldstone boson of a spontaneously broken global symmetry.

The global symmetry is explicitly broken by gauge and Yukawa interactions; however no single interaction breaks all the symmetry protecting the Higgs mass: need more than one interaction to generate Higgs mass ("collective breaking").

- 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.



Electroweak precision constraints

Csáki et al, PRD67:115002 (2003); hep-ph/0303236; Hewett et al, hep-ph/0211218; Gregoire et al, hep-ph/0305275

In general, the new heavy gauge bosons in Little Higgs models modify the electroweak (EW) precision observables because they couple to SM fermions (DIS, Z pole) and also mix with the W and/or Z (oblique corrs).

EW precision data puts lower bounds on the masses of the new heavy gauge bosons of roughly $1.5-2$ TeV, depending on the particular model.

In models with a product gauge group, like the Littlest Higgs, EW precision favors parameter regions where the new heavy gauge bosons are approximately decoupled from the SM fermions (suppressing 4-fermi ops and Drell-Yan production).

EW precision does not directly constrain the mass of the top-partner; but this is related to the heavy gauge bosons by the structure of the model. For naturalness, the top-partner should be as light as possible (lower bounds $\sim 1-2$ TeV in most models).

A Plethora of Little Higgs models

Big Moose Arkani-Hamed et al, PLB513:232 (2001) [hep-ph/0105239]

Minimal Moose Arkani-Hamed et al, JHEP 0208:021 (2002) [hep-ph/0206020]

Littlest Higgs SU(5)/SO(5) Arkani-Hamed et al, JHEP 0207:034 (2002) [hep-ph/0206021]

SU(6)/Sp(6) Low, Skiba, Smith, PRD66:072001 (2002) [hep-ph/0207243]

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

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

SU(9)/SU(8) Simple Group Skiba, Terning, hep-ph/0305302

SO(9)/[SO(5)×SO(4)] Chang, hep-ph/0306034

The "Littlest Higgs" – a concrete model

Arkani-Hamed, Cohen, Katz, Nelson, JHEP 0207, 034 (2002)

Global symmetry is SU(5), broken to SO(5) by nonlinear sigma model vev:

$$\Sigma_0 = \begin{pmatrix} & & \mathbb{1} \\ & 1 & \\ \mathbb{1} & & \end{pmatrix} \qquad (5 \times 5 \text{ matrix})$$

Gauged subgroup $[SU(2)\times U(1)]^2$ is broken to diagonal $SU(2)\times U(1)$: identified with SM gauge group

Goldstone bosons: $24 - 10 = 14$
-4 eaten by broken gauge generators
$= 10$ left: doublet h and triplet ϕ.

Pseudo-Goldstone bosons and gauge structure

Nonlinear sigma model:

$$\Sigma = e^{2i\Pi/f}\Sigma_0 = \Sigma_0 + \frac{2i}{f}\begin{pmatrix} & \phi^\dagger & h^\dagger/\sqrt{2} & \\ h^*/\sqrt{2} & & & h/\sqrt{2} \\ & & h^T/\sqrt{2} & \phi \end{pmatrix} + \cdots$$

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

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

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

Gauge generators each preserve part of the global symmetry:

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

Gauge structure and h mass quadratic divergence

$\Sigma_0 \to$ mass for one linear combination:

$$W_H^a = -cW_1^a + sW_2^a \qquad M_{W_H} = \frac{gf}{2sc}$$

$$B_H = -c'B_1 + s'B_2 \qquad M_{B_H} = \frac{g'f}{2\sqrt{5}s'c'}$$

where for the gauge couplings,

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

h couplings through collective breaking:

$$\begin{aligned} \mathcal{L} &= \frac{1}{4}\left(g_1 g_2 W_1^a W_2^a + g_1' g_2' B_1 B_2\right) h^\dagger h \\ &= \frac{1}{4}\left[g^2 \left(W^a W^a - W_H^a W_H^a\right) + g'^2 \left(BB - B_H B_H\right)\right] h^\dagger h + \cdots \end{aligned}$$

$\to$ Quadratic divergences in h mass from gauge loops cancel!

Top quark sector

To cancel the top loop quadratic divergence, have to generate the Higgs-top coupling through collective breaking:

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

where $Q_i = (b_3, t_3, \tilde{t})$ and $\tilde{t}$, $\tilde{t}'^c$ are a pair of vector-like fermions. The λ_1 term preserves global $SU(3)_2$ and the λ_2 term preserves global $SU(3)_1$.

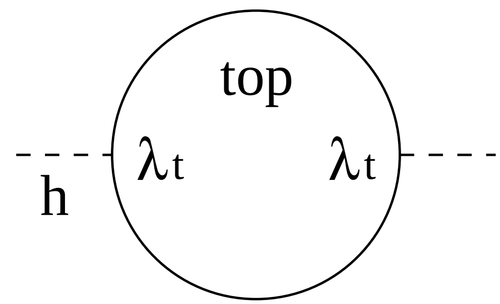
$\Sigma_0 \to$ mass for the extra quark: $\tilde{t}$ marries $\tilde{t}^c$ where

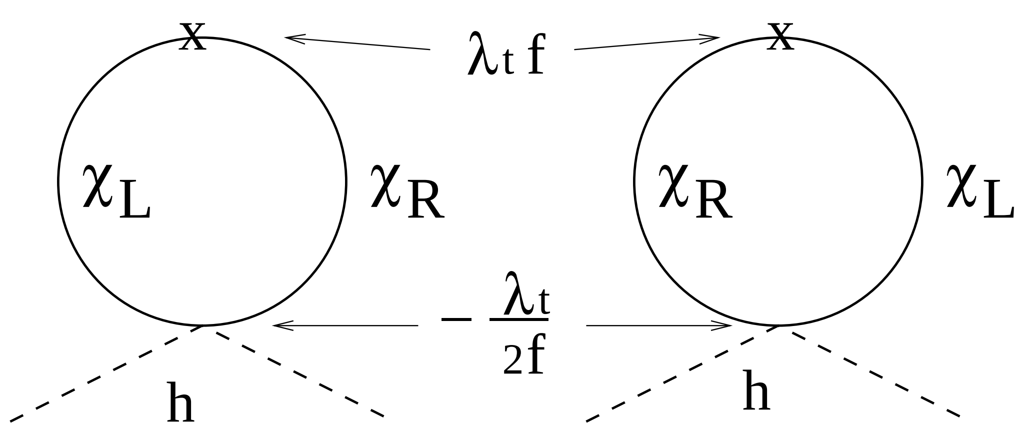
$$\tilde{t}^c = \frac{\lambda_2 \tilde{t}'^c + \lambda_1 u_3'^c}{\sqrt{\lambda_1^2 + \lambda_2^2}} \qquad M_T = f\sqrt{\lambda_1^2 + \lambda_2^2}$$

Top quark mass and coupling to h through collective breaking:

$$m_t = \frac{\lambda_1 \lambda_2}{\sqrt{\lambda_1^2 + \lambda_2^2}} v$$

Quadratic divergence in h mass from top quark loop is cancelled by "heavy top" loop!



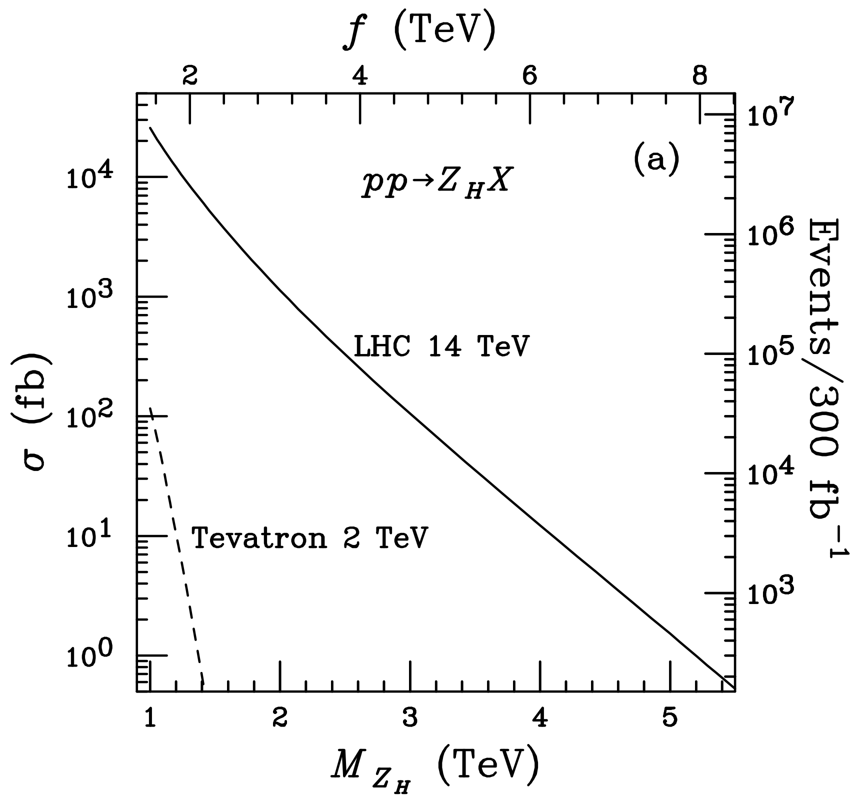


Similarly, the quadratic divergence in the h mass from the Higgs loop itself is cancelled by a loop of ϕ.

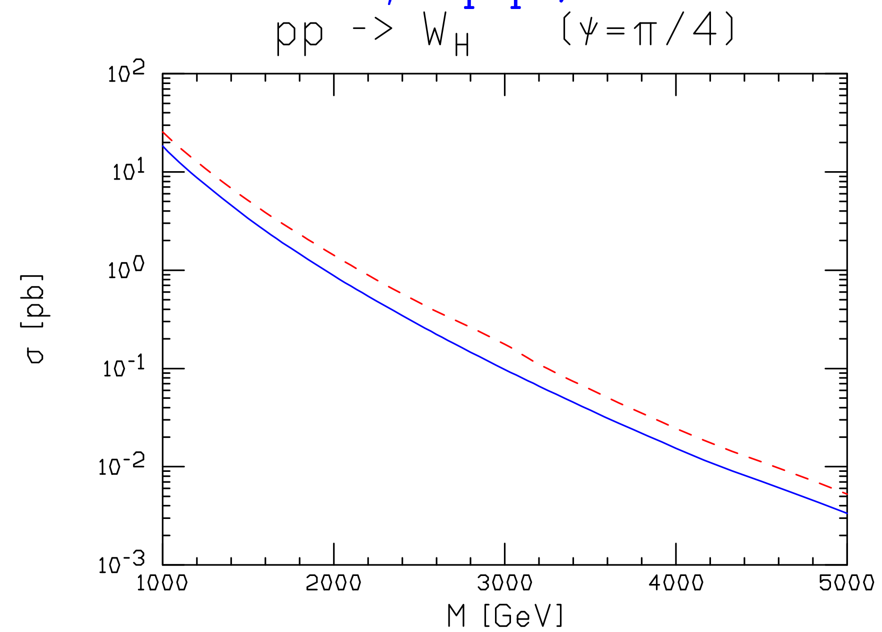
Particle content of the Littlest Higgs model

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

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



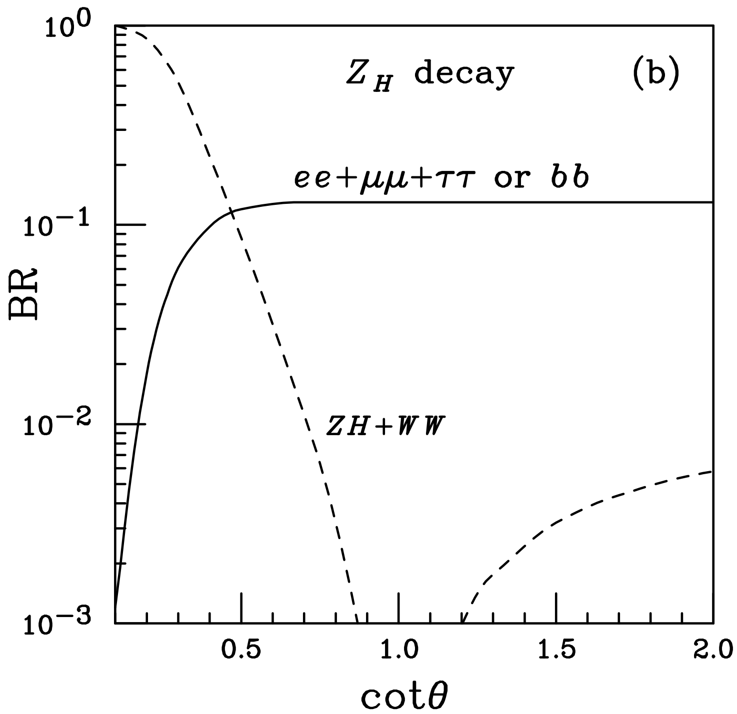
Burdman et al, **hep-ph/0212228**

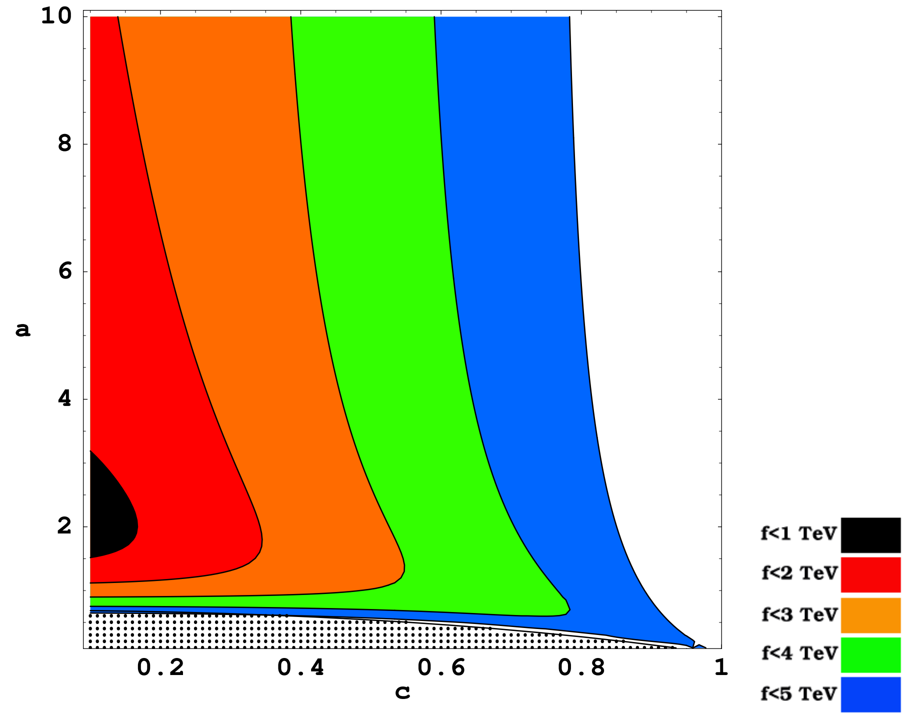


Dashes: $W_H^{\pm}$; solid: Z_H

Cross section $\propto \cot^2\theta \equiv c^2/s^2$ [$\cot\theta = 1$ in these plots]

Csaki et al, hep-ph/0303236





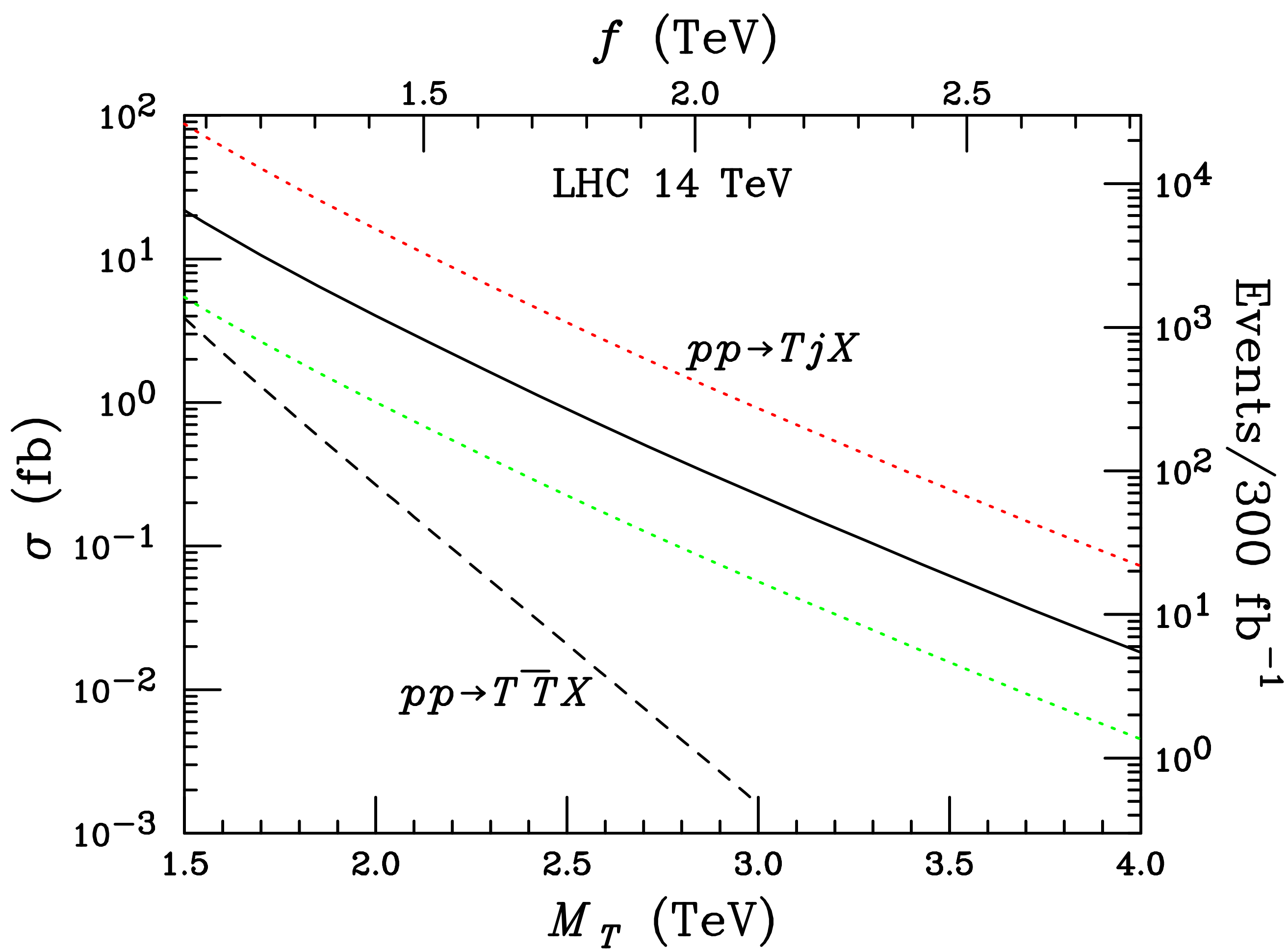
Z_H, $W_H^{\pm} \to \bar{f} f^{(\prime)}$ (SU(2)$_L$ doublets) $\propto g^2 \cot^2\theta$
$\to$ Equipartition among fermions.

$Z_H \to ZH, W^+W^-$ ($W_H^{\pm} \to W^{\pm}H, W^{\pm}Z$) $\propto g^2 \cot^2 2\theta$
$\to$ Test of model structure.

EW prec. favors low $\cot\theta \sim 0.2 \longrightarrow \sigma \sim 40$ fb for $M_{Z_H} = 2$ TeV.
Validity of effective theory: $g_1, g_2 \leq \sqrt{4\pi} \longrightarrow c \geq 0.18$

Phenomenology: Heavy top quark partner T

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

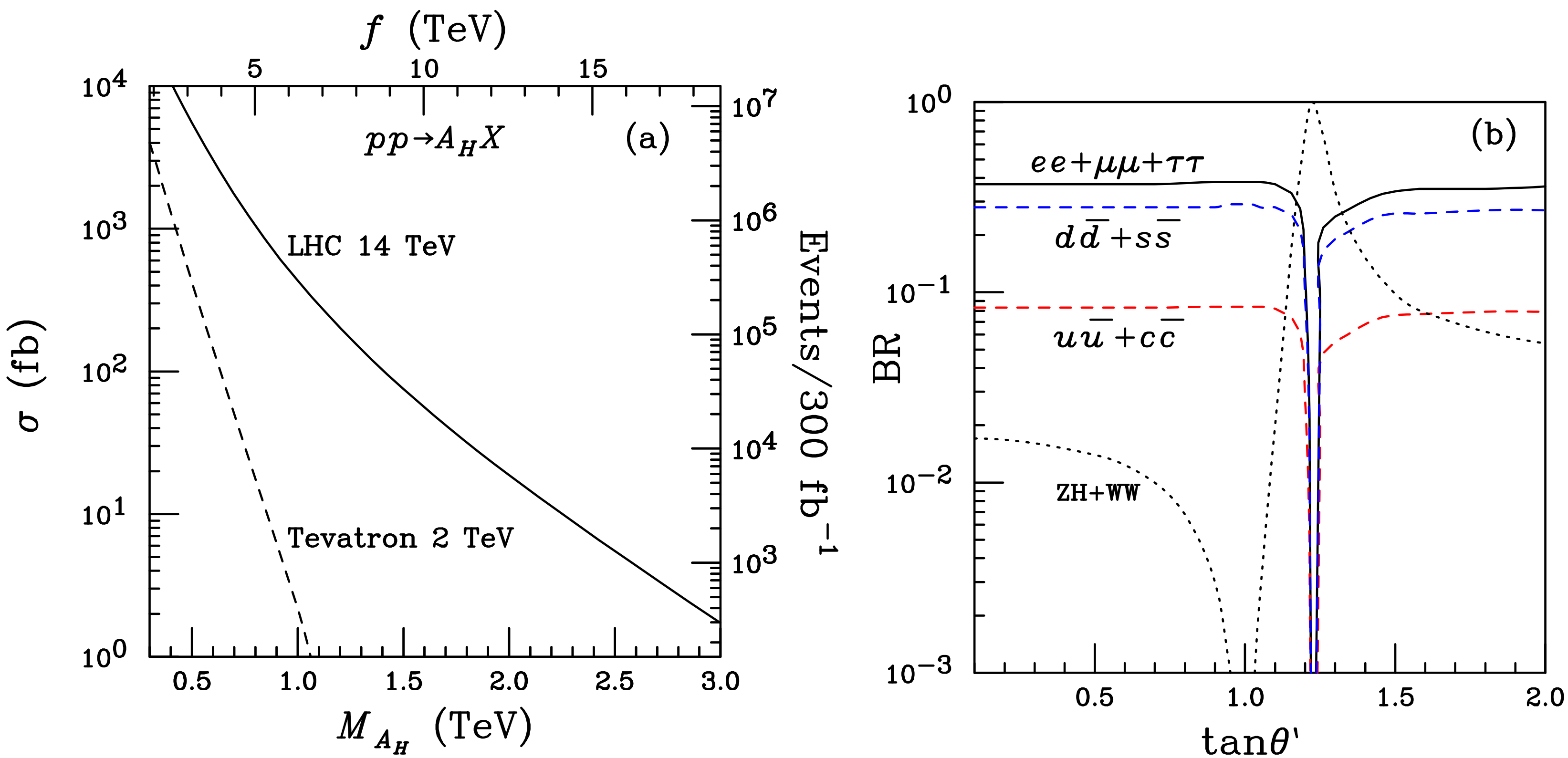


Solid line: $\lambda_1/\lambda_2 = 1$; Dotted: $\lambda_1/\lambda_2 = 2$, $1/2$

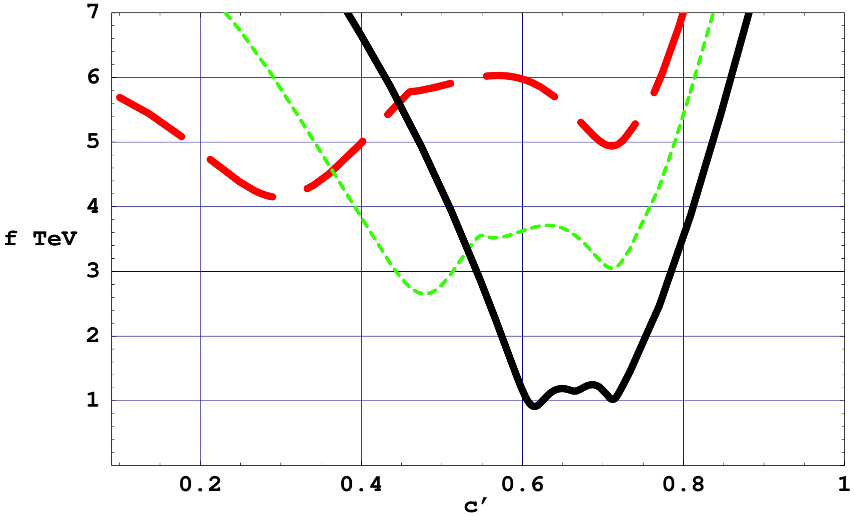
T decays: Equipartition $T \longrightarrow tH : tZ : bW = 1 : 1 : 2$.

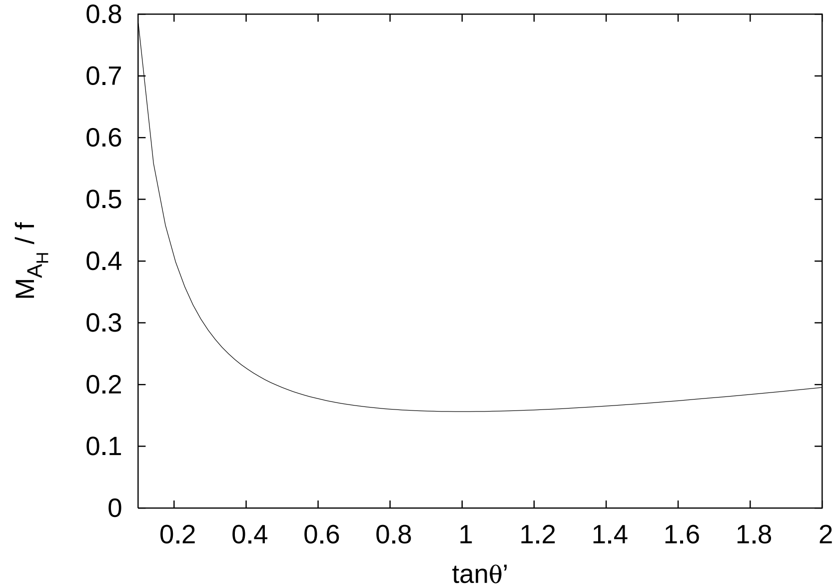
Phenomenology: Heavy U(1) boson B_H

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



Csaki et al, `hep-ph/0303236`





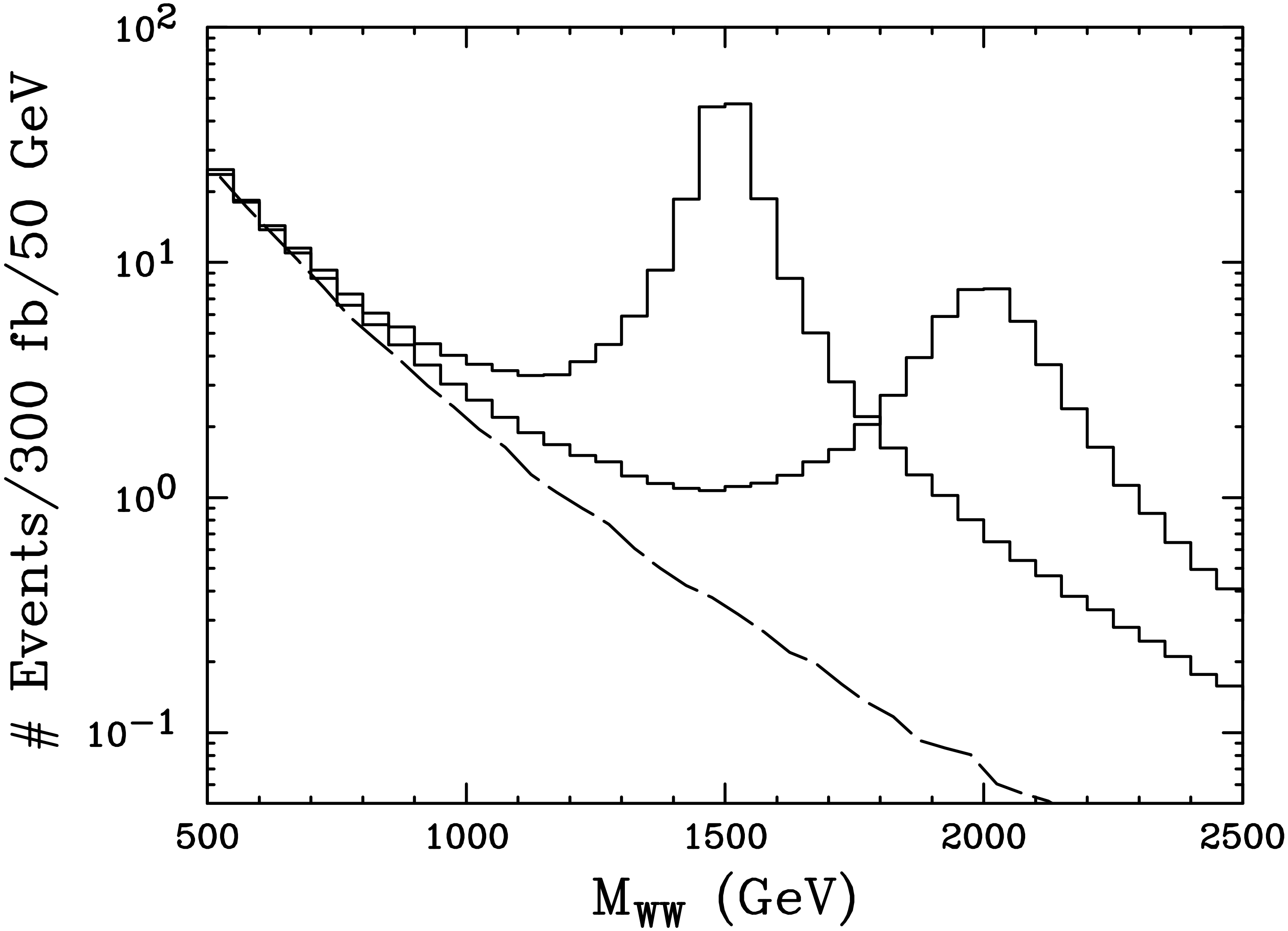
Gauge invariance + anomaly cancellation + naturalness
$\to c' \sim \sqrt{2}$, $\tan\theta' \sim 1$ $\longrightarrow$ $M_{B_H} \sim g' f/\sqrt{20} \sim 0.2 f$.

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 $\mathrm{U}(1)_Y$ is gauged $\to$ no B_H particle.

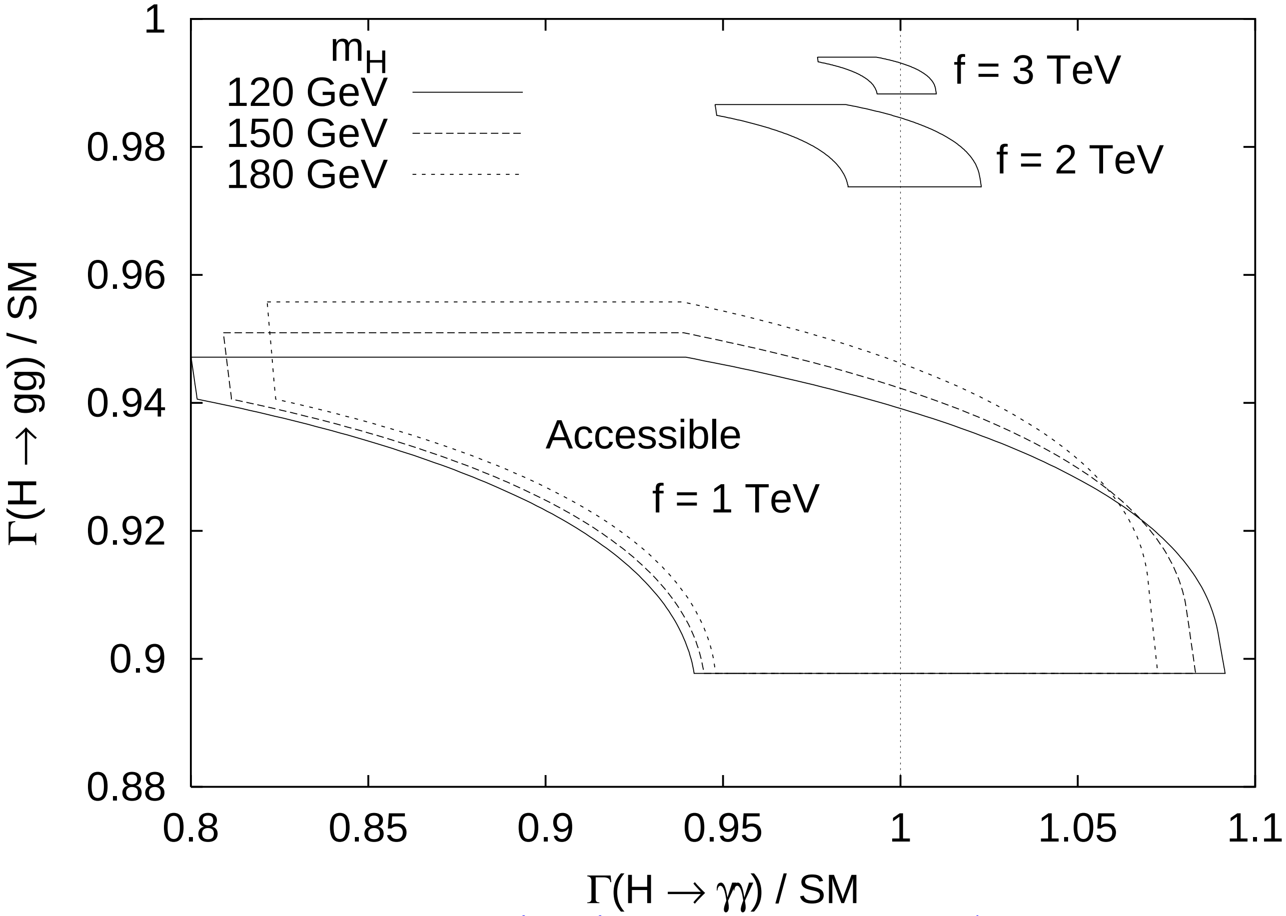
Phenomenology: Scalar triplet Φ

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



Cross section $\propto (v'/v)^2 = (0.1/\sqrt{2})^2$ for this plot

Phenomenology: Loop-induced H decays to 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.

Outlook and Conclusions

The Little Higgs idea is a new way to address the little hierarchy problem of the Standard Model.

The Higgs is a PNGB of a global symmetry. Gauge and Yukawa interactions break the symmetry, but no single interaction breaks all the symmetry protecting the Higgs mass; this forbids quadratically divergent radiative corrections at one-loop and allows the cutoff to be pushed one loop factor higher, to ~ 10 TeV.

Bottom-up view: the quadratically divergent radiative corrections due to top, gauge, and Higgs loops are cancelled by new heavy quarks, gauge bosons and scalars. Details of the phenomenology depend on the specific model.

There is some tension between the precision electroweak constraints pushing up the new particle masses and the requirement that the new particles be light to avoid fine tuning. However, clever model building can satisfy both requirements. The new particles should live in the $1-2$ TeV mass range and should be accessible at the LHC.