TRIUMF Summer Institute 2006

Collider and Energy Frontier Physics

Beyond the Standard Model

Lecture 4

Heather Logan

Carleton University

Plan

Lecture 1 Monday July 17

- Why BSM?
- Supersymmetry

Lecture 2 Monday July 17

- Supersymmetry continued: phenomenology

Lecture 3 Wednesday July 19

- Large extra dimensions: ADD
- Universal extra dimensions; particle spins and UED vs. SUSY

Lecture 4 Thursday July 20

- Deconstruction and the Little Higgs
- T-parity

Lecture 5 Friday July 21

- Warped extra dimensions: RS
- RS and Technicolour

Extra dimensional theories became very popular, but calculating some things in them was hard.

The gauge couplings run like a power law, instead of logarithmically

The theory requires a cutoff, where physics becomes strongly coupled

Physical results become dependent on details of the cutoff procedure

In the 4-D picture, problem was the infinite tower of KK modes.

Need a "toy theory" with only the first few KK modes.

$\rightarrow$ "Dimensional deconstruction"!

Hill, Pokorski & Wang, hep-th/0104035; Arkani-Hamed, Cohen & Georgi, hep-th/0104005

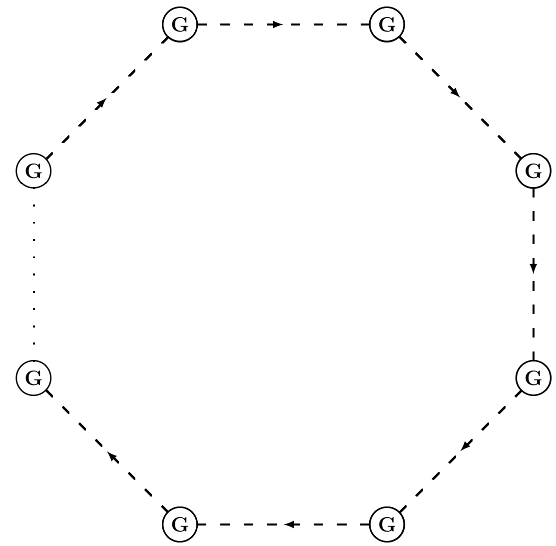
Discretize (or "latticize") the 5th dimension.

Introduce n copies of the extra-dimensional gauge group

"Connect" them with scalar fields

Give the scalar fields a vev to break all but one of the gauge symmetries

The broken gauge generators are the $n-1$ KK modes



To avoid scalars, use trick from Technicolour:

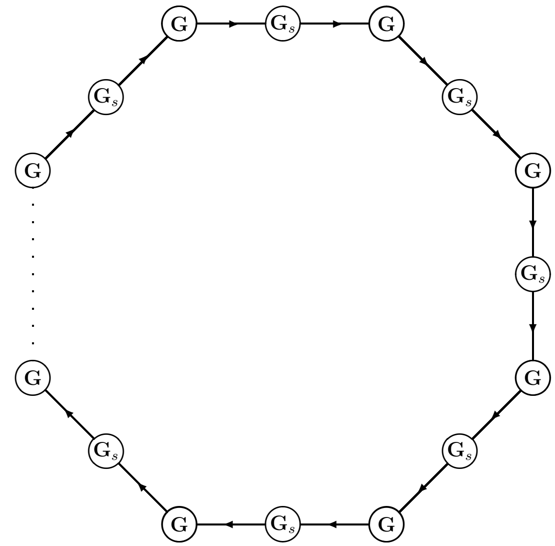
Add a different gauge group "in between" each pair of lattice sites

Connect pairs of gauge groups with fermions

Send the "in between" gauge couplings strong

Fermions condense and make a nonlinear sigma model (just like the pions in QCD)

All the extra Goldstone bosons get eaten by the massive gauge bosons



This diagram is called a moose

In 4-dim, the moose gives a light scalar field which is the totally symmetric linear combination of all the condensed scalars.

Classically it is massless: a (Nambu-)Goldstone boson.

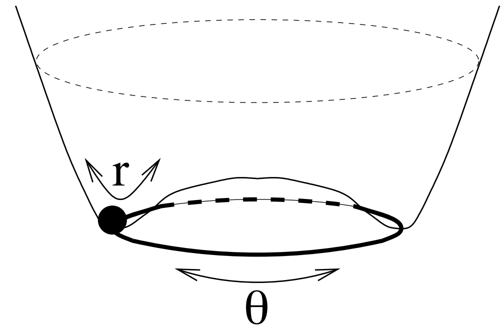
From quantum effects in the low-energy theory it picks up a quadratically divergent mass.

But because it is a "nonlocal" object (stretched around the moose), the quadratic divergence is cut off by the energy scale of the moose (would be $1/R$ in the continuum extra-dim version).

No longer massless: a pseudo-Nambu-Goldstone boson (PNGB).

Why is the "Goldstone boson" massless?

There is a global symmetry, which spontaneously breaks, giving a Goldstone boson:
the flat direction around the bottom of the potential.



Why does the "pseudo-Nambu-Goldstone boson" get a mass?

The global symmetry is explicitly broken.
There are some terms in the Lagrangian (interactions) that are not symmetric under the global symmetry.
Interactions (in loops!) communicate that breaking to the PNGB.

Why does it get only a small mass?

Any one interaction preserves enough global symmetry to forbid the PNGB from getting a mass.
Need multiple interactions acting together to generate the mass.
To get multiple interactions, need to go to a higher loop order.
PNGB mass is "protected" at 1-loop order!

This idea is called "collective symmetry breaking".

Collective symmetry breaking offers a possible solution to the Little Hierarchy.

What is the Little Hierarchy?

The big hierarchy is the hierarchy between m_W and $M_{\rm Pl}$.

There are strong constraints on Technicolour (and strongly-coupled theories in general) from precision electroweak measurements [at LEP].

A general analysis indicates that new strongly-coupled physics [without R- or KK-parity] shouldn't be lighter than roughly 10 TeV.

$\Delta m^2 \sim (g^2/16\pi^2)\Lambda^2 \to m_W \sim (g/4\pi)\Lambda \sim 0.1\,\Lambda$ for naturalness.

So we want $\Lambda \sim$ TeV.

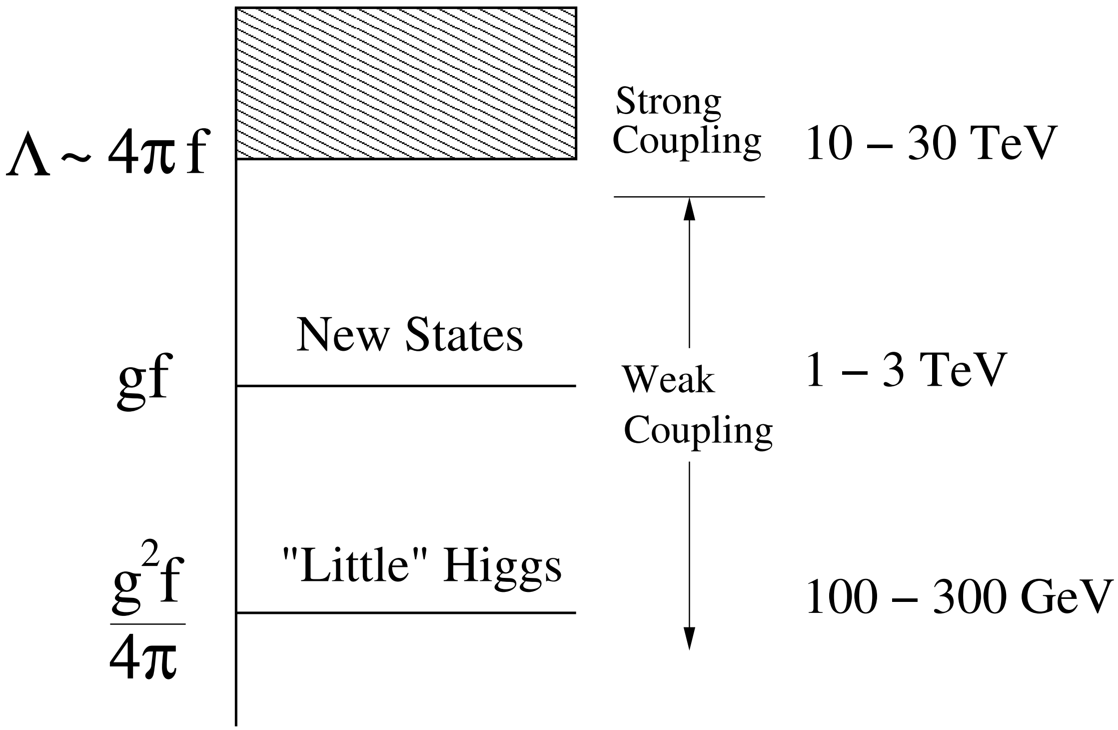
Because of EW precision constraints, this is difficult!

But if Δm^2 appeared only at 2-loops, then:

$\Delta m^2 \sim (g^2/16\pi^2)^2\Lambda^2 \to m_W \sim (g/4\pi)^2\Lambda \sim 0.01\,\Lambda$

So $\Lambda \sim 10$ TeV is ok!

Collective symmetry breaking offers a possible solution to the "Little Hierarchy problem".



Still need new states at $\sim$ 1 TeV to implement the collective breaking mechanism.

In order to make a global symmetry, need to add new things that transform into the SM under the global symmetry.

The global symmetry gets spontaneously broken, giving mass to the new things around 1 TeV.

This is the idea behind Little Higgs models.

Top-down picture:
Higgs is a pseudo-Nambu-Goldstone boson of a spontaneously broken global symmetry. Explicit breaking of the global symmetry by gauge and Yukawa interactions generates Higgs mass and couplings.

Bottom-up picture:
New particles at the TeV scale cancel off the SM quadratic divergence of the Higgs mass from top, gauge and Higgs loops.
The new particles correspond to the extra gauge bosons, fermions, and scalars that have to be introduced to enlarge the global symmetry, and that get masses at the TeV scale when the global symmetry is spontaneously broken.

How collective symmetry breaking works in Little Higgs models

"Littlest Higgs" model gauge sector makes a nice example.

Global symmetry is SU(5), broken down to SO(5).

The "pions" make up a nonlinear sigma model:

$$\Sigma = e^{2i\Pi/f}\Sigma_0 = \begin{pmatrix} & & \mathbb{1} \\ & 1 & \\ \mathbb{1} & & \end{pmatrix} + \frac{2i}{f}\begin{pmatrix} \phi^\dagger & h^\dagger/\sqrt{2} & \\ h^*/\sqrt{2} & & h/\sqrt{2} \\ & h^T/\sqrt{2} & \phi \end{pmatrix} + \cdots$$

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

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

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

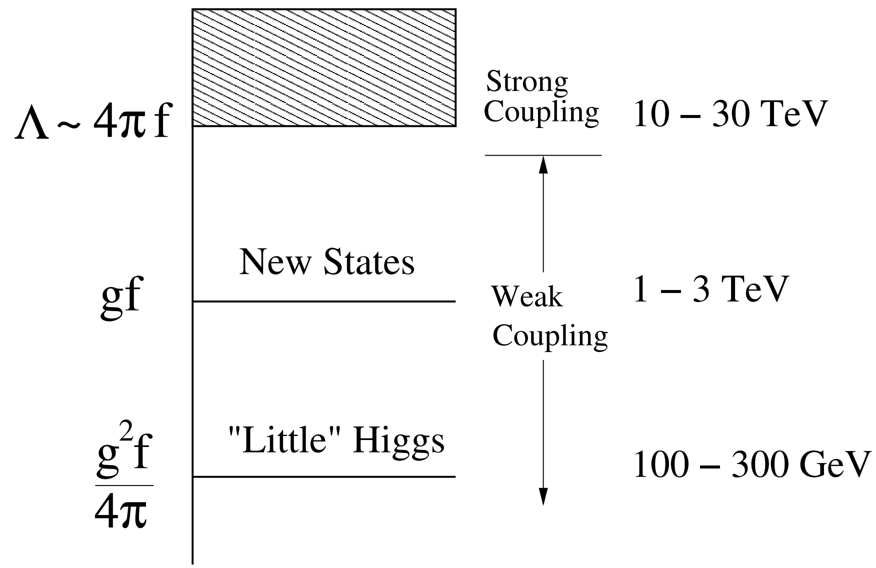
Gauge generators each preserve part of the global symmetry:

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

Need both $\mathrm{SU}(2)_1$ and $\mathrm{SU}(2)_2$ interactions to give h a mass.

Mass scales, again:

- 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.



Still have to deal with "big hierarchy" between 10 TeV and $M_{\rm Pl}$.

Little Higgs models are just effective theories below their cutoff scale $\Lambda \sim 10$ TeV.

Need an "ultraviolet (UV) completion": a theory valid up to $M_{\rm Pl}$.

Usually this is some Technicolour-like theory with strong coupling and composite particles.

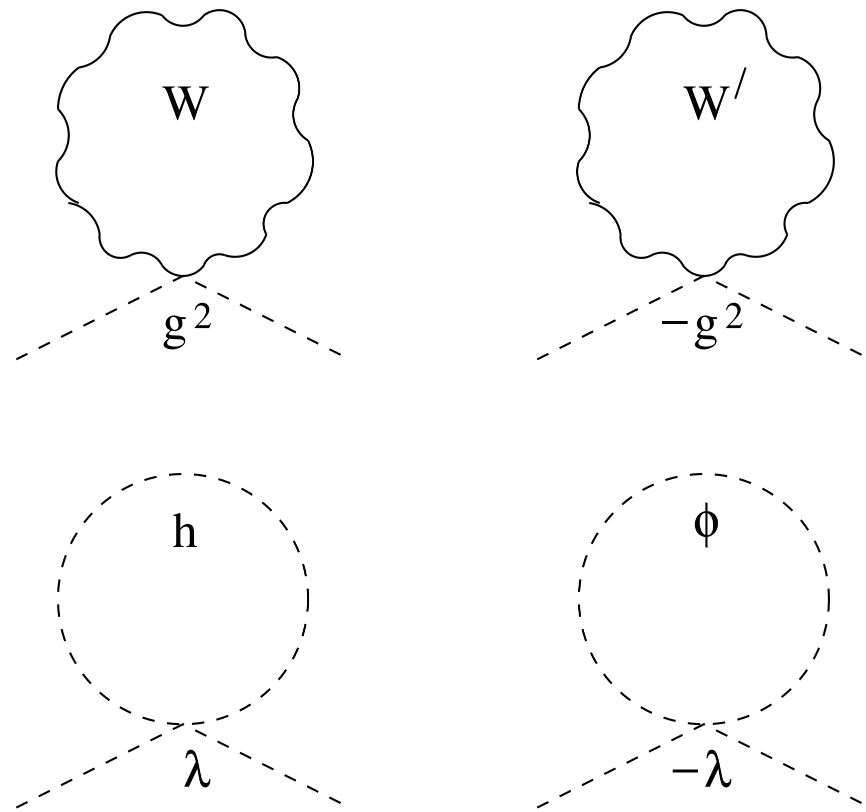
What are the new states?

Little Higgs models include:

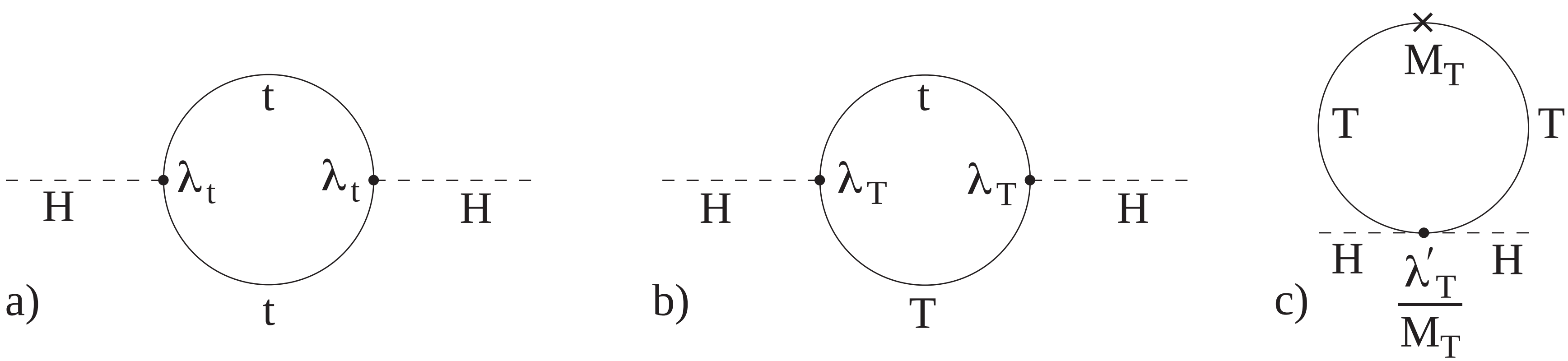
- New gauge bosons to cancel the SM gauge loops

- New scalars to cancel the Higgs self-interaction loop

- New "top-quark-partner" to cancel the top loop



diagrams from Schmaltz, hep-ph/0210415



diagrams from Han, Logan & Wang, hep-ph/0506313

New gauge bosons to cancel the SM gauge loops:

Two different types of models with different gauge structure.

Product group models

SM $SU(2)_L$ gauge group comes from diagonal breaking of a product gauge group:

$SU(2)\times SU(2)\rightarrow SU(2)_L$

Prototype: Littlest Higgs

Also includes:

Moose models,

SU(6)/Sp(6) model,

Littlest Higgs with custodial SU(2)

Simple group models

SM $SU(2)_L$ gauge group comes from breaking of a simple gauge group:

$SU(N)\rightarrow SU(2)_L$

Prototype: SU(3) Simple Group

Also includes:

SU(4) Simple Group,

SU(9)/SU(8) model

Product group models:

Littlest Higgs

$SU(2)_1 \times SU(2)_2 \times U(1)_Y \rightarrow SU(2)_L \times U(1)_Y$

Broken generators:
SU(2) triplet $W_H^\pm$, Z_H

Couplings to fermions:

Left-handed doublets transform under $SU(2)_1$

Free mixing angle
$\cot\theta = g_1/g_2$

Simple group models:

SU(3) Simple Group

$SU(3) \times U(1)_X \rightarrow SU(2)_L \times U(1)_Y$

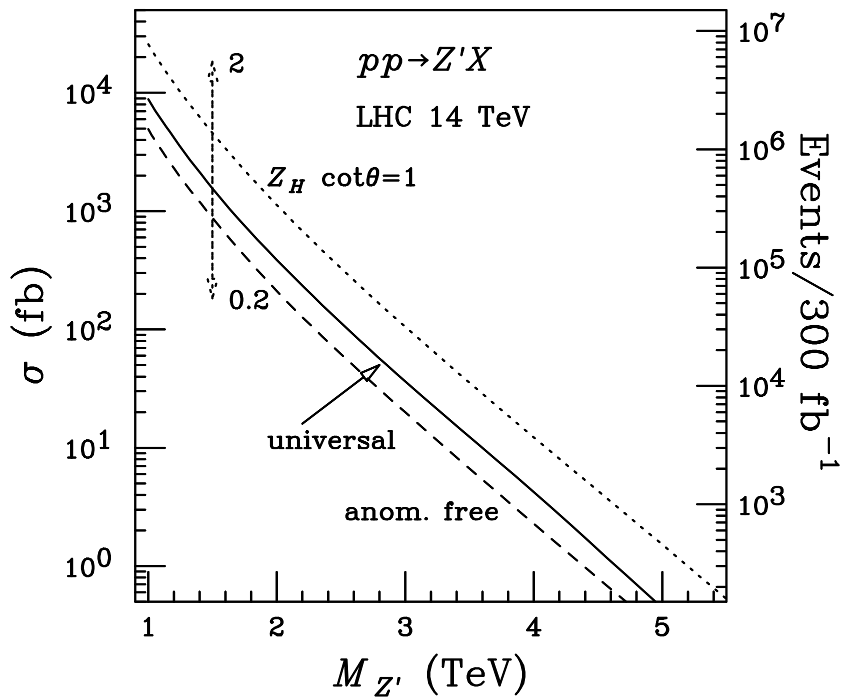
Broken diagonal generator Z'; broken off-diagonal generators $X^\pm$, Y^0

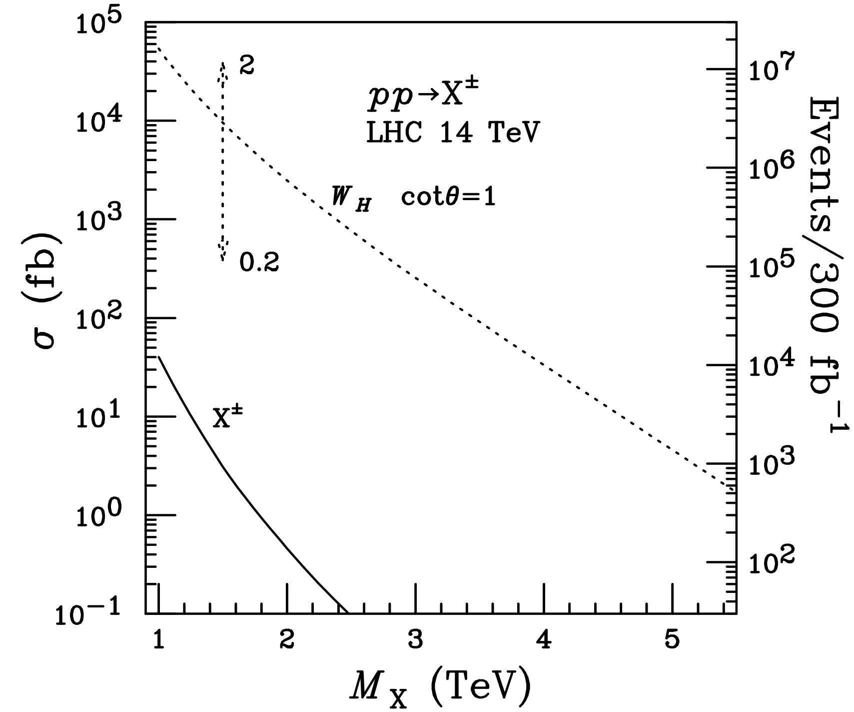
Couplings to fermions:

Left-handed doublets embedded in SU(3); $U(1)_X$ charges fixed by hypercharges.

Two possible embeddings: universal and anomaly-free, each with fixed couplings.

Phenomenology: Z_H, W_H production at LHC





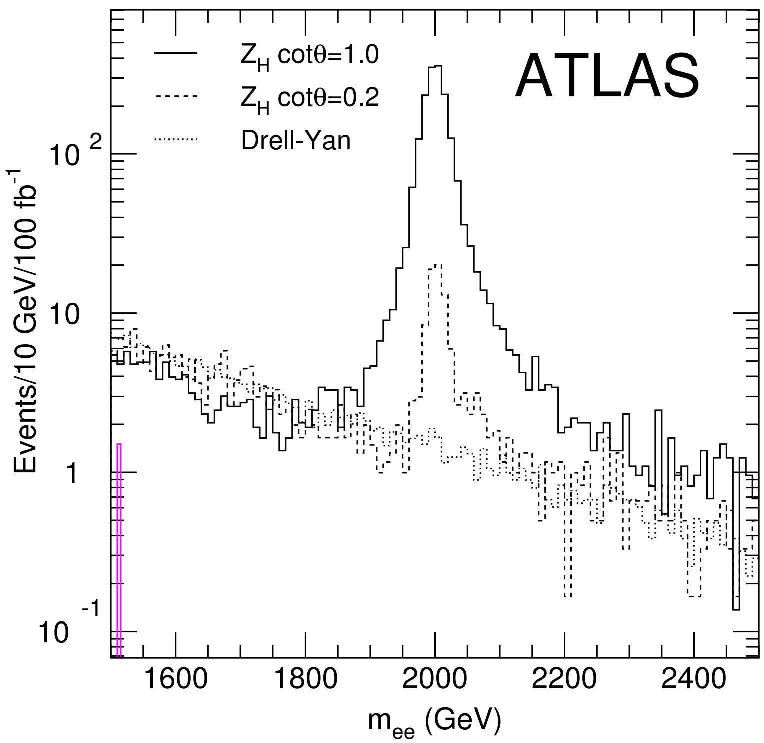
Han, Logan, & Wang, hep-ph/0506313

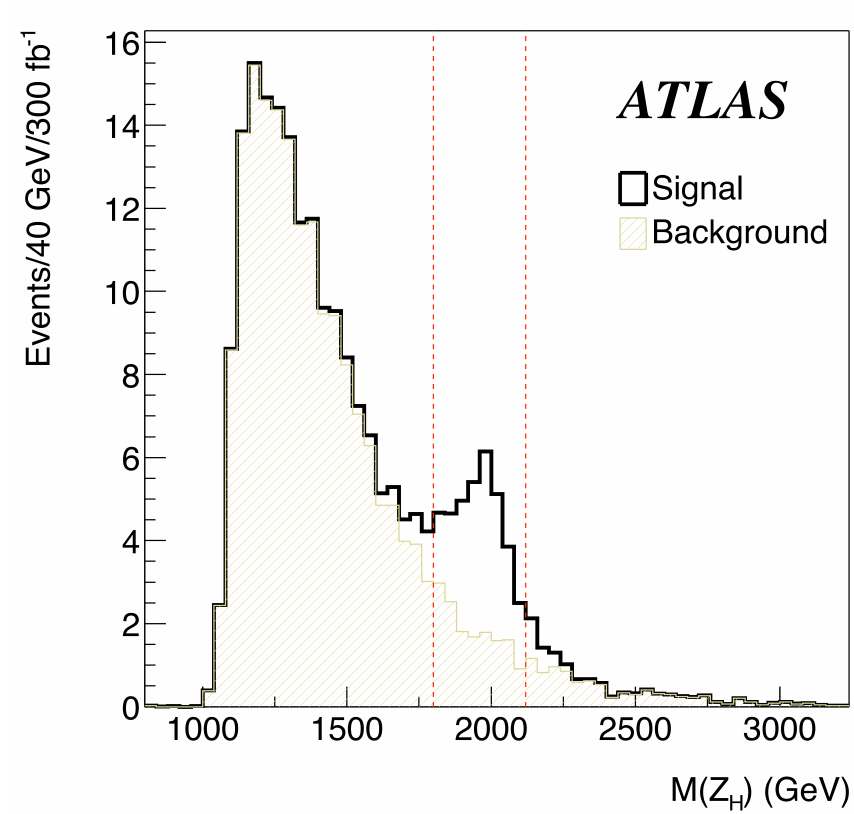
Littlest Higgs [dots]: $M_{Z_H} = M_{W_H}$. Cross section $\propto \cot^2\theta$.

SU(3) Simple Group [solid & dashes]: Z' cross section depends only on fermion embedding (discrete choice). $M_X = 0.82 M_{Z'}$; $X^{\pm}$ production very suppressed.

Littlest Higgs: Search for Z_H.

$Z_H \to \ell^+\ell^-$ and $Z_H \to Zh$ signals at LHC





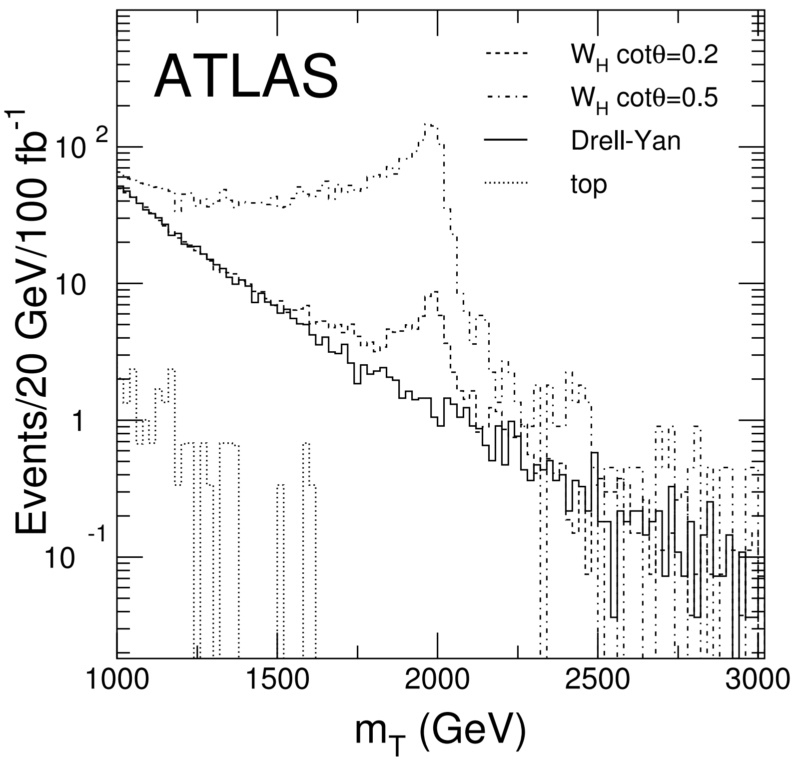
plots from Azuelos et al, hep-ph/0402037

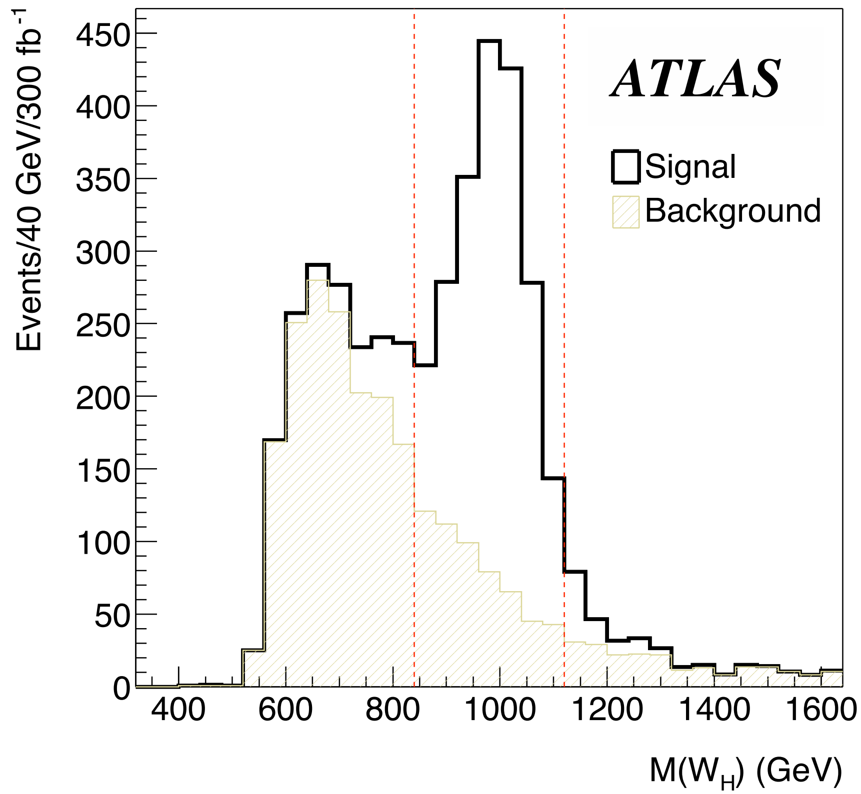
$\cot\theta = 0.5$

$M_{Z_H} = 2$ TeV with 300 fb^{-1}

Littlest Higgs: Search for W_H

$W_H \to \ell\nu$ and $W_H \to Wh$ signals at LHC



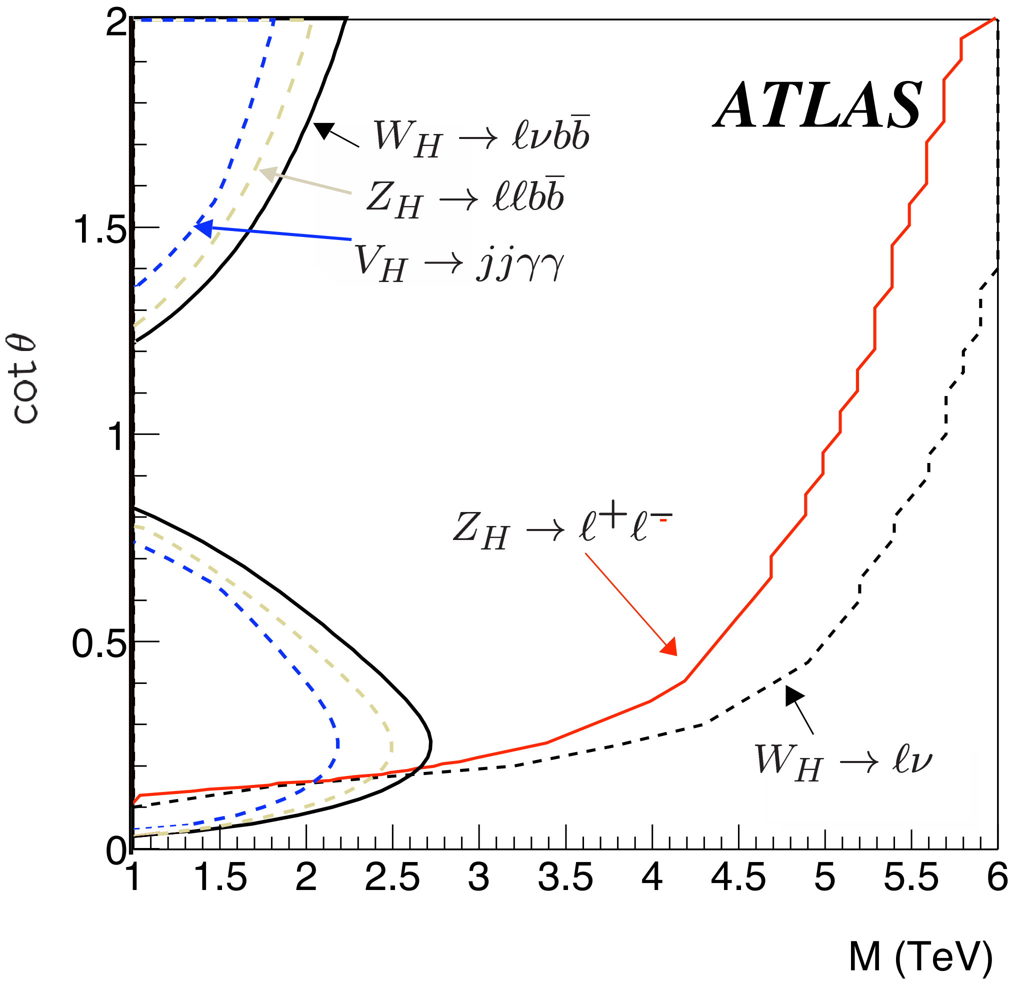


plots from Azuelos et al, hep-ph/0402037

$\cot\theta = 0.5$

$[M_{W_H} = 1$ TeV only$]$

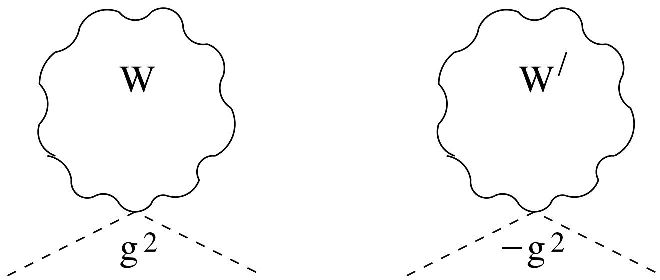
LHC 5σ discovery reach of Z_H, W_H in Littlest Higgs model



from Azuelos et al, hep-ph/0402037

for 300 fb^{-1}

Gauge divergence cancellation: sum rule for couplings



$$\sum_i G_{HHV_iV_i^*} = 0$$

SM couplings:

$$G_{HHW^+W^-} = g^2/4 \qquad G_{HHZZ} = g^2/8c_W^2$$

Littlest Higgs model (product group):

$$G_{HHW_H^+W_H^-} = -g^2/4 \qquad G_{HHZ_HZ_H} = -g^2/8$$

SU(3) Simple Group model:

$$G_{HHX^+X^-} = -g^2/4 \qquad G_{HHZ'Z'} = -g^2/8c_W^2$$

Gauge boson couplings to the Higgs are critical for cancellation of the quadratic divergence:

Product group models:

Littlest Higgs

$SU(2)_1 \times SU(2)_2 \times U(1)_Y$
$\to SU(2)_L \times U(1)_Y$

Broken generators:
SU(2) triplet $W_H^\pm$, Z_H

Couplings to Higgs:
Collective breaking structure:
Higgs transforms under both SU(2)s

$$\mathcal{L} \supset g_1 g_2 W_1 W_2 h h^\dagger /4$$
$$= g^2[WW - W_H W_H$$
$$-2 \cot 2\theta W W_H] h h^\dagger /4$$

Simple group models:

SU(3) Simple Group

$SU(3) \times U(1)_X \to SU(2)_L \times U(1)_Y$

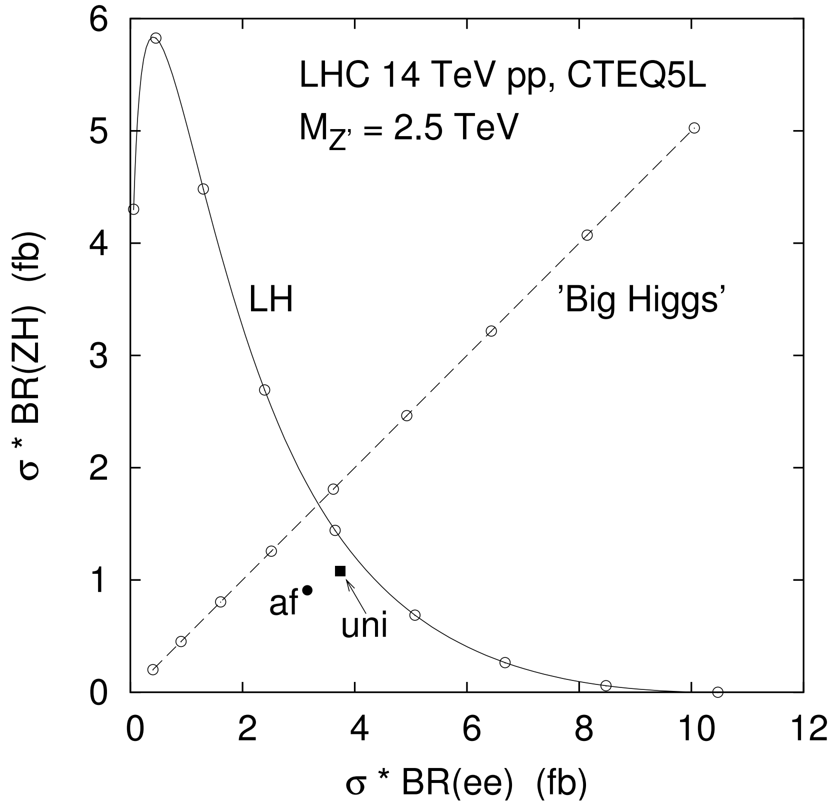
Broken diagonal generator Z';
broken off-diagonal generators $X^\pm$, Y^0

Couplings to Higgs:
Higgs embedded in SU(3) triplet as a "pion"

$$\mathcal{L} \supset g^2[W^+W^- - X^+X^-]H^2/4$$
$$+(g^2/8c_W^2)[ZZ - Z'Z'$$
$$+2c_W(1-t_W^2)/\sqrt{3-t_W^2} ZZ']H^2$$

Gauge-Higgs couplings fix the bosonic decay widths of the Z_H, W_H relative to their fermionic widths.

Test of the Higgs mass stabilization mechanism:



Han, Logan, & Wang, hep-ph/0506313

Littlest Higgs: (LH)

Production $\propto \cot^2\theta$

Decay to fermions $\propto \cot^2\theta$

Decay to bosons $\propto \cot^2 2\theta$

SU(3) Simple Group: (af, uni)

Production and decay couplings fixed once fermion embedding is chosen.

"Big Higgs":

$SU(2)_1 \times SU(2)_2 \to SU(2)_L$ model with Higgs transforming linearly under $SU(2)_1$.

No quadratic div. cancellation.

Production and decay couplings all $\propto \cot^2\theta$.

Want the top loop to be cancelled also:

Need to implement collective symmetry breaking in top sector.

To set up the required global symmetry, have to enlarge the top sector.

Give the top something to transform into under the global symmetry.

Upshot: have to add an extra "top-partner" quark T.

T is an electroweak singlet (has no SU(2) partner "heavy b").

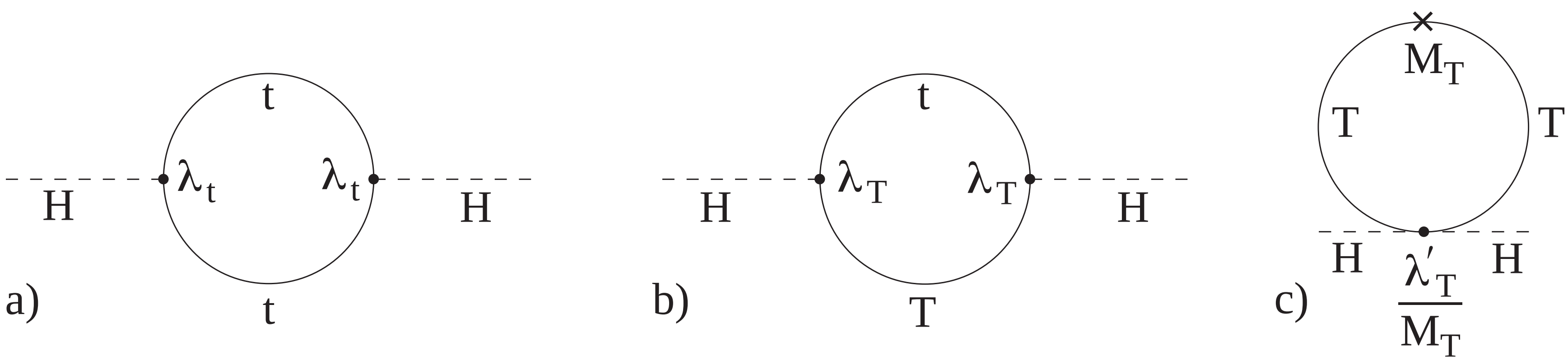
T has both left- and right-handed components: a Dirac fermion.

[T mass $\sim$ TeV; does not come from EWSB]

T mixes a little with the SM top quark [get TbW, TtZ, Tth couplings]

Coupling sum rule for top divergence cancellation:

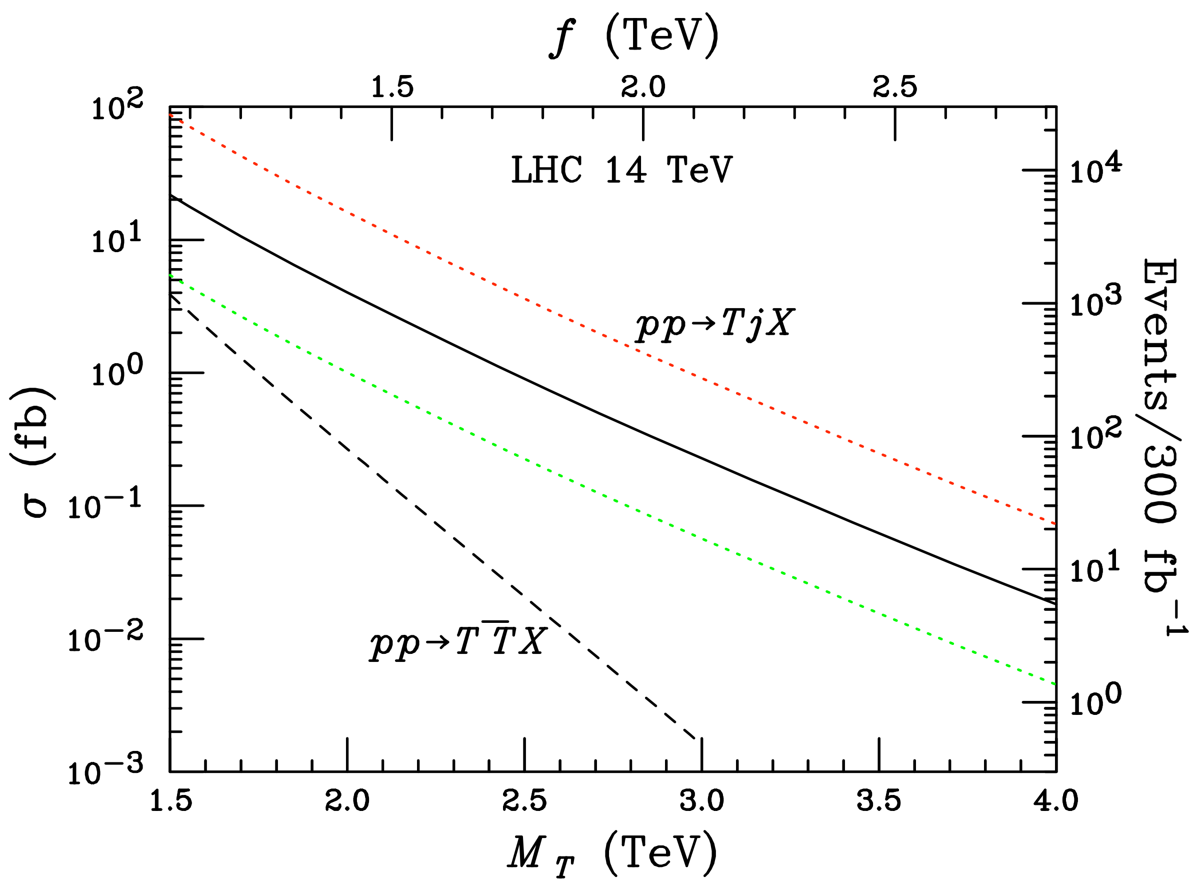
$$\lambda_t^2 + \lambda_T^2 = \lambda'_T$$



diagrams from Han, Logan & Wang, hep-ph/0506313

Production of the top-partner T in the Littlest Higgs model:

$Wb \to T$

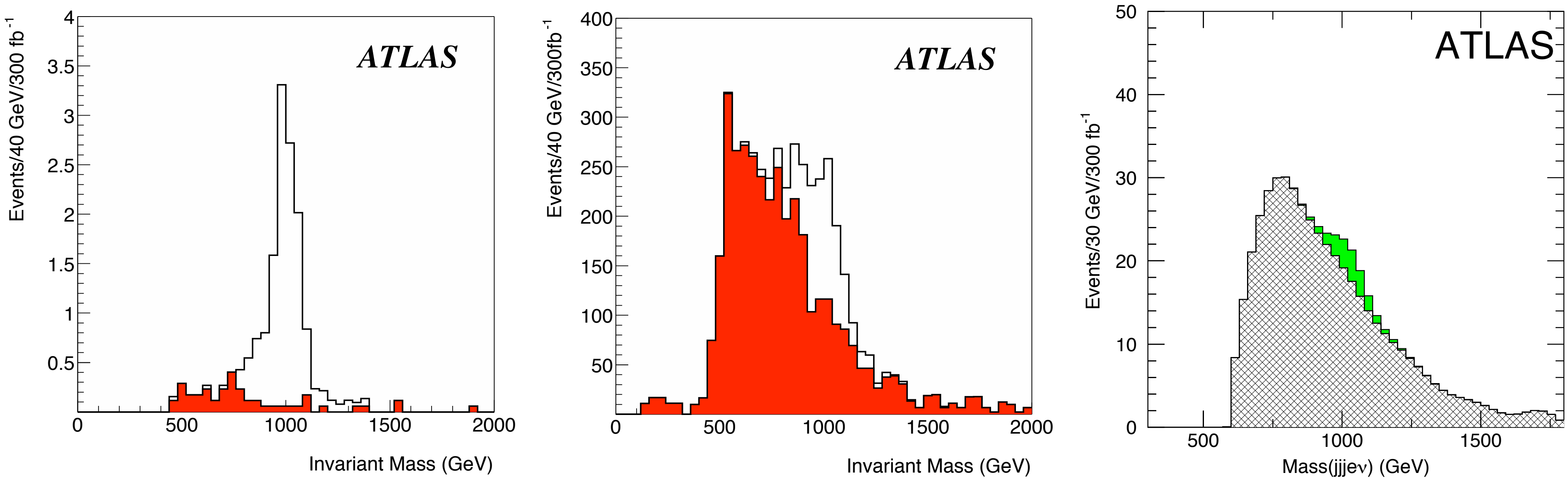


from Han, Logan, McElrath, & Wang, hep-ph/0301040

T decays into the 3rd-gen left-handed quark doublet (t_L, b_L) and the components of the Higgs doublet $(G^+, (h + G^0)/\sqrt{2})$:

$T \to tZ$ (25%), $T \to bW$ (50%), $T \to th$ (25%).

$T \to tZ$, $T \to bW$, and $T \to th$ decay mode searches at LHC:

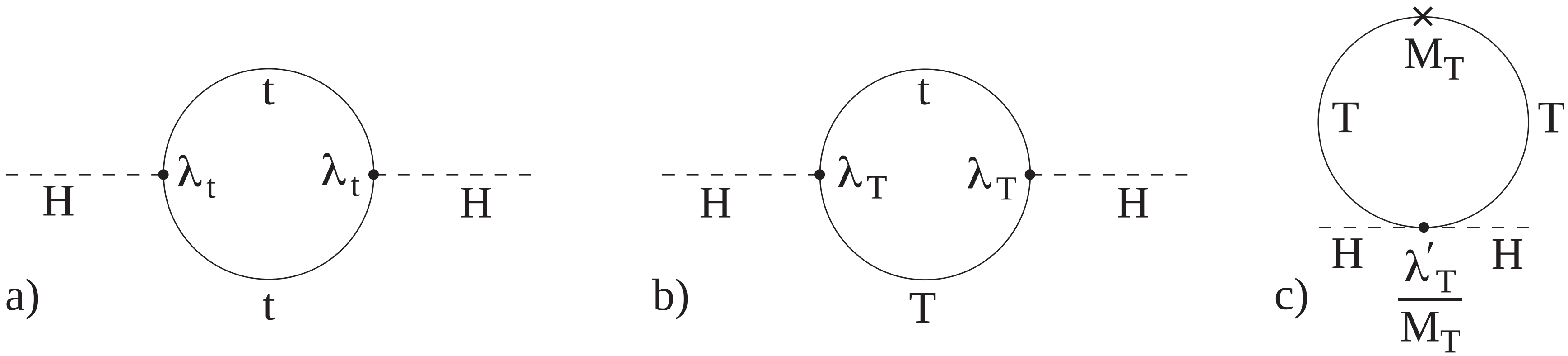


plots from Azuelos et al, hep-ph/0402037

[for $m_h = 120$ GeV]

Testing the coupling sum rule in the top sector:

$$\lambda_t^2 + \lambda_T^2 = \lambda_T'$$



diagrams from Han, Logan & Wang, hep-ph/0506313

In Littlest Higgs model the free parameters are λ_T, M_T and f.

λ_T fixes the TbW coupling: measure from single T production.

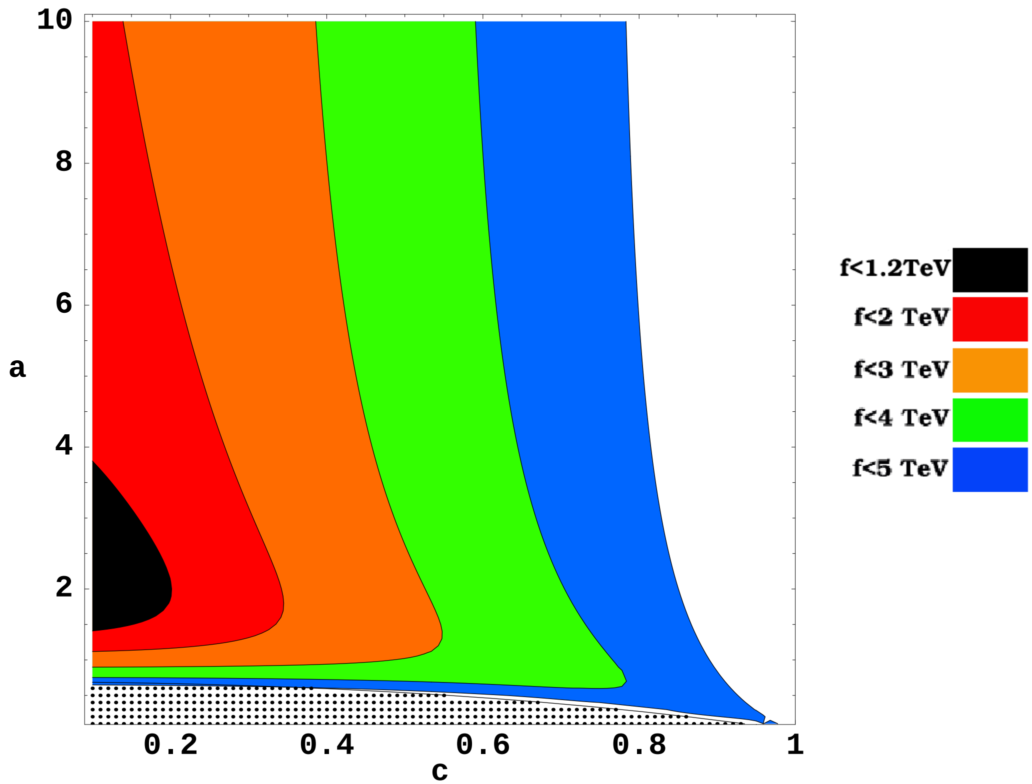
Measure the T mass M_T.

Measure f from the gauge sector.

In other models [e.g., SU(3) Simple Group] the top sector is more complicated. Need to measure one more mixing angle from heavy partners of the light quarks.

Electroweak precision constraints on Little Higgs models

As in UED, strongest constraints come from tree-level exchange of new gauge bosons between fermions.



Plot for Littlest Higgs model with only one U(1) group gauged (hypercharge).

from Csáki, Hubisz, Kribs, Meade, & Terning, hep-ph/0303236

The scale f is rather tightly constrained: $M_{Z_H}, M_{W_H} \geq 2$ TeV usually required.

Top-partner mass is linked to f:

Tends to be pushed above 1–3 TeV by EW precision constraints on f: Higgs mass becoming fine-tuned again.

If we could eliminate tree-level exchange of W_H, Z_H, the EW precision constraints would become much looser.

Is there an analogue of KK-parity for the little Higgs?
If the extra gauge bosons are odd under some parity, they won't contribute to precision EW observables at tree level!
Parity-odd extra gauge bosons can still do their jobs in the loops.
Then new particles can be light enough to cancel the Higgs mass divergence without fine-tuning.

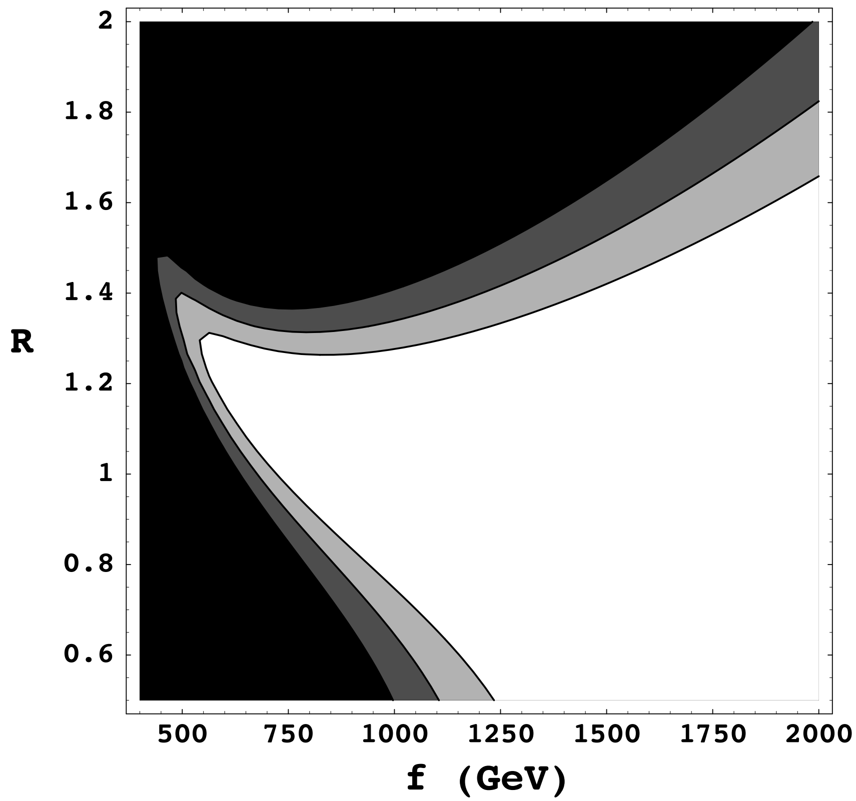
The answer is yes: T-parity!

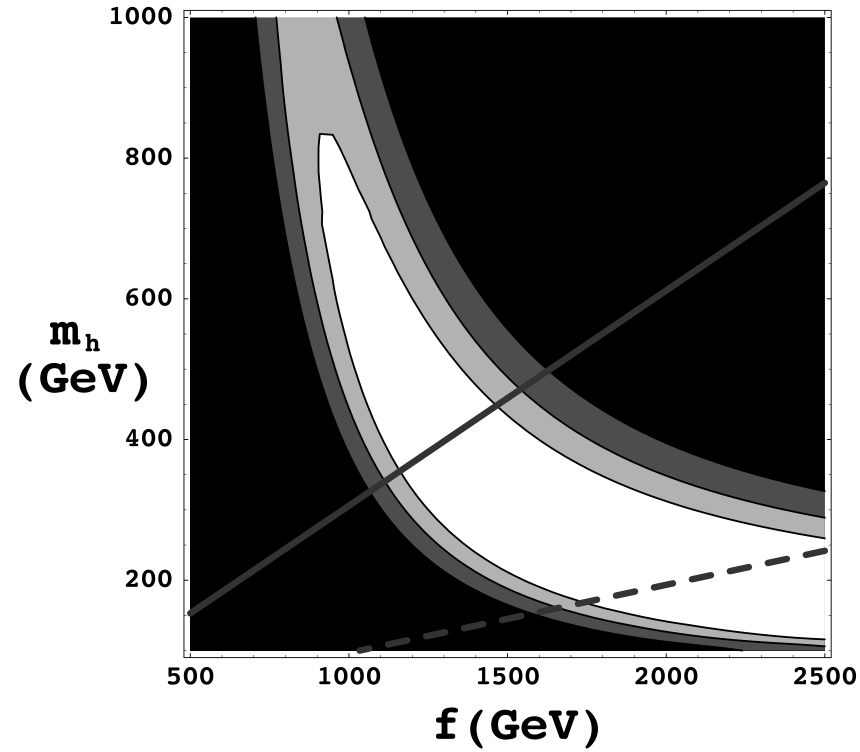
For moose models it is exactly analogous to KK-parity:
The "moose" represents a latticized extra dimension.
T-parity is just a symmetry flipping the moose left-to-right.
Analogous to the reflection symmetry that gives K-parity in UED.

Can also construct a "Littlest Higgs"-type model with T-parity:
Need to add a few more fermions, set various couplings equal so that a Z_2 parity is conserved.

As in UED, including T-parity allows new particles to be much lighter: several hundred GeV range.

"Littlest Higgs with T-parity":





from Hubisz, Meade, Noble, & Perelstein, hep-ph/0506042

Fine-tuning is greatly improved:

Grey solid line: m_h fine-tuned to 10%

Grey dashed line: m_h fine-tuned to 1%

Phenomenology of the Littlest Higgs with T-parity:
Very similar to UED phenomenology!

Still have the Z_H, W_H, A_H gauge bosons of Littlest Higgs model
Now they are T-odd: must be pair-produced.
A_H is the lightest: "LTP"

Missing energy signatures

Dark matter candidate

Still have the T of Littlest Higgs model
Two versions of the T-parity model: one with T_+ (T-even) and one with T_- (T-odd).
T_+: single-production is the same; decays are the same.
T_-: must be pair-produced; decays to top and LTP.

Get extra T-odd fermion "partners" of each SM generation
They are needed to make model T-symmetric
Can mix in general: flavour-changing issue (as in SUSY!)
Need to assume T-odd fermions do not mix between generations

The latest new direction in Higgs-as-a-PNGB: "Twin Higgs"

Rather than using a global symmetry like SU(5) or $[\mathrm{SU}(3)]^2$ to protect the Higgs from radiative corrections, use a second Higgs doublet and a discrete symmetry.
Set it up so H and $\hat{H}$ transform into each other under Z_2.
Get an accidental global SU(4) as a result: $(H, \hat{H})$, under which the SM Higgs is a PNGB: mass is protected at one loop.

First implementation: have to "twin" the entire SM to preserve the symmetries!
Higgs mass divergence is cancelled by Mirror-World particles!
Mirror world particles very hard to detect at colliders; can screw up early universe cosmology.

Second implementation: don't need to duplicate the entire SM.
Enlarges weak gauge group to $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ ($\mathrm{SU}(2)_R$ contains $\mathrm{U}(1)_Y$): "Left-Right symmetry".
Discrete symmetry is the Z_2 that swaps $\mathrm{SU}(2)_L \leftrightarrow \mathrm{SU}(2)_R$.
Rich set of new particles to study at LHC.

Summary

Little Higgs models are sort of a “deconstructed” version of UED, but with more freedom:
Littlest Higgs-type models have no extra-dimensional analogue.
No “KK gluon” because $SU(3)_c$ is not replicated.

Higgs mass is stabilized by cancellation between SM loops and new particle loops
Different from SUSY: fermion loops cancelled by fermions; boson loops cancelled by bosons!
Also: cancellation only works at 1 loop! 2-loop quadratic divergence must be cut off at $\Lambda \sim 10$ TeV for a “natural” theory.
Need something new at 10 TeV or so: the UV completion.

[Something like Technicolour?]

Key measurements are the couplings involved in the Higgs mass divergence cancellation.
Shed light on the symmetry structure of the theory.