Beyond the Standard Model at Colliders

(part 1 of 2)

Heather Logan

Carleton University

TRIUMF Summer Institute 2009

TRIUMF

Carleton
UNIVERSITY

Outline

== Lecture 1 ==

1. Why Beyond the Standard Model

2. Resonances

== Lecture 2 ==

3. Decay chains to a dark matter particle

4. Exotica

5. Summary

Why go Beyond the Standard Model?

The Standard Model has been stringently tested at colliders and so far spectacularly confirmed.

- QCD
    - strong interactions at colliders
    - lattice QCD and hadron masses

- Flavour sector
    - CKM matrix
    - rare decays

- Electroweak
    - consistency of electroweak measurements
   - limits on New-Physics contributions

QCD − High-precision QCD becoming an "industry standard"

Tremendous progress in past 5 years; still much to understand

| Process ($V \in \{Z, W, \gamma\}$)	Comments	Motivation
pre Les Houches 2007	(completed)	
1. $pp \to VV$ jet	$V = Z$ cases missing, W-decays included	Higgs background
2. $pp \to$ Higgs+2jets	NLO QCD+EW to VBF	
3. $pp \to VVV$	γ cases missing	new physics background
4. $pp \to t\bar{t}b\bar{b}$	$m_b = 0$, no t-decay	background for $t\bar{t}H$
5. $pp \to W$+3jets	W-decay included	new physics background
Les Houches 2007	(in progress)	
6. $pp \to t\bar{t}$+2jets		relevant for $t\bar{t}H$
7. $pp \to WW b\bar{b}$,		relevant for $t\bar{t}$ benchmark process
8. $pp \to VV$+2jets	V-decays useful	VBF $\to H \to VV$
9. $pp \to b\bar{b}b\bar{b}$		Higgs and new physics signatures
	two-loop observables	
10. $gg \to W^*W^*$	NLO QCD	Higgs background
11. $pp \to t\bar{t}$	NNLO QCD	benchmark process
12. $pp \to Z/\gamma$+jet	NNLO QCD	pdf, jet-energy measurements
13. $pp \to W/Z$	NNLO QCD $\oplus$ NLO EW	benchmark process
Les Houches 2009		
14. $pp \to W$+3jets	W-decay included	new physics background
15. $pp \to Wb\bar{b}j$	$m_b = 0$ sufficient (?)	Higgs search
16. $pp \to jjjj$		new physics background
17. $pp \to t\bar{t}t\bar{t}$		new physics background
18. $pp \to Wjjjj$	leading color sufficient (?)	new physics background
19. $H \to f\bar{f}f'\bar{f}'$	NLO EW+QCD (completed)	Higgs search
	(two-loop)	
20. $gg \to H$	NLO EW (completed)	Higgs search
21. $pp \to VV$	NNLO	benchmark process
22. $pp \to Hj$	NNLO ($m_t \to \infty$)	Higgs search

QCD – High-precision QCD becoming an "industry standard"

Tremendous progress in past 5 years; still much to understand
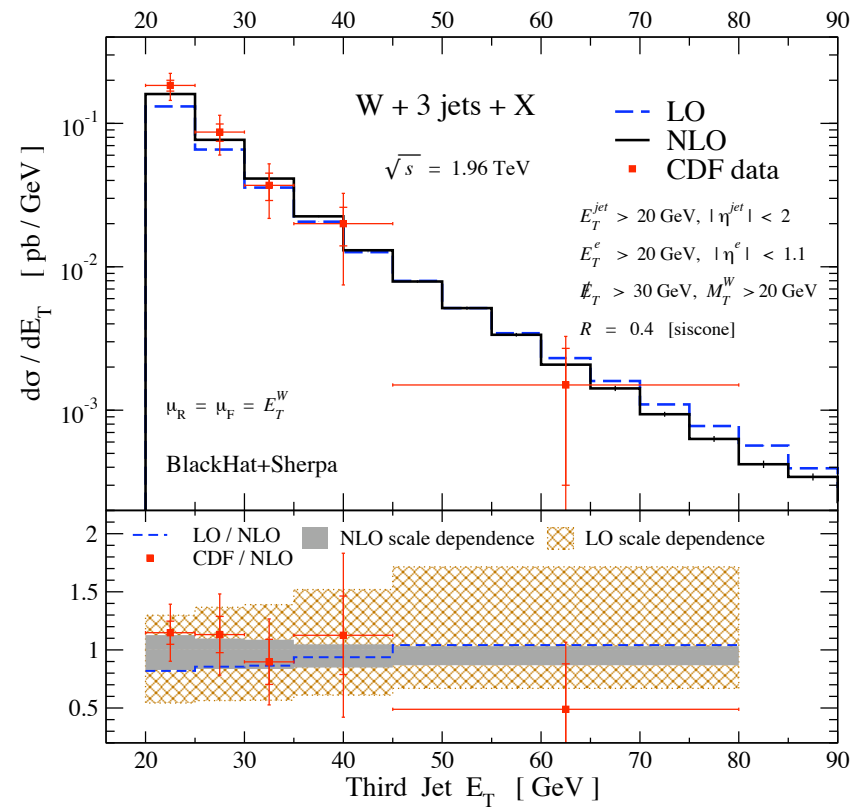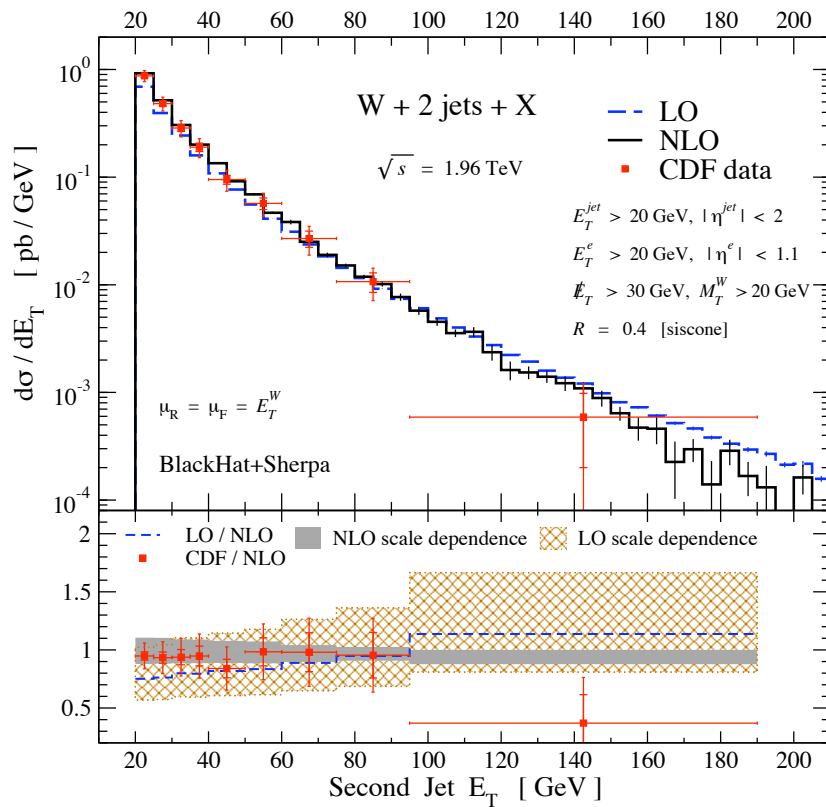
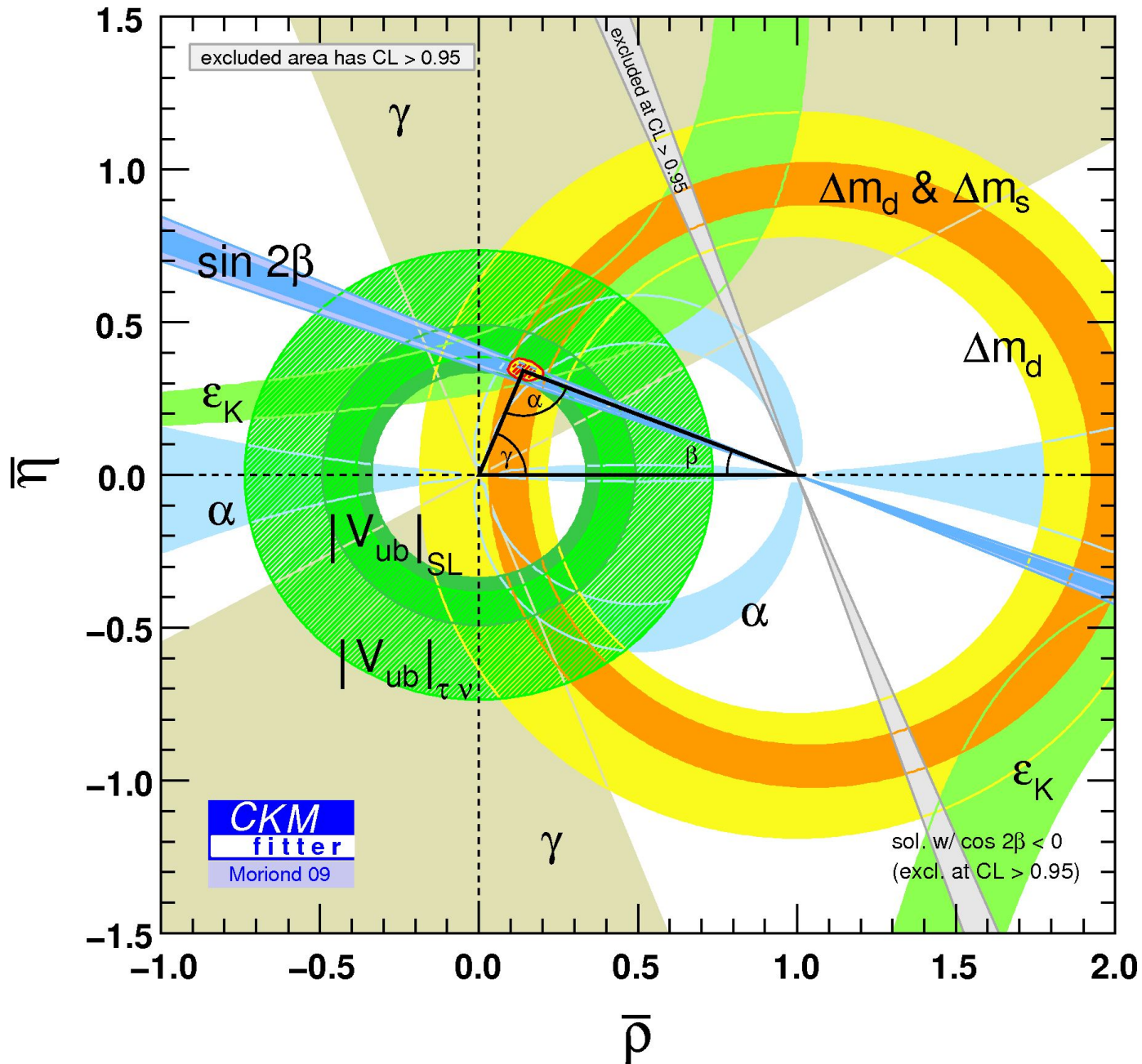$W + 3$ jets at NLO   C. Berger et al, arXiv:0907.1984

QCD

Lattice QCD now at few-percent precision.
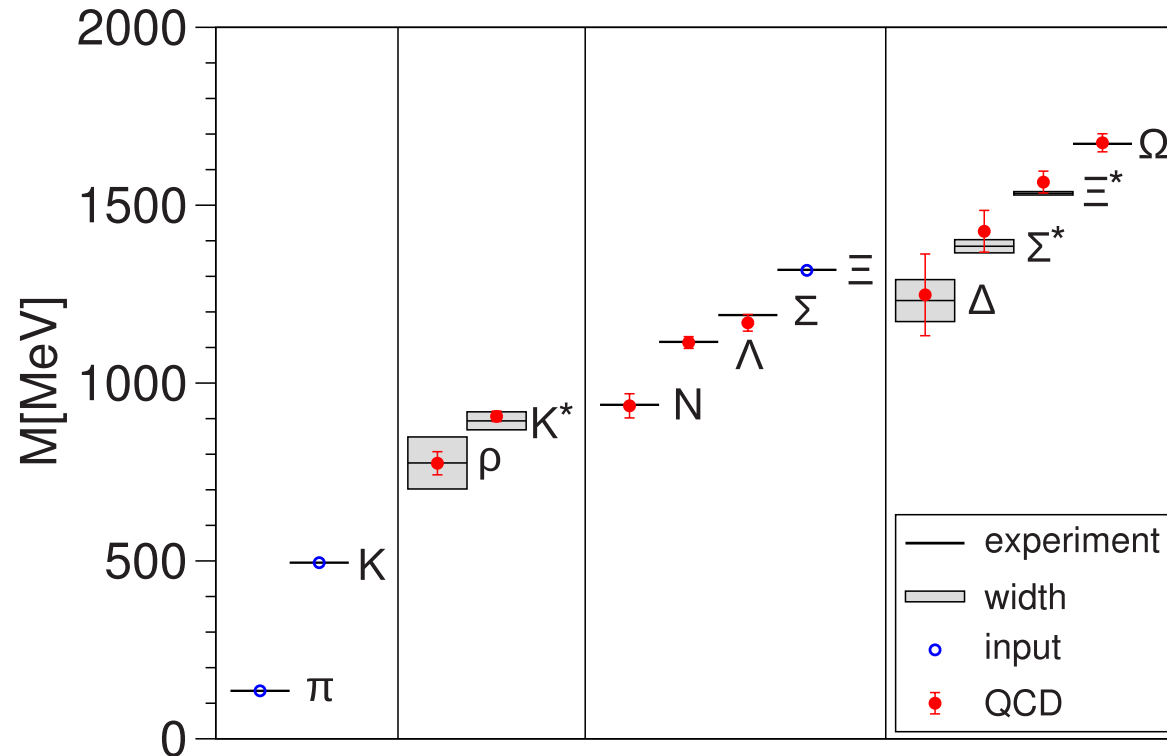
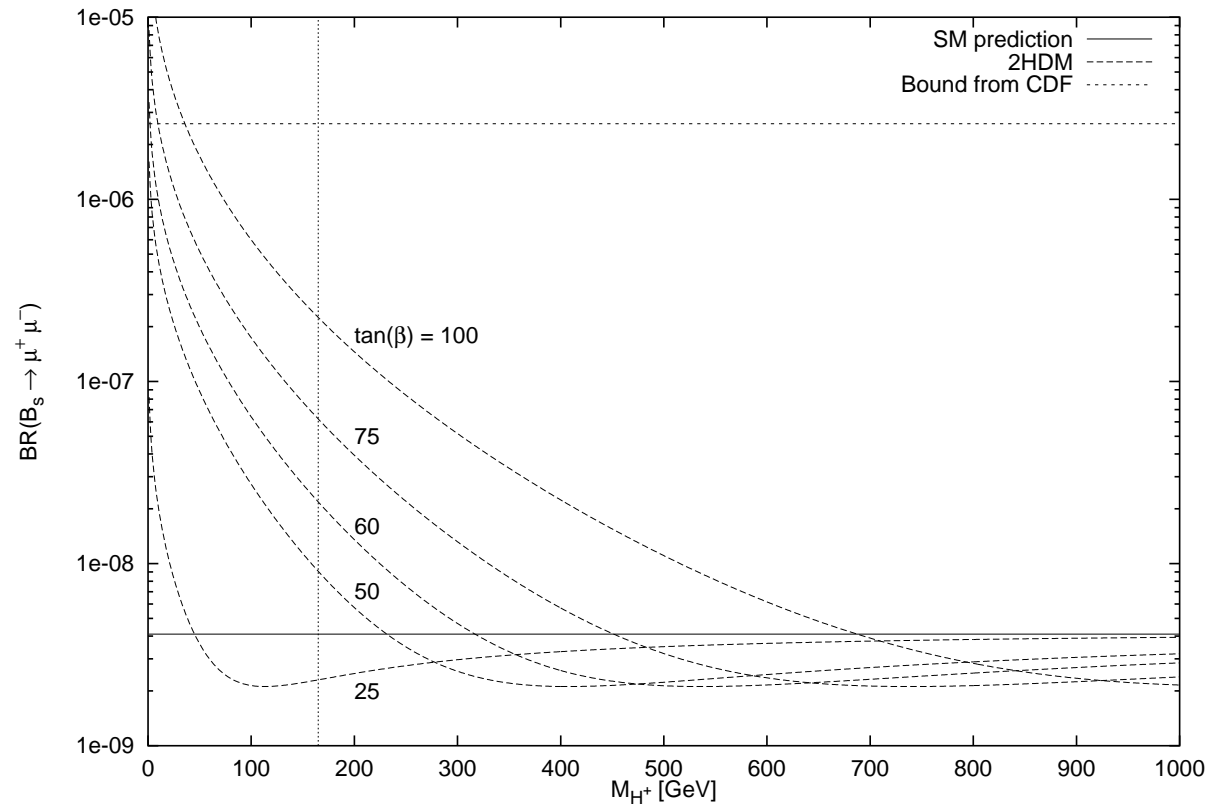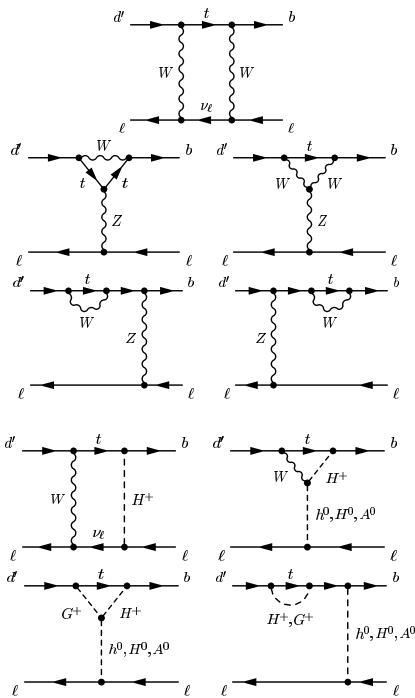Dürr et al, Science **322**, 1224 (2008)

Successful post- and pre-dictions of hadron masses.
Essential input for hadron decay constants.

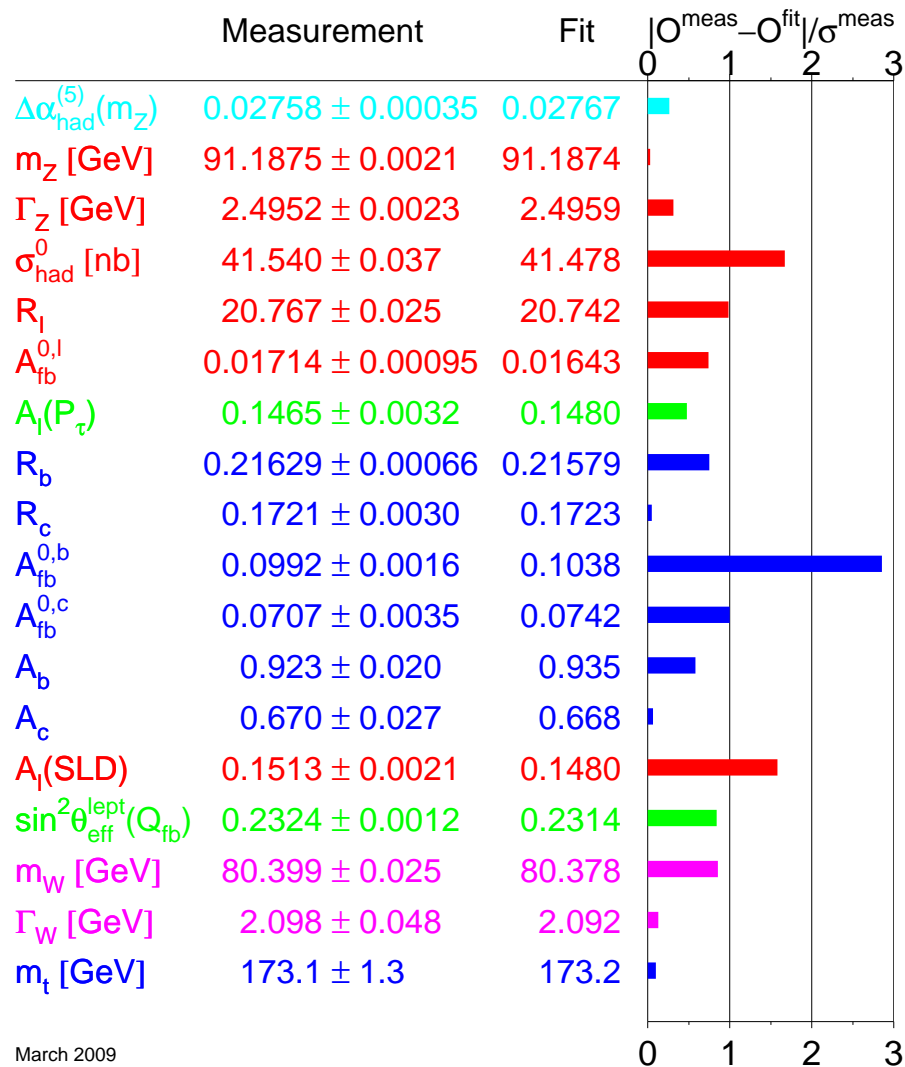# Flavour sector – consistent with CKM structure of SM

Flavour sector − rare decays sensitive to new physics

Example: $B_s^0 \to \ell^+\ell^-$: No evidence of deviation from SM

Current limit: $BR < 4.7 \times 10^{-8}$

Electroweak

	Measurement	Fit	$|O^{meas}-O^{fit}|/\sigma^{meas}$
			0 1 2 3
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959	
σ_{had}^0 [nb]	41.540 ± 0.037	41.478	
R_l	20.767 ± 0.025	20.742	
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01643	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480	
R_b	0.21629 ± 0.00066	0.21579	
R_c	0.1721 ± 0.0030	0.1723	
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038	
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
$A_l(SLD)$	0.1513 ± 0.0021	0.1480	
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.399 ± 0.025	80.378	
Γ_W [GeV]	2.098 ± 0.048	2.092	
m_t [GeV]	173.1 ± 1.3	173.2	

March 2009

Most measurements at the per-mille level.

Sensitivity at the level of electroweak loop corrections.

All consistent with Standard Model.

Use measurements to put strict limits on New Physics:

e.g., new W' exchanged at tree-level ≥ 2 TeV.

Why go Beyond the Standard Model?

The Standard Model has been stringently tested at colliders and so far spectacularly confirmed.

QCD
- strong coupling: detailed understanding still being developed
- no indication of deviation from SM predictions

Flavour sector
- extremely strong bounds on tree-level FC interactions
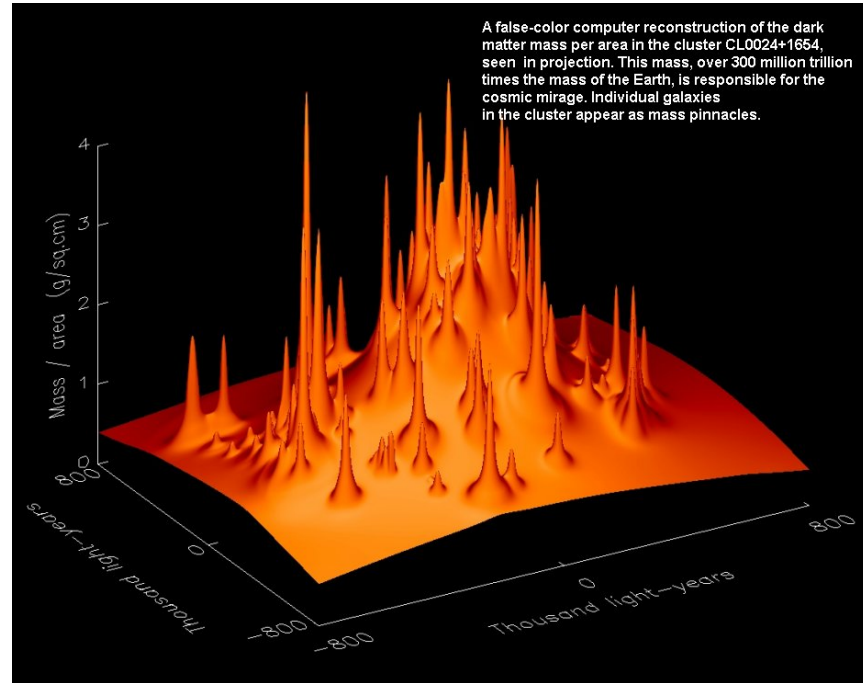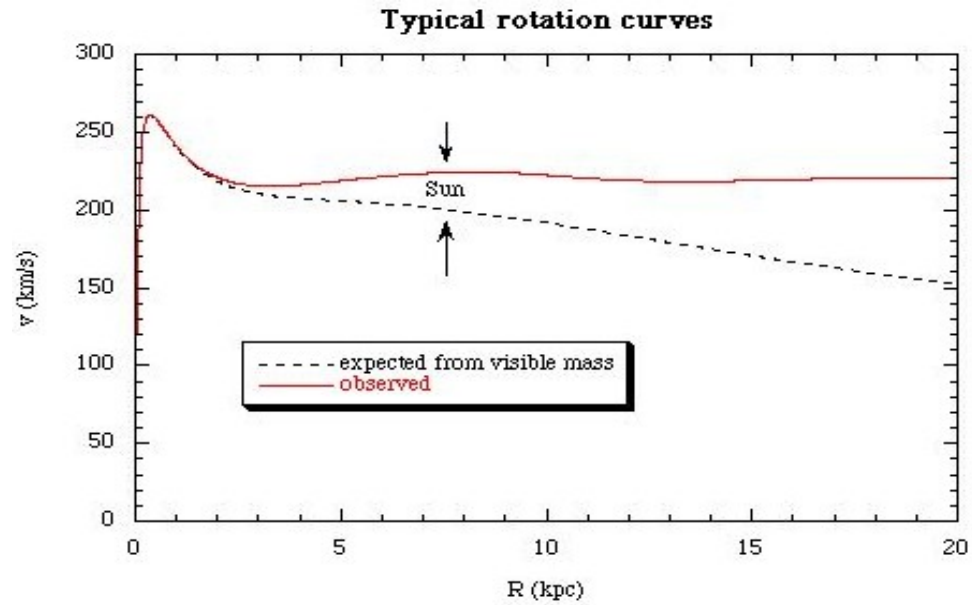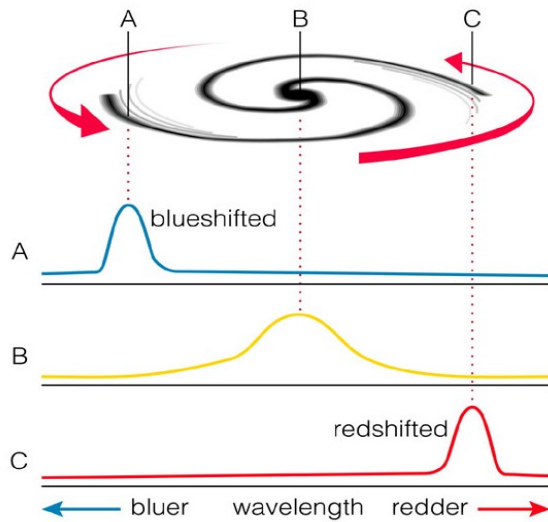- no evidence for FC beyond CKM structure

Electroweak
- strong bounds on new tree-level exchange
- strongly-coupled new physics difficult to squeeze in

Why go Beyond the Standard Model?

But despite the successes of the SM, there are problems.

- Dark matter

- Hierarchy problem (Higgs mass scale)

- Baryon asymmetry (matter/antimatter imbalance) of the universe

- A whole slew of other "Why?" questions

Dark matter – We see its gravitational effects

Typical rotation curves

A false-color computer reconstruction of the dark matter mass per area in the cluster CL0024+1654, seen in projection. This mass, over 300 million trillion times the mass of the Earth, is responsible for the cosmic mirage. Individual galaxies in the cluster appear as mass pinnacles.

Dark matter – it is not modified gravity

Pink – hot gas via x-ray emission

Blue – mass density as reconstructed from gravitational lensing

No SM particle has the right properties to be the dark matter.

Hierarchy problem – Radiative corrections to the Higgs mass

a)
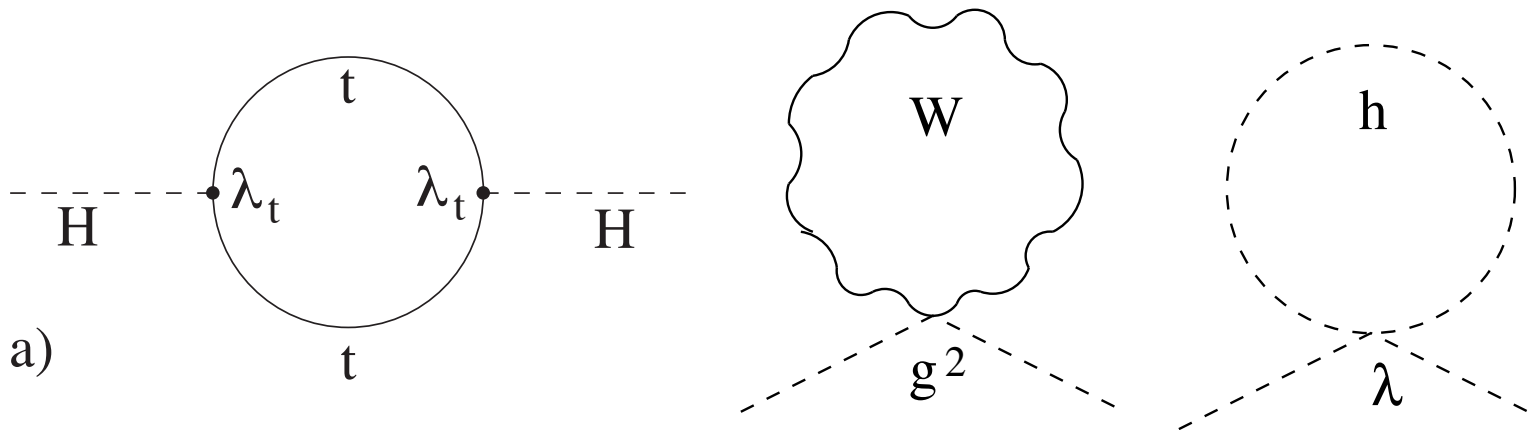
Radiative correction to mass-squared parameter: $\mu^2 = \mu_0^2 + \delta\mu^2$
E.g., top quark loop.

$$\delta\mu^2 \sim \text{diagram} = \int \frac{d^4p}{(2\pi)^4}(-)N_c\text{Tr}\left[i\lambda_t\frac{i}{\not{p}-m_t}i\lambda_t\frac{i}{\not{p}-m_t}\right]$$

$$= -\frac{4N_c\lambda_t^2}{(2\pi)^4}\int\frac{d^4p}{p^2}$$

Integral is divergent like two powers of p. Cut it off at a high scale Λ (e.g., Planck scale) $\rightarrow \delta\mu^2 \sim -\frac{\lambda_t^2}{16\pi^2}\Lambda^2 \sim -10^{33}\times\mu^2$.

Hierarchy problem − Radiative corrections to the Higgs mass

Renormalization: $\mu^2 = \mu_0^2 + \delta\mu^2$

Loops: $\delta\mu^2 \sim \frac{\text{coupling}^2}{16\pi^2}\Lambda^2$

But we know $\mu^2 \sim (100 \text{ GeV})^2 = \mu_0^2 + \delta\mu^2$.

Normal procedure is to adjust μ_0^2 to absorb the (divergent part of the) radiative correction.

But for a high cutoff, $\rightarrow$ have to engineer a ridiculous cancellation between μ_0^2 and $\delta\mu^2$.

High-scale "true" value of μ_0^2 is ridiculously finely-tuned.

Or:

- SM cutoff Λ is low, ~ 1 TeV.

- New physics comes in at ~ 1 TeV to cancel the bad Λ^2 behavior of $\delta\mu^2$.

Baryon asymmetry of the universe:

SM electroweak baryogenesis would only have worked with a much lighter Higgs. $\rightarrow$ New physics?

A whole slew of other "Why?" questions:

- Do the forces unify at a high scale?
- Why are there so many kinds of particles?
- Are there any new forces? New symmetries of nature?
- Where do neutrino masses come from?
- Are there extra dimensions of space?
- ...

Hierarchy problem: in some sense aesthetic (it could just be ridiculous fine-tuning). Most BSM models are built to fix this.

– SUSY
– Little Higgs (various versions)
– Technicolour
– Randall-Sundrum / warped extra dimensions

Dark matter: direct experimental evidence that we need something new. Not guaranteed to be a new weak-scale particle. Many BSM models provide a dark matter candidate.

– SUSY
– Little Higgs with T-parity
– Universal extra dimensions

There are many models: I'll organize things by signatures.
I'll try to sketch the model motivation, the main features, and what they look like at colliders.

We'll see that common motivations often lead to common signatures.

Outline

== Lecture 1 ==

1. Why Beyond the Standard Model ✓

2. Resonances

== Lecture 2 ==

3. Decay chains to a dark matter particle

4. Exotica

5. Summary

Start with the hierarchy problem: caused by bad renormalization properties of scalar mass μ^2.

Simplest solution: get rid of the scalar!
Can we still do electroweak symmetry breaking? Yes!
- Technicolour
- Higgsless models [via an interlude on warped extra dimensions]
... but it can be hard to squeeze into allowed range of electroweak precision data.

Next-simplest solution: keep the scalar, but add new physics at $\sim$ TeV scale to cancel the Λ^2 divergence.
- Little Higgs models

Common feature: new particles at $\sim$ TeV scale, which show up in colliders as resonances.

Technicolour

We haven't discovered any fundamental scalars.

The only scalar particles that we know of are the mesons of QCD, composite quark+antiquark bound-states confined by the strong interaction.

Let's take a closer look at this in QCD.

Ignore the electroweak couplings and masses of the quarks. To QCD, all the quarks look alike; without masses the quarks are chiral (q_L and q_R are separate states).

There is a global chiral flavour symmetry [$n_G = \#$ of generations]:
$$\mathcal{G}_\chi = \text{SU}(2n_G)_L \times \text{SU}(2n_G)_R.$$

The strong coupling runs stronger in the infrared (low energies) until QCD confines.

After confinement there is a quark condensate $\langle \bar{q}_L q_R \rangle \neq 0$.
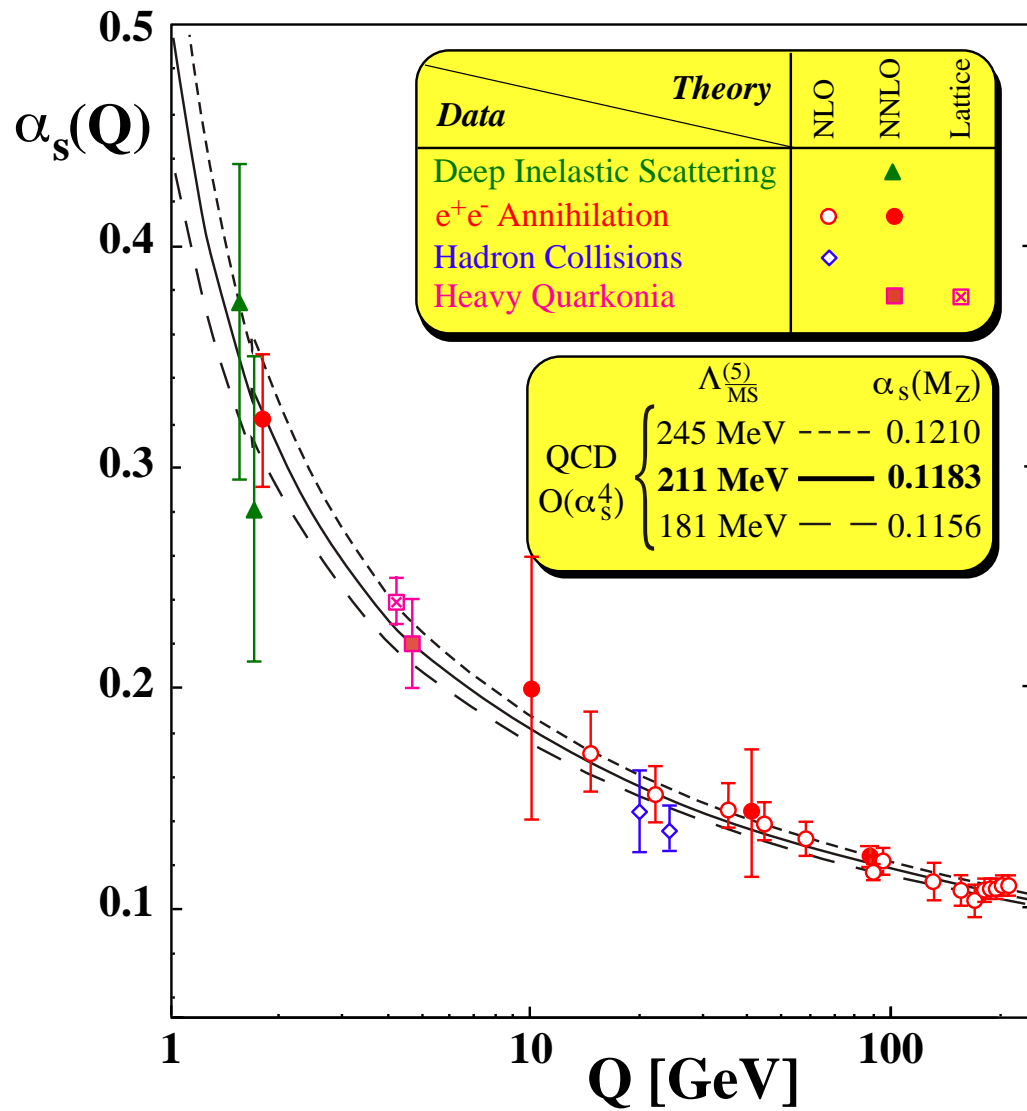
Experimental plot of the running of α_s.

Note the fit to Λ_{QCD} and the corresponding $\alpha_s(M_Z)$.

from Bethke, hep-ex/0211012

The quark condensate breaks the global chiral flavour symmetry:
$$\text{SU}(2n_G)_L \times \text{SU}(2n_G)_R \longrightarrow \text{SU}(2n_G)_V.$$

[$\text{SU}(2n_G)_V$ is the diagonal subgroup.]

There are thus $(2n_G)^2 - 1$ Goldstone bosons (massless pseudoscalar mesons): these are the pions ($\bar{q}q$ bound states).

Now turn the electroweak interactions back on. The quark condensate $\langle \bar{q}_L q_R \rangle \neq 0$ breaks $\text{SU}(2)_L \times \text{U}(1)_Y$ down to $\text{U}(1)_{\text{EM}}$. The $W^\pm$ and Z get masses from the pion decay constant f_π:
$$m_W = g\sqrt{n_G}f_\pi/2, \qquad m_Z = \sqrt{g^2 + g'^2}\sqrt{n_G}f_\pi/2$$
where the "pion decay constant" $f_\pi \simeq 93$ MeV is related to the condensate by $\langle \bar{q}_L q_R \rangle \sim 4\pi f_\pi^3$.

Electroweak symmetry has been broken! and notice $m_W = m_Z \cos\theta_W$
Unfortunately f_π gives way too small masses:
$m_W \simeq 52.7$ MeV, $m_Z \simeq 59.6$ MeV.
Compare actual masses: $m_W = 80.42$ GeV, $m_Z = 91.188$ GeV.

This points the way to Technicolour.

Replicate QCD at 1 TeV instead of 1 GeV. $\quad$ (1976/1979)

New gauge group G_{TC} that gets strong around a TeV

Have N_D doublets of fermions charged under G_{TC}

"Pion decay constant" becomes:

$$\sqrt{n_G} f_\pi \rightarrow \sqrt{N_D} F_{\pi_T} = 246 \text{ GeV}$$
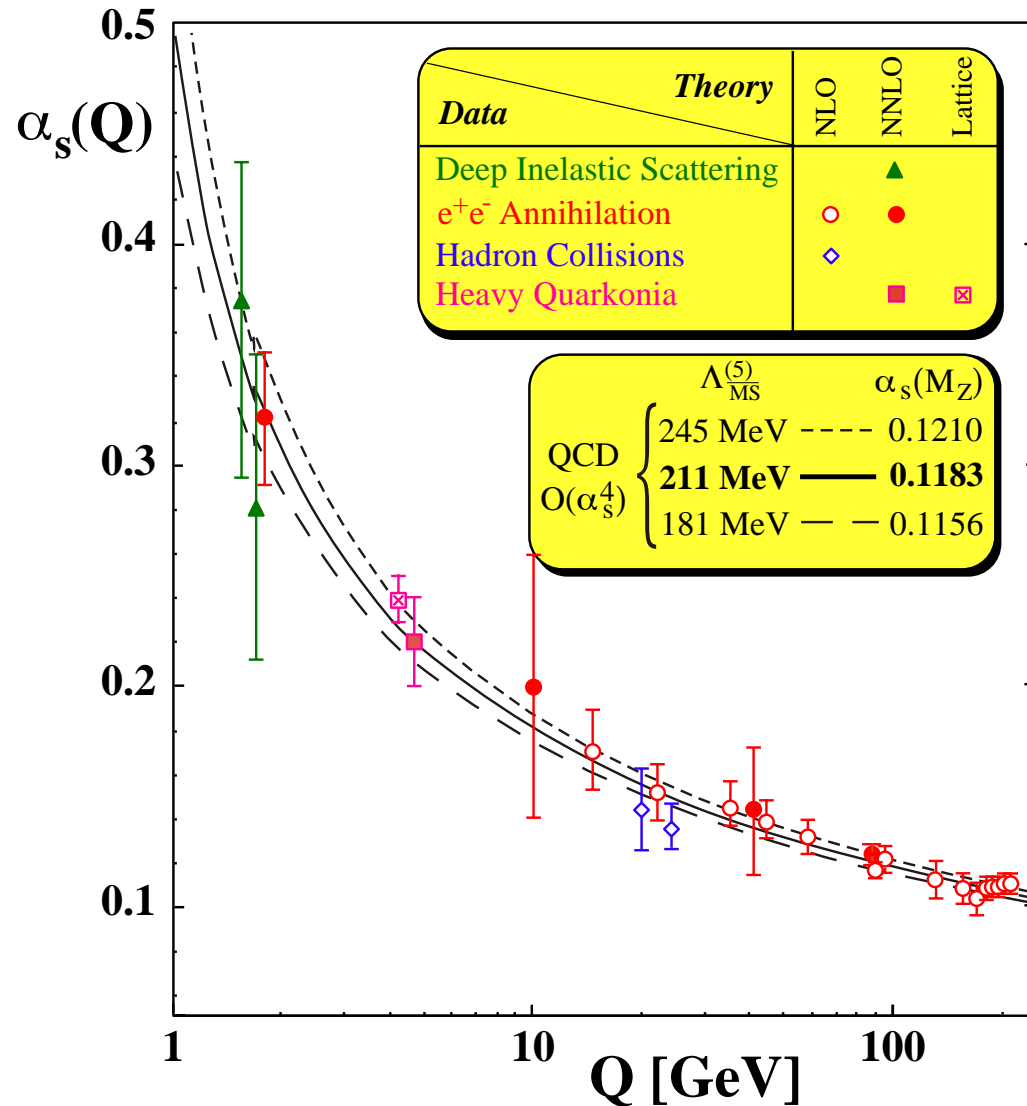
"QCD compositeness scale" becomes:

$$\Lambda_{QCD} \rightarrow \Lambda_{TC} = \text{few} \times F_{\pi_T}$$

As in QCD, the model should have an infinite tower of bound states – technihadrons.

E.g., techni-rho ρ_T (isotriplet vector meson); techni-omega ω_T (isosinglet vector meson).

Both are colour singlets: produced by weak interactions. W', Z' searches.

Technicolour scale Λ_{TC} is where the gauge coupling α_{TC} runs strong: just like for Λ_{QCD}.

Data \ Theory	NLO	NNLO	Lattice
Deep Inelastic Scattering		▲	
e^+e^- Annihilation	○	●	
Hadron Collisions	◇		
Heavy Quarkonia		■	⊠

	$\Lambda_{\overline{MS}}^{(5)}$		$\alpha_s(M_Z)$
QCD $O(\alpha_s^4)$	245 MeV	- - - -	0.1210
	211 MeV	——	**0.1183**
	181 MeV	— —	0.1156

Experimental plot of the running of α_s.

Note the fit to Λ_{QCD} and the corresponding $\alpha_s(M_Z)$.

from Bethke, hep-ex/0211012

Scale of Λ_{TC}, and hence the EW scale, is ultimately set by the starting value of α_{TC} at M_{Pl}.

Constraints and problems of Technicolour

There are two main problems with QCD-like Technicolour:

Flavour-changing neutral currents

New interactions needed to generate quark masses also give flavour-changing interactions.

These cause big problems if their scale is below ~ 100 TeV.

But we need their scale low to generate c, b (t??) masses.

Electroweak precision constraints

Technicolour is a strongly coupled theory: we can't calculate things well.

But we have QCD as a model: assume TC is QCD-like, then read off corrections to EW precision observables.

It's ruled out. :P

The way around both of these problems is Technicolour that is not like QCD. But without the guidance of QCD data, we don't know how to calculate things.

And there Technicolour lingered half-dead for many years, until the end of the 20th century...

Randall-Sundrum (RS) model: a warped extra dimension (1999)

Model introduces a 5th dimension, but unlike our 4 dimensions:
5th dimension is "warped" (the metric is not flat).

$$ds^2 = e^{-2kr|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu - r^2 d\phi^2$$
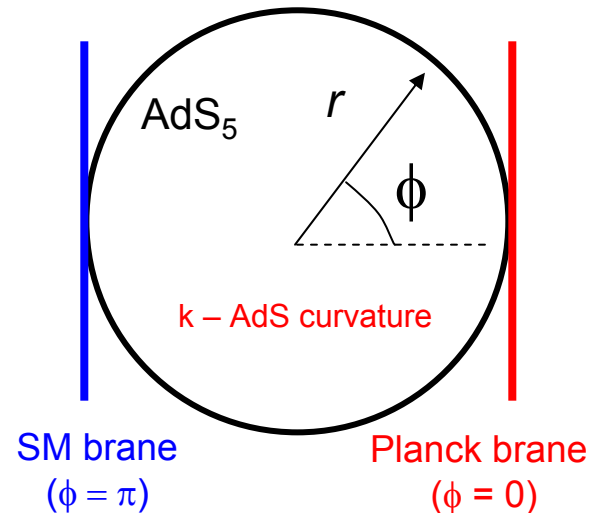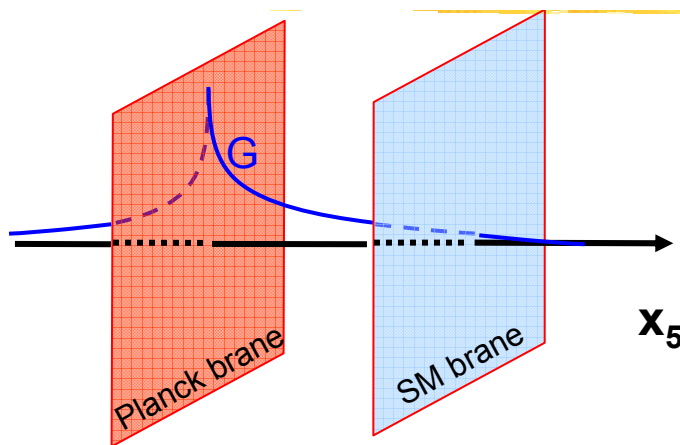
figures from talk by Landsberg, SLAC Summer Institute 2004

$e^{-2kr|\phi|}$ is called the "warp factor".

$\phi = [0, \pi]$ is the coordinate in the 5th dimension.

Scales from the Planck brane ($\phi = 0$) get "warped down" on the SM brane ($\phi = \pi$):

The SM brane cutoff is $\Lambda_\pi = \overline{M}_{\text{Pl}}e^{-kr\pi}$.

For $kr \sim 11$, $\Lambda_\pi \sim$ TeV: hierarchy problem solved!

To explain fermion masses, let the SM particles propagate in the bulk.

Gauge fields in the bulk: meaningful theory up to M_{Pl}; can talk about gauge coupling unification.

Choose appropriate set of particles to enter the bulk: can even get unification with only SM on the TeV brane.

from Randall & Schwartz, hep-th/0108114
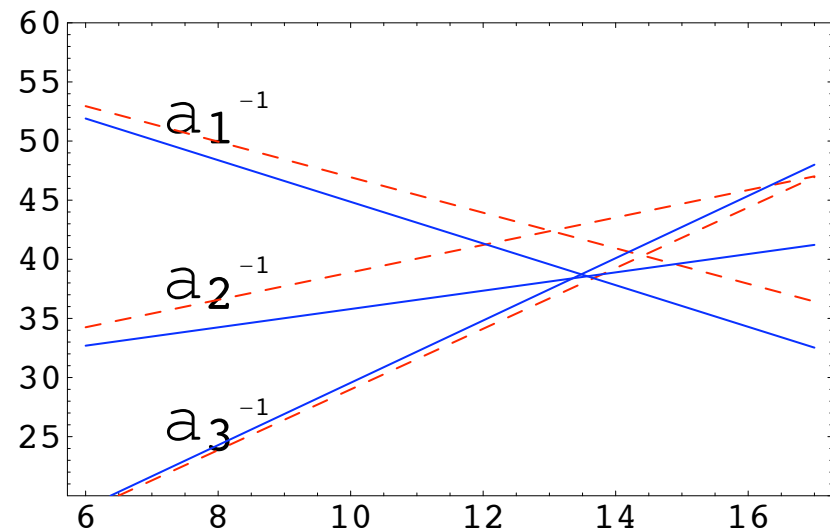
Fermions in the bulk: avoid possible FCNC operators cut off by $\Lambda_\pi \sim$ TeV by putting them near the Planck brane: effective cutoff becomes very high.

Higgs must still be localized on or near the "TeV brane":
Want the Higgs to feel the low cutoff $\Lambda_\pi \sim$ TeV to retain solution to the hierarchy problem.

Higgs-fermion couplings: fermion wavefunctions have to overlap with the Higgs wavefunction.

Light fermions can be localized near the Planck brane: offers warped-extra-dimensional explanation of large fermion mass hierarchy: warp exponential converts reasonable parameter range to huge mass hierarchy.

Top quark is heavy: need large overlap with the Higgs: must be localized near the TeV brane.
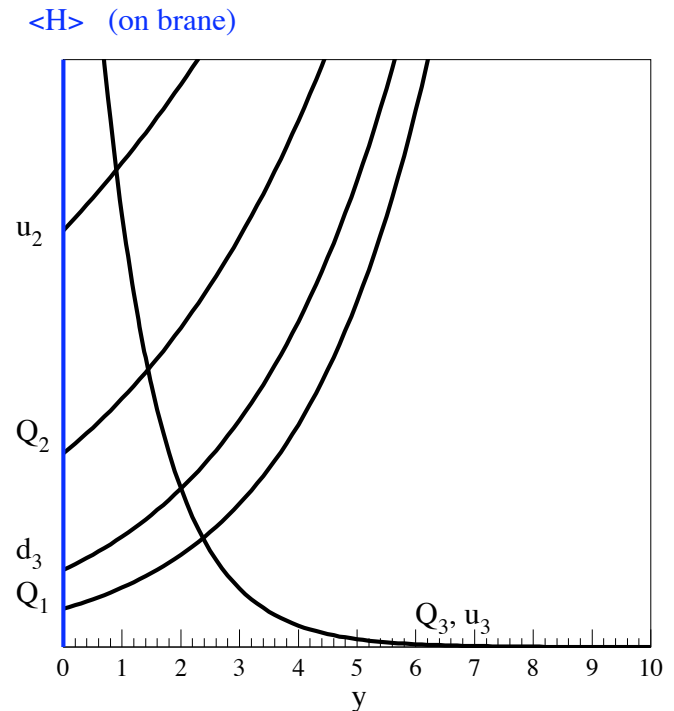
from Kaplan & Tait, hep-ph/0110126

Expect to get new physics operators affecting the top quark with a low cutoff $\Lambda_\pi \sim$ TeV.

Everything that lives in the bulk gets Kaluza-Klein modes starting at the scale Λ_π. Spacing of the modes depends on warp factor and where the zero-mode is localized in the bulk.

Couplings between particles depend on the overlap of the wave-functions in the 5-dim space.

Can get enhancements or suppressions of KK mode production cross sections, flavour dependence, etc.

Phenomenology:

KK modes are produced as resonances.

Gauge boson KK excitations: Z', W' searches; also g' KK gluon. Because of shape of fermion wavefunctions in the bulk, KK gauge excitations couple preferentially to t_R.

Fermion KK excitations: produce them in pairs, or singly if they mix with the SM fermions [mixing is constrained by FCNC considerations].

KK gluon $\rightarrow t\bar{t}$: highly boosted top jets

Parton-level study, 3 TeV g':
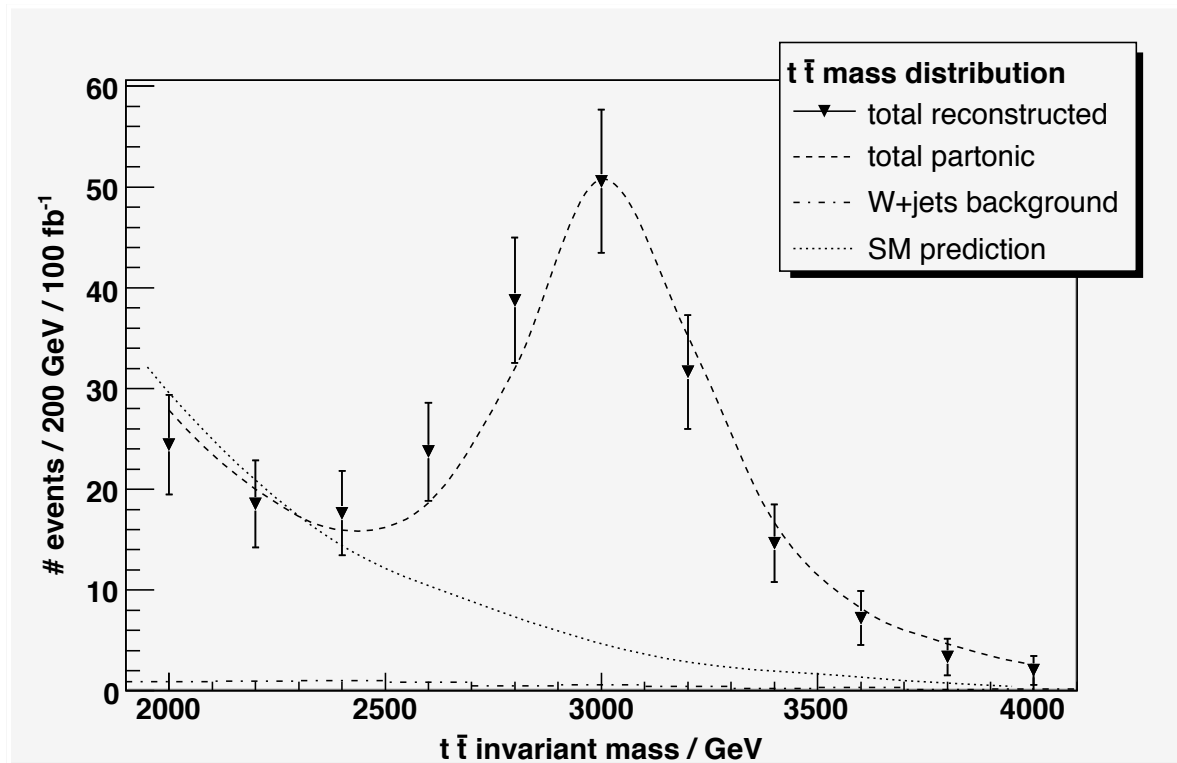
Agashe et al., PRD 77, 015003 (2008)

Connection with Technicolour?

Randall-Sundrum warped spacetime is an Anti–de Sitter (AdS) space: a space with negative curvature (in the 5th dimension). There is a (conjectured) correspondence between theories in AdS space and conformal field theories (CFT) on the edge bounding the space [AdS/CFT or Maldacena conjecture (1997)] Conformal means scale-invariant: the couplings don't run. Walking Technicolour is approximately conformal in the energy range we're interested in.

The AdS is weakly curved (gravity is weakly coupled) where the CFT is strongly coupled: this gives us a way to calculate! (to the extent that the correspondence is valid.)

5-dim states on or near the TeV brane correspond to bound states of the CFT. 5-dim states on or near the Planck brane correspond to fundamental (pointlike) particles.

Stripped-down version: "Higgsless models"

5-dim picture: SM gauge sector is in the bulk.
Boundary conditions chosen so there is no zero mode: Lightest
gauge boson is 1st KK excitation!
EWSB is caused by extra-dimensional boundary conditions.

Go down to 4-dim: Models contain KK excitations of the W, Z
which play some of the role of the Higgs in regularizing longitu-
dinal gauge boson scattering.
Presumably corresponds to a Walking Technicolour–like CFT
theory: new vectors interpreted as techni-rho–like states.
The theory stays under control up to somewhat higher energies
than the SM without a Higgs.

EW precision constraints:
Walking Technicolour wasn't calculable.
But now the 5-dim theory is (more or less) calculable:
Generically constraints from EWP are severe, but can build good
models that evade them.

Use RS to mock up an actual technicolour model, study phenomenology Two models, $W'_{1,2} \to WZ, W\gamma$
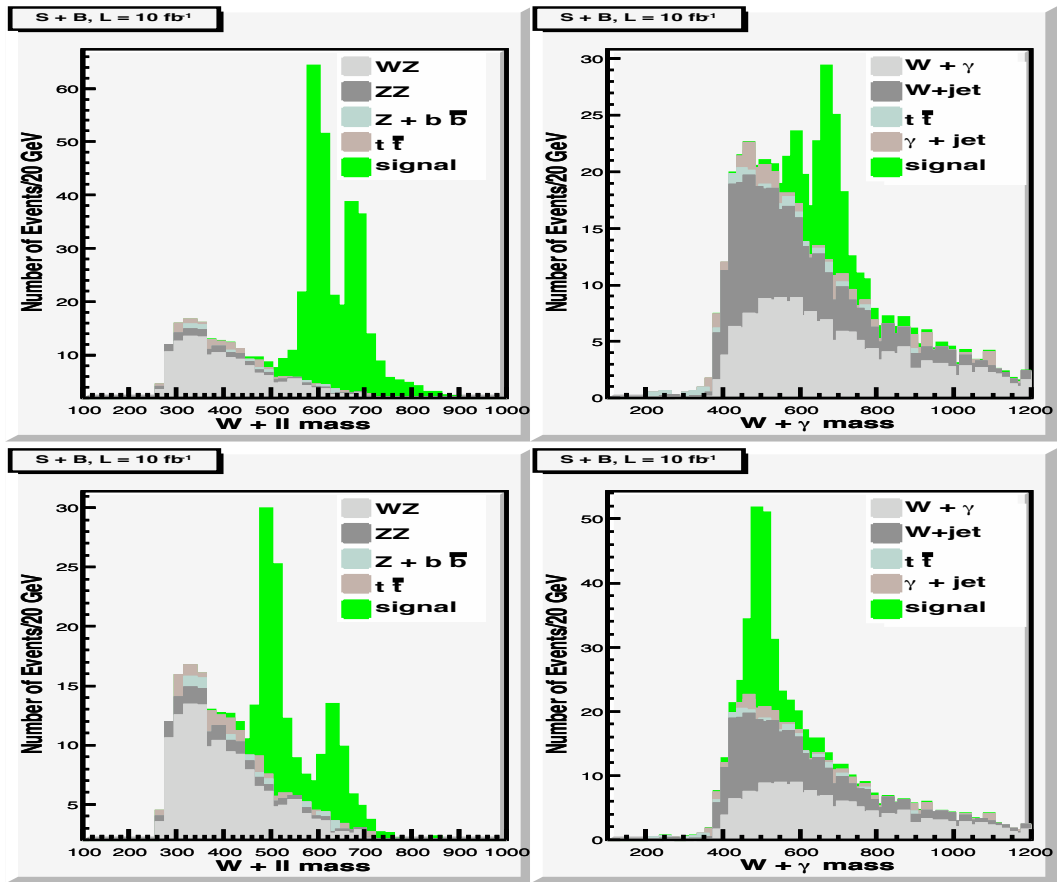
FIG. 1: HTC1 (upper) and HTC2 (lower) - WZ (left) and $W\gamma$ (right) channels ($\mathcal{L} = 10\,\mathrm{fb}^{-1}$).

Hirn, Martin & Sanz, JHEP 0805, 084 (2008)

Use RS to mock up an actual technicolour model, study phenomenology Another TC model, more paired resonances.

Collider signals: vector resonances
- produced via $q\bar{q} \to V'$
- decay via $V' \to f\bar{f}$ or $V' \to VV$

$Z' \to \ell\ell$ $W' \to \ell\nu$ $W' \to ZW \to \ell\ell\ell\nu$
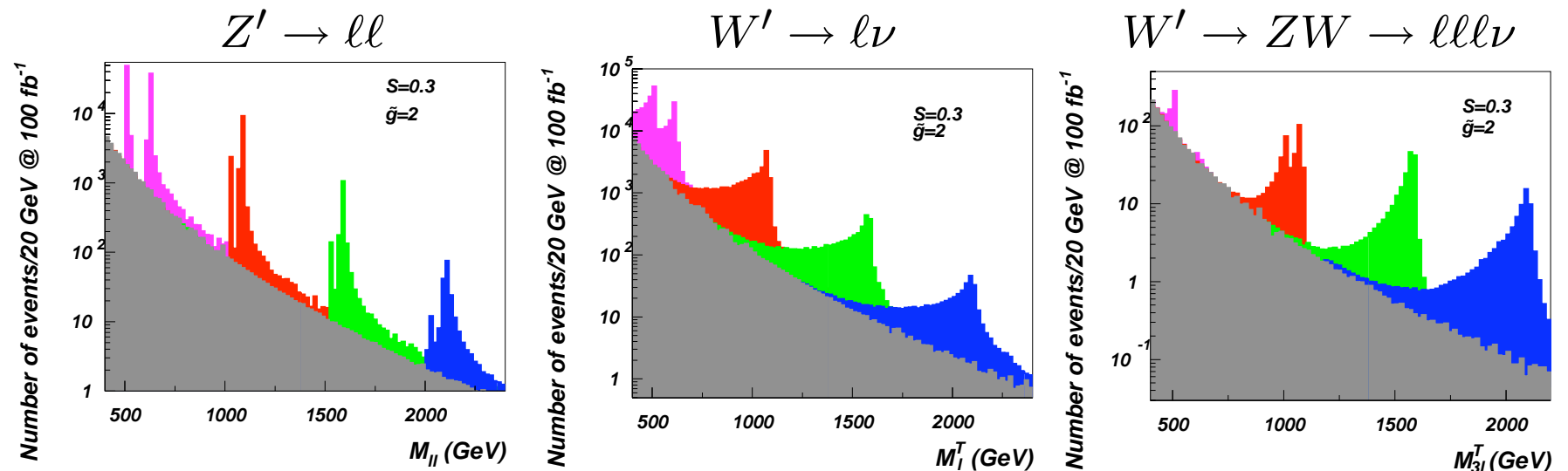
Belyaev et al., PRD 79, 035006 (2009)

Generic features:

New heavy spin-1 resonances, decaying to $\bar{f}f$ or VV

$\rightarrow$ construct the invariant mass peak

$\rightarrow$ use features of decay to learn about model parameters

$W' \rightarrow ZW$ decays are a signal that W' is mixed up with the SM gauge groups.

New fermions (KK excitations of SM fermions)

− often very heavy, few TeV

Generic problem:
− have to stretch to conform to electroweak precision constraints
− generally difficult without a light Higgs
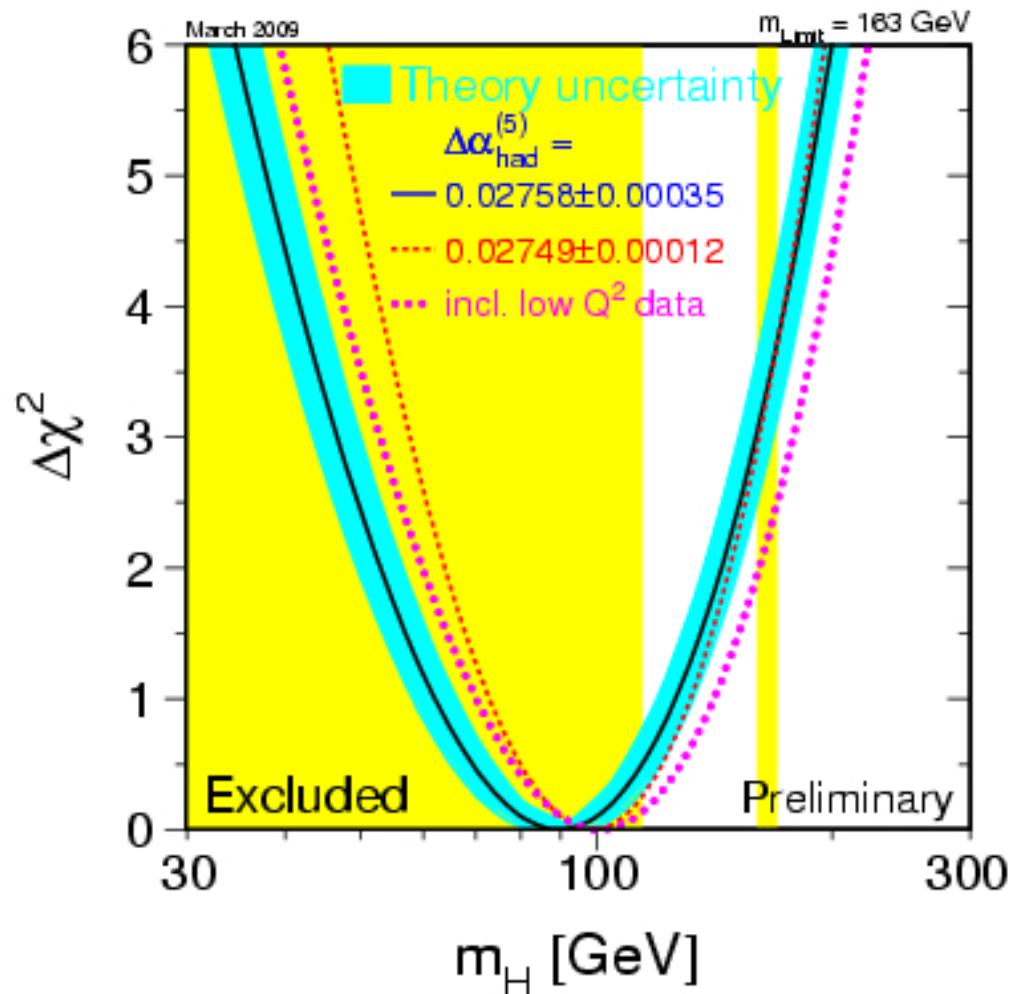
Best fit mass within SM is 90 GeV.

LEP excludes $m_H < 114.4$ GeV; Tevatron excludes 160–170 GeV.

One-sided 95% CL upper limit 163 GeV (or 191 GeV including LEP exclusion).

So what happens if we add a Higgs back in?

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

A general analysis indicates that new strongly-coupled physics (exchanged at tree level) shouldn't be lighter than roughly 10 TeV.

$\delta\mu^2 \sim (g^2/16\pi^2)\Lambda^2 \rightarrow m_H \sim (g/4\pi)\Lambda \sim 0.1\,\Lambda$ for naturalness.

So we want $\Lambda \sim$ TeV.

Because of EW precision constraints, this is difficult!

But if $\delta\mu^2$ appeared only at 2-loops, then:

$\delta\mu^2 \sim (g^2/16\pi^2)^2\Lambda^2 \rightarrow m_H \sim (g/4\pi)^2\Lambda \sim 0.01\,\Lambda$

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

This split (1 TeV $\rightarrow$ 10 TeV) is sometimes called the "Little Hierarchy" (as opposed to the Big Hierarchy between M_W and M_{Pl}).

We want something like this:

$$\Lambda \sim 4\pi f \qquad \text{Strong Coupling} \quad 10 - 30 \text{ TeV}$$

New States

$$gf \qquad \text{Weak Coupling} \quad 1 - 3 \text{ TeV}$$

"Little" Higgs

$$\frac{g^2 f}{4\pi} \qquad\qquad 100 - 300 \text{ GeV}$$
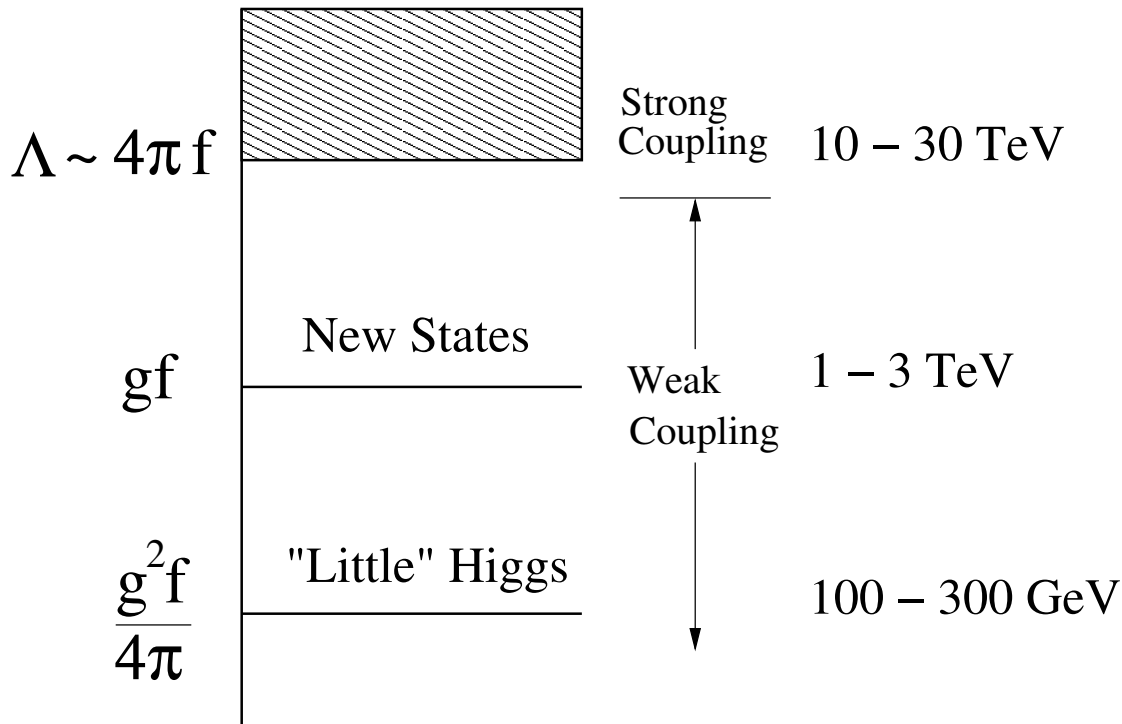
Still need new states at ~ 1 TeV to cancel the 1-loop Higgs mass divergence.

Enforce cancellation using 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.

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

$W \qquad g^2 \qquad\qquad W' \qquad -g^2$

$h \qquad \lambda \qquad\qquad \phi \qquad -\lambda$
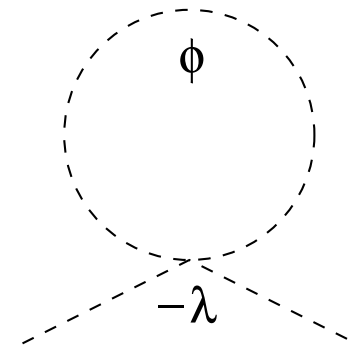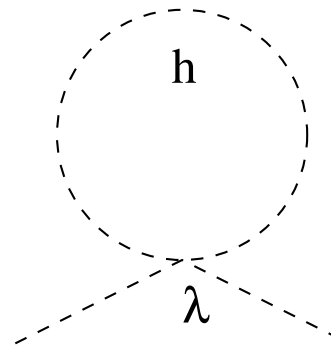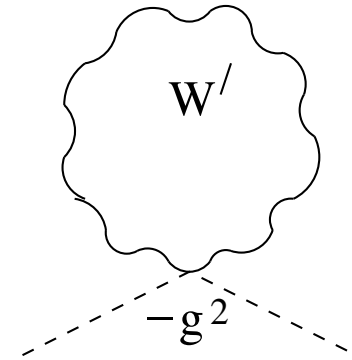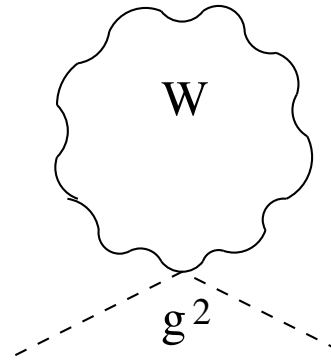
diagrams from Schmaltz, hep-ph/0210415

a) $H \quad \lambda_t \quad t \quad \lambda_t \quad H \quad t$

b) $H \quad \lambda_T \quad t \quad \lambda_T \quad H \quad T$

c) $T \quad M_T \quad T \quad H \quad \dfrac{\lambda'_T}{M_T} \quad H$
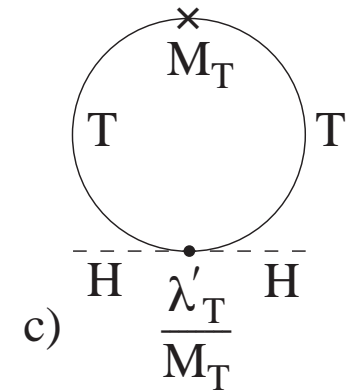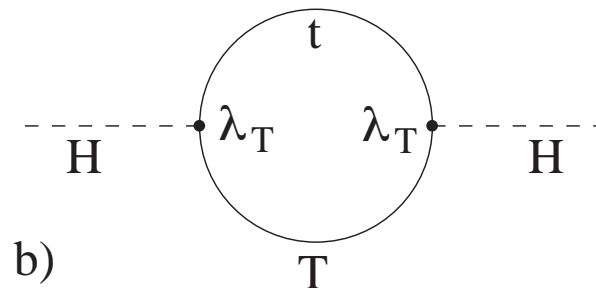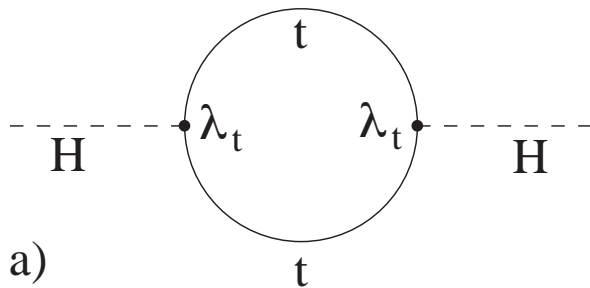
diagrams from Han, Logan & Wang, hep-ph/0506313

39

New gauge bosons to cancel the SM gauge loops:

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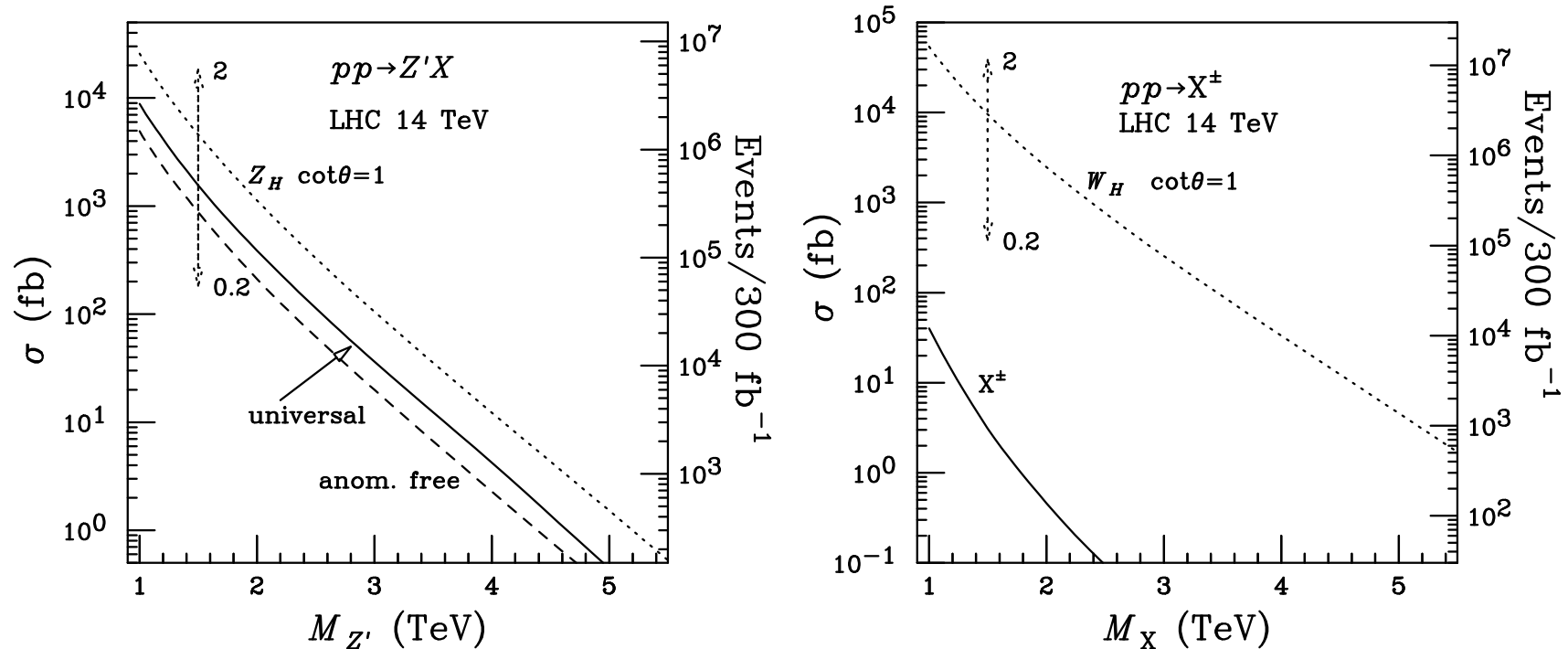
Han, Logan, & Wang, hep-ph/0506313

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

Trick: reconstruct invariant mass peak of $\ell^+\ell^-$ or $Zh \to \ell^+\ell^- bb$

$$m_{ab}^2 = (p_a + p_b)^2$$
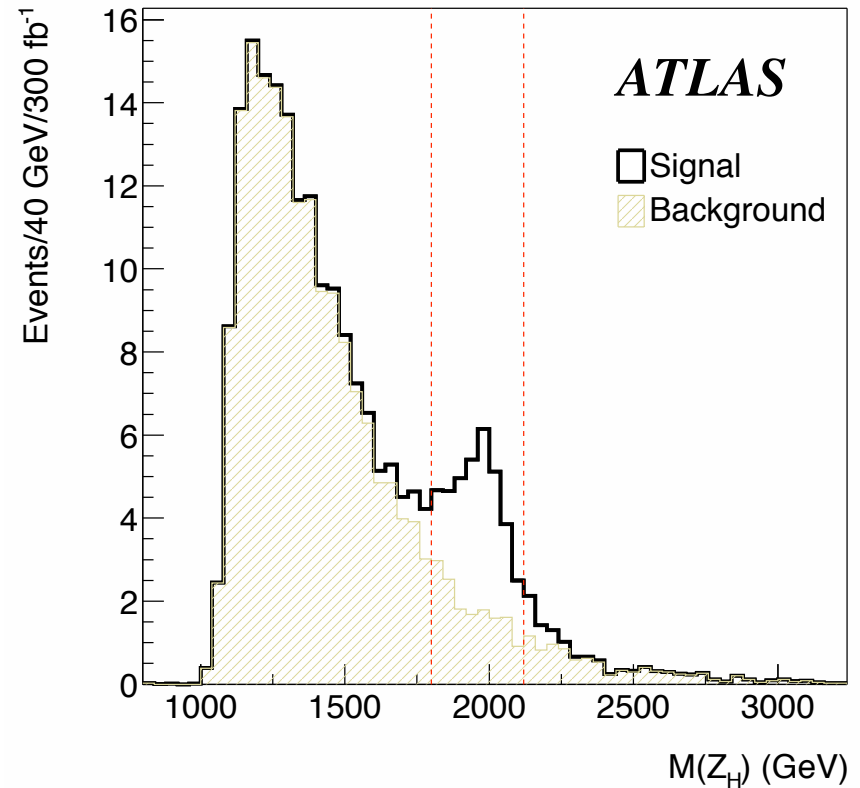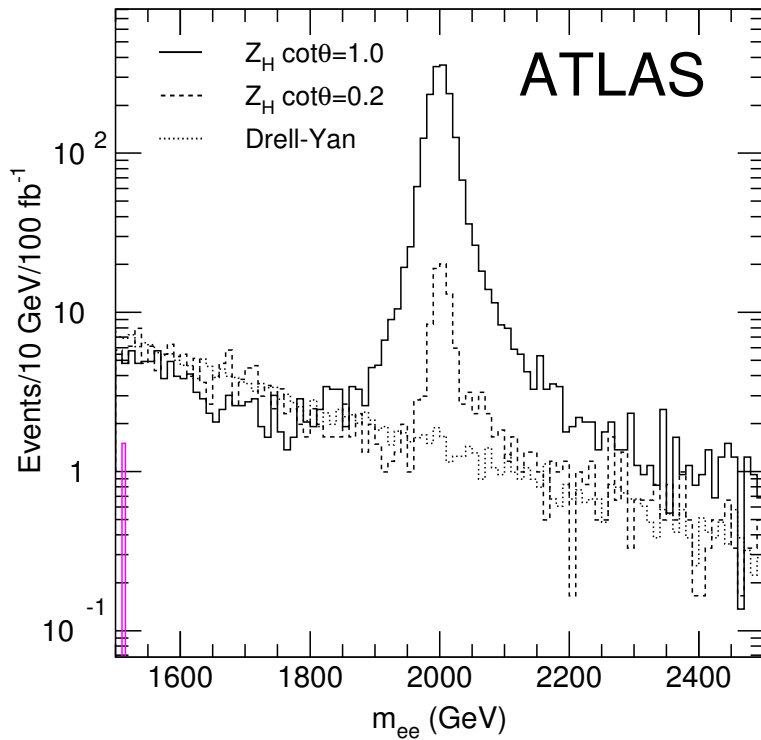
plots from Azuelos et al, hep-ph/0402037

$\cot\theta = 0.5$

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

Littlest Higgs: Search for W_H

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

Trick: (1) reconstruct transverse mass of ℓ p_T^{miss} or (2) reconstruct W knowing its mass then reconstruct Wh invariant mass
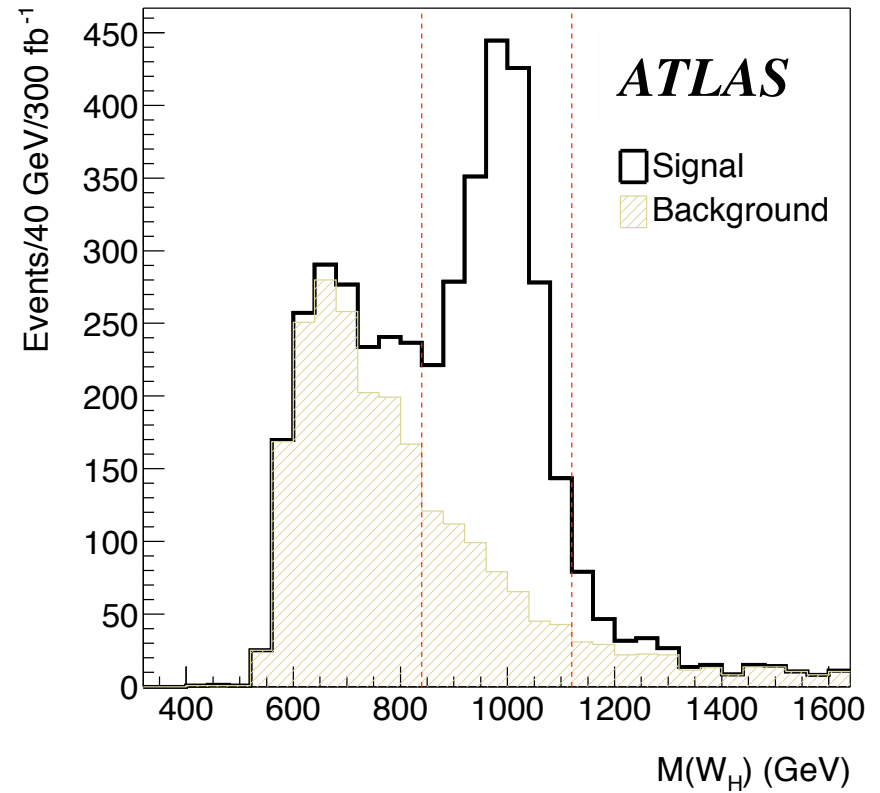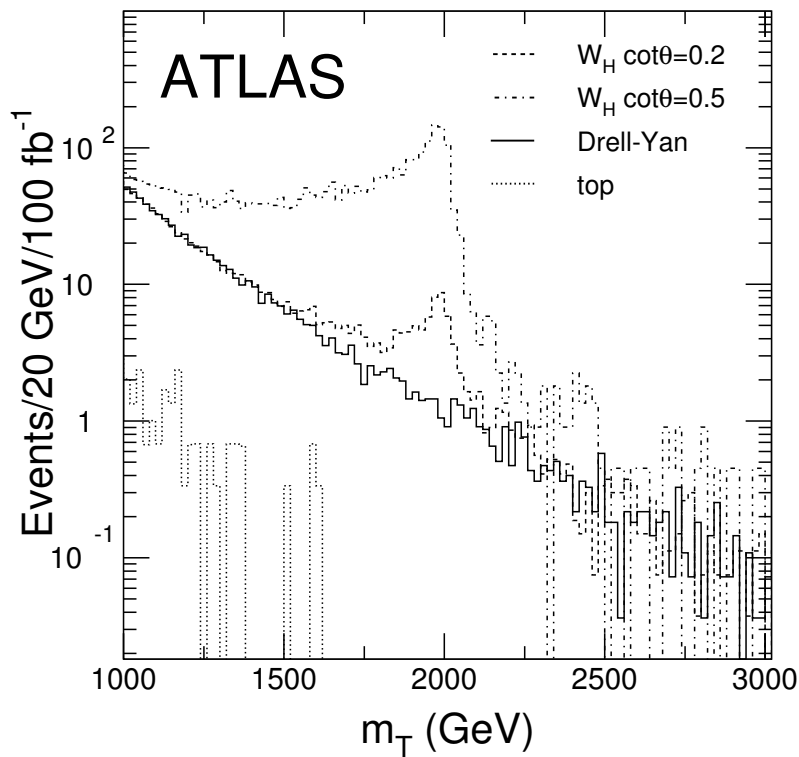
plots from Azuelos et al, hep-ph/0402037

$\cot\theta = 0.5$

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

Definition of transverse mass:

Usual invariant mass is:

$$m_{ab}^2 = (p_a + p_b)^2 \;=\; m_a^2 + m_b^2 + 2p_a \cdot p_b$$
$$=\; m_a^2 + m_b^2 + 2E_a E_b - 2\vec{p}_a \cdot \vec{p}_b$$

But if one of the particles is a neutrino, all we know are its transverse energy and transverse momentum.

Transverse mass is defined as [4-vector $p_T = (E_T, \vec{p}_T, 0)$]:

$$m_T^2 = (p_{Ta} + p_{Tb})^2 \;=\; 2E_{Ta} E_{Tb} - 2\vec{p}_{Ta} \cdot \vec{p}_{Tb}$$

m_T is always less than the parent particle's true mass.

Testing the gauge coupling structure to fermions:
$$Z' \to \mu^+\mu^- \text{ vs. } b\bar{b} \text{ vs. } t\bar{t}$$

S. Godfrey & T. Martin, PRL 101, 151803 (2008)
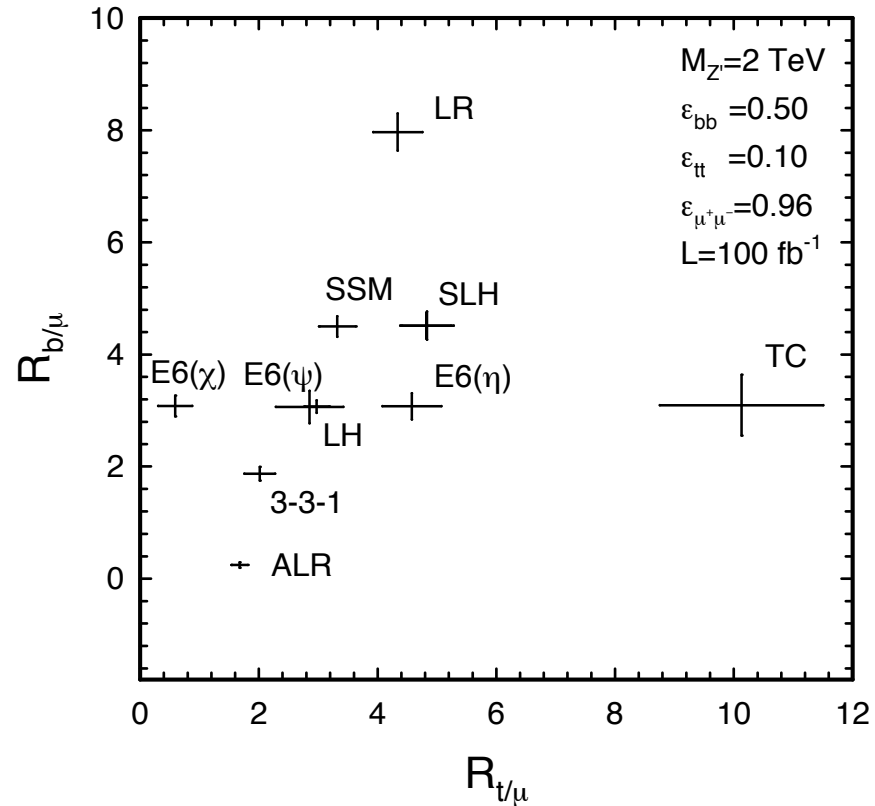
LR = Left-Right Symmetric model
ALR = Alternate Left-Right Symmetric model
SLH = Simplest Little Higgs model
LH = Littlest Higgs
TC = Topcolour

Also useful: Forward-backward asymmetries: probe left- / right-handed structure of vector boson couplings to fermions.

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.
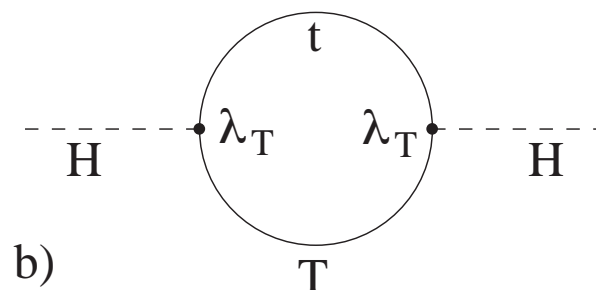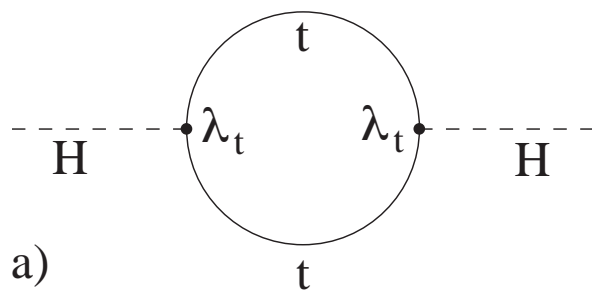T is an electroweak singlet (has no SU(2) partner "heavy b").
T has both left- and right-handed components: a Dirac fermion.
[T mass $\sim$ TeV; does not come from EWSB]
T mixes a little with the SM top quark [get TbW, TtZ, Tth couplings]

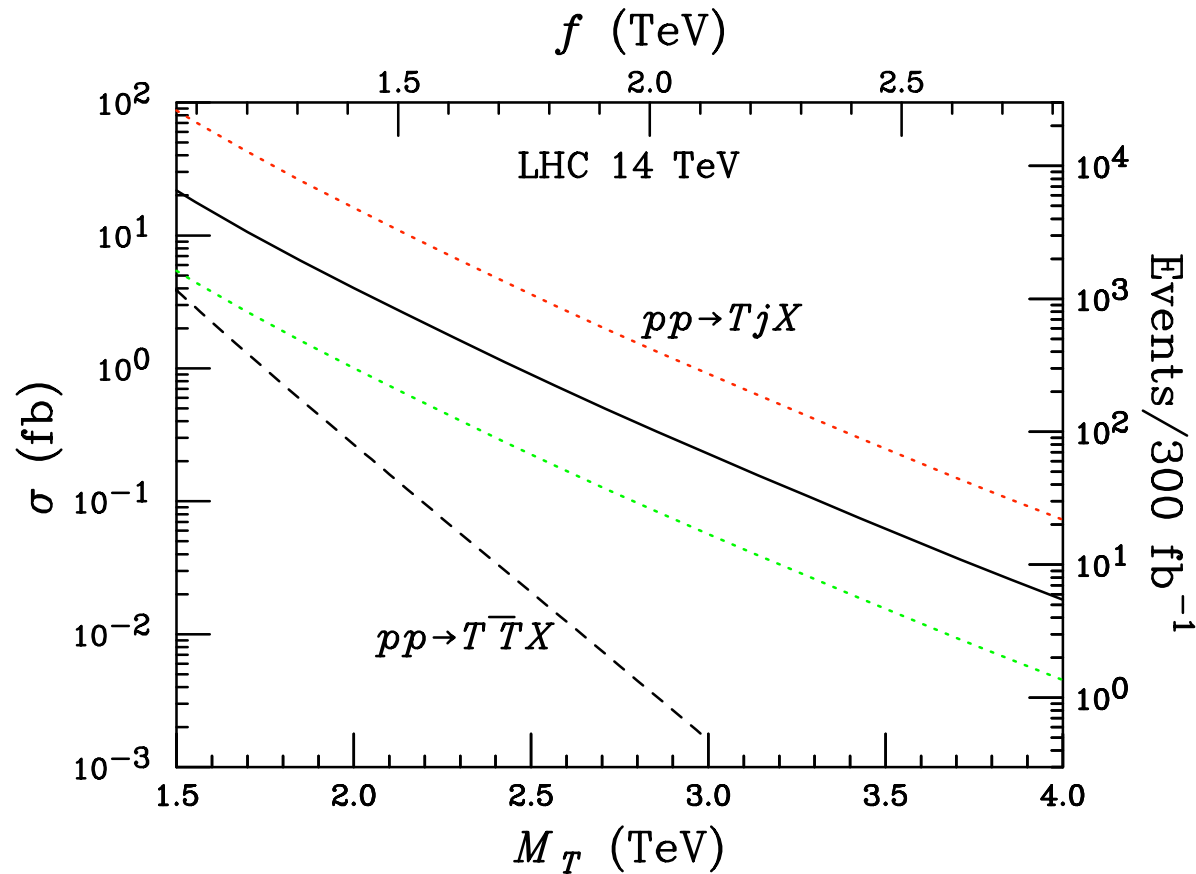**Coupling sum rule for top divergence cancellation:**

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

46
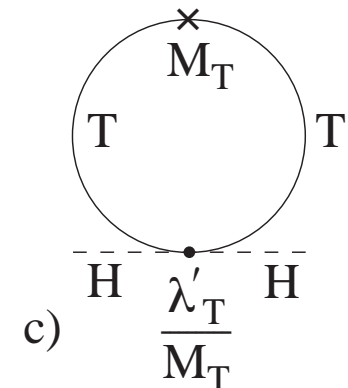
Production of the top-partner T in the Littlest Higgs model:
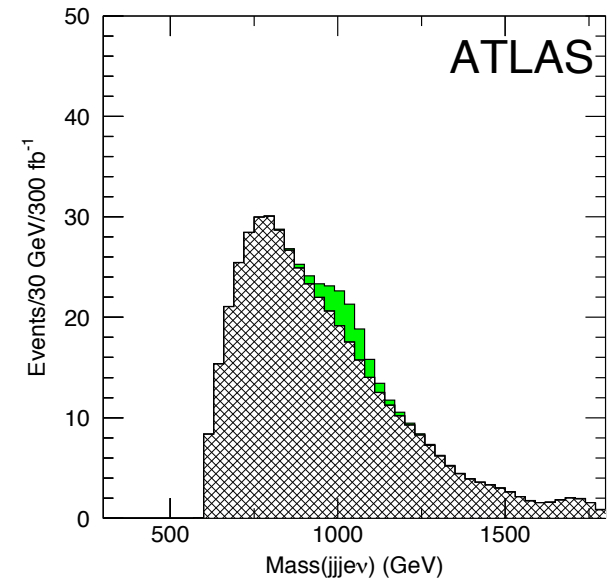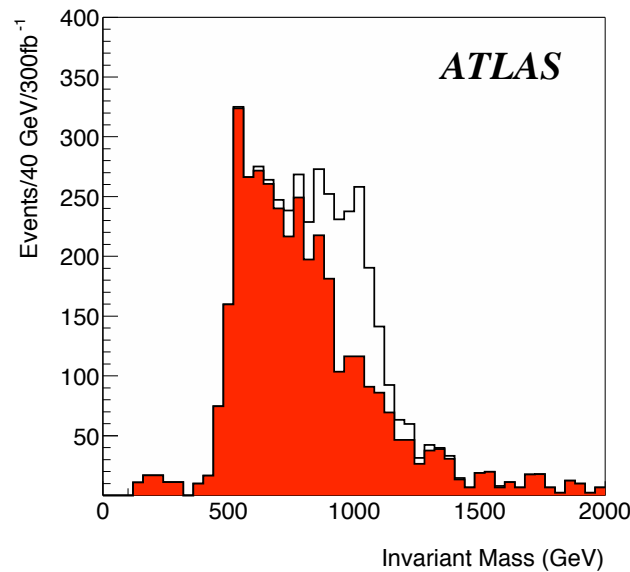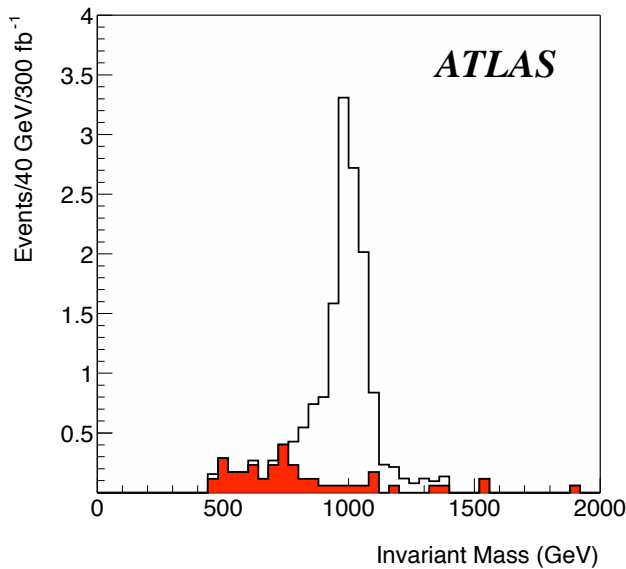
$Wb \to T$

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]

Where we are so far: trying to solve the hierarchy problem

Simplest solution: get rid of the scalar!
Can we still do electroweak symmetry breaking? Yes!
    - Technicolour
    - Higgsless models [via an interlude on warped extra dimensions]
... but it can be hard to squeeze into allowed range of electroweak precision data.

Next-simplest solution: keep the scalar, but add new physics at $\sim$ TeV scale to cancel the Λ^2 divergence.
    - Little Higgs models

Common feature: new particles at $\sim$ TeV scale, which show up in colliders as resonances.

What about SUSY?
What about dark matter?
We'll see next that a small but important addition to the theoretical structure leads to very different experimental signatures.