What Could There Be Besides Supersymmetry?

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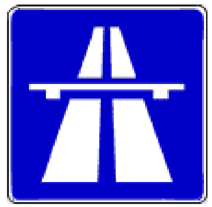
The Highway to Unification

HEP status 2006 (experimental): the Standard Model accomodates all HEP data (so far).

HEP status 2006 (theoretical): the Standard Model is a nice effective theory, but explains nothing.

Fortunately, theorists have an elegant framework beyond the SM . . .

- A Higgs boson with $m \sim 100\ \mathrm{GeV}$ accompanies EWSB
- Supersymmetric partners exist at $100\text{-}1000\ \mathrm{GeV}$ and stabilize quantum corrections to the Higgs potential
- Dynamical supersymmetry breaking somewhere between 10^9 and $10^{16}\ \mathrm{GeV}$ generates the SUSY partner masses
- The gauge couplings unify at about $10^{16}\ \mathrm{GeV}$, and the underlying unified gauge theory is comparatively simple
- Field theory and gravity unify into superstring theory at about $10^{19}\ \mathrm{GeV}$, and everything is predicted.



This makes up a straight highway to the ultimate theory. But it may be completely wrong.

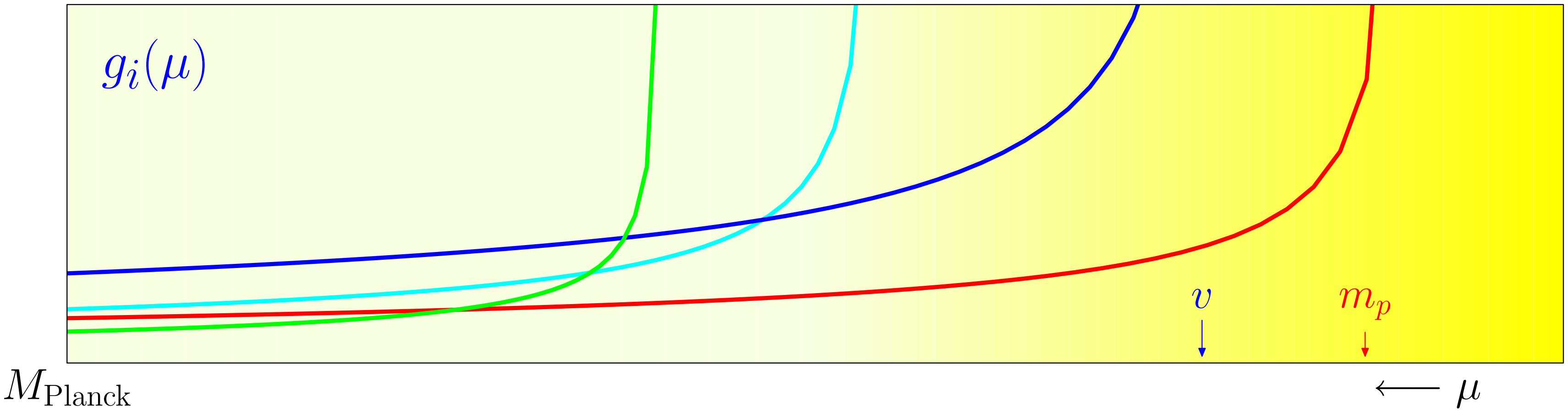
The alternatives are dirt roads: non-perturbative, non-predictive. But they must be considered.

Dynamical EWSB

There might be no Higgs boson. (LHC will establish this, if true.) Then, we leave the well-paved road right around the next corner, the TeV scale.

In this case interactions of W bosons become strong at 1 TeV. There is a template for a possible underlying theory: dynamical symmetry breaking analogous to QCD (Technicolor)

Weinberg, Susskind, Dimopoulos, Eichten, Lane 1976–1980



However, we know very little about the details of such models, except that a true theory of dynamical EWSB would look very different from QCD.

NB: This mechanism is also a probable origin of SUSY breaking, taking place in a Hidden Sector.

Dynamical EWSB

In principle, Csaki, Grojean, Murayama, Pilo, Terning 2003

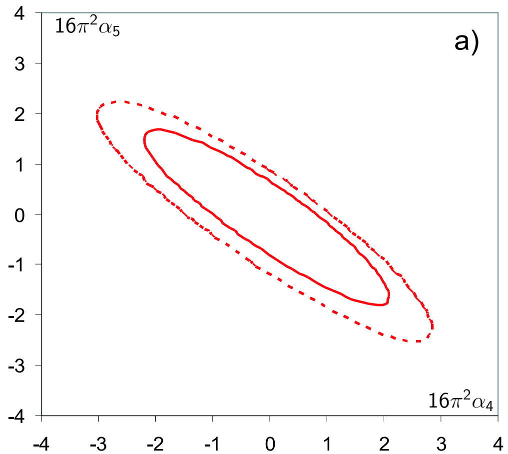
- dynamical EWSB fits into string-inspired scenarios (higgsless models / extra dimensions)
- it avoids the introduction of arbitrary scales and thus has no hierarchy problem

In practice,

- it may be impossible to accomodate flavor physics in any simple way
- strong interactions at 1 TeV induce large corrections to LEP observables. These have to be eliminated or cancelled.

Nevertheless, nature may have chosen this path. At least, we are prepared:

(ILC) Beyer, WK, Krstonošić, Mönig, Reuter, Schmidt, Schröder 2006



- LHC/ILC can measure the parameters that describe the rise of WW scattering
- LHC can directly detect new resonances in WW scattering
- ILC low-energy parameters disentangle resonances
- LHC/ILC can detect technipions etc.

Three-Scale Models

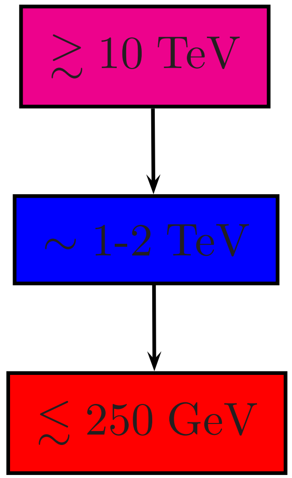
Large effects of new dynamics could be avoided if any new strong interactions occur at scales much higher than the TeV scale

⇒ 10 TeV would be ok (for most observables)

⇒ This requires a Higgs boson significantly below 1 TeV

⇒ and an intermediate extended model at about 1 TeV that by itself is weakly interacting

Model structure:



- Scale Λ:

  Strong interactions, dynamical symmetry breaking

- Scale F:

  New weakly interacting particles

- Scale v:

  SM: Higgs, Vector bosons, fermions

⇒ Indirect symmetry breaking

Three-Scale Models

This setup applies to many models of EWSB

- Models of SUSY breaking: SUSY partners at scale F, SUSY breaking (dynamical) at scale Λ

  $\Rightarrow \Lambda \gg F$ is easy (all-order cancellations of the Higgs self-energy)

  – Renormalization group mixes F and v

  – $v \ll F$ (no SUSY partners observed so far) is possible only by fine-tuning the MSSM parameters: Little hierarchy problem

- Little Higgs models: New particles realize extended global symmetries at scale F, symmetry breaking (dynamical) at scale Λ

  $\Rightarrow v \ll F$ is possible, but Λ is not far away (cancellations only to leading order)

  – Presence of Λ limits accuracy of calculations

- Models with TeV-scale extra dimensions: KK resonances at scale F, compactification scale $1/\Lambda$

  $\Rightarrow v \ll F$ is no problem, but Λ is not too far away

  $\Rightarrow$ Presence of infinitely many resonances limits validity of calculations

Three-Scale Models

The non-SUSY models models lead us off the main highway:
they do not easily fit into the conventional GUT/gravity/string framework

(. . . but they may eventually lead back to it)

Little Higgs Models

How can we realize this in practice?

We need a model with a scalar doublet (Higgs) where

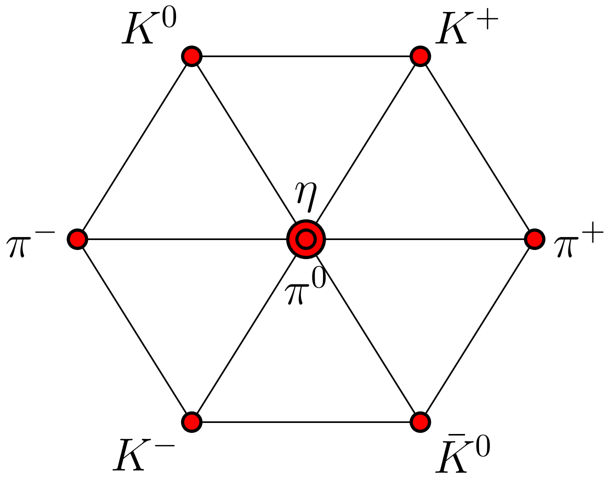
(1) the scalar is massless to leading order (i.e., viewed from the scale F)

(2) we can add an interaction that induces a small negative $m_H^2 \Rightarrow$ EWSB

Natural candidate for a mechanism: spontaneous symmetry breaking and the appearance of massless Goldstone bosons

We know that (1) works! Look at chiral symmetry breaking in QCD:

- Neglecting EW interactions, chiral rotations $u \leftrightarrow d \leftrightarrow s$ correspond to massless Goldstone bosons: pions, ηs and kaons



Little Higgs Models

People have tried to realize (2) for the Higgs for two decades – and failed: why?

$\Rightarrow$ There is an effective Higgs potential at one-loop order

$$V(h) = m^2_{\text{1-loop}} h^2 + \lambda_{\text{1-loop}} h^4 + \dots$$

$\Rightarrow$ Loop graphs are cut off at the scale $\Lambda \sim 4\pi F$

Two possibilities:

1. There is no cancellation in the loop graphs. The leading terms are quadratically divergent and cut off by Λ:

   $$m^2 \sim g^2 \frac{\Lambda^2}{16\pi^2} \qquad \text{and} \qquad \lambda \sim \frac{g^2}{F^2}\frac{\Lambda^2}{16\pi^2} \qquad \Rightarrow \text{If } m^2 < 0\text{, we get EWSB with} \quad v^2 \sim \frac{m^2}{\lambda} \sim F^2$$

2. A symmetry forces the leading terms in the loop graphs to cancel. The leading terms are effectively cut off by F:

   $$m^2 \sim g^2 \frac{F^2}{16\pi^2} \qquad \text{and} \qquad \lambda \sim g^2 \frac{1}{16\pi^2} \qquad \Rightarrow \text{If } m^2 < 0\text{, we get EWSB with} \quad v^2 \sim \frac{m^2}{\lambda} \sim F^2$$

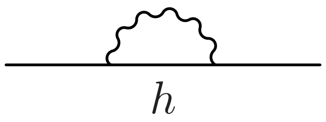
$\Rightarrow$ Neither gives $v \ll F$!

Little Higgs Models

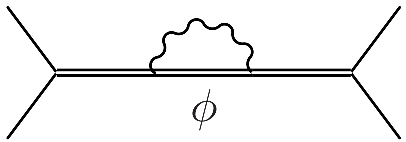
So, what is the trick? Arkani-Hamed, Cohen, Georgi, Gregoire, Wacker, ... (2001)

- Make a model such that, if there was only a single coupling $(g, \lambda_t, \ldots)$, the Higgs would be a Goldstone boson
- Two couplings together break the Goldstone symmetry

Result: m^2 small but λ large

$m^2 \sim$ 

$\sim g^2 \frac{F^2}{16\pi^2}$

$\lambda \sim$ 

$\sim \frac{g^2}{F^2} \frac{\Lambda^2}{16\pi^2}$

So, if $m^2 < 0$:

$$v^2 \sim \frac{m^2}{\lambda} \sim \frac{F^4}{\Lambda^2} \sim \frac{F^2}{16\pi^2}$$

A model that makes this work necessarily involves particles that cancel the SM graphs for m^2:

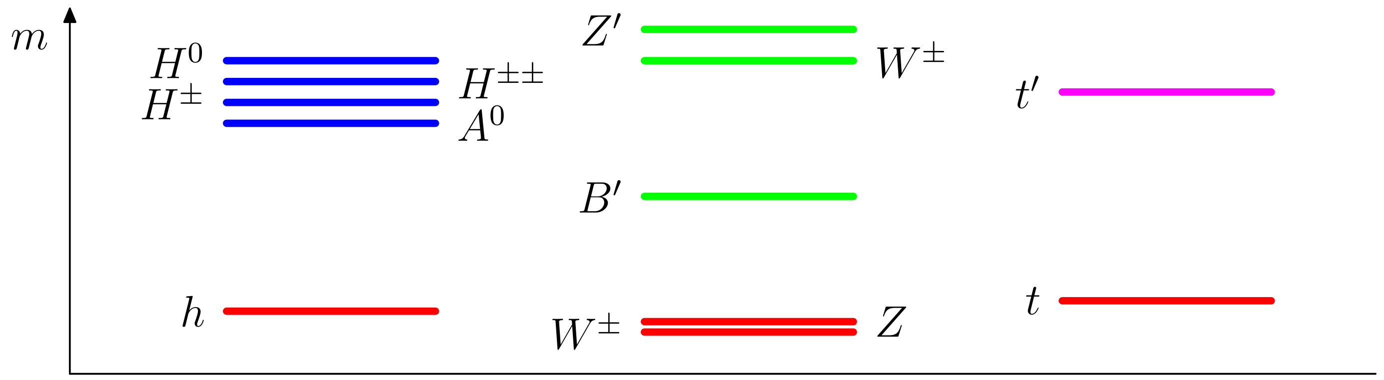
$\Rightarrow$ New vector bosons W', Z', new fermions t', new scalars ϕ with masses of order F

Little Higgs Phenomenology

Test case: "Littlest Higgs" Arkani-Hamed, Cohen, Katz, Nelson 2002

Heavy states: vector triplet, 1 vector singlet, 1 fermion singlet, 1 scalar triplet $(Y = 2)$

$\Rightarrow$ Typical spectrum:



Model-dependent features:

- Only one light Higgs h (minimal SM)
- Doubly charged heavy scalar H^{++}
- One of the extra gauge bosons (B') is considerably lighter than the rest

  $\Rightarrow$ Stronger limits at this particular model

LEP: Precision Observables

Effects on electroweak precision data:

1. Oblique corrections ΔS and ΔT
2. Shift in effective Fermi coupling:

Han, Logan, McElrath, Wang 2003; Csaki, Hubisz, Kribs, Meade, Terning 2003; WK, Reuter 2003

$$G_F = \frac{1}{v^2}(1 - \alpha\Delta T + \delta) \qquad \text{with} \quad \delta = c^4 \frac{v^2}{F^2}$$

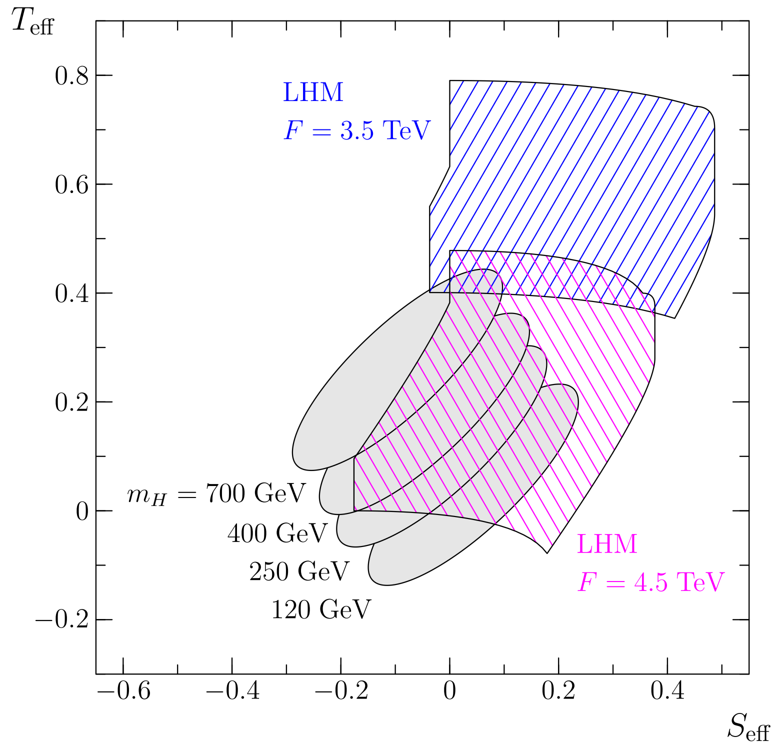
$\Rightarrow$ modified effective parameters

$$S_{\text{eff}} = \Delta S$$

$$T_{\text{eff}} = \Delta T - \frac{1}{\alpha}\delta$$

$$U_{\text{eff}} = \frac{4s_w^2}{\alpha}\delta$$

$\Rightarrow$ Partial cancellation in T, positive U due to nonvanishing δ



ILC: Precision Observables

- Triple gauge couplings:

$$\Delta g_\gamma = \Delta\kappa_\gamma = 0$$

$$\Delta g_Z = \Delta\kappa_Z = 2M_Z^2 \frac{c^2(c^2 - s^2)}{g^2 F^2}$$

(equals ΔS correction, but triplet part only)

- Higgs boson couplings:
  Anomalous ZZH, WWH vertices, sensitive to coefficient of $\mathrm{Tr}\,[V_\mu V^\mu]$
  (nonvanishing if heavy vectors decouple, contains piece due to nonlinear representation)

- Corrections to Higgs Yukawa couplings, extra $HHf\bar{f}$ terms (sensitive to scalar sector)

- Higgs contact terms: $f\bar{f}HW$, $f\bar{f}HZ$
  $\Rightarrow$ include these in analysis of Higgs couplings

- Anomalous $t\bar{t}Z$ and $t\bar{b}W$ couplings (sensitive to heavy-top chirality)

- Modified quartic couplings $HHWW$, $HHZZ$

- Modified Higgs self-coupling HHH

Can the heavy particles be observed?

Heavy vector bosons: Tevatron and LHC cover large fraction of allowed mass range

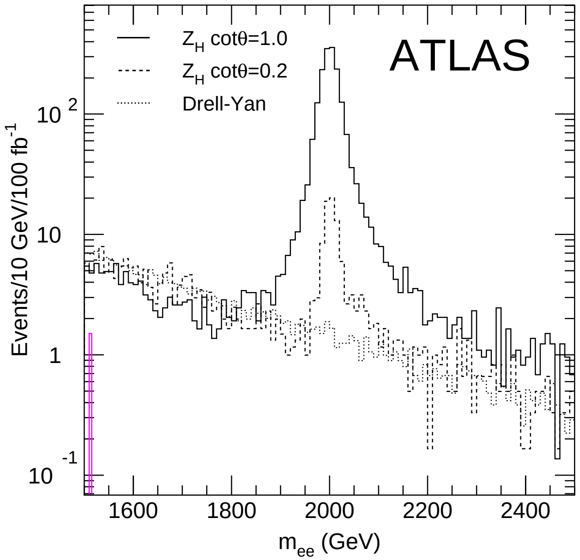
ATLAS study: hep-ph/0402037

Production: $q\bar{q}' \to V$

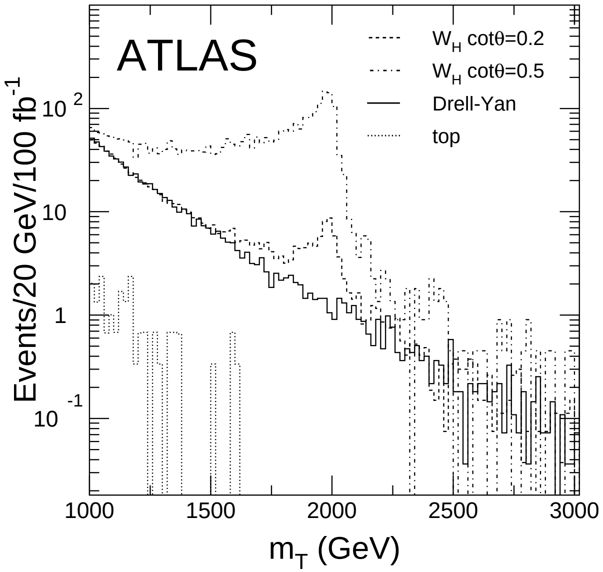
Decay: $V \to \ell\ell, \ell\nu$

Parameter measurement:

Higgs/Goldstone decays Zh, Wh



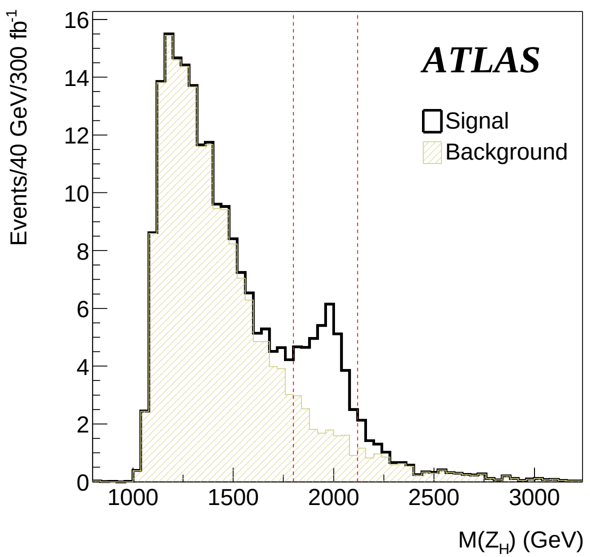
$Z_H \to e^+e^-$



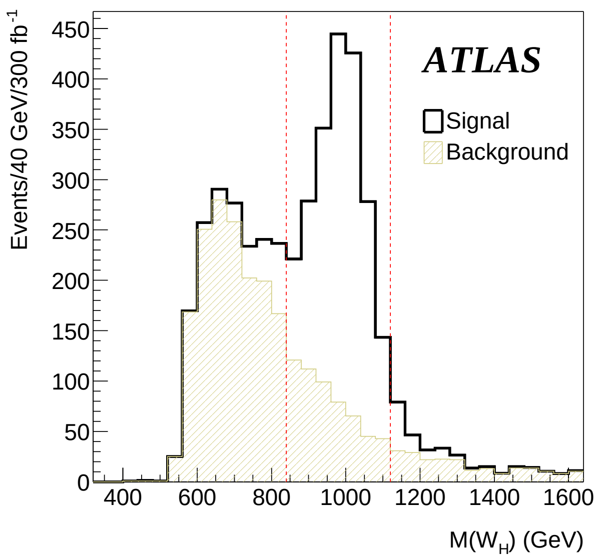
$W_H \to e\nu$

LHC: New Particles of Little Higgs Models

Higgs decays of heavy vector bosons:



$Z_H \to Zh$



$W_H \to Wh$

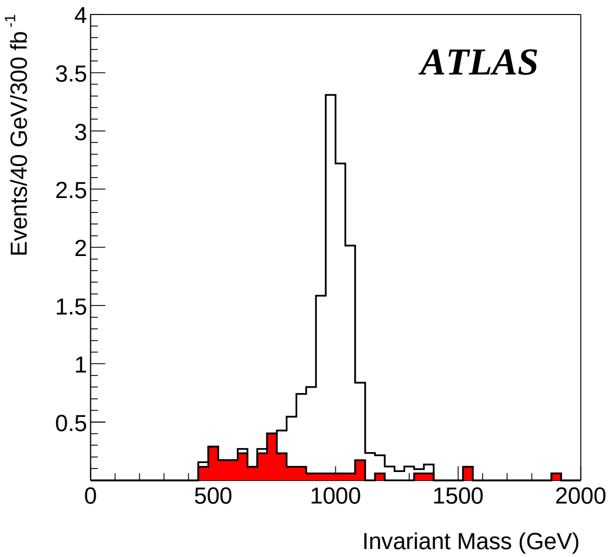
LHC: New Particles of Little Higgs Models

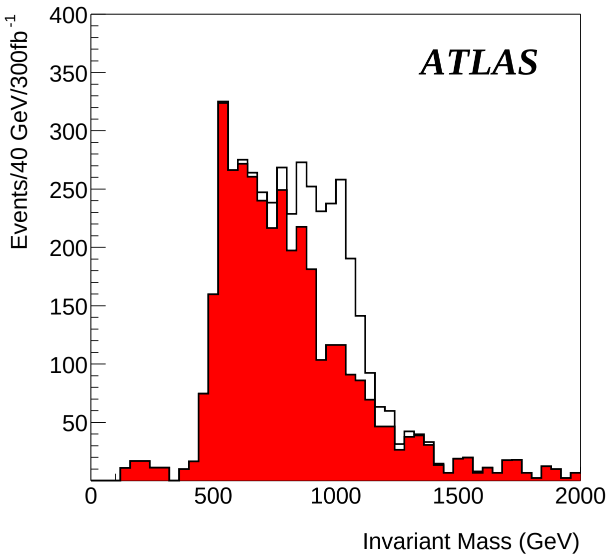
Heavy T quark:

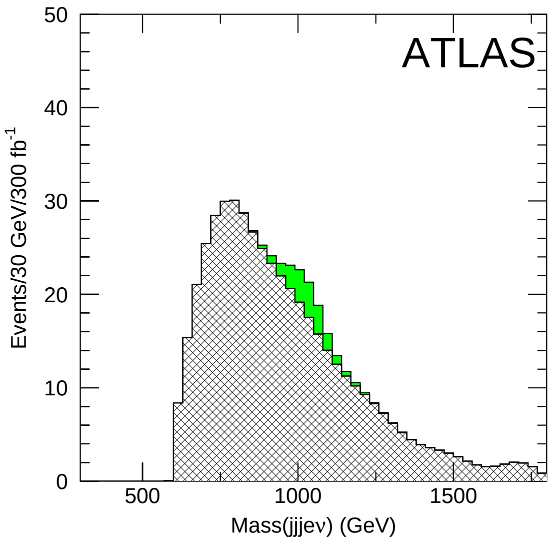
Production: $gg \to T\bar{T}$ and $bq \to Tq'$

Decay modes accessible at LHC ($m_T = 1\ \mathrm{TeV}$):

$T \to tZ$ $\qquad$ $T \to bW$ $\qquad$ $T \to th$

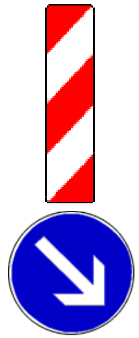






Pseudo-Axions

Can we avoid the lighter Z' (that causes trouble with LEP data)?



- The associated $U(1)'$ symmetry may not be a gauge symmetry

  $\Rightarrow$ Then, we have an extra light pseudoscalar boson η in the spectrum

- Many models contain such light particles: Little Higgs, technicolor, topcolor, ...

Properties?

- No tree-level couplings to WW, ZZ
- No mixing with Higgs doublet
- Sizable interactions only with heavy fermions $T, \ldots$
- ...and therefore loop-induced couplings to gg, $\gamma\gamma$

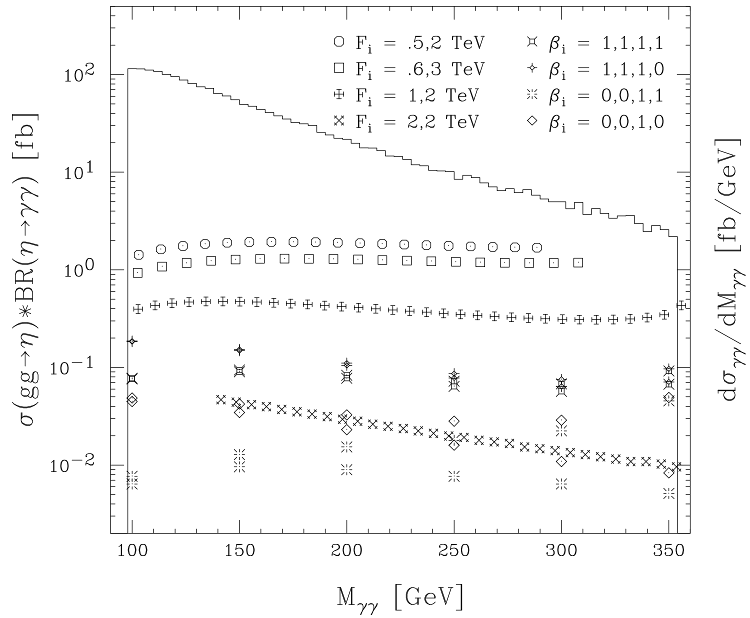
$\bar{T}TH$	$\frac{v}{F}$
$\bar{T}tH$	$P_L + \frac{v}{F}P_R$
$\bar{t}tH$	1

$\bar{T}T\eta$	γ_5
$\bar{T}t\eta$	$P_R + \frac{v}{F}P_L$
$\bar{t}t\eta$	$\frac{v}{F}\gamma_5$

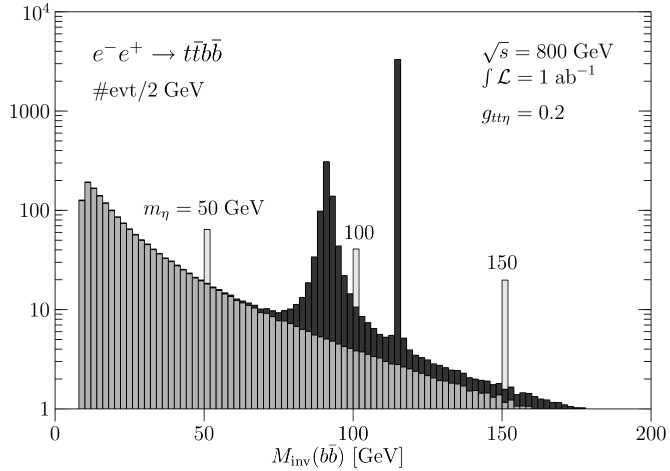
Pseudo-Axions

η detection is difficult (small coupling to SM particles), but not impossible:

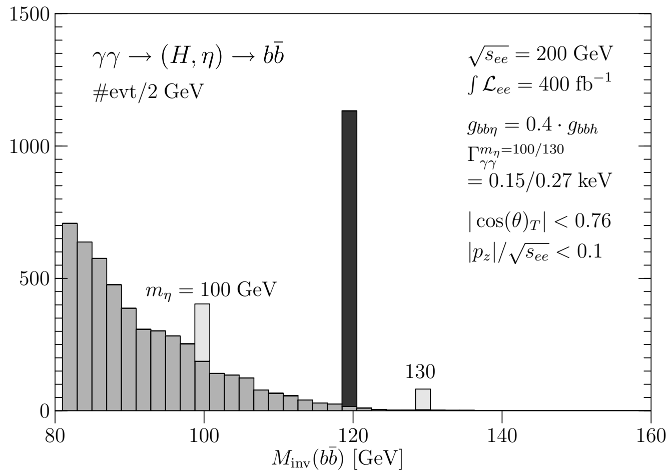
LHC



ILC



ILC/$\gamma\gamma$



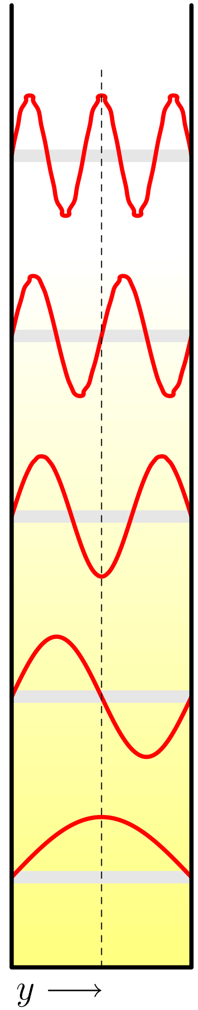
WK, Rainwater, Reuter 2004

TeV-Scale Extra Dimensions

Little Higgs models: heavy particles similar to resonances of W, Z, t

Infinitely many resonances: may be interpreted as stationary states in compact extra dimension(s) y

Arkani-Hamed, Dimopoulos, Dvali 1998; Randall, Sundrum 1999, . . .



Now, we're really leaving the safe grounds of predictivity!
(field theories with $D > 4$ are non-renormalizable)

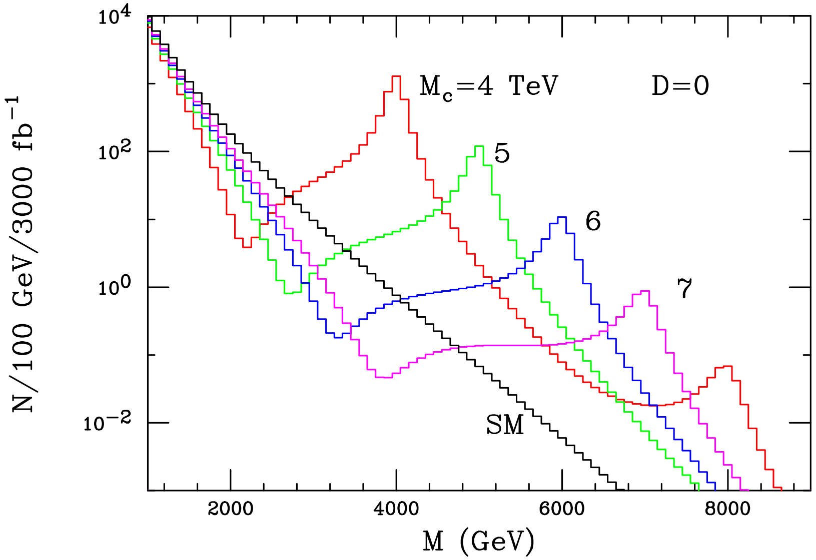
Possible qualitative features:

- Resonances of SM particles that propagate in the D-dimensional bulk
- Form factors for SM particles that are confined to the 3-dim boundary
- New particles with unknown properties (e.g. string states)
- Strong effects of gravitation (e.g. RS model)
- Conserved y momentum $\Rightarrow$ parity $\Rightarrow$ dark matter
- LEP data: situation unclear

TeV-Scale Extra Dimensions

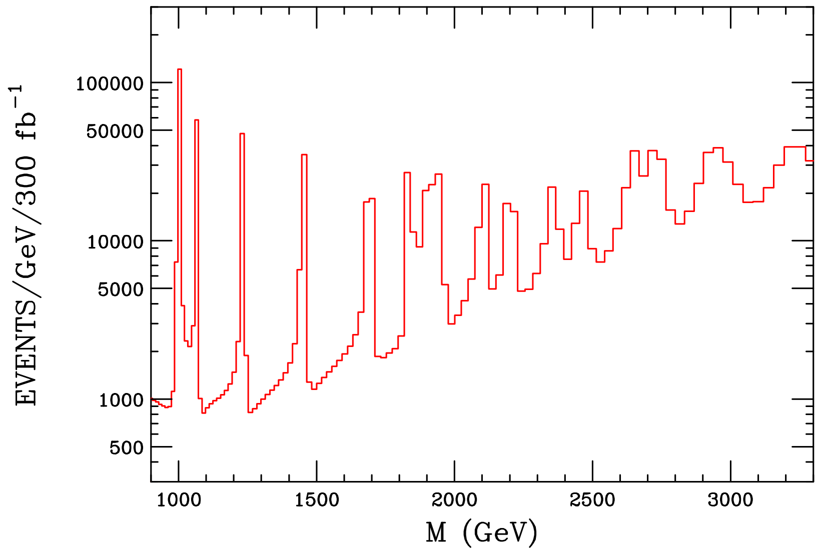
Collider signatures: unexpected strong enhancement / complicated peak structure in simple channels such as Drell-Yan

LHC: Z/γ resonances in e^+e^- production



Rizzo 2003

LHC: Graviton resonances in e^+e^- production



Davoudiasl, Hewett, Rizzo 2002

Split Supersymmetry

Finally, what about SUSY?

- SUSY looks like a natural ingredient for theories that unify gravitation and field theory
- The SUSY spectrum makes the gauge couplings unify exactly
- SUSY solves the naturalness problem: the Higgs mass is stabilized near the SUSY-breaking scale
- SUSY (i.e., SUGRA) has an unsolved flavor problem

Solving the naturalness problem is fine – but if we artificially put the SUSY-breaking scale much higher than the Higgs mass, the flavor problem would be solved.

This is unsatisfactory – but it removes all phenomenological problems of SUSY models!

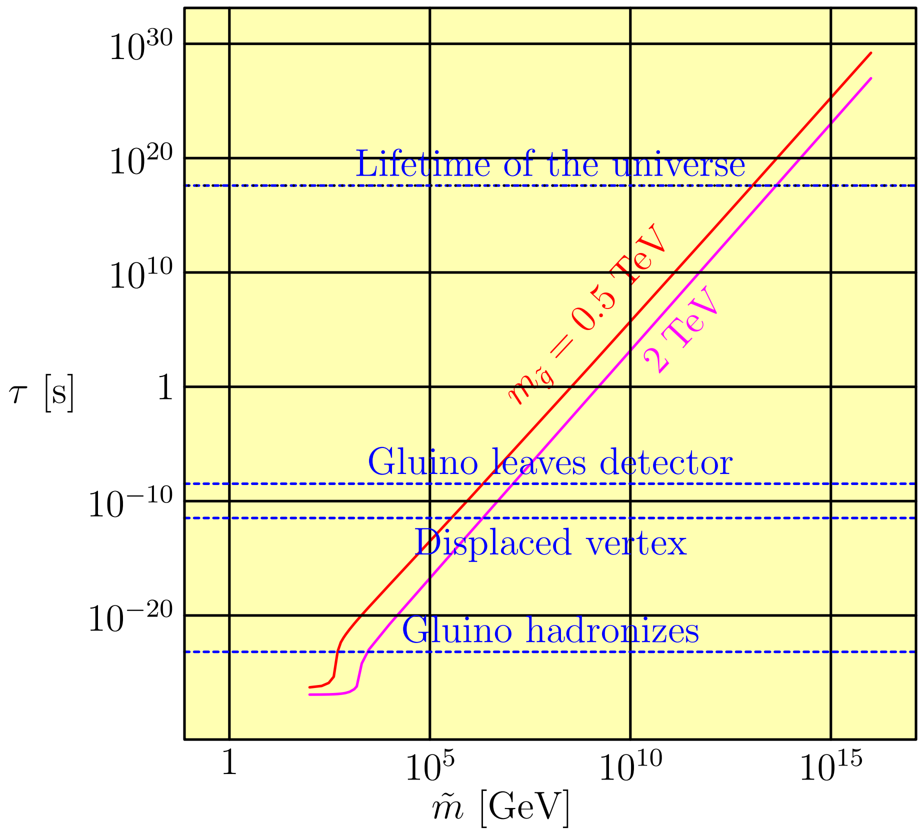
Arkani-Hamed, Dimopoulos, Giudice, Romanino 2004

Split Supersymmetry

Collider phenomenology of Split SUSY:

WK, Plehn, Richardson, Schmidt 2004

- Squarks, sleptons and the extra MSSM Higgses are superheavy and thus unobservable
- The gluino can decay only via virtual squarks and thus becomes long-lived
- Gluino hadronizes into charged or neutral R-hadrons



A heavy metastable gluino loses energy but is not necessarily stopped in the calorimeter
$\Rightarrow$ heavy-muon and/or missing-energy signature

Split Supersymmetry

- The Higgs boson is somewhat heavier than in the MSSM, up to $200\ \mathrm{GeV}$

  $\Rightarrow$ Decay into WW/ZZ may be dominant, easy signature at LHC

- Charginos and neutralinos should be near the EW scale (dark matter!)

  $\Rightarrow$ Production at LHC in Drell-Yan, but not necessarily in cascade decays

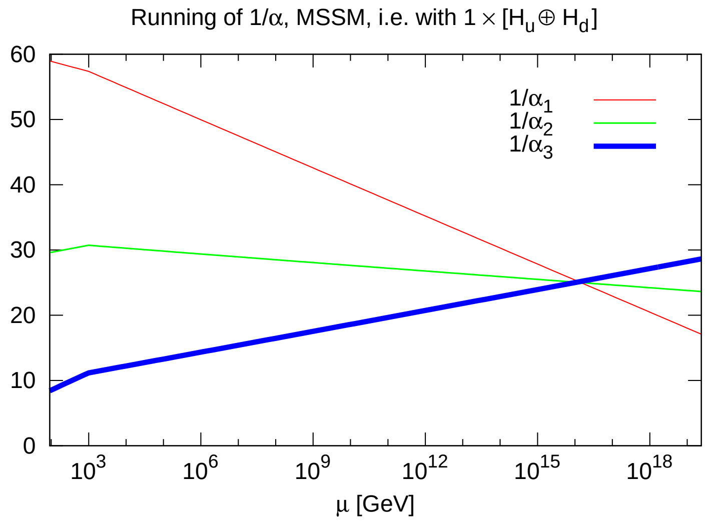
  $\Rightarrow$ ILC can precisely measure thresholds and couplings

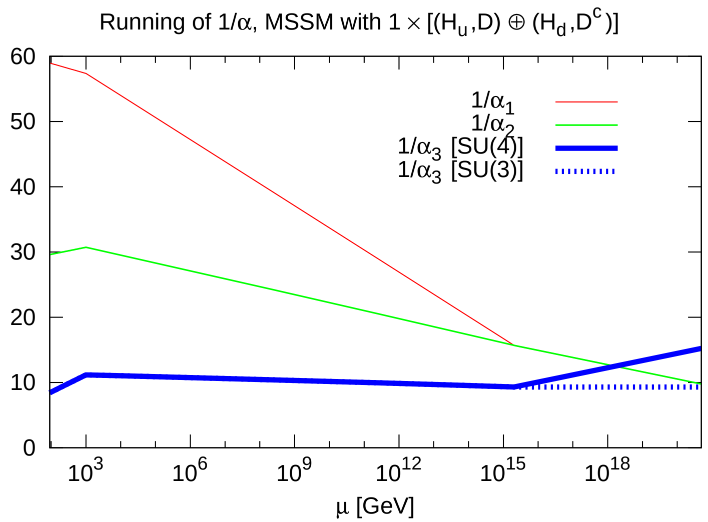
- Chargino mixing matrices are anomalous compared to MSSM

  $\Rightarrow$ Precise measurement is necessary to establish the model (ILC)

Unconventional Unification

WK, Reuter 2006





MSSM-GUT shortcomings:

- Doublet-triplet splitting: colored D superfields in Higgs multiplet
- No Higgs-matter unification
- Unification scale too low for strings [+proton decay?]
- Neutrino Majorana mass scale?

$\Rightarrow$ Add D superfields (leptoquarks/-inos) and two extra 'unhiggs' generations to MSSM spectrum

- Pati-Salam partial unification at neutrino scale
- E_6 unification at string scale
- No proton decay due to underlying flavor symmetry
- Unhiggses $=$ dark matter?

$\Rightarrow$ rich LHC (and ILC) phenomenology

Summary: Signatures of New Physics

Where will this lead us?

- Light Higgs: MSSM or Little Higgs or extra dimensions or . . .
- Missing energy: MSSM or any LH/TC/ED/. . . model with parity
- Same-sign leptons + jets: Gluinos or gluon resonances or colored technipions or . . .
- Z' resonance(s): Little Higgs or extra dimensions or extended MSSM or . . .
- Pseudo-axions: Little Higgs or technicolor or NMSSM . . .

  ⋮

⇒ Most new-physics signatures are ambiguous. But a combination of observations and precision measurements can select one of the possible roads to the fundamental theory.