LHC Phenomenology

Heather Logan
Carleton University

31st Symposium on Physics in Collision
Vancouver, Canada, 28 Aug–1 Sep, 2011
Outline

Introduction: why we expect new discoveries at the LHC

Higgs constraints and phenomenology

Frameworks for physics beyond the Standard Model I: Supersymmetry

Frameworks for physics beyond the Standard Model II: Composite models

Summary and outlook
The Standard Model is extremely successful so far.

Can’t we get by with just the degrees of freedom that we’ve observed?

- 3 generations of quarks; CKM matrix for flavor physics
- 3 generations of charged leptons
- Neutrinos with mass *(might need something new there)*
- gluons from SU(3) strong interaction
- photon plus massive $W^\pm$ and $Z$ from SU(2) $\times$ U(1)
  *(Electroweak symmetry is broken, but do we really have to worry about how?)*
  
  - (Dark matter?)
  - (How to bring gravity into the quantum theory?)
The Standard Model is extremely successful so far.

Can’t we get by with just the degrees of freedom that we’ve observed?

- 3 generations of quarks; CKM matrix for flavor physics
- 3 generations of charged leptons
- Neutrinos with mass (might need something new there)
- gluons from SU(3) strong interaction
- photon plus massive $W^\pm$ and $Z$ from SU(2) × U(1)
  (Electroweak symmetry is broken, but do we really have to worry about how?)
- (Dark matter?)
- (How to bring gravity into the quantum theory?)

The answer is no: the SM without a Higgs is intrinsically incomplete.
Scattering of longitudinally-polarized $W$s exposes need for a Higgs$^*$

$$\text{SU}(2) \times \text{U}(1) @ E^4$$

<table>
<thead>
<tr>
<th>Graphs</th>
<th>$g^2 \frac{E^4}{m_w^4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>$-3 + 6 \cos \theta + \cos^2 \theta$</td>
</tr>
<tr>
<td>(b)</td>
<td>$-4 \cos \theta$</td>
</tr>
<tr>
<td>(c)</td>
<td>$+3 - 2 \cos \theta - \cos^2 \theta$</td>
</tr>
<tr>
<td>Sum</td>
<td>0</td>
</tr>
</tbody>
</table>

$\epsilon_{L}^{\mu}(k) = \frac{k^{\mu}}{m_w} + \mathcal{O} \left( \frac{m_w}{E} \right)$

*or something to play its role
Scattering of longitudinally-polarized $W$s exposes need for a Higgs

\[ SU(2) \times U(1) \oplus E^2 \]

\[ g^2 \frac{E^2}{m_W^2} \]

(a) \[ +2 - 6 \cos \theta \]
(b) \[ - \cos \theta \]
(c) \[ - \frac{3}{2} + \frac{15}{2} \cos \theta \]
(d + e) \[ - \frac{1}{2} - \frac{1}{2} \cos \theta \]

\[ \Theta(E^0) \Rightarrow 4d \ m_H \ \text{bound:} \ m_H < \sqrt{16\pi/3} v \simeq 1.0 \text{ TeV} \]

\[ \Theta(E^2) \Rightarrow E < \sqrt{8\pi v} \simeq 1.2 \text{ TeV} \]

Sum including (d+e) = 0

*or something to play its role

Graphics from R.S. Chivukula, LHC4ILC 2007
Standard Model Higgs mechanism:

Electroweak symmetry broken by an SU(2)-doublet scalar field:

\[ H = \left( \frac{G^+}{(h + v)/\sqrt{2} + iG^0/\sqrt{2}} \right) \]

- \( G^+ \) and \( G^0 \) are the Goldstone bosons (eaten by \( W^+ \) and \( Z \)).
- \( v \) is the SM Higgs vacuum expectation value (vev), \( v = 2m_W/g \simeq 246 \) GeV.
- \( h \) is the SM Higgs field, a physical particle.

Electroweak symmetry breaking comes from the Higgs potential:

\[ V = \mu^2 H^\dagger H + \lambda(H^\dagger H)^2 \]

where \( \lambda \sim \mathcal{O}(1) \) and \( \mu^2 \sim -\mathcal{O}(M_{EW}^2) \).

\[ v^2 = -\mu^2/\lambda = (246 \text{ GeV})^2, \]
\[ M_h^2 = 2\lambda v^2 = -2\mu^2. \]
Direct SM Higgs searches – LEP expts final combination

Figure 10: The 95% confidence level upper bound on the ratio \( \xi^2 \) (see text). The dark and light shaded bands around the median expected line correspond to the 68% and 95% probability bands. The horizontal lines correspond to the Standard Model coupling. (a): For Higgs boson decays predicted by the Standard Model; (b): for the Higgs boson decaying exclusively into \( b \bar{b} \) and (c) into \( \tau^+ \tau^- \) pairs.

\( e^+e^- \rightarrow Z^* \rightarrow ZH \)

SM Higgs decay BRs assumed

\( \xi = \) scaling factor on \( ZZH \) relative to SM

SM limit:

\( M_H \geq 114.4 \text{ GeV} \)


Heather Logan (Carleton U.) LHC Phenomenology Physics In Collision 2011
Latest SM Higgs results from Tevatron (EPS-HEP 2011)

Tevatron Run II Preliminary, $L \leq 8.6 \text{ fb}^{-1}$

Tevatron combined, arXiv:1107.5518 [hep-ex], shown at EPS-HEP 2011

Heather Logan (Carleton U.) LHC Phenomenology Physics In Collision 2011
Latest SM Higgs results from LHC (Lepton-Photon 2011)

ATLAS-CONF-2011-135

CMS PAS HIG-11-022 (LP2011)

CMS + ATLAS exclude (at 95% CL) all mass regions except: below 145 GeV, 288–296 GeV, and above 464 GeV.

Higgs with suppressed gluon-fusion production coupling and/or suppressed \( WW, ZZ \) decay BRs still allowed in the SM-excluded mass regions.

Heather Logan (Carleton U.) LHC Phenomenology Physics In Collision 2011
Precision electroweak SM Higgs mass fit (summer 2011)

Precision EW favors low-mass allowed window, 114.4–145 GeV.
(Fit valid only in SM context; new physics can change preferred mass range.)

Heather Logan (Carleton U.)  LHC Phenomenology  Physics In Collision 2011
LHC Higgs channels: focus on SM, low-mass range

- $W/ZH, H \rightarrow b\bar{b}$
- $H \rightarrow \tau\tau$
- $H \rightarrow ZZ \rightarrow 4\ell$
- $H \rightarrow \gamma\gamma$
- $H \rightarrow WW \rightarrow \ell\nu\ell\nu$

ATLAS-CONF-2011-135

CMS Preliminary, $\sqrt{s} = 7$

Not yet done: VBF $\rightarrow H \rightarrow \tau\tau, WW, ZZ, \gamma\gamma$; $ttH, H \rightarrow bb, \gamma\gamma, WW$; $WH, H \rightarrow \gamma\gamma$

Heather Logan (Carleton U.)

LHC Phenomenology

Physics In Collision 2011
Low-mass range most interesting for extracting Higgs couplings.
- Ratios of rates give ratios of partial widths.
- Add theory assumption: \( hWW, hZZ \leq SM \Rightarrow \) fit Higgs coups.

\begin{align*}
width \text{ ratios} & \\
\Gamma_b/\Gamma_\tau & \quad \Gamma_\tau/\Gamma_\gamma & \quad \Gamma_\gamma/\Gamma_\nu & \quad \Gamma_\gamma/\Gamma_\nu & \quad \Gamma_\gamma/\Gamma_\nu
\end{align*}

\[ m_H \text{ (GeV)} \]

[\text{L}] 200 \text{ fb}^{-1} (except 300 \text{ fb}^{-1} for \text{ttH}(\rightarrow \text{bb}), \text{WH}(\rightarrow \text{bb})). Zeppenfeld, hep-ph/0203123


Plus input from Tevatron at low end of mass range?

Heather Logan (Carleton U.) LHC Phenomenology Physics In Collision 2011
Measure tensor structure of $HVV$ coupling in VBF:

**Most general $HVV$ vertex $T^\mu\nu(q_1, q_2)$**

\[ T^\mu\nu = a_1 g^{\mu\nu} + a_2 (q_1 \cdot q_2 g^{\mu\nu} - q_1^\gamma q_2^\mu) + a_3 \varepsilon^{\mu\nu\rho\sigma} q_1^\rho q_2^\sigma \]

The $a_i = a_i(q_1, q_2)$ are scalar form factors

**Physical interpretation of terms:**

- **SM Higgs** $\mathcal{L}_I \sim HV_\mu V^\mu \rightarrow a_1$
  loop induced couplings for neutral scalar

- **CP even** $\mathcal{L}_{eff} \sim HV_\mu V^{\mu\nu} \rightarrow a_2$

- **CP odd** $\mathcal{L}_{eff} \sim HV_\mu \tilde{V}^{\mu\nu} \rightarrow a_3$

Must distinguish $a_1, a_2, a_3$ experimentally

*Slide from D. Zeppenfeld, plenary talk at SUSY'06 conference*
$HVV$ vertex structure gives different distributions in $jj$ azimuthal angle $\Delta \phi$:

\[ \frac{1}{\sigma} \frac{d\sigma}{d\Delta \phi_{jj}} \]

mixed CP case:  
$a_2 = a_3, a_1 = 0$

pure CP-even case:  
$a_2$ only

pure CP odd case:  
$a_3$ only

Figy, Hankele, Klämke, & Zeppenfeld, hep-ph/0609075; plot for $M_H = 120$ GeV

$HV^\mu V^\nu$ structure is “smoking gun” for Higgs mechanism EWSB. Check for CP violation and/or loop-induced $HV^{\mu \nu}V_{\mu \nu}$ structure. Can also use $H \rightarrow ZZ, WW$ lepton distributions.
Why expect more than just SM Higgs: The Hierarchy Problem

The Higgs mass-squared parameter $\mu^2$ gets quantum corrections that depend quadratically on the high-scale cutoff of the theory.

Calculate radiative corrections from, e.g., a top quark loop.

$$\mu^2 = \mu_0^2 + \Delta \mu^2$$

For internal momentum $p$, large compared to $m_t$ and external $h$ momentum:

$$\text{Diagram} = \int \frac{d^4p}{(2\pi)^4} (-) N_c \text{Tr} \left[ i \frac{\lambda_t}{p} i \frac{\lambda_t}{p} \right]$$

$$= -N_c \lambda_t^2 \int \frac{d^4p}{(2\pi)^4} \text{Tr} \left[ \frac{1}{p^2} \right]$$

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

Momentum cutoff $\Lambda$: Integral diverges like $\Lambda^2$. 

Heather Logan (Carleton U.) LHC Phenomenology Physics In Collision 2011
Full 1-loop calculation gives

$$\Delta \mu^2 = \frac{N_c \lambda_t^2}{16 \pi^2} \left[ -2 \Lambda^2 + 6 m_t^2 \ln(\Lambda/m_t) + \cdots \right]$$

We measure $\mu^2 \sim -O(M_{EW}^2) \sim -(100 \text{ GeV})^2 = -10^4 \text{ GeV}^2$.

Nature sets the bare parameter $\mu_0^2$ at the cutoff scale $\Lambda$.

If $\Lambda = M_{Pl} = \frac{1}{\sqrt{8\pi G_N}} \sim 10^{18} \text{ GeV}$, then $\Delta \mu^2 \sim -10^{35} \text{ GeV}^2$!

- Not an inconsistency in the theory.
  Renormalizable: absorb the divergence into the bare parameter $\mu_0^2$.

- But it is an implausibly huge top-down coincidence that $\mu_0^2$ and $\Delta \mu^2$ cancel to 31 decimal places! Looks horribly fine-tuned.
  and not just at one loop – must cancel two-, three-, four-, ... loop contributions

Want $|\Delta \mu^2| \sim (100 \text{ GeV})^2 \Rightarrow \Lambda \sim 1 \text{ TeV}$.

Expect New Physics that solves hierarchy problem at TeV scale!
Aside: Can the SM be valid all the way to the Planck scale?

$$m_t = 175 \text{ GeV}$$
$$\alpha_s(M_Z) = 0.118$$

**Landau Pole:**

Higgs self-coupling too large; blows up at scale $$\Lambda$$

**Vacuum Instability:**

Higgs self-coupling too small compared to top Yukawa; runs negative at scale $$\Lambda$$

Hambye & Riesselmann, hep-ph/9708416

SM Higgs sector is perturbative and stable (but terribly fine-tuned) all the way to the Planck scale for $$M_H \simeq 134-180 \text{ GeV}$$.

∃ window for $$\sim 134-145 \text{ GeV}$$. For a nice review see Quigg, arXiv:0905.3187

Smaller top mass ⇒ lower bound decreases a little.

Heather Logan (Carleton U.) LHC Phenomenology Physics In Collision 2011
Two main classes of solutions to the hierarchy problem:

1) Supersymmetry
SUSY relates $\mu^2$ to a fermion mass, which only runs logarithmically. Guarantees cancellation between SM loop diagrams and SUSY loop diagrams.

2) Composite Higgs
Higgs is some kind of bound state (“meson”) of fundamental fermions, held together by a new force that gets strong at the TeV scale. Above a TeV there are no fundamental scalars, so no hierarchy problem.

[Includes extra-dimension / RS models by AdS/CFT duality.]
Supersymmetry

SUSY signals depends hugely on the SUSY mass spectrum: controls cascade decays

\[
\begin{array}{c}
\tilde{g} \quad \tilde{q}_L \quad \tilde{N}_2 \quad \tilde{f} \quad \tilde{N}_1
\end{array}
\]

Generic features:
- **Jets + MET:** strong squark and/or gluino production, cascade decays to invisible LSP.
- **Leptons + MET:** electroweak production of sleptons, gauginos: typically lighter than squarks/gluino due to renormalization-group running.
- **3rd generation + MET:** renormalization-group running tends to drive top, bottom squarks lighter than others.
- **Photons + MET:** SUSY-breaking at an intermediate scale \(\Rightarrow\) gravitino is LSP, cascade decays to NLSP (bino).
General features of the SUSY mass spectrum

- Squarks start with common mass at high scale to avoid flavour problems
- Run down using RGEs ⇒ coloured particles heavier
- Large Yukawa coupling (\(\bar{t}; \bar{b}, \bar{\tau}\)) pulls the mass down
- Left-right mixing large when Yukawa is large ⇒ mass splitting
- Heavier stops pull up the \(h^0\) mass, but too-heavy stops reintroduce fine-tuning. 1 TeV stops are nice; 2 TeV I think are a bit stretched.
- Gluino mass is an independent parameter from squark masses
- Gluino:Wino:Bino mass ratios fixed by SUSY-breaking mechanism.
* mSUGRA, GMSB: 7 : 2 : 1
* AMSB: 8.3 : 1 : 2.8

Martin, hep-ph/9709356
Supersymmetry definitely predicts a Higgs boson.
- $h^0$: tends to be SM-like
- $H^0, A^0, H^\pm$: tend to be degenerate; decays depend on $\tan \beta$

MSSM with top squarks below 1 TeV requires $M_h \lesssim 135$ GeV.

Carena & Haber, hep-ph/0208209

Heather Logan (Carleton U.)
LHC Phenomenology
Physics In Collision 2011
MSSM light-Higgs discovery can be tricky due to mixing and modification of loop-induced couplings by SUSY particles.

For a large region of parameter space, suppression of the $\gamma\gamma$ mode at the LHC

$M_h \sim 115 - 125$ GeV

Suppression still sizable for $m_A$ as large as 500 GeV

Heather Logan (Carleton U.)  LHC Phenomenology  Physics In Collision 2011
LHC reach for the MSSM SM-like Higgs

Important to improve on early LHC reach in tau tau mode
MSSM Higgses: $\tau\tau$ resonance search (from $A^0/H^0/h^0$)

Most of “difficult” light-$A^0$ region is already excluded.
Is SUSY compatible with a Higgs above 135 GeV?

Yes, but it requires modifications. Options:
- “Hard” or very-low-scale SUSY breaking
- NMSSM (coupling $\lambda S H_u H_d$) with large $\lambda \Rightarrow$ Landau pole
  $\Rightarrow$ Supersymmetric “Fat Higgs” model and variants:
  Higgs $\sim 200$–$450$ GeV. (Still viable with mixing, new decay modes)

- Make the top squarks heavier (reintroduces fine-tuning)

Harnik, Kribs, Larson, Murayama, hep-ph/0311349

Heather Logan (Carleton U.) LHC Phenomenology Physics In Collision 2011
Supersplit Supersymmetry* predicts $128 \pm 2 - 141 \pm 2$ GeV

Fox, Kaplan, Katz, Poppitz, Sanz, Schmaltz, Schwartz & Weiner, hep-ph/0503249

Figure 2: The Higgs mass prediction in the SM for theories where the boundary condition for the quartic coupling at $\tilde{m}$ is given by Eq. (2), for fixed values of $\tilde{m} = 10^{14}$ GeV and $\alpha_s(M_Z) = 0.1176$.

The solid red curve gives the Higgs mass prediction for $m_t = 173.1$ GeV, while the haded red band shows the uncertainty that arises from the experimental uncertainty of $\pm 1.3$ GeV. The horizontal line shows the corresponding asymptotes of the prediction for large $\tan\beta$. For $\beta < 1$, an identical figure results provided the horizontal axis is labeled by $\cot\beta$.

In a general supersymmetric model, the SM Higgs doublet may be a combination of supersymmetric Higgs doublets having opposite hypercharge so that, before including threshold corrections, the boundary condition on the quartic coupling is given by Eq. (2). The resulting prediction is actually a correlation between the Higgs boson mass and the parameter $\tan\beta$, as shown by the solid red curve in Figure 2. Remarkably, even as $\beta$ varies over all possible values, the Higgs mass lies in a narrow, high-scale supersymmetry, window of $\simeq (128 - 141)$ GeV. Furthermore, for large values of $\tan\beta$ the Higgs mass rapidly asymptotes to $\simeq 141$ GeV, shown by

Plot: $m_t = 173.1$ GeV, $\tilde{m} = 10^{14}$ GeV; uncert. from $\Delta m_t, \Delta \alpha_s$.

*more than just the best April Fool’s joke in particle physics!

Heather Logan (Carleton U.) LHC Phenomenology Physics In Collision 2011
Same as high-cutoff SM with stable, perturbative Higgs potential; GUT boundary condition fixes Higgs quartic at $10^{14-16}$ GeV.

![Graphical representation showing the relationship between $M_H$ and $\Lambda$ for different boundary conditions.](image)

- **Landau Pole:**
  - Higgs self-coupling too large; blows up at scale $\Lambda$
- **Vacuum Instability:**
  - Higgs self-coupling too small compared to top Yukawa; runs negative at scale $\Lambda$

Hambye & Riesselmann, hep-ph/9708416

∃ window for $\sim 134-145$ GeV.

Compare Supersplit SUSY: $\sim 128-141$ GeV

Lower edge of "window" depends sensitively on top mass.

Heather Logan (Carleton U.) LHC Phenomenology Physics In Collision 2011
Less extreme: **Split Supersymmetry**
Preserves gauge coupling unification, dark matter candidate; less fine-tuned. Gauginos at TeV scale pull up Higgs mass compared to Supersplit

![Graph showing the value of the Higgs mass as a function of \( \tilde{m} \). The bands include 1-σ errors on \( m_t \) and \( \alpha_s(M_Z) \). The upper band corresponds to \( \tan \beta = 50 \) and the lower one to \( \tan \beta = 1.5 \).](image)

\[ \tan \beta = 50 \]
\[ \tan \beta = 1.5 \]

Gluino signatures are key: can have displaced vertices, CHAMPs.


*Heather Logan (Carleton U.) LHC Phenomenology Physics In Collision 2011*
Composite Models

Compositeness models trace EWSB to some new strong dynamics at or above the TeV scale.

Three broad classes of possibilities:

Technicolor (or Higgsless models)
- No Higgs state per se
- Goldstone bosons eaten by $W, Z$ are bound states (“pions”) of strongly-coupled dynamics

Composite-Higgs models
- Genuine Higgs (or Higgs-like) particle exists: bound state of strongly-coupled theory

Little Higgs models
- Higgs kept light by an extra layer of global symmetries; allows strong-coupling scale to be pushed higher
- Minimal extra matter content (top-partner, $W', Z'$, ...) near TeV scale
Technicolor

Strongly coupled theory: hard to calculate reliably
Original analyses used QCD measurements ⇒ too large effect on precision EW. Technicolor can’t be just like QCD.

New understanding:
- Better techniques for strongly-coupled gauge theories
- AdS/CFT correspondence: calculate in 5-dim “dual” theory

“Deconstruct” the 5-dim theory to 4-dim for phenomenologically-useful “Higgsless” model:
- Expect techni-rho spin-1 resonances \( (W', Z') \) below TeV scale
  Exchange of these unitarizes \( WW \) scattering up to \( \sim 1.5 \) TeV
  resonance decays into \( WW, WZ \)
- Can have physical techni-pions depending on global symmetries

Hard to make top quark heavy enough ⇒ top-color, etc.
- Expect top-Higgs, top-pions
  Implications from LHC Higgs searches
Top-Higgs

Dedicated (composite) scalar doublet to generate most of top quark mass: common add-on for models of dynamical EWSB.
- topcolor-assisted technicolor
- deconstructed “top triangle” 3-site Moose

Top-Higgs doublet has vev \( f = v_{\text{SM}} \sin \omega \)
(Strong dynamics responsible for most of EWSB: \( v_{\text{SM}} \cos \omega \))

Top-Higgs particle \( H_t \) couples only to \( t\bar{t}, WW, ZZ \) at tree level
- \( WW, ZZ \) couplings suppressed \( \sim \sin \omega \)
- \( t\bar{t} \) coupling enhanced \( \sim 1/\sin \omega \)
- \( gg \to H_t \) enhanced \( \sim 1/\sin^2 \omega \): LHC production enhanced!

Typical mass is \( M_{H_t} \lesssim 2m_t \) for dynamical top mass generation in topcolor-assisted technicolor (TC2)
LHC Higgs search: relevant channels are $gg \rightarrow H_t \rightarrow WW, ZZ$

$\text{BR}(H_t \rightarrow WW, ZZ)$ is suppressed when decays to top-pions ($W^\pm \Pi_t^\mp$, $Z\Pi_t^0$, $\Pi_t\Pi_t$) are kinematically accessible.

Top-pion mass constrained by exotic top decay limits: $t \rightarrow \Pi_t^+ b$.

Chivukula, Simmons, Coleppa, HEL, & Martin, arXiv:1108.4000 (updated with LP11 limits)

Heather Logan (Carleton U.) LHC Phenomenology Physics In Collision 2011
Most of the interesting TC2 top-Higgs parameter space has been excluded this summer!

Chivukula, Simmons, Coleppa, HEL, & Martin, arXiv:1108.4000 (updated with LP11 limits)

Other options:
Top seesaw ⇒ much heavier top-Higgs: still viable

Heather Logan (Carleton U.)  LHC Phenomenology  Physics In Collision 2011
**Composite Higgs:** model based on Randall-Sundrum

Has a physical Higgs state
Higgs lives on or near IR brane:
interpreted as composite

Top quark near IR brane: need overlap with Higgs to pick up large enough mass

**KK excitations of $Z$, $W$, gluon**
- Enhanced coupling to right-handed top
- $Z'$, $G'$ decay preferentially to $t\bar{t}$: TeV resonances in top pairs

**KK excitations of quarks**
- Single production via $qW$, $qZ$ fusion
  Cross section is larger than for pair production for heavy masses
- Decays back to $qW$, $qZ
Electroweak constraints

Generic models of New Physics tend to be tightly constrained by electroweak precision data.
- New particles contribute to measured SM processes, e.g., $f \bar{f} \rightarrow f \bar{f}$.
- New features in SU(2) and top sectors constrained by $S, T$ and $R_b$.

EW precision constraints generically push $\Lambda_{\text{NP}}^{\text{eff}}$ well above “natural” TeV scale, especially for strongly coupled new physics: called the “little hierarchy” problem.

Tricks:

- **Little Higgs models**: Use global symmetries to kill off 1-loop correction to Higgs mass: push strong dynamics up to $\sim 10$ TeV.
- $\Delta \mu^2 \sim (g^2/16\pi^2)^2\Lambda^2$ instead of $(g^2/16\pi^2)\Lambda^2$

- **Little Higgs with T-parity**: make extra TeV-scale states T-parity odd: produced only in pairs, exchanged only in loops. Escape EW precision constraints; get dark matter candidate.
Little Higgs models

Need “partners” at TeV scale for top, $W$, $Z$, Higgs to cancel one-loop $\mu^2$ corrections.

Top partner $T$:

SU(2)-singlet “vectorlike” quark.

Production: $\bar{T}T$ via QCD, $Tj$ via t-channel W.

Decays: $T \rightarrow bW, tZ, tH$.

$T \rightarrow tZ \rightarrow b\nu\ell\ell$

Azuelos et al, hep-ph/0402037
Gauge partners $W_H$, $Z_H$ (and sometimes $B_H$):
- Come from $SU(2) \times SU(2) \to SU(2)_L$ breaking
- Couplings to left-handed fermions like SM $W_{\mu,3}^\pm$, with strength $g \cot \theta$
- Extra decays $Z_H \to HZ, WW$; $W_H \to HW, ZW$

$W_H \to WH \to \ell\nu bb$

5σ discovery w/ 300 fb$^{-1}$:

Azuelos et al, hep-ph/0402037

Heather Logan (Carleton U.) LHC Phenomenology Physics In Collision 2011
$W' \rightarrow \ell\nu$ search:
Probes production coupling strength, decay BRs.


Heather Logan (Carleton U.)  LHC Phenomenology  Physics In Collision 2011
**Little Higgs with T-parity**

Looser electroweak constraints ⇒ new particles can be lighter
- less fine-tuned

T-parity ⇒ T-odd particles pair-produced, stable “LTP”
- $T \to t + \text{invisible}$
- gauge partner pair signals reminiscent of SUSY

Higgs mass range preferred by precision EW + fine-tuning can be rather heavy.
- very model-dependent statement
- major implications from Higgs search
- needs to be systematically explored

Little Higgs with T-parity, Hubisz, Meade, Noble, Perelstein, hep-ph/0506042

*Heather Logan (Carleton U.) LHC Phenomenology Physics In Collision 2011*
Summary and outlook

Early LHC data already having impacts on huge range of models.
- Major task for phenomenologists to incorporate the new LHC exclusions into model “landscape” (fine-tuning, etc.)

None of the major classes of new-physics models is “dead yet”
- but some are starting to be tightly constrained (e.g., TC2).

Outcome of Higgs search in 5–10 fb$^{-1}$ will be very important.

We eagerly await experimental input on the dynamics of electroweak symmetry breaking!
Backup slides
MSSM Higgs search:
Low-mass Tevatron and LHC channels are complementary.

M. Casarsa, talk at PLHC 2011

CMS-PAS-HIG-11-022 (LP2011)

Heather Logan (Carleton U.)  LHC Phenomenology  Physics In Collision 2011
Supersymmetry: key measurements

1) Mass spectrum

- Use **kinematic edges** to get mass differences in decay chain

- Exact kinematic relations: “solve” individual decay chains

  Kawagoe, Nojiri & Polesello, PRD71, 035008 (2005), Cheng et al., PRL 100, 252001 (2008)

- **MT2** (“stransverse mass”), kinks, cusps, $\sqrt{s_{\text{min}}}$, etc.

  Recent review: Barr et al., arXiv:1105.2977

Heather Logan (Carleton U.) LHC Phenomenology Physics In Collision 2011
Supersymmetry: key measurements

2) Spin of superpartners

Universal Extra Dimensions can mimic SUSY
Stable “LKP” → jets + missing energy signatures.

UED, $L = (500 \text{ GeV})^{-1}$
Supersymmetry: key measurements

2) Spin of superpartners

Need to be clever to find distinguishing observables!
Kinematic distributions, etc.

Datta, Kong & Matchev, hep-ph/0509246
Supersymmetry: key measurements

3) Coupling relations
gauge couplings $\leftrightarrow$ gaugino Yukawa couplings

Freitas & Skands, hep-ph/0606121

Requires ILC input for squark decay BRs.
LHC reach for the MSSM SM-like Higgs

Important to improve on early LHC reach in tau tau mode
MSSM Higgses: $\tau\tau$ resonance search (from $A^0/H^0/h^0$)

Most of “difficult” light-$A^0$ region is already excluded.

Heather Logan (Carleton U.) LHC Phenomenology Physics In Collision 2011

Tevatron - early LHC combined reach: MSSM SM-like Higgs

3 sigma evidence of the SUSY Higgs responsible for EWSB
Z' $\rightarrow ll$ search: 5-event discovery reach in dimuons

Godfrey & Martin, 2011

Discovery Reach (GeV)