New Ideas of Electroweak Symmetry Breaking
LHC phenomenology

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DESY LHC Workshop, 6. March 2006
Outline

Hierarchy Problem

The Little Higgs mechanism

Cancellations of divergencies

Generic properties

Examples of Models

LHC phenomenology
  Heavy Quark States
  Heavy Vectors
  Heavy Scalars
  Pseudo Axions in LHM
  $T$ parity and Dark Matter

Open Points/Discussion
Motivation: Hierarchy Problem

- Effective theories below a scale $\Lambda \Rightarrow$
- Loop integration cut off at order $\sim \Lambda$:

$\sim \Lambda^2$

Problem: Naturally, $m_h \sim \mathcal{O}(\Lambda^2)$:

$m_h^2 = m_0^2 + \Lambda^2 \times \text{(loop factors)}$

Light Higgs favoured by EW precision observables
($m_h < 0.5$ TeV)

$m_h \ll \Lambda \iff$ Fine-Tuning !?

Solutions: Large number of ideas since 1970s
Overview of Solutions

(1) **Light Scalar as Pseudo-Goldstone Boson**
   
   a) Higgs as massless Goldstone Boson, Higgs mass connected to explicit symmetry breaking
   
   b) No fundamental scalars in Nature: Technicolor (Repetition of QCD); EW Precision Data problematic
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(2) **Mechanism of Elimination of Loop Corrections:**
   
   a) **Supersymmetry:** Spin-Statistics $\Rightarrow$ Loops of bosons and fermions cancel $\Rightarrow$ W. Kilian’s talk
   
   b) **Little Higgs mechanism:** Global symmetries $\Rightarrow$ Loops of particles of like statistics cancel  
      Incorporates the ideas of (1a) and (1b)
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      Incorporates the ideas of (1a) and (1b)

(3) Removal of Hierarchy:
   a) Large Extra Dimensions: Gravity looks only weak; no fundamental scalars, but components of (higher-dem.) gauge fields
   b) Warped Extra Dimensions (Randall-Sundrum): Gravity only weak in our world

(4) Numbers chosen by Providence
   - Anthropic principle: Values are because we can observe them
Little Higgs paradigm

Old Idea: Georgi/Pais, 1974; Georgi/Dimopoulos/Kaplan, 1984

*Light Higgs as Pseudo-Goldstone boson* ⇔ spontaneously broken (approximate) *global* symmetry; non-linear sigma model

- w/o Fine-Tuning: \( v \sim \Lambda/4\pi \)
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Collective Symmetry Breaking: no quadratic div. @ 1-loop

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\Phi_1 = \exp [i \cos \beta h/f] f, \quad \Phi_2 = \exp [i \sin \beta h/f] f
$$

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\Phi_1^\dagger \Phi_1 + \Phi_2^\dagger \Phi_2 = \frac{g^2}{16\pi^2} \Lambda^2 (|\Phi_1|^2 + |\Phi_2|^2) \sim \frac{g^2}{16\pi^2} f^2
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\[
\Phi_1 \Phi_1^\dagger \Phi_2 \Phi_2^\dagger = \frac{g^4}{16\pi^2} \log \left( \frac{\Lambda^2}{\mu^2} \right) |\Phi_1 \Phi_2|^2 \Rightarrow \frac{g^4}{16\pi^2} \log \left( \frac{\Lambda^2}{\mu^2} \right) f^2(h^\dagger h)
\]
Cancellations of Divergencies in Yukawa sector

\[ \propto \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2(k^2 - m^2_T)} \left\{ \lambda_t^2(k^2 - m^2_T) + k^2\lambda_T^2 - \frac{m_T}{F}\lambda_Tk^2 \right\} \]
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**Little Higgs global symmetry** imposes relation

\[ \frac{m_T}{F} = \frac{\lambda_t^2 + \lambda_T^2}{\lambda_T} \]

\[ \Rightarrow \text{Quadratic divergence cancels} \]

- Proof these relations experimentally!

Han et al., 03/05; Kilian/JR, 05
Generic properties — Scales and Masses

- Extended scalar (Higgs-) sector
  - Extended global symmetry

- Specific form of scalar potential

- Extended Gauge Sector: $B', Z', W' \pm$

- Extended top sector: new heavy quarks, $t, t'$ loops $\Rightarrow M_h^2 < 0$
  $\Rightarrow$ EWSB
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- Extended top sector: new heavy quarks, \( t, t' \) loops \( \Rightarrow M_h^2 < 0 \)
  \( \Rightarrow \) EWSB

- Scale \( \Lambda \): global SB, new dynamics, UV embedding
- Scale \( F \): Pseudo-Goldstone bosons, new vector bosons and fermions
- Scale \( v \): Higgs, \( W^\pm, Z, \ell^\pm, \ldots \)
Little Higgs Models

Plethora of “Little Higgs Models” in 3 categories:

- **Moose Models**
  - Orig. Moose (Arkani-Hamed/Cohen/Georgi, 0105239)
  - Simple Moose (Arkani-Hamed/Cohen/Katz/Nelson/Gregoire/Wacker, 0206020)
  - Linear Moose (Casalbuoni/De Curtis/Dominici, 0405188)

- **Product (Gauge) Group Models**
  - Littlest Higgs (Arkani-Hamed/Cohen/Katz/Nelson, 0206021)
  - Antisymmetric Little Higgs (Low/Skiba/Smith, 0207243)
  - Custodial $SU(2)$ Little Higgs (Chang/Wacker, 0303001)
  - Littlest Custodial Higgs (Chang, 0306034)
  - Little SUSY (Birkedal/Chacko/Gaillard, 0404197)

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  - Simplest T parity (Martin, Kilian/Rainwater/JR/Schmaltz,...)
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Varieties of Particle spectra

\[ \mathcal{H} = \frac{SU(5)}{SO(5)}, \quad G = \frac{[SU(2) \times U(1)]^2}{SU(2) \times U(1)} \]

Arkani-Hamed/Cohen/Katz/Nelson, 2002

\[ h, \Phi, \Phi^\pm, W', W'^\pm, Z', T, B', \Phi_P, \Phi^\pm, h, W'^\pm, Z' \]
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\[ \mathcal{H} = \frac{[SU(3)]^2}{[SU(2)]^2}, \mathcal{G} = \frac{SU(3) \times U(1)}{SU(2) \times U(1)} \]

Schmaltz, 2004

\[ [SU(4)]^4 \rightarrow [SU(3)]^4 \]

Kaplan/Schmaltz, 2003

2HDM, \( h_{1/2}, \Phi_1, 2, 3, \Phi'_1, 2, 3, Z'_1, ..., 8, W'_{1,2}, q', \ell' \)
EW Precision Observables

Making the Higgs heavier reduces amount of fine-tuning

Higgs mass variable
(Coleman-Weinberg, UV completion)

$$\Delta S = \frac{1}{12\pi} \ln \frac{m_H^2}{m_0^2}$$

$$\Delta T = -\frac{3}{16\pi c_w^2} \ln \frac{m_H^2}{m_0^2}$$

Csaki et al.; Hewett et al.; Kilian/JR, 2003
Heavy Quark States

- EW single dominates QCD pair production: Perelstein/Peskin/Pierce, '03

Characteristic branching ratios:
\[ \Gamma(T \to t h) \approx \Gamma(T \to t Z) \approx \frac{1}{2} \Gamma(T \to b W^+ ) \approx \frac{M_T \lambda_T^2}{64 \pi}, \]
\[ \Gamma_T \sim 10^{-50} \text{ GeV} \]

Proof of T as EW singlet; but:
\[ T \to Z', W', b, t \eta \]

AIM: Determination of \( M_T, \lambda_T, \lambda_T' \) indirectly (\( T \bar{T} \) impossible)
Heavy Quark States

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![Graphs showing production rates vs. mass](image)

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- **Proof of** $T$ **as EW singlet; but:** $T \to Z'T, W'b, t\eta$

**AIM:** **Determination of** $M_T, \lambda_T, \lambda_{T'}$  

$\lambda_{T'}$ indirect ($T\bar{T}h$ impossible)
$T \rightarrow Zt \rightarrow \ell^+\ell^-\ell\nu b$  

SN-ATLAS-2004-038

- $E_T > 100$ GeV, $\ell\ell\ell$, $p_T > 100/30$ GeV, $b, p_T > 30$ GeV
- Bkgd.: $WZ, ZZ, btZ$
- Observation for $M_T \lesssim 1.4$ TeV
\[ T \rightarrow Wb \rightarrow \ell\nu b \quad \text{SN-ATLAS-2004-038} \]

- \[ E_T > 100 \text{ GeV}, \ell, p_T > 100 \text{ GeV}, b, p_T > 200 \text{ GeV}, \text{max. } jj, p_T > 30 \text{ GeV} \]
- Bkgd.: \( t\bar{t}, Wb\bar{b}, \) single \( t \)
- Observation for \( M_T \lesssim 2.5 \text{ TeV} \)
$T \rightarrow th \rightarrow \ell \nu bbb$  \hspace{1cm} SN-ATLAS-2004-038

- $\ell, p_T > 100$ GeV, $jjj, p_T > 130$ GeV, at least 1 $b$-tag
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Additional heavy quarks (Simple Group Models): \( U, C \) or \( D, S \) Han et al., 05

- Large cross section: \( u \) or \( d \) PDF
- Huge final state \( \ell \) charge asymmetry
- Good mass reconstruction
$T \rightarrow th \rightarrow ℓνbbb$  

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Heavy Vectors

Drell-Yan Production: Tevatron Limits $\sim 500 - 600$ GeV

- Dominant decays:
  - Product group: $Z' \rightarrow Z h, W W$
  - $W' \rightarrow W h, W Z$
  - Simple group: $Z' \rightarrow qq$, $X \rightarrow f F$

\[
\frac{\Gamma_{Z'}}{\Gamma_X} \sim 10^{-5} \text{ GeV}, \quad \frac{\Gamma_X}{\Gamma_{Z'}} \sim 0.1 - 10 \text{ GeV}
\]
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- **Dominant decays:**
  - Product group: $Z' \rightarrow Zh, WW$
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![Graph showing the relationship between $M_X$ and $\sigma$ with annotations for discovery channels and Tevatron limits.](image)
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- $\Gamma_{Z'} \sim 10 - 50$ GeV, $\Gamma_X \sim 0.1 - 10$ GeV
Proof: Sum rule for cancellation of divergences: \( g_{HVV'V} + g_{HVV'V'} = 0 \), associated production \( pp \rightarrow V'h \)
Heavy Scalars

Generally: Large model dependence
   no states  complex singlet  complex triplet

- Littlest Higgs, complex triplet:
  \( \Phi^0, \Phi_P, \Phi^\pm, \Phi^{\pm\pm} \)

Cleanest channel:
\( q \bar{q} \rightarrow \Phi^{++}, \Phi^{--} \rightarrow \ell\ell\ell\ell \):

Killer: PS

WW-Fusion:
\( dd \rightarrow uu \Phi^{++} \rightarrow uuW+W^+ \)

2 hard forward jets, hard close \( \ell+\ell+\ell+\ell^+ \)

Unstudied channels:

- \( q \bar{q} \rightarrow \Phi_P h \rightarrow ZZh \)
- \( q \bar{q} \rightarrow \Phi^0 W^- \rightarrow WWZ \)
- \( q \bar{q} \rightarrow \Phi^0 Z \rightarrow ZZZ, Zhh \)

Alternative: Model-Independent search in WW fusion:
A TLAS-note, Kilian/JR/(Schumacher)
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  \( p_T\)-unbalanced

![Graph showing ATLAS data]

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  ATLAS-note, Kilian/JR/(Schumacher)\(^2\)
Pseudo Axions in LHM

- broken diagonal generator: $\eta$ in QCD; *pseudoscalar*
- analogous particles: techni-axion, topcolor-axion, (N)MSSM-axion
- $m_\eta \lesssim v \sim 250$ GeV
- $\eta$ EW singlet, couplings to SM particles $v/F$ suppressed
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- new Higgs decays $H \rightarrow Z\eta, H \rightarrow \eta\eta$: $\text{BR}(H \rightarrow \eta\eta) \sim 10\%$ possible!
- LHC: \textbf{Gluon Fusion} (axial $U(1)_\eta$ anomaly), Diphoton Peak
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![Graph showing BR vs $m_\eta$ and $M_{\gamma\gamma}$ vs $d\sigma_{\gamma\gamma}/dM_{\gamma\gamma}$]
\( T \) parity and Dark Matter

- \( T \) parity: \( T^a \rightarrow T^a, \quad X^a \rightarrow -X^a \)
- analogous to \( R \) parity in SUSY, KK parity in extra dimensions
- Bounds on \( f \) MUCH relaxed,
- \textit{but}: Pair production!, typical \textit{cascade decays}
- \( T \): \( T \)-even \( \Rightarrow \) phenomenology unchanged, \( Z' \) can also be even
- Lightest heavy quark \( T' \) is \( T \)-odd, similar to Simple Group Models
- Lightest \( T \)-odd particle (LTP) \( \Rightarrow \) \textit{Candidate for Cold Dark Matter}
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Littlest Higgs: $A'$ LTP

$W', Z' \sim 650$ GeV

$\Phi \sim 1$ TeV

$T, T' \sim 0.7$-1 TeV

Annihilation:

$A'A' \rightarrow h \rightarrow WW, ZZ, hh$

- Other LTP candidates: **Pseudo-Axion $\eta$ LTP**, heavy neutral leptons
Open Points/Discussion

- Generics: new heavy gauge bosons, scalars, quarks
- Pseudoaxions: Gluon fusion, $T \rightarrow t\eta, ZH\eta$
- Simple Group Models: $U, D$ production, discrimination from other states
- Extensions of $SU(2)_L$ e.g. in Simple Group Models: Pheno of Heavy Vectors, e.g. $X^0 \leftrightarrow Y^0$
- Measurement and Discrimination of $W'$; asymmetries?
- Pheno of Little Higgs with $T$ parity, Little Higgs cascades vs. SUSY/UED cascades
- Physics from UV completions accessible?
- Tools: O’MEGA/WHIZARD multi-partice event generator: contains both LH models
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