Little Higgs Model Discrimination at the LHC and ILC

Jürgen Reuter

Albert-Ludwigs-Universität Freiburg

Kilian, JR *PRD* 70 (2004), 015004; Kilian, Rainwater, JR *PRD* 71 (2005), 015008;
*PRD* 74 (2006), 095003, and work in progress

SUSY 07, Karlsruhe, July 27th, 2007
What if not SUSY?
Higgs as Pseudo-Goldstone boson

**Nambu-Goldstone theorem:** Spontaneous Breaking of a global symmetry: massless (Goldstone) bosons in the spectrum

**Old idea:**
Georgi/Pais, 1974; Georgi/Dimopoulos/Kaplan, 1984

Light Higgs as (Pseudo)-Goldstone boson of a spontaneously broken global symmetry

**Analogous: QCD**

Scale $\Lambda$: chiral symmetry breaking, quarks, $SU(3)_c$  
Scale $\nu$: pions, kaons, …
Higgs as Pseudo-Goldstone boson

**Nambu-Goldstone theorem:** Spontaneous Breaking of a global symmetry: massless (Goldstone) bosons in the spectrum

**Old idea:**

Georgi/Pais, 1974; Georgi/Dimopoulos/Kaplan, 1984

Light Higgs as *(Pseudo)-Goldstone boson* of a spontaneously broken global symmetry

\[ \Lambda \]

\[ v \]

\( \mathcal{O}(1 \text{ TeV}) \)

\( \mathcal{O}(250 \text{ GeV}) \)

Scale \( \Lambda \): global symmetry breaking, new particles, new (gauge) IA

Scale \( v \): Higgs, \( W/Z \), \( \ell^\pm \), ...

Without Fine-Tuning: experimentally excluded
Collective symmetry breaking and 3-scale models


2 different global symmetries; one of them unbroken ⇒ Higgs exact Goldstone boson

Coleman-Weinberg: boson masses by radiative corrections, but: \( m_H \) only at 2-loop level

\[ m_H \sim \frac{g_1}{4\pi} \frac{g_2}{4\pi} \Lambda \]

Scale \( \Lambda \): global SB, new IA
Scale \( F \): Pseudo-Goldstone bosons, new vectors/fermions
Scale \( v \): Higgs, W/Z, \( \ell^\pm \), . . .
Properties of Little-Higgs models

- Extended global symmetry
- Specific functional form of the potential
- Extended gauge symmetry: $\gamma', Z', W'\pm$
- New heavy fermions: $T$, but also $U, C, \ldots$

Example: Littlest Higgs

Arkani-Hamed/Cohen/Katz/Nelson, 2002
Pseudo-Axions in Little Higgs

- gauged $U(1)$ group: $Z' \leftrightarrow$ ungauged: $\eta$
- couples to fermions like a pseudoscalar
- $m_\eta \lesssim 400$ GeV
- SM singlet, couplings to SM particles $v/F$ suppressed
- $\eta$ axion-like particle:

\[ \text{Anomalous } U(1): \quad \rightarrow \quad \frac{1}{F} \frac{\alpha_s}{8\pi^2} \eta F_{\mu\nu} F_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma} \]

- $U(1)$ explicitly broken $\Rightarrow$ Axion limits from astroparticle physics not applicable
Classification of Axions in Little Higgs Models

Number of Pseudo-Axions: $n = g - l$
Mismatch between global ($g$) and local rank reduction ($l$)

Product Group Models

Arkani-Hamed, . . .

- Doubling of electroweak gauge group: $SU(2) \times SU(2) \rightarrow SU(2)_L$, $U(1) \times U(1) \rightarrow U(1)_Y$ (latter not necessary) $\Rightarrow l = 1$
  - Littlest Higgs, g: $SU(5) \rightarrow SO(5) \Rightarrow n = (4 - 2) - 1 = 1$
  - antisymmetric, g: $Sp(6)/SO(6)$, $n = (3 - 2) - 1 = 0$

Simple Group Models

Kaplan, Schmaltz, . . .

- Simple gauge group: $SU(N) \times U(1) \rightarrow SU(2) \times U(1) \Rightarrow l = N - 2$
- Higgs is distributed over several global symmetry multiplets
- Simplest Little Higgs, g: $[SU(3)]^2/[SU(2)]^2$ $n = g - l = 2 - 1 = 1$
- Original Simple Group Model, g: $[SU(4)]^3/[SU(3)^3 \times SU(2)]$, $l: SU(4) \rightarrow SU(2)$ $n = g - l = 4 - 2 = 2$

Moose Models

Arkani-Hamed, . . .

- “Minimal” Moose: g $[SU(3)]^4 \rightarrow SU(3)$, $l [SU(3) \times SU(2)]/SU(2)$ $n = g - l = 6 - 2 = 4$
- 3-site model: g $[SU(2)]^4/[SU(2)]^2$, $l [SU(2)]^2 \rightarrow SU(2)$, $n = 2 - 1 = 1$
ZH$\eta$ coupling as a discriminator

- **pseudo-axion:** $\xi = \exp[i\eta/F]$, $\Sigma = \exp[i\Pi/F]$ non-linear representation of the remaining Goldstone multiplet $\Pi$

$$\mathcal{L}_{\text{kin.}} \sim F^2 \text{Tr} \left[ (D^\mu (\xi \Sigma) \dagger (D_\mu (\xi \Sigma))) \right] = \ldots -2F(\partial_\mu \eta) \text{Im} \text{Tr} \left[ (D^\mu \Sigma) \dagger \Sigma \right] + O(\eta^2)$$

- **Use special structure of covariant derivatives:**

$$D_\mu \Sigma = \partial_\mu \Sigma + A_{1,\mu}^a \left( T_1^a \Sigma + \Sigma (T_1^a)^T \right) + A_{2,\mu}^a \left( T_2^a \Sigma + \Sigma (T_2^a)^T \right),$$

$$\text{Tr} \left[ (D^\mu \Sigma) \dagger \Sigma \right] \sim W_\mu^a \text{Tr} \left[ \Sigma \dagger (T_1^a + T_2^a) \Sigma + (T_1^a + T_2^a)^* \right] = 0.$$

- **Little Higgs mechanism cancels this coupling**

- **Simple Group Models:** $\Phi = \exp[i\Sigma/F]$, $\zeta = (0, \ldots, 0, F)^T$ VEV directing in the $N$ direction
\[ \mathcal{L}_{\text{kin.}} \sim F^2 D^\mu (\zeta^\dagger \Phi^\dagger) D_\mu (\Phi \zeta) = \ldots + \frac{i}{F} (\partial_\mu \eta) \zeta^\dagger (\Phi^\dagger (D_\mu \Phi) - (D_\mu \Phi^\dagger) \Phi) \zeta \]

\[ = \ldots + iF (\partial_\mu \eta) (\Phi^\dagger (D_\mu \Phi) - (D_\mu \Phi^\dagger) \Phi)_{N,N}. \]

\[ \Sigma = \begin{pmatrix} 0 & h \\ h^\dagger & 0 \end{pmatrix}, \quad V_\mu = \begin{pmatrix} W_\mu & 0 \\ 0 & 0 \end{pmatrix} + \text{heavy vector fields} \]

\[ V_\mu + \frac{i}{F} [\Sigma, V_\mu] - \frac{1}{2F^2} [\Sigma, [\Sigma, V_\mu]] + \ldots \]

\[ = \begin{pmatrix} W_\mu & 0 \\ 0 & 0 \end{pmatrix} + \frac{i}{F} \begin{pmatrix} 0 & -W_\mu h \\ h^\dagger W_\mu & 0 \end{pmatrix} - \frac{1}{2F^2} \begin{pmatrix} h h^\dagger W + W h h^\dagger & 0 \\ 0 & -2h^\dagger W h \end{pmatrix} + \ldots \]

- 1st term cancels by multiple Goldstone multiplets
- 2nd term cancels by EW symmetry
- 3rd term

\[ (\partial^\mu \eta) h^\dagger W_\mu h \sim v H Z_\mu \partial^\mu \eta. \]
More properties of Pseudo-Axions

- Take e.g. one specific model: Simplest Little Higgs
- Simple Group Model, two Higgs-triplets with a $\tan \beta$-like mixing angle

\[ \tan \beta = \frac{1}{2} \]

\[ m_\eta \text{ [GeV]} \]

\[ \mu \text{ [GeV]} \]

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

- $\tan \beta \sim 1$: heavy Higgs, (very) light pseudoscalar
- Heavy top decays:

\[ F' = 4 \text{ TeV} \]

\[ F_1 = 0.5 \text{ TeV} \]

\[ F_2 = 2 \text{ TeV} \]
Discovery of Pseudo-axions

LHC: Gluon fusion, diphoton signal for $m_\eta \gtrsim 200$ GeV, 7$\sigma$ possible

LHC: $T \rightarrow t\eta$

ILC: $e^+ e^- \rightarrow t\bar{t}\eta$
Discovery of Pseudo-axions

LHC: Gluon fusion, diphoton signal for $m_\eta \gtrsim 200$ GeV, $7\sigma$ possible

LHC: $T \rightarrow t\eta$

ILC: $e^+e^- \rightarrow t\bar{t}\eta$

\[
\int L = 1 \text{ ab}^{-1}
\]

$g_{tt\eta} = 0.2$

$m_\eta = 50$ GeV

#evt/2 GeV

$\sqrt{s} = 800$ GeV

$M_{\text{inv}(b\bar{b})}$ [GeV]
Discovery of Pseudo-axions


LHC: Gluon fusion, diphoton signal for $m_\eta \gtrsim 200$ GeV, $7\sigma$ possible
LHC: $T \to t\eta$
ILC: $e^+ e^- \to t\bar{t}\eta$

$Z H \eta$ coupling forbidden in Product Group Models

Discriminator of diff. model classes

$$gg \to \begin{cases} H \to Z \eta & \to \ell\bar{\ell}bb \\ \eta \to Z H & \to \ell\bar{\ell}bb, \ell\ell jj \end{cases}$$
## Discovery of Pseudo-axions

**LHC:** Gluon fusion, diphoton signal for \( m_\eta \gtrsim 200 \text{ GeV} \), 7\( \sigma \) possible

**LHC:** \( T \rightarrow t\eta \)

**ILC:** \( e^+e^- \rightarrow t\bar{t}\eta \)

### ZH\( \eta \) coupling

Forbidden in Product Group Models

**Discriminator of diff. model classes**

\[
\begin{align*}
\text{gg} & \rightarrow \begin{cases} 
H \rightarrow Z\eta & \rightarrow \ell\ell bb \\
\eta \rightarrow ZH & \rightarrow \ell\ell bb, \ell\ell jj
\end{cases}
\end{align*}
\]
Discovery of Pseudo-axions


LHC: Gluon fusion, diphoton signal for \( m_\eta \gtrsim 200 \text{ GeV} \), 7\( \sigma \) possible

LHC: \( T \rightarrow t\eta \)

ILC: \( e^+ e^- \rightarrow t\bar{t}\eta \)

**ZH\( \eta \) coupling**

forbidden in Product Group Models

**Discriminator of diff. model classes**

\[ gg \rightarrow \begin{cases} 
H \rightarrow Z\eta \rightarrow \ell\ell bb \\
\eta \rightarrow ZH \rightarrow \ell\ell bb, \ell\ell jj
\end{cases} \]
Discovery of Pseudo-axions

LHC: Gluon fusion, diphoton signal for $m_\eta \gtrsim 200$ GeV, $7\sigma$ possible
LHC: $T \rightarrow t\eta$
ILC: $e^+e^- \rightarrow t\bar{t}\eta$

$ZH\eta$ coupling
forbidden in Product Group Models

Discriminator of diff. model classes

$gg \rightarrow \begin{cases} H \rightarrow Z\eta \rightarrow \ell\ell bb \\ \eta \rightarrow ZH \rightarrow \ell\ell bb, \ell\ell jj \end{cases}$
If $ZH\eta$ coupling present: $H\eta$ production in analogy to $HA$:

- Light pseudoaxion, $\eta \rightarrow bb$, final state $Hbb$
- Intermediate range, $\eta \rightarrow gg$, final state $Hjj$
- $\eta \rightarrow ZH$: $ZHH$ final state

More detailed insights from photon collider option
If $ZH\eta$ coupling present: $H\eta$ production in analogy to $HA$:

- Light pseudoaxion, $\eta \rightarrow bb$, final state $Hbb$
- Intermediate range, $\eta \rightarrow gg$, final state $Hjj$
- $\eta \rightarrow ZH$: $ZHH$ final state

More detailed insights from photon collider option
Invisible Higgs decays (?)

- “Invisible decay” $H \rightarrow \eta \eta$ [quite similar to $H \rightarrow \alpha \alpha$ in NMSSM] but only due to mixing effects because $U(1)_\eta$ protective symmetry

\[
\Gamma_{H \rightarrow \eta \eta} \sim \frac{1}{16\pi} \sqrt{1 - \frac{4m^2_\eta}{m^2_H} \frac{v^5}{F^4}} \sim \frac{15}{(F [\text{TeV}])^4} \text{MeV}
\]

- Light Higgs might become invisible at the LHC
  - Not possible in Simplest Little Higgs
  - Possible in other Simple Group Models (together with $\eta, A$ mixing)
  - Can become the dominant decay (with BR $\sim .8 - .95$)

- ILC can cover that hole!

JR, 2007
Summary

- Higgs is generically heavy in LHM; will be captured by $VV$ mode
- Little Higgs models generally have extra pseudoscalars
- Pseudo-Axions *not ruled out* by astro-limits
- Discriminator between Product and Simple Group Models: $ZH\eta$, $Z' H\eta$ coupling

- LHC has first option:
  - $gg \rightarrow H \rightarrow Z\eta$ (only on-shell)
  - $gg \rightarrow \eta \rightarrow ZH$ (only on-shell)
  - $Z' \rightarrow Z\eta$, $W' \rightarrow W\eta$, $T \rightarrow t\eta$

- Cross references from heavy quark and $Z'$, $W'$ discoveries
- ILC is sensitive in all parameter regions
- Possible degeneracies between Higgs/pseudoaxion ($\gamma\gamma$ option)
- Importance of “invisible” decays?