“No Higgs Scenario” in Little Higgs Models in the early stage at LHC

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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

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

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, \( W/Z, \ell^{\pm}, \ldots \)
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
Varieties of Particle spectra

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

Arkani-Hamed/Cohen/Katz/Nelson, 2002

\[ m \]

\[ \Phi \quad \Phi^\pm \quad \Phi_P \quad \Phi_{\pm\pm} \quad Z' \quad W' \pm \quad T \quad B' \]

\[ h \quad W^\pm \quad Z \quad t \]

\[ \mathcal{H} = \frac{SO(6)}{Sp(6)} , \quad \mathcal{G} = \frac{[SU(2) \times U(1)]^2}{SU(2) \times U(1)} \]

Low/Skiba/Smith, 2002

\[ m \]

\[ \Phi \quad \Phi_P \quad B' \quad Z' \quad W' \pm \quad T \quad A \quad H \quad H^\pm \]

\[ h \quad W^\pm \quad Z \quad t \]

\[ \mathcal{H} = \frac{[SU(3)]^2}{[SU(2)]^2} , \quad \mathcal{G} = \frac{SU(3) \times U(1)}{SU(2) \times U(1)} \]

Schmaltz, 2004

\[ m \]

\[ Z' \quad W' \pm \quad X^0/Y^0 \quad T \quad U, C \]

\[ h \quad \eta \quad W^\pm \quad Z \quad t \]

2HDM, \( h_{1/2}, \Phi'^{1,2,3}, \Phi^P_{1,2,3} \), \( Z'_1,\ldots,8, W'_1,2, \pm, q', \ell' \)

Kaplan/Schmaltz, 2003
Constraints from the Electroweak Fit

$$Z_L \rightarrow Z_L$$

$$Z_T \rightarrow Z_T$$

$$\Delta T \sim \Delta \rho$$

$$\Delta S$$

Tree-Level mixing $Z, Z'$ induces big corrections

Scale $F \gtrsim 1 - 3$ TeV

Higgs compensates for $Z'$

Naturally heavy Higgs in LHM

Kilian/JR, 2003
Reconstruction of Little-Higgs models

- Goldstone-Boson nature of the Higgs (nonlinear representation)
- Mechanism to eliminate the quantum corrections to $m_H$

**STRATEGY:**

- **LHC:** $Z', W' \Rightarrow M_{Z'}, M_{W'}$ up to $5 - 6$ TeV  
  ILC: contact terms $\Rightarrow M_{Z'}, M_{W'}$ up to $10 - 20$ TeV  
  Extraction of $F$ and $c \equiv \cos \phi$
- **LHC:** $T \Rightarrow M_T$ and mixing parameter
- **ILC:** Higgsstrahlung and $WW$ fusion (Angular distributions/energy spectra) $\Rightarrow$ Higgs couplings/potential
- **ILC/$\gamma\gamma$:** Higgs decays $\Rightarrow$ Goldstone-Boson structure
- **ILC/GigaZ:** Measurement of $\Delta T \Rightarrow$ Contributions of heavy scalars
- **Global Fit to LHC/ILC data**
No (early) Higgs signal in Little Higgs model

- How to miss a Higgs signal in the early phase of LHC in Little Higgs models?
  - There **is always** a Higgs boson in LHM
  - Very light Higgs needs time to be discovered
  - Heavier Higgs
    maybe unusual decay modes (almost always beaten by $VV$)
- LHM usually have rather heavy Higgs
  - will be discovered very soon (cf. Kyle Cranmer’s talk)
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- How to miss a Higgs signal in the early phase of LHC in Little Higgs models?
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- LHM usually have rather heavy Higgs
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    - if $M_H \lesssim 550$ GeV
      - will be very difficult for larger Higgs masses
  - Assumption: some info about $Z'$, $W'$ or heavy top excluding the SM
  - Search for light Higgs states (2HDM, or single heavy Higgs)
- Confusion with a Higgs-like signal from a different particle possible with other (pseudo-)scalars in the game
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:
  
  \[
  \text{Anomalous } U(1): \quad \rightarrow \frac{1}{F} \frac{\alpha_s}{8\pi^2} \eta F_{\mu\nu} F_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma}
  \]

- $U(1)$ explicitly broken $\Rightarrow$ Axion limits from astroparticle physics not applicable
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:

$$D_\mu \Sigma = \partial_\mu \Sigma + A^a_{1,\mu} \left( T^a_1 \Sigma + \Sigma (T^a_1)^T \right) + A^a_{2,\mu} \left( T^a_2 \Sigma + \Sigma (T^a_2)^T \right),$$

$$\text{Tr} \left[ (D^\mu \Sigma)^\dagger \Sigma \right] \sim W^a_\mu \text{Tr} \left[ \Sigma^\dagger (T^a_1 + T^a_2) \Sigma + (T^a_1 + T^a_2)^* \right] = 0.$$ 

- 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
\[ L_{\text{kin.}} \sim F^2 D^\mu (\zeta \Phi^\dagger) D_\mu (\Phi \zeta) = \ldots + \frac{i}{F} (\partial_\mu \eta) \zeta (\Phi^\dagger (D_\mu \Phi) - (D_\mu \Phi^\dagger) \Phi) \zeta \]

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

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

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

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

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

\[ (\partial^\mu \eta) h^\dagger W_\mu h \sim vHZ_\mu \partial^\mu \eta \cdot \]
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

$tan \beta \sim 1$: heavy Higgs, (very) light pseudoscalar

Heavy top decays:
Discovery of Pseudo-axions

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

LHC: $T \rightarrow t\eta$

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

$$\frac{\# evt}{2 \text{ GeV}} \sqrt{s} = 800 \text{ GeV} \int L = 1 \text{ ab}^{-1}$$

$m_\eta = 50 \text{ GeV}$

$g_{tt\eta} = 0.2$

$M_{inv}(b\bar{b}) \text{ [GeV]}$
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ZH$\eta$ coupling forbidden in Product Group Models

Discriminator of diff. model classes

$$gg \rightarrow \left\{ \begin{array}{l} H \rightarrow Z\eta \rightarrow \ell\ell bb \\ \eta \rightarrow ZH \rightarrow \ell\ell bb, \ell\ell j j \end{array} \right\}$$
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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 $Hjj$
- $\eta \rightarrow ZH$: $ZH\eta$ 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 $Hbb$
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- $\eta \rightarrow ZH$: $ZHH$ final state

More detailed insights from photon collider option
Invisible Higgs decays

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

$$\Gamma_{H \rightarrow \eta\eta} \sim \frac{1}{16\pi} \sqrt{1 - \frac{4m_{\eta}^2}{m_H^2}} \frac{\nu^5}{F^4} \sim \frac{15}{(F [\text{TeV}])^4} \text{MeV}$$

- Not possible in Simplest Little Higgs
- Possible in other Simple Group Models (together with $\eta, A$ mixing)
- Can become the dominant decay

- Light Higgs might become invisible
- Heavy Higgses observable
- Differences to NMSSM?

“This is not exactly, what theory predicted for the Higgs decay!”
Outlook/Discussion

- Higgs is always present in Little Higgs models
- **Higgs is generically heavy in LHM**; will be captured by $VV$ mode
- Higgs might be confused with other members from its Goldstone multiplet, especially with light pseudo-axions

- Three possible scenarios interesting for ILC:
  - very heavy and broad Higgs, (very) light pseudoaxion; both missed at early stage of LHC
  - heavy Higgs detected in $H \rightarrow ZZ \rightarrow 4\ell$; light partner missing
  - **inverted hierarchy**: Higgs light, pseudoaxion heavy; both are missed at early stage of LHC

- Possible degeneracies between Higgs/pseudoaxion
- Cross references from heavy quark and $Z'$, $W'$ discoveries
- LHM mimicking Higgsless models?
- Importance of invisible decays?