

Light Pseudoscalars in Little Higgs Models at the ILC

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

DESY, June 2nd, 2007

What if not SUSY?



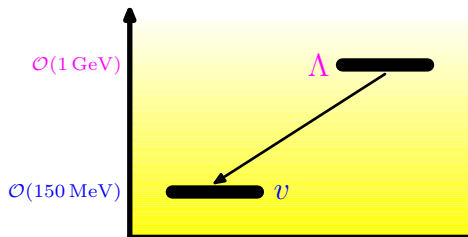
Higgs as Pseudo-Goldstone boson

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 Λ : chiral symmetry breaking, quarks, $SU(3)_c$

Scale v : pions, kaons, ...

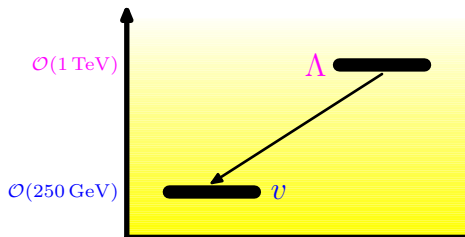
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Scale Λ : global symmetry breaking, new particles, new (gauge) IA

Scale v : Higgs, W/Z , ℓ^\pm , ...

Without Fine-Tuning: experimentally excluded

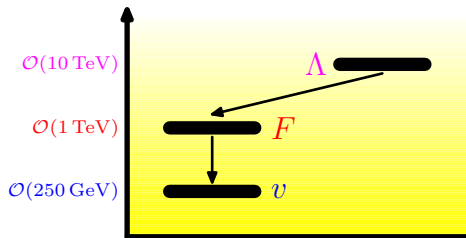
Collective symmetry breaking and 3-scale models

Collective symmetry breaking: Arkani-Hamed/Cohen/Georgi/Nelson/..., 2001

2 different global symmetries; one of them unbroken \Rightarrow 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 Λ : global SB, new IA

Scale F : Pseudo-Goldstone bosons, new vectors/fermions

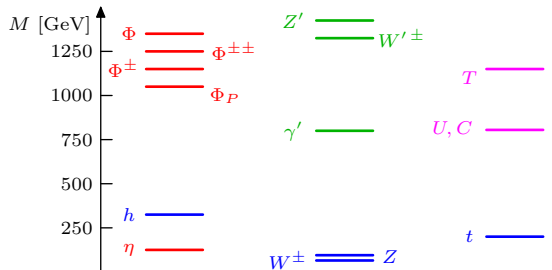
Scale v : Higgs, W/Z , ℓ^\pm , ...

Properties of Little-Higgs models

- Extended global symmetry
- **Specific functional form of the potential**
- Extended gauge symmetry:
 γ', Z', W'^{\pm}
- New heavy fermions: T , but also U, C, \dots

Example: Littlest Higgs

Arkani-Hamed/Cohen/Katz/Nelson, 2002

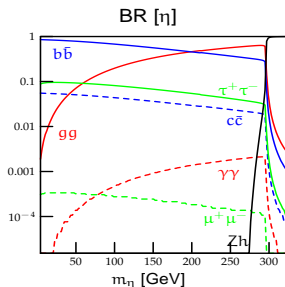
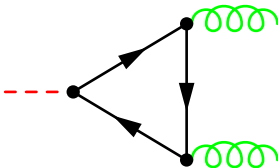


Pseudo-Axions in Little Higgs

Kilian/Rainwater/JR, 2004, 2006; JR, 2007

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

Anomalous $U(1)$: $---$



$$\longrightarrow \frac{1}{F} \frac{\alpha_s}{8\pi^2} \eta F_{\mu\nu} F_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma}$$

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

$ZH\eta$ coupling as a discriminator

Kilian/Rainwater/JR, 2006

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

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

- ▶ Use special structure of covariant derivatives:

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

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

- ▶ Little Higgs mechanism cancels this coupling
- ▶ Simple Group Models: $\Phi = \exp[i\Sigma/F]$, $\zeta = (0, \dots, 0, F)^T$ VEV directing in the N direction

$$\begin{aligned}\mathcal{L}_{\text{kin.}} &\sim F^2 D^\mu (\zeta^\dagger \Phi^\dagger) D_\mu (\Phi \zeta) = \dots + \frac{i}{F} (\partial_\mu \eta) \zeta^\dagger (\Phi^\dagger (D_\mu \Phi) - (D_\mu \Phi^\dagger) \Phi) \zeta \\ &= \dots + iF (\partial_\mu \eta) (\Phi^\dagger (D_\mu \Phi) - (D_\mu \Phi^\dagger) \Phi)_{N,N}.\end{aligned}$$

$$\Sigma = \begin{pmatrix} 0 & h \\ h^\dagger & 0 \end{pmatrix}, \quad \mathbb{V}_\mu = \begin{pmatrix} \mathbb{W}_\mu & 0 \\ 0 & 0 \end{pmatrix} + \text{heavy vector fields}$$

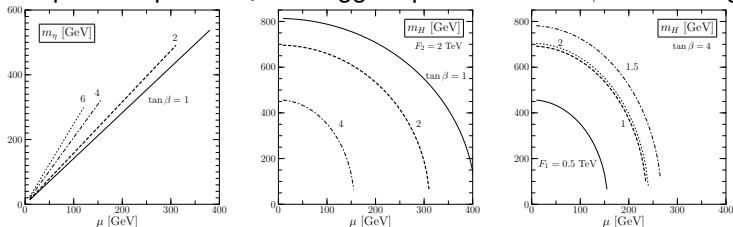
$$\begin{aligned}&\mathbb{V}_\mu + \frac{i}{F} [\Sigma, \mathbb{V}_\mu] - \frac{1}{2F^2} [\Sigma, [\Sigma, \mathbb{V}_\mu]] + \dots \\ &= \begin{pmatrix} \mathbb{W}_\mu & 0 \\ 0 & 0 \end{pmatrix} + \frac{i}{F} \begin{pmatrix} 0 & -\mathbb{W}_\mu h \\ h^\dagger \mathbb{W}_\mu & 0 \end{pmatrix} - \frac{1}{2F^2} \begin{pmatrix} hh^\dagger \mathbb{W} + \mathbb{W} h h^\dagger & 0 \\ 0 & -2h^\dagger \mathbb{W} h \end{pmatrix} + \dots\end{aligned}$$

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

$$(\partial^\mu \eta) h^\dagger \mathbb{W}_\mu h \sim v H Z_\mu \partial^\mu \eta.$$

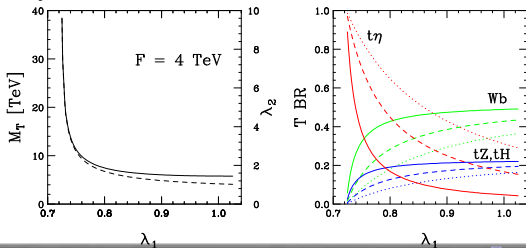
More properties of Pseudo-Axions

- ▶ Take e.g. one specific model: Simplest Little Higgs Schmaltz, JHEP **0408** (2004) 056
- ▶ 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:

Kilian/Rainwater/JR, 2006



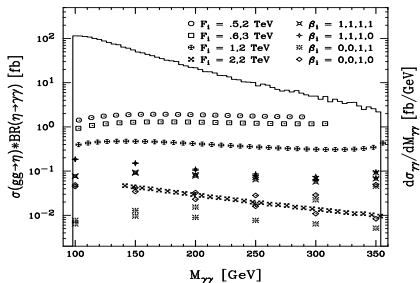
Discovery of Pseudo-axions

Kilian/Rainwater/JR, 2004, 2006

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

LHC: $T \rightarrow t\eta$

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



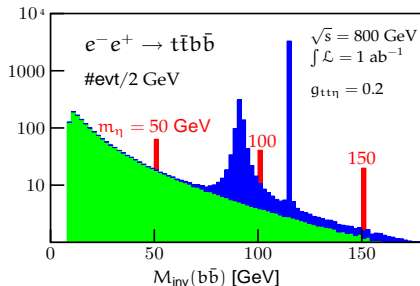
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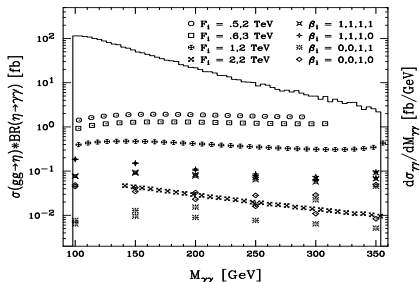
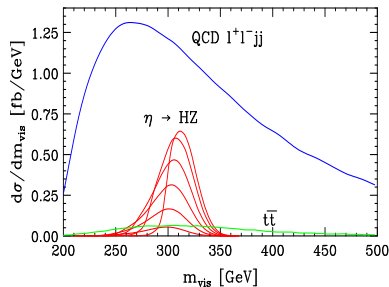
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ZHη coupling

forbidden in Product Group Models

Discriminator of diff. model classes

$$gg \rightarrow \left\{ \begin{array}{ll} H \rightarrow Z\eta & \rightarrow llbb \\ \eta \rightarrow ZH & \rightarrow llbb, llljj \end{array} \right\}$$

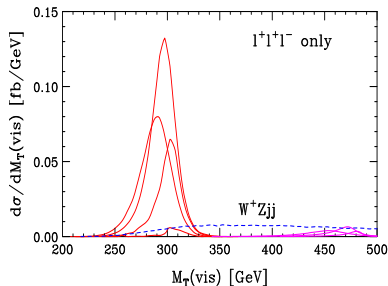
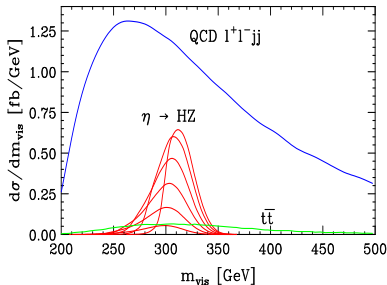
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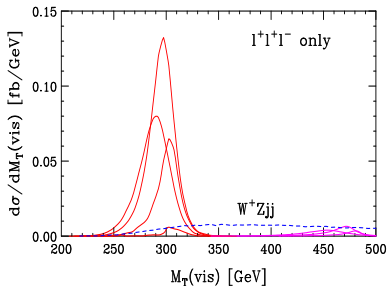
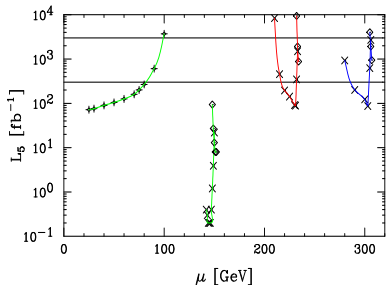
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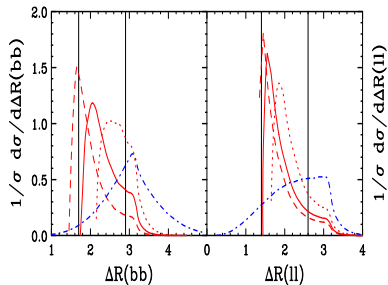
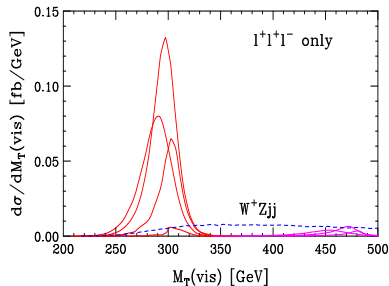
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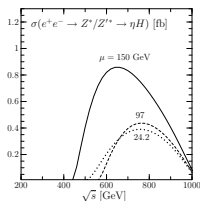
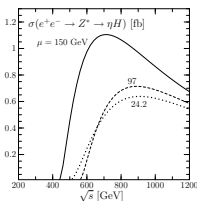
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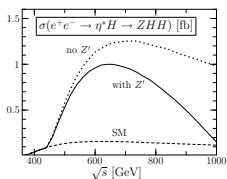
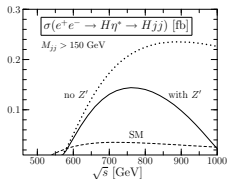
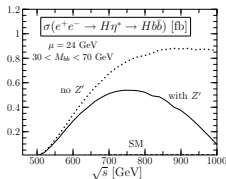
η pheno at ILC

Kilian/Rainwater/JR, 2006

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

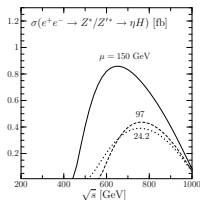
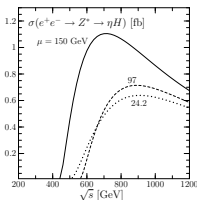


More detailed insights from photon collider option

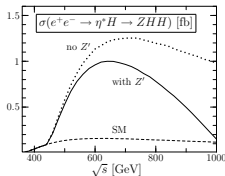
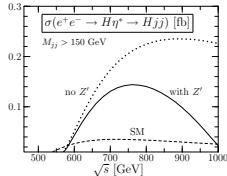
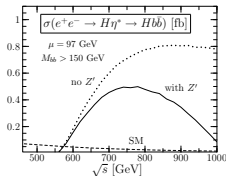
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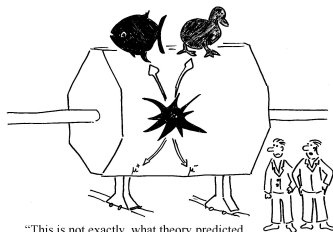
More detailed insights from photon collider option

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

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

- ▶ Light Higgs might become invisible at the LHC $H \rightarrow \eta\eta \rightarrow jjjj$
 - ▶ Not possible in Simplest Little Higgs
 - ▶ Possible in other Simple Group Models (together with η, A mixing)
 - ▶ Can become the dominant decay (with BR $\sim .8 - .95$)
- ▶ ILC can cover that hole!



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

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)
 - ▶ $Z' \rightarrow Z\eta \quad W' \rightarrow W\eta \quad T \rightarrow t\eta$
- ▶ 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?