Little Higgs Model Discrimination at the LHC and ILC

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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

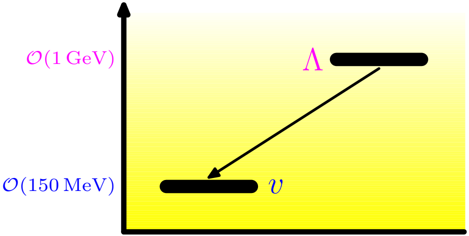
What if not SUSY?

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

Scale v: pions, kaons, . . .

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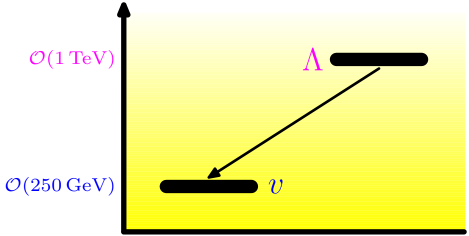


Scale Λ: global symmetry breaking, new particles, new (gauge) IA

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

Without Fine-Tuning: experimentally excluded

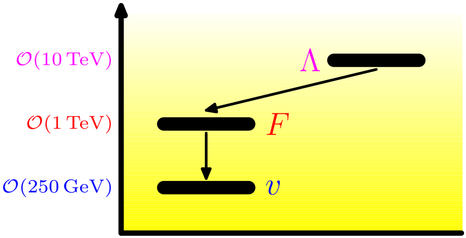
Collective symmetry breaking and 3-scale models

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

$$\boxed{m_H \sim \frac{g_1}{4\pi}\frac{g_2}{4\pi}\Lambda}$$



Scale Λ: global SB, new IA

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

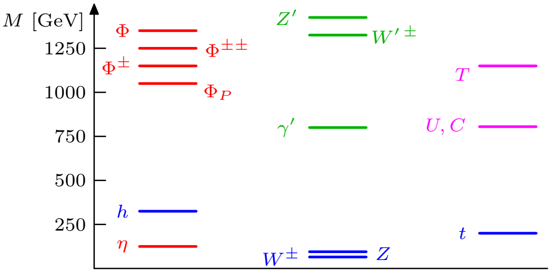
Scale v: Higgs, W/Z, $\ell^\pm$, . . .

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

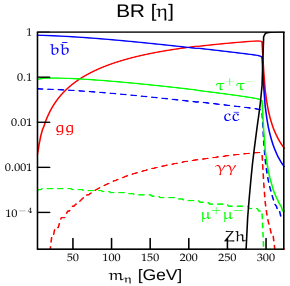
Arkani-Hamed/Cohen/Katz/Nelson, 2002



Pseudo-Axions in Little Higgs

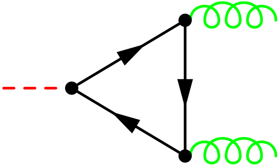
Kilian/Rainwater/JR, 2004, 2006; JR, 2007

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



- η axion-like particle:

Anomalous $U(1)$:



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

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

Simple Group Models

Kaplan,Schmaltz, ...

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

Moose Models

Arkani-Hamed, ...

- "Minimal" Moose: g $[SU(3)]^4 \to SU(3)$, 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 $[SU(2)]^2 \to SU(2)$, $n = 2 - 1 = 1$

$ZH\eta$ 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

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

- 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

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

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

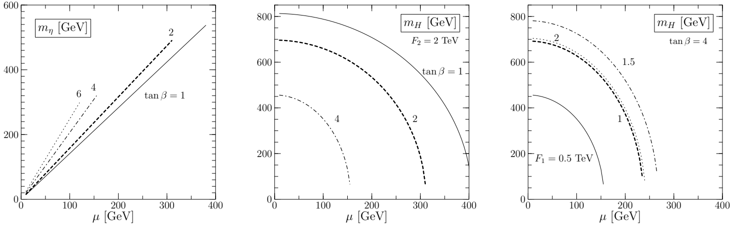
$$\mathbb{V}_\mu + \frac{i}{F}[\Sigma, \mathbb{V}_\mu] - \frac{1}{2F^2}[\Sigma, [\Sigma, \mathbb{V}_\mu]] + \ldots$$
$$= \begin{pmatrix} \mathbb{W}_\mu & 0 \\ 0 & 0 \end{pmatrix} + \frac{i}{F}\begin{pmatrix} 0 & -\mathbb{W}_\mu h \\ h^\dagger\mathbb{W}_\mu & 0 \end{pmatrix} - \frac{1}{2F^2}\begin{pmatrix}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

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

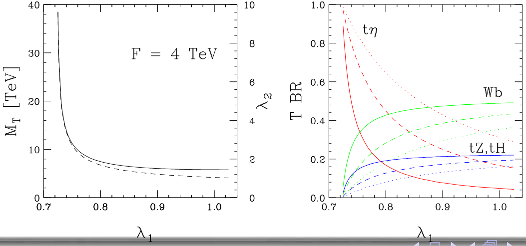
$$(\partial^\mu\eta)h^\dagger\mathbb{W}_\mu h \sim vHZ_\mu\partial^\mu\eta .$$

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



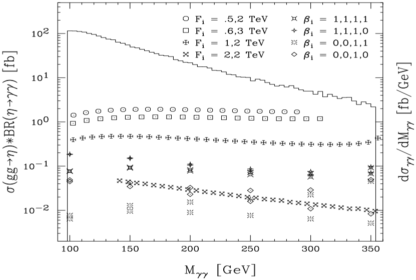
Discovery of Pseudo-axions

Kilian/Rainwater/JR, 2004, 2006

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

LHC: $T \to t\eta$

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



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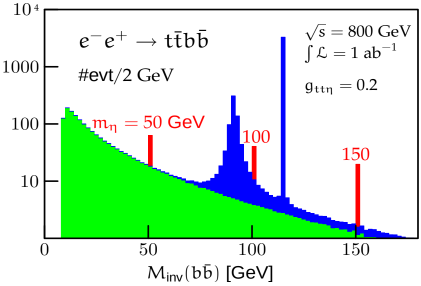

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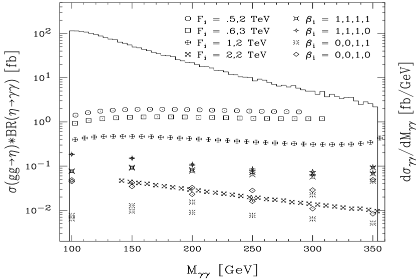

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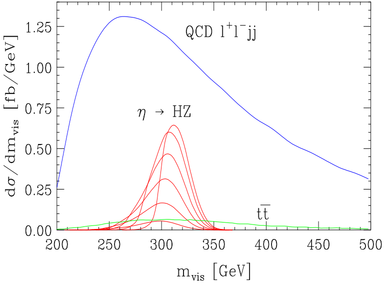

$ZH\eta$ coupling

forbidden in Product Group Models

Discriminator of diff. model classes

$$gg \to \left\{ \begin{array}{lll} H \to Z\eta & \to \ell\ell bb \\ \eta \to ZH & \to \ell\ell bb, \ell\ell\ell jj \end{array} \right\}$$

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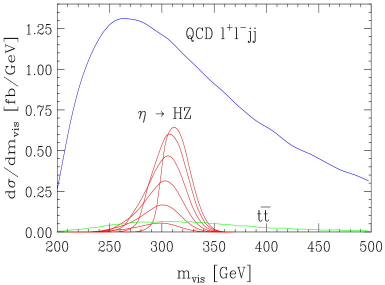

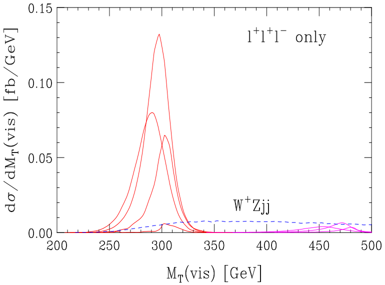

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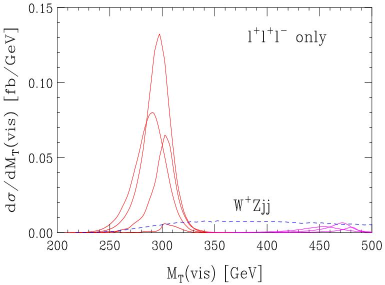

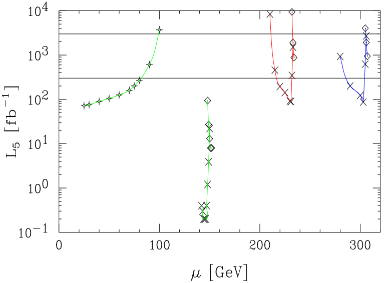

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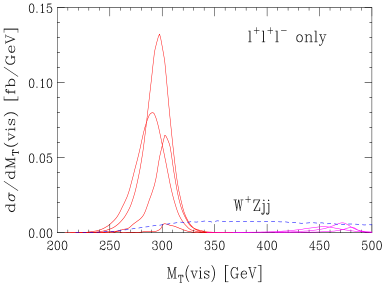

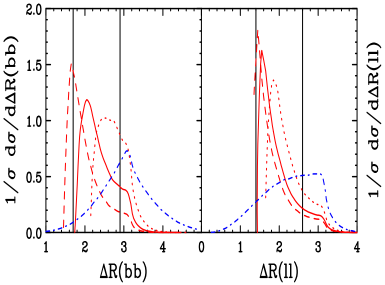

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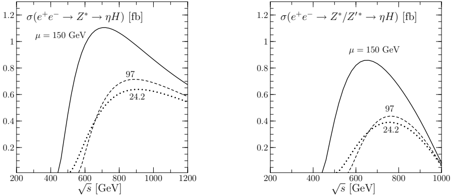
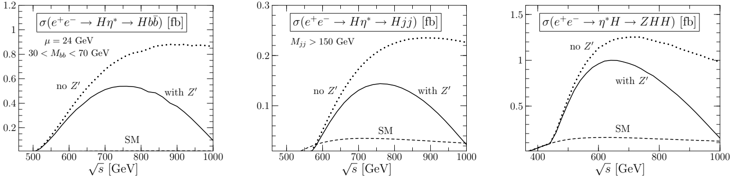
η pheno at ILC

Kilian/Rainwater/JR, 2006

If $ZH\eta$ coupling present: $H\eta$ production in analogy to HA:



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



More detailed insights from photon collider option

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Kilian/Rainwater/JR, 2006

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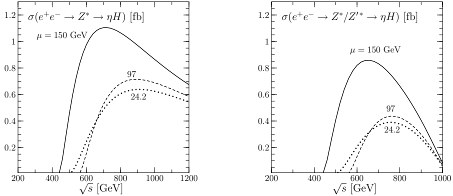

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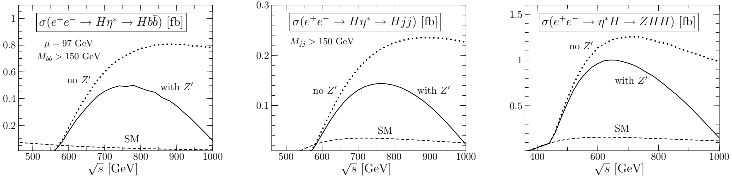


More detailed insights from photon collider option

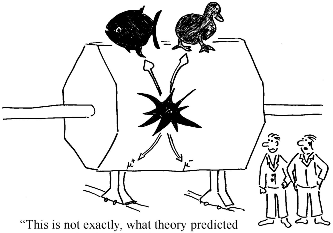
Invisible Higgs decays (?)

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

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

- Light Higgs might become invisible at the LHC $H \to \eta\eta \to jjjj$
  - 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!

JR, 2007



"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:
  - $gg \to H \to Z\eta$ (only on-shell)
  - $gg \to \eta \to ZH$ (only on-shell)
  - $Z' \to Z\eta$ $W' \to W\eta$ $T \to t\eta$
- 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?