"No Higgs Scenario" in Little Higgs Models in the early stage at LHC

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Fermilab, April 12th, 2007

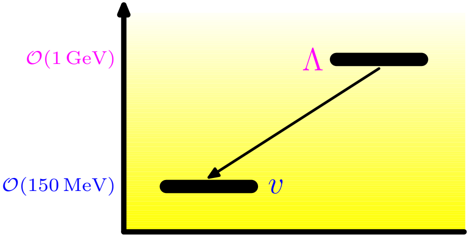
What if not SUSY?

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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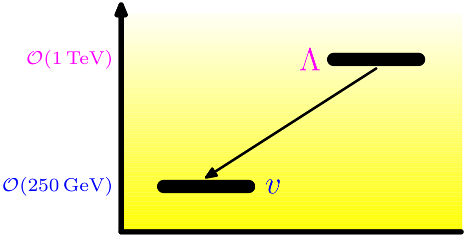


Scale Λ: global symmetry breaking, new particles, new (gauge) IA

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

Without Fine-Tuning: experimentally excluded

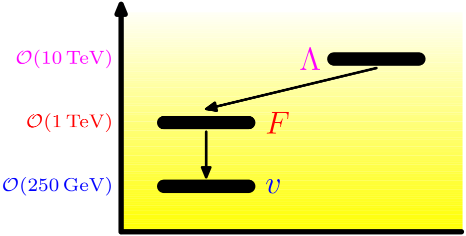
Collective symmetry breaking and 3-scale models

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

> 2 different global symmetries; one of them unbroken ⇒ 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

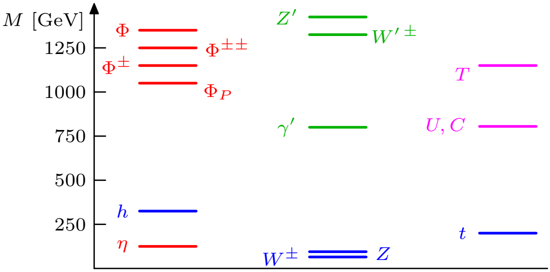
Scale v: Higgs, W/Z, $\ell^\pm$, . . .

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

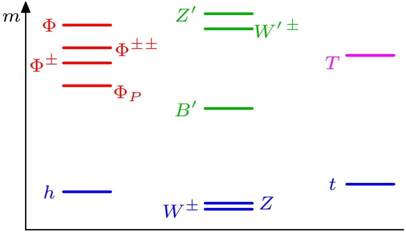
Arkani-Hamed/Cohen/Katz/Nelson, 2002



Varieties of Particle spectra

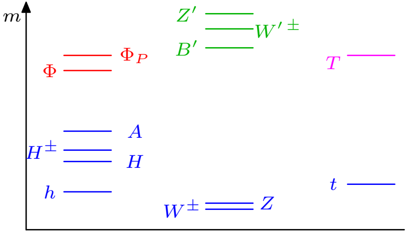
- $\mathcal{H} = \frac{SU(5)}{SO(5)}, \mathcal{G} = \frac{[SU(2) \times U(1)]^2}{SU(2) \times U(1)}$

  Arkani-Hamed/Cohen/Katz/Nelson, 2002



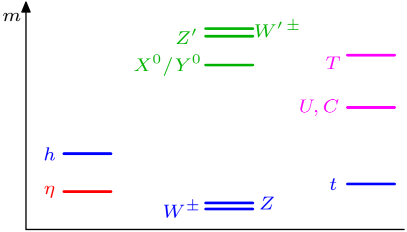
- $\mathcal{H} = \frac{SO(6)}{Sp(6)}, \mathcal{G} = \frac{[SU(2) \times U(1)]^2}{SU(2) \times U(1)}$

  Low/Skiba/Smith, 2002



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

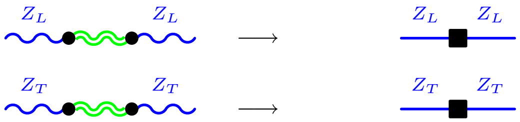
  Schmaltz, 2004



- $[SU(4)]^4 \longrightarrow [SU(3)]^4$ Kaplan/Schmaltz, 2003

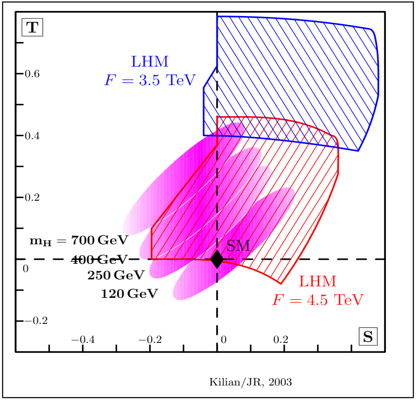
  2HDM, $h_{1/2}$, $\Phi'_{1,2,3}$, $\Phi'_{P\,1,2,3}$, $Z'_{1,\ldots,8}$, $W'^{\pm}_{1,2}$, q', ℓ'

Constraints from the Electroweak Fit



$\Delta T \sim \Delta\rho$

ΔS



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

Kilian/JR, 2003; Han et al., 2005

- ◇ 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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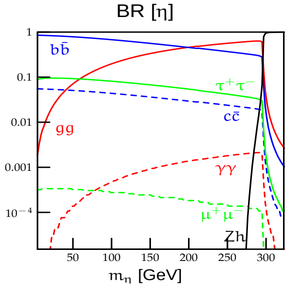
- LHM usually have rather heavy Higgs
  - will be discovered very soon (cf. Kyle Cranmer's talk)
    if $M_H \lesssim 550\,\text{GeV}$
    will be very difficult for larger Higgs masses
  - Assumption: some info about Z', W' or heavy top excluding the SM
  - Search for light Higgs states (2HDM, or single heavy Higgs)
- Confusion with a Higgs-like signal from a different particle
  possible with other (pseudo-)scalars in the game

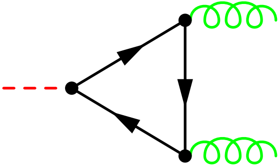
Pseudo-Axions in Little Higgs

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



- gauged $U(1)$ group: Z' $\longleftrightarrow$ ungauged: η
- couples to fermions like a pseudoscalar
- $m_\eta \lesssim 400\,\mathrm{GeV}$
- 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: $\xi = \exp\left[i\eta/F\right]$, $\Sigma = \exp\left[i\Pi/F\right]$ 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

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

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

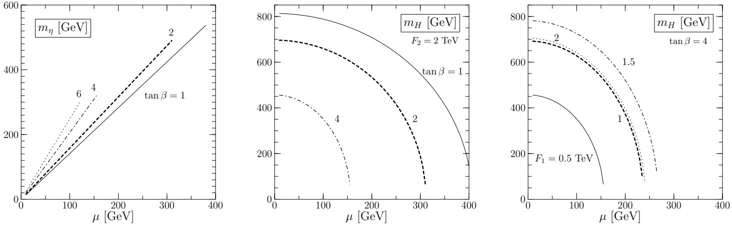
$$\mathbb{V}_\mu + \frac{i}{F}[\Sigma, \mathbb{V}_\mu] - \frac{1}{2F^2}[\Sigma,[\Sigma,\mathbb{V}_\mu]] + \ldots$$
$$= \begin{pmatrix} \mathbb{W}_\mu & 0 \\ 0 & 0 \end{pmatrix} + \frac{i}{F}\begin{pmatrix} 0 & -\mathbb{W}_\mu h \\ h^\dagger \mathbb{W}_\mu & 0 \end{pmatrix} - \frac{1}{2F^2}\begin{pmatrix}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

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

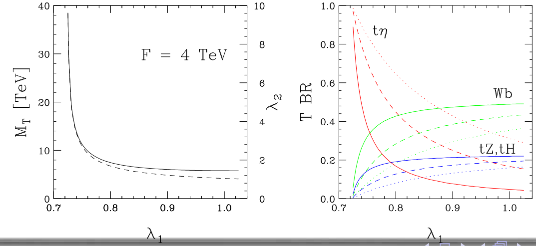
$$(\partial^\mu\eta)h^\dagger\mathbb{W}_\mu h \sim vHZ_\mu\partial^\mu\eta \, .$$

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



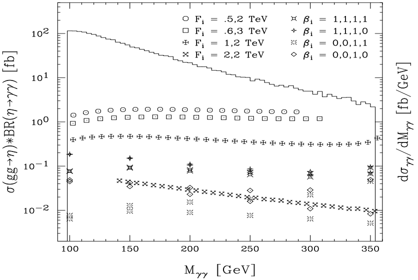
Discovery of Pseudo-axions

Kilian/Rainwater/JR, 2004, 2006

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

LHC: $T \to t\eta$

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



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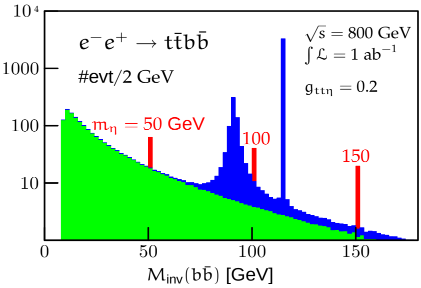

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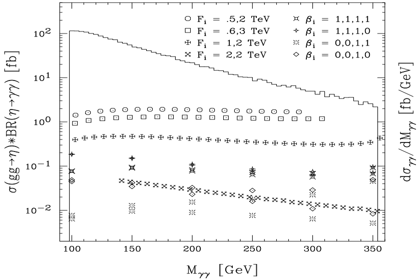

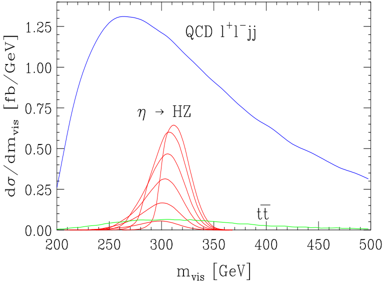

$ZH\eta$ coupling

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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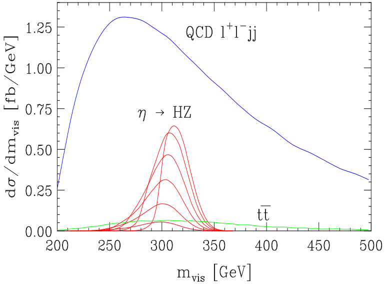

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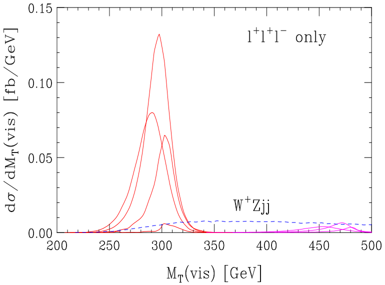

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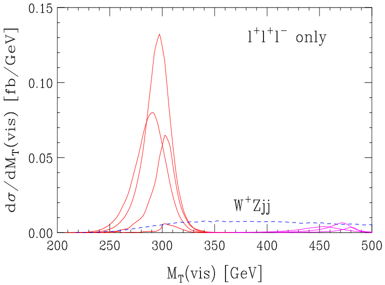

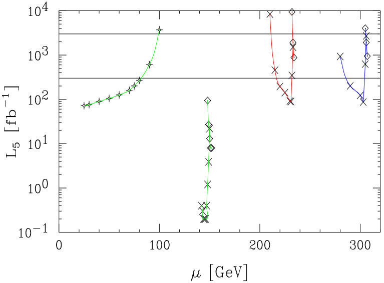

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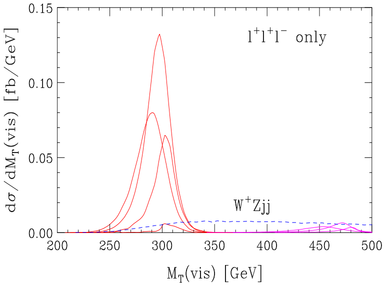

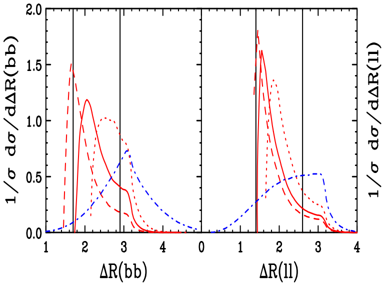

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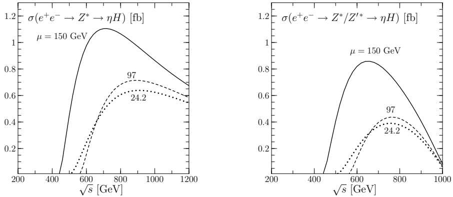
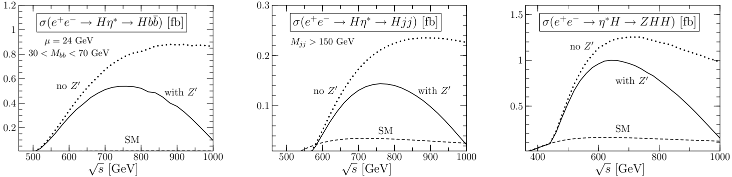
η pheno at ILC

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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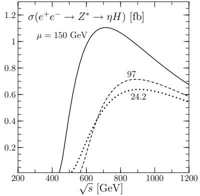

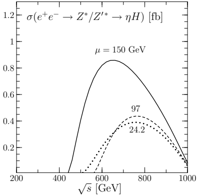

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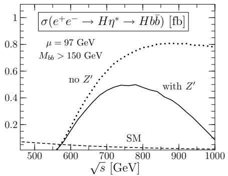
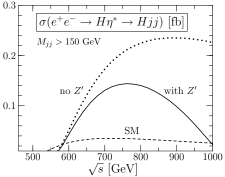
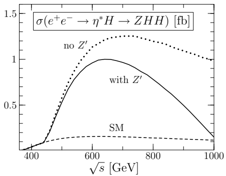






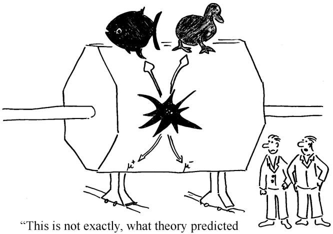
More detailed insights from photon collider option

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

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

  - Not possible in Simplest Little Higgs
  - Possible in other Simple Group Models (together with η, 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 $H \to ZZ \to 4\ell$; 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?