# Little Higgs Models
# Concepts and Phenomenology

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

Theorie-Seminar RWTH Aachen, December 6th, 2007

# Outline

## Hierarchy Problem

- Higgs as Pseudo-Nambu-Goldstone Boson (PNGB)
- The Little Higgs mechanism

## Generic properties – Examples of Models

## Phenomenology

- Effective Field Theories
- Electroweak Precision Observables
- Neutrino masses
- LHC pheno – Heavy Quark States
- LHC pheno – Heavy Vectors
- LHC pheno – Heavy Scalars
- Reconstruction of Little Higgs Models

## Pseudo-Axions in Little Higgs Models

- ZH eta coupling as a discriminator
- $T$ parity and Dark Matter

## Summary and Conclusions

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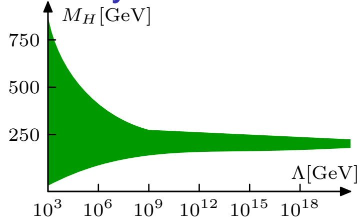
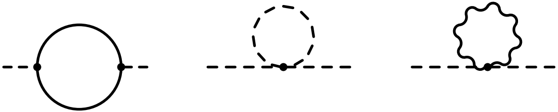
# Hierarchy Problem




**Motivation: Hierarchy Problem**

- Effective theories below a scale $\Lambda \quad \Rightarrow$
- Loop integration cut off at order $\sim \Lambda$:



$\sim \Lambda^2$

**Problem:** Naturally, $m_h \sim \mathcal{O}(\Lambda^2)$:

$$m_h^2 = m_0^2 + \Lambda^2 \times \text{(loop factors)}$$

◊ *Light* Higgs favoured by EW precision observables ($m_h < 0.5$ TeV)

- $m_h \ll \Lambda \quad \Leftrightarrow \quad$ Fine-Tuning !?
- **Solutions:** Large number of ideas since 1970s

# Overview of Solutions since 1970

(1) **New strong interactions**

- Technicolour: Higgs as a bound state of strongly-interacting partons

(2) **Symmetry for cancellation of quantum corrections:**

- Supersymmetry: Spin-Statistics ⇒ corrections from bosons and fermions cancel each other
- Little Higgs mechanism: Global symmetries ⇒ corrections from like-statistics particles cancel each other

(3) **Non-trivial Space-time structure eliminates hierarchy:**

- Large Extra Dimensions: Gravity appears only weak
- Higgsless models:c omponents of (higher-dem.) gauge fields
- Warped Extra Dimensions (Randall-Sundrum): Gravity only weak in our world

(4) **Ignoring the Hierarchy**

- Anthropic principle: parameters have their values, *because* we (can) measure them

# Higgs as Pseudo-Goldstone boson

Nambu-Goldstone Theorem: For each *spontaneously broken global symmetry generator* there is a massless boson in the spectrum.

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

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

$$\pi_i \to i\theta^a T^a_{ik}\pi_k \quad \Rightarrow \quad \frac{\partial \mathcal{V}}{\partial \pi_i} T^a_{ij}\pi_j = 0 \quad \Rightarrow \quad \underbrace{\frac{\partial^2 \mathcal{V}}{\partial \pi_i \partial \pi_j}\bigg|_F}_{=(m^2)_{ij}} T^a_{jk} f_k + \underbrace{\frac{\partial \mathcal{V}}{\partial \pi_j}\bigg|_F}_{=0} T^a_{ji} = 0$$

Nonlinear Realization (Example $SU(3) \to SU(2)$):

$$\mathcal{V}(\Phi) = \left(f^2 - (\Phi^\dagger \Phi)\right)^2 \Rightarrow \Phi = \exp\left[\frac{i}{f}\left(\begin{array}{c|c} 0 & \vec{\pi} \\ \hline \vec{\pi}^\dagger & \pi_0 \end{array}\right)\right]\begin{pmatrix} 0 \\ f+\sigma \end{pmatrix} \equiv e^{i\pi}\Phi_0$$

$\vec{\pi} \in$ fundamental $SU(2)$ rep., $\pi_0$ singlet

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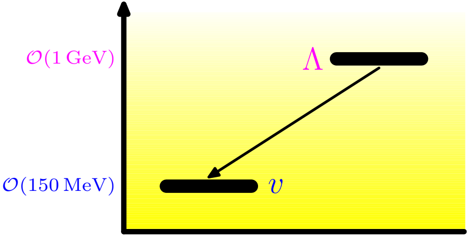


Analogous: QCD

Scale $\Lambda$: chiral symmetry breaking, quarks, $SU(3)_c$

Scale $v$: pions, kaons, ...

Without Fine-Tuning: experimentally excluded

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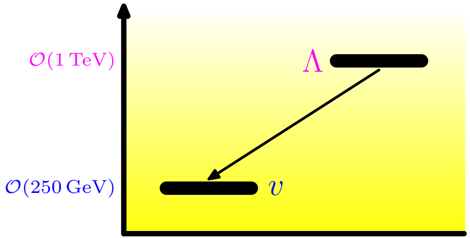



Scale $\Lambda$: global symmetry breaking, new particles, new (gauge) IA

Scale $v$: Higgs, $W/Z$, $\ell^{\pm}$, $\ldots$

Without Fine-Tuning: experimentally excluded

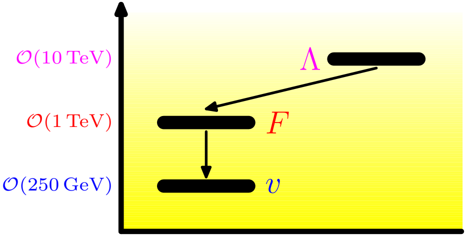
# Collective symmetry breaking and 3-scale models

**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 $\Lambda$: global SB, new IA

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

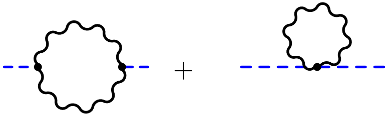
Scale $v$: Higgs, $W/Z$, $\ell^\pm$, . . .

# Prime Example: Simple Group Model

- enlarged gauge group: $SU(3) \times U(1)$; globally $U(3) \to U(2)$
- **Two** nonlinear $\Phi$ representations $\boxed{\mathcal{L} = |D_\mu \Phi_1|^2 + |D_\mu \Phi_2|^2}$

$$\Phi_{1/2} = \exp\left[\pm i \frac{f_{2/1}}{f_{1/2}} \Theta\right] \begin{pmatrix} 0 \\ 0 \\ f_{1/2} \end{pmatrix} \qquad \Theta = \frac{1}{\sqrt{f_1^2 + f_2^2}} \begin{pmatrix} \eta & 0 & \\ 0 & \eta & h^* \\ & h^T & \eta \end{pmatrix}$$

Coleman-Weinberg mechanism: Radiative generation of potential



$$= \frac{g^2}{16\pi^2} \Lambda^2 \left( |\Phi_1|^2 + |\Phi_2|^2 \right) \sim \frac{g^2}{16\pi^2} f^2$$

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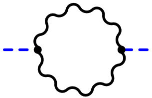

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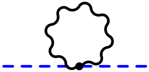
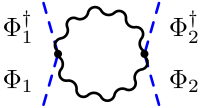


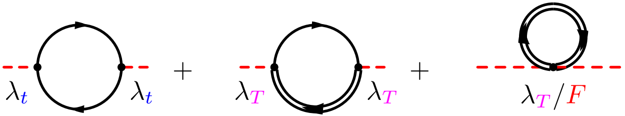
$$= \frac{g^2}{16\pi^2} \Lambda^2 \left( |\Phi_1|^2 + |\Phi_2|^2 \right) \sim \frac{g^2}{16\pi^2} f^2$$

but:




$$= \frac{g^4}{16\pi^2} \log\left(\frac{\Lambda^2}{\mu^2}\right) |\Phi_1^\dagger \Phi_2|^2 \Rightarrow \frac{g^4}{16\pi^2} \log\left(\frac{\Lambda^2}{\mu^2}\right) f^2 (h^\dagger h)$$

# Cancellations of Divergencies in Yukawa sector

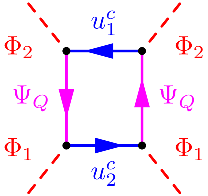



$$\propto \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2(k^2 - m_T^2)} \left\{ \lambda_t^2 (k^2 - m_T^2) + k^2 \lambda_T^2 - \frac{m_T}{F} \lambda_T k^2 \right\}$$

**Little Higgs global symmetry** imposes relation

$$\boxed{\frac{m_T}{F} = \frac{\lambda_t^2 + \lambda_T^2}{\lambda_T}} \quad \Longrightarrow \quad \textbf{Quadratic divergence cancels}$$

**Collective Symm. breaking:** $\lambda_t \propto \lambda_1 \lambda_2$ , $\lambda_1 = 0$ *or* $\lambda_2 = 0 \Rightarrow SU(3) \to [SU(3)]^2$




$$\sim \frac{\lambda_1^2 \lambda_2^2}{16\pi^2} \log\left(\frac{\Lambda^2}{\mu^2}\right) |\Phi_1^\dagger \Phi_2|^2$$

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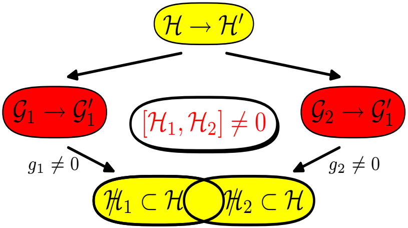
# Generic properties of Little-Higgs models

- Extended global symmetry (extended scalar sector)
- Specific functional form of the potential
- Extended gauge symmetry:
  $\gamma', Z', W'^{\pm}$
- New heavy fermions: $T$, but also $U, C, \ldots$

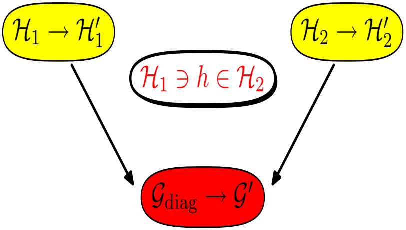
**Product Group Models**

(e.g. Littlest Higgs)




**Simple Group Models**

(e.g. Simplest Little Higgs)



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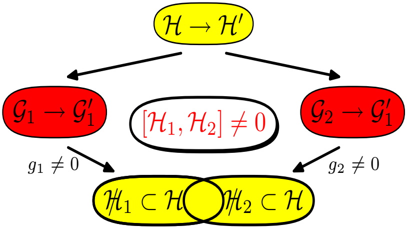
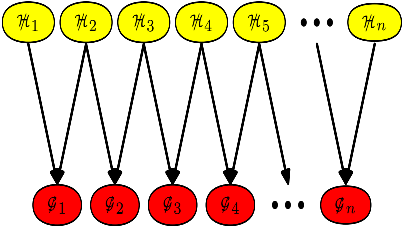



**Moose Models**

(e.g. Minimal Moose Model)



# Little Higgs Models

Plethora of "Little Higgs Models" in 3 categories:

- **Moose Models**
  - Orig. Moose (Arkani-Hamed/Cohen/Georgi, 0105239)
  - Simple Moose (Arkani-Hamed/Cohen/Katz/Nelson/Gregoire/Wacker, 0206020)
  - Linear Moose (Casalbuoni/De Curtis/Dominici, 0405188)
- **Simple (Goldstone) Representation Models**
  - Littlest Higgs (Arkani-Hamed/Cohen/Katz/Nelson, 0206021)
  - Antisymmetric Little Higgs (Low/Skiba/Smith, 0207243)
  - Custodial $SU(2)$ Little Higgs (Chang/Wacker, 0303001)
  - Littlest Custodial Higgs (Chang, 0306034)
  - Little SUSY (Birkedal/Chacko/Gaillard, 0404197)
- **Simple (Gauge) Group Models**
  - Orig. Simple Group Model (Kaplan/Schmaltz, 0302049)
  - Holographic Little Higgs (Contino/Nomura/Pomarol, 0306259)
  - Simplest Little Higgs (Schmaltz, 0407143)
  - Simplest Little SUSY (Roy/Schmaltz, 0509357)
  - Simplest T parity (Kilian/Rainwater/JR/Schmaltz,...)

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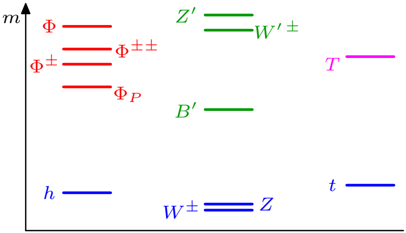
# Varieties of Particle spectra

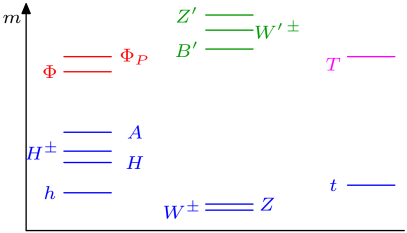
$$\mathcal{H} = \frac{SU(5)}{SO(5)}, \mathcal{G} = \frac{[SU(2)\times U(1)]^2}{SU(2)\times U(1)}$$

Arkani-Hamed/Cohen/Katz/Nelson, 2002




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

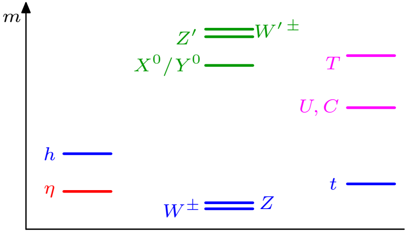
Low/Skiba/Smith, 2002




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

Schmaltz, 2004

$\Longrightarrow$




- $[SU(4)]^4 \rightarrow [SU(3)]^4$

  Kaplan/Schmaltz, 2003

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

# Effective Field Theories

How to *clearly* separate effects of heavy degrees of freedom?

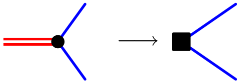
Toy model: Two interacting scalar fields $\varphi, \Phi$

$$\mathcal{Z}[j,J] = \int \mathcal{D}[\Phi]\,\mathcal{D}[\varphi]\;\exp\left[i\int dx\left(\tfrac{1}{2}(\partial\varphi)^2 - \tfrac{1}{2}\Phi(\Box + M^2)\Phi - \lambda\varphi^2\Phi - \ldots + J\Phi + j\varphi\right)\right]$$

**Low-energy effective theory** $\Rightarrow$ integrating out heavy degrees of freedom (DOF) in path integrals, set up Power Counting Kilian/JR, 2003

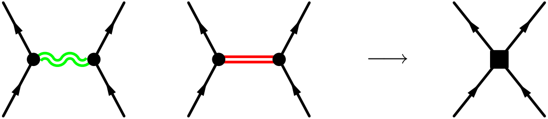
Completing the square:

$$\Phi' = \Phi + \frac{\lambda}{M^2}\left(1 + \frac{\partial^2}{M^2}\right)^{-1}\varphi^2 \Rightarrow$$

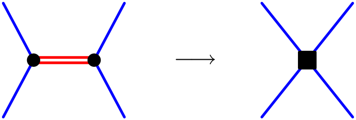


$$\frac{1}{2}(\partial\Phi)^2 - \frac{1}{2}M^2\Phi^2 - \lambda\varphi^2\Phi = -\frac{1}{2}\Phi'(M^2 + \partial^2)\Phi' + \frac{\lambda^2}{2M^2}\varphi^2\left(1 + \frac{\partial^2}{M^2}\right)^{-1}\varphi^2.$$

# Effective Dim. 6 Operators

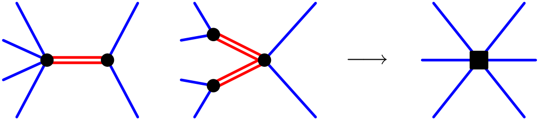


$$\mathcal{O}_{JJ}^{(I)} = \frac{1}{F^2}\,\mathrm{tr}[J^{(I)}\cdot J^{(I)}]$$

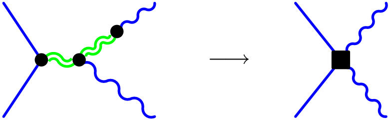


$$\mathcal{O}'_{h,1} = \frac{1}{F^2}\left((Dh)^\dagger h\right)\cdot\left(h^\dagger (D^h)\right) - \frac{v^2}{2}|Dh|^2$$

$$\mathcal{O}'_{hh} = \frac{1}{F^2}(h^\dagger h - v^2/2)\,(Dh)^\dagger\cdot(Dh)$$



$$\mathcal{O}'_{h,3} = \frac{1}{F^2}\frac{1}{3}(h^\dagger h - v^2/2)^3$$



$$\mathcal{O}'_{WW} = -\frac{1}{F^2}\frac{1}{2}(h^\dagger h - v^2/2)\,\mathrm{tr}\,W_{\mu\nu}W^{\mu\nu}$$
$$\mathcal{O}_B = \frac{1}{F^2}\frac{i}{2}(D_\mu h)^\dagger (D_\nu h) B^{\mu\nu}$$
$$\mathcal{O}'_{BB} = -\frac{1}{F^2}\frac{1}{4}(h^\dagger h - v^2/2) B_{\mu\nu}B^{\mu\nu}$$

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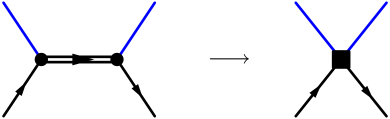
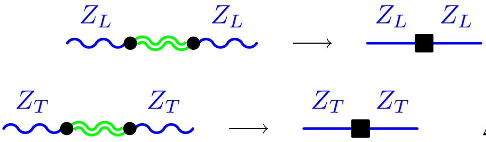


$$\mathcal{O}_{Vq} = \frac{1}{F^2}\overline{q}h(\not{D}h)q$$

# Oblique Corrections: $S$, $T$, $U$




$$\Delta T \sim \Delta\rho \sim \Delta M_Z^2 Z \cdot Z$$

$$\Delta S \sim {W^0}_{\mu\nu} B^{\mu\nu}, \Delta U \sim {W^0}_{\mu\nu} W^{0\,\mu\nu}$$

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- ◇ All low-energy effects order $v^2/F^2$ (Wilson coefficients)
- ◇ Low-energy observables with low-energy input $G_F$, $\alpha$, $M_Z$ affected by **non-oblique** contributions:

$$G_F = \frac{1}{v} \longrightarrow \frac{1}{v}(1 - \alpha\Delta T + \delta),$$

$$\boxed{\delta \equiv = -\frac{v^2}{4} f^{(3)}_{JJ} \overset{\text{LHM}}{\longrightarrow} -\frac{c^4 v^2}{F^2}}$$

$$S_{\text{eff}} = \Delta S$$
$$T_{\text{eff}} = \Delta T - \frac{1}{\alpha}\delta$$
$$U_{\text{eff}} = [\Delta U = 0] + \frac{4 s_w^2}{\alpha}\delta$$

- ▶ Little Higgs Models: $S_{\text{eff}}$, $T_{\text{eff}}$, $c$, $c'$
- ▶ non-oblique flavour-dependent corrections ⇒ enforce flavour-dependent EW fit

# Constraints on LHM

Constraints from contact IA: ( $f^{(3)}_{JJ}, f^{(1)}_{JJ}$ ) $4.5\,\text{TeV} \lesssim F/c^2$ $10\,\text{TeV} \lesssim F/c'^2$

◊ **Constraints evaded** $\Longleftrightarrow$ $c, c' \ll 1$
$B', Z', W'^{\pm}$ superheavy ($\mathcal{O}(\Lambda)$) *decouple from fermions*

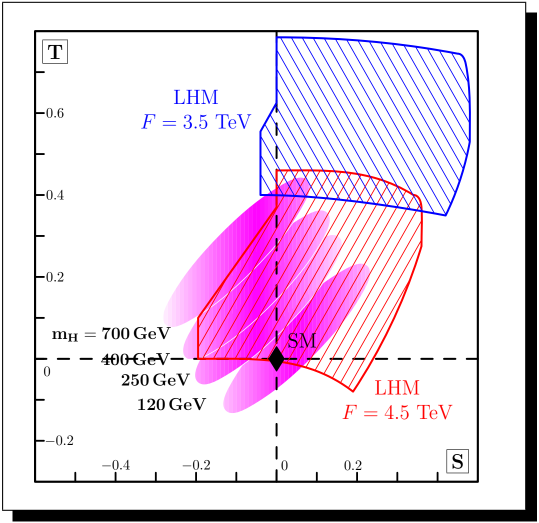
**$\Delta S$, $\Delta T$ in the Littlest Higgs model, violation of Custodial SU(2):** Csáki et al., 2002; Hewett et al., 2002; Han et al., 2003; Chen/Dawson, 2003; Kilian/JR, 2003

$$\frac{\Delta S}{8\pi} = -\left[\frac{c^2(c^2-s^2)}{g^2} + 5\frac{c'^2(c'^2-s'^2)}{g'^2}\right]\frac{v^2}{F^2} \to 0 \qquad \alpha\Delta T \to \frac{5}{4}\frac{v^2}{F^2} - \frac{2v^2\lambda^2_{2\phi}}{M^4_\phi} \gtrsim \frac{v^2}{F^2}$$

**General models**

- Triplet sector: (almost) identical to Littlest Higgs ($\Delta S$ only)
- More freedom in $U(1)$ sector: ($\Delta T$)

# EW Precision Observables




- Higgs mass *variable* (Coleman-Weinberg, UV completion)

$$\Delta S = \frac{1}{12\pi} \ln \frac{m_H^2}{m_0^2}$$

$$\Delta T = -\frac{3}{16\pi c_w^2} \ln \frac{m_H^2}{m_0^2}$$

Peskin/Takeuchi, 1992; Hagiwara et al., 1992

*Making the Higgs heavier reduces amount of fine-tuning*

# Neutrino masses

Kilian/JR, 2003; del Aguila et al., 2004; Han/Logan/Wang, 2005

⋆ *Naturalness does not require cancellation mechanism for light fermions*

Lepton-number violating interactions can generate **neutrino masses** (due to presence of triplet scalars)

Lagrangian invariant under **full gauge symmetry**

$$\boxed{\mathcal{L}_N = -g_N F (\bar{L}^c)^T \Xi L} \quad \text{with} \quad L = (\mathrm{i}\tau^2 \ell_L, 0, 0)^T$$

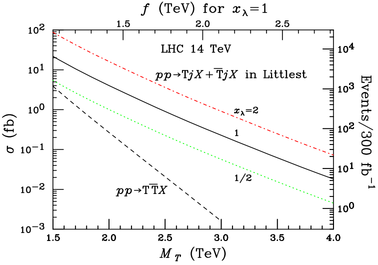
EWSB: Generation of neutrino masses $\boxed{m_\nu \sim g_N v^2 / F}$

Caveat: $m_\nu$ too large compared to observations

$\Rightarrow g_N$ small, e.g. $F/\Lambda'$, where $\Lambda'$ : scale of lepton number breaking

# Heavy Quark States

- EW single dominates QCD pair production: Perelstein/Peskin/Pierce, '03



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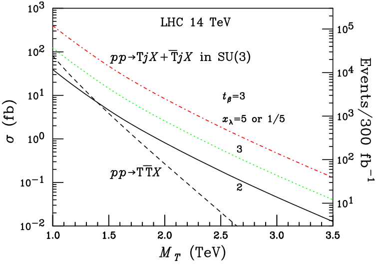
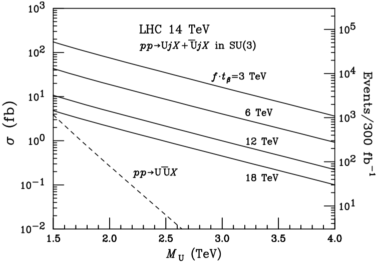



- Characteristic branching ratios :

$$\Gamma(T \to th) \approx \Gamma(T \to tZ) \approx \frac{1}{2}\Gamma(T \to bW^+) \approx \frac{M_T \lambda_T^2}{64\pi}, \qquad \Gamma_T \sim 10\text{–}50\,\text{GeV}$$

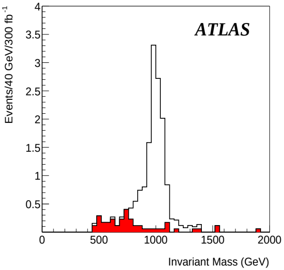
- Proof of $T$ as EW singlet; but: $T \to Z'T, W'b, t\eta$ !

AIM: *Determination of* $M_T, \lambda_T, \lambda_{T'}$

$\lambda_{T'}$ indirect ($T\bar{T}h$ impossible)

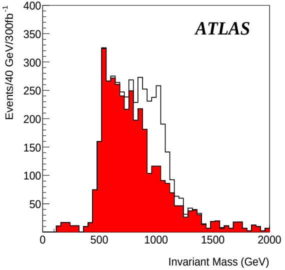
$T \to Zt \to \ell^+\ell^-\ell\nu b$ SN-ATLAS-2004-038

- $\not{E}_T > 100\,$GeV, $\ell\ell\ell, p_T > 100/30\,$GeV, $b, p_T > 30\,$GeV
- Bkgd.: $WZ, ZZ, btZ$
- Observation for $M_T \lesssim 1.4\,$TeV



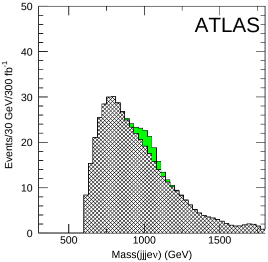
$T \to Wb \to \ell\nu b$ SN-ATLAS-2004-038

- $\not{E}_T > 100$ GeV, $\ell, p_T > 100$ GeV, $b, p_T > 200$ GeV, max. $jj, p_T > 30$ GeV
- Bkgd.: $t\bar{t}, Wb\bar{b}$, single $t$
- Observation for $M_T \lesssim 2.5$ TeV



$T \to th \to \ell\nu bbb$ SN-ATLAS-2004-038

- $\ell, p_T > 100$ GeV, $jjj, p_T > 130$ GeV, at least 1 $b$-tag
- Bkgd.: $t\bar{t}, Wb\bar{b}$, single $t$
- Observation for $M_T \lesssim 2.5$ TeV



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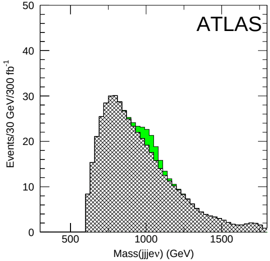
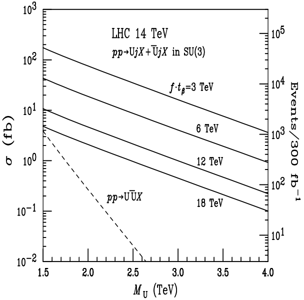



Additional heavy quarks (Simple Group Models): $U, C$ or $D, S$ Han et al., 05

- Large cross section: $u$ or $d$ PDF
- Huge final state $\ell$ charge asymmetry
- Good mass reconstruction



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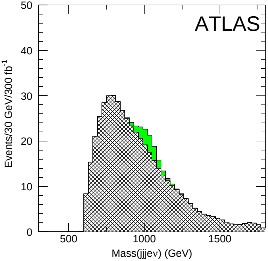


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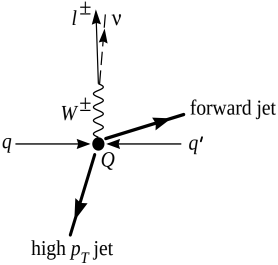

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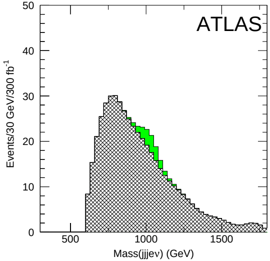


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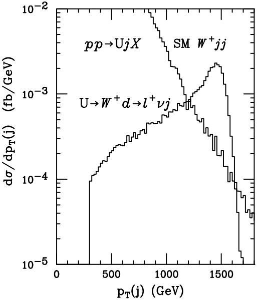


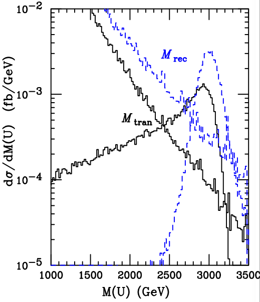

# Heavy Vectors

**Drell-Yan Production:** Tevatron Limits $\sim 500 - 600$ GeV

- Dominant decays:
  Product group: $Z' \to Zh, WW$,
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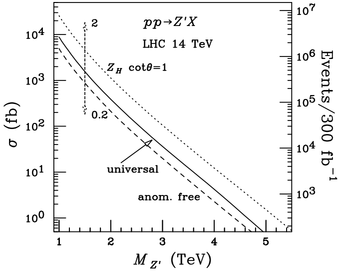
  Simple group: $Z' \to qq, \quad X \to fF$



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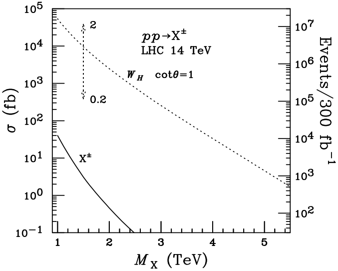

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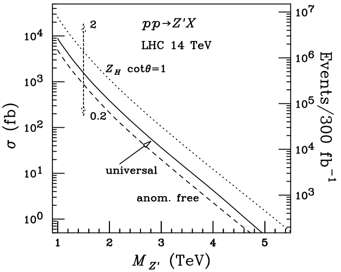
- $\Gamma_{Z'} \sim 10 - 50$ GeV, $\Gamma_X \sim 0.1 - 10$ GeV



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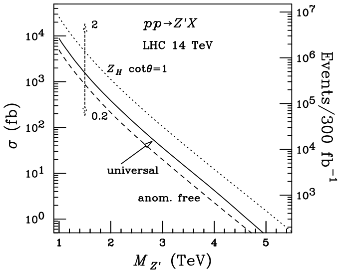
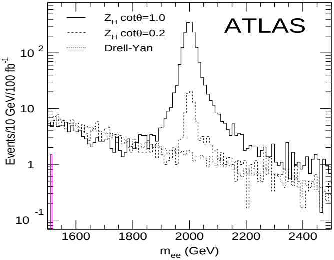
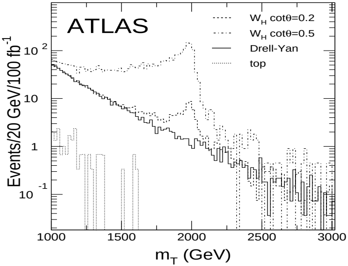
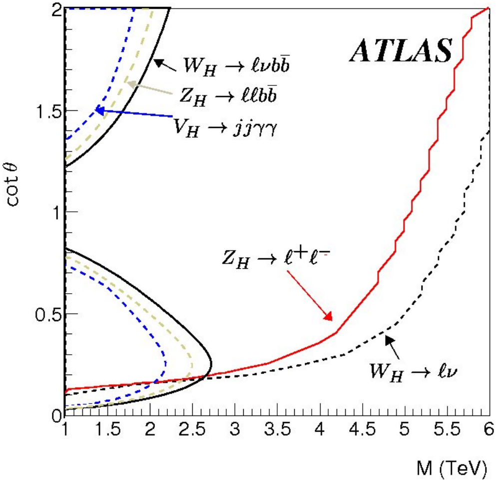




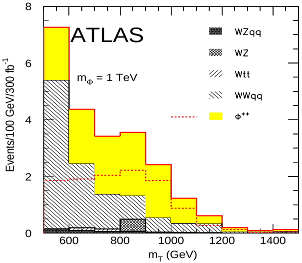

**Proof:** Sum rule for cancellation of divergences: $g_{HHVV} + g_{HHV'V'} = 0$, associated production $pp \to V'h$

# Heavy Scalars

Generally: **Large model dependence**

no states complex singlet complex triplet

- Littlest Higgs, complex triplet: $\Phi^0, \Phi_P, \Phi^\pm, \Phi^{\pm\pm}$
- Cleanest channel: $q\bar{q} \to \Phi^{++}\Phi^{--} \to \ell\ell\ell\ell$: Killer: PS
- $WW$-Fusion: $dd \to uu\Phi^{++} \to uuW^+W^+$
- 2 hard forward jets, hard close $\ell^+\ell^+$ $p_T$-unbalanced




**Alternative: Model-Independent search** in $WW$ fusion:

ILC: Beyer/Kilian/Krstonosic/Mönig/JR/Schmidt/Schröder, 2006

LHC: Kilian/Kobel/Mader/JR/Schumacher/Schumacher

# Reconstruction of Little Higgs Models

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

- ◇ Goldstone-boson nature of Higgs boson (nonlinear representation)
- ◇ Mechanism for cancellation of $\delta m_H$ quantum corrections

**STRATEGY:** Kilian/JR, 2003

- 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 parameters
- 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

# Outline


Hierarchy Problem

Higgs as Pseudo-Nambu-Goldstone Boson (PNGB)

The Little Higgs mechanism

Generic properties – Examples of Models

Phenomenology

Effective Field Theories

Electroweak Precision Observables

Neutrino masses

LHC pheno – Heavy Quark States

LHC pheno – Heavy Vectors

LHC pheno – Heavy Scalars

Reconstruction of Little Higgs Models

Pseudo-Axions in Little Higgs Models

ZH eta coupling as a discriminator

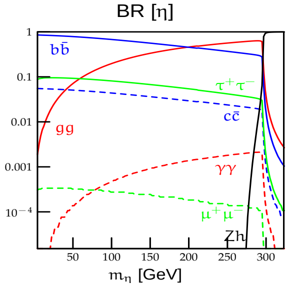
$T$ parity and Dark Matter

Summary and Conclusions

# Pseudo-Axions in Little Higgs

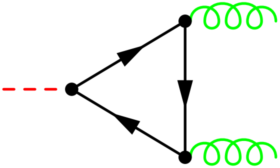
Kilian/Rainwater/JR, 2004, 2006; JR, 2007

- gauged $U(1)$ group: $Z'$ $\longleftrightarrow$ 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:

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 $\Pi$

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

- Use special structure of covariant derivatives:

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

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

- 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

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

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

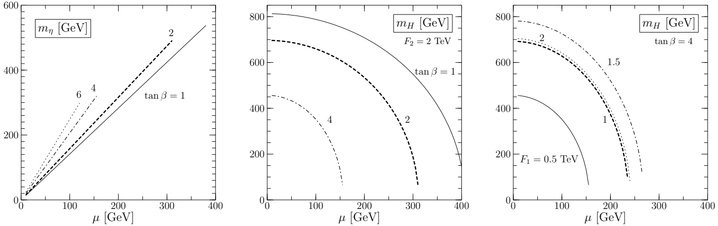
$$\mathbb{V}_\mu + \frac{i}{F}[\Sigma, \mathbb{V}_\mu] - \frac{1}{2F^2}[\Sigma,[\Sigma,\mathbb{V}_\mu]] + \ldots$$
$$= \begin{pmatrix} \mathbb{W}_\mu & 0 \\ 0 & 0 \end{pmatrix} + \frac{i}{F}\begin{pmatrix} 0 & -\mathbb{W}_\mu h \\ h^\dagger \mathbb{W}_\mu & 0 \end{pmatrix} - \frac{1}{2F^2}\begin{pmatrix}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

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

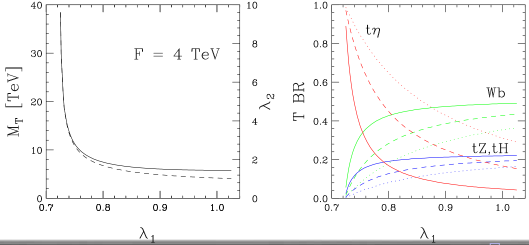
$$(\partial^\mu\eta)h^\dagger\mathbb{W}_\mu h \sim vHZ_\mu\partial^\mu\eta .$$

# More properties of Pseudo-Axions

- Take e.g. one specific model: Simplest Little Higgs Schmaltz, 2004
- 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



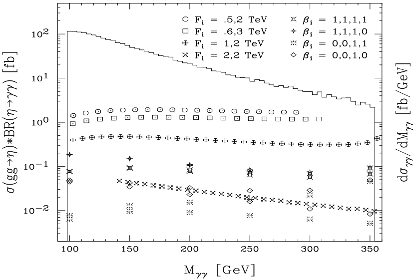
# Discovery of Pseudo-axions

Kilian/Rainwater/JR, 2004, 2006

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

LHC: $T \to t\eta$

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



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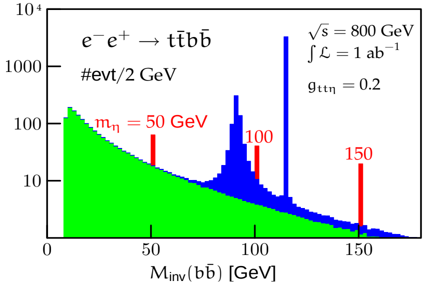

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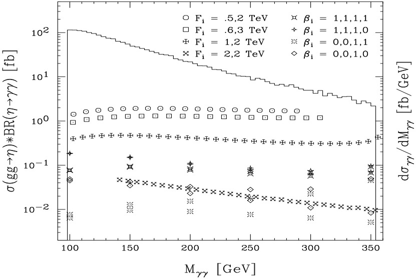


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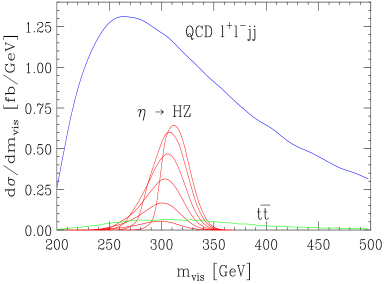


$ZH\eta$ coupling

forbidden in Product Group Models

Discriminator of diff. model classes

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

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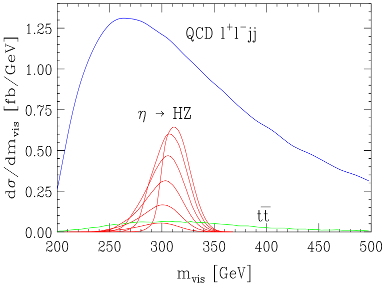


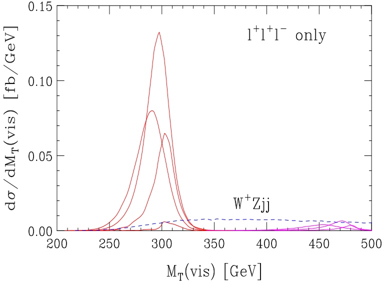


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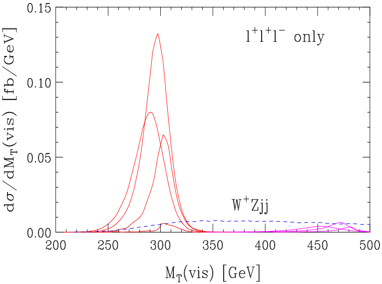


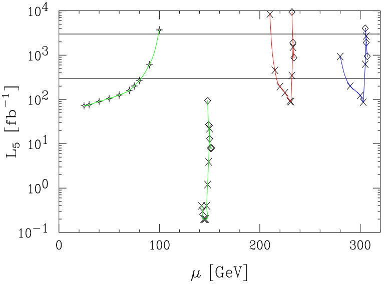


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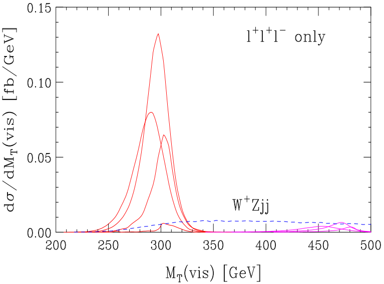


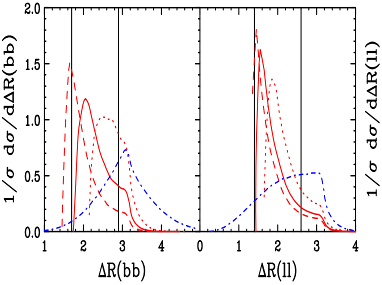


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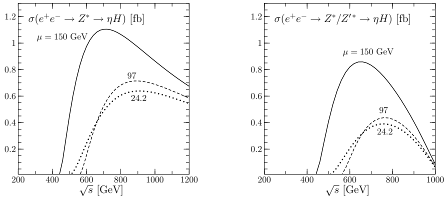
$$gg \to \left\{ \begin{array}{lll} H \to Z\eta & \to \ell\ell bb \\ \eta \to ZH & \to \ell\ell bb, \ell\ell\ell jj \end{array} \right\}$$

# $\eta$ 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 $Hjj$
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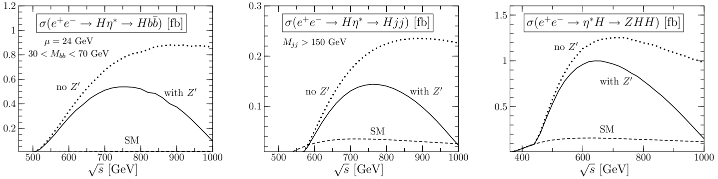


More detailed insights from photon collider option

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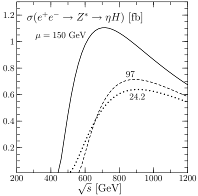


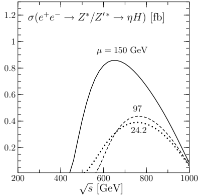


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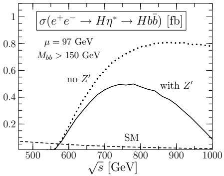
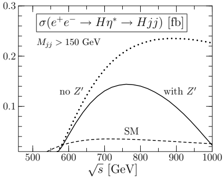
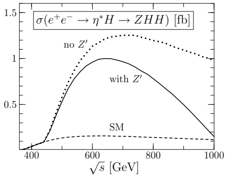



More detailed insights from photon collider option

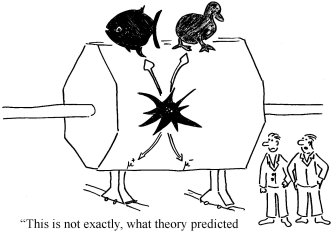
# Invisible Higgs decays (?)

- "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

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

- 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 $\eta, A$ mixing)
  - Can become the dominant decay (with BR $\sim .8 - .95$)
- ILC can cover that hole!

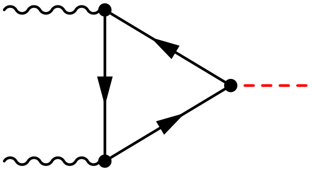
JR, 2007



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

# Pseudo Axions at the Photon Collider

- Photon Collider as precision machine for Higgs physics ($s$ channel resonance, anomaly coupling)



- S/B analogous to LC
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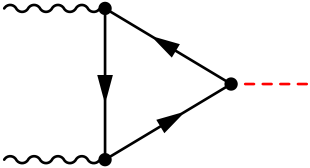

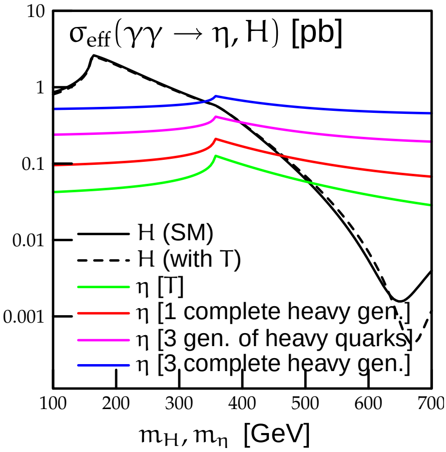


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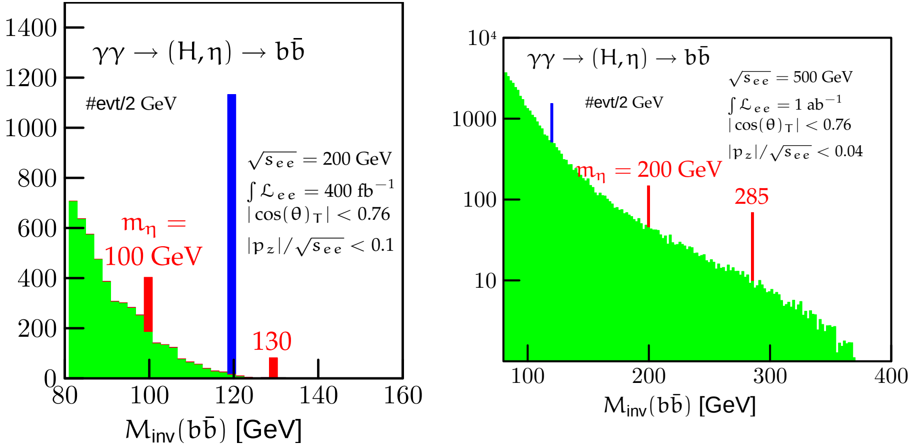
$$g_{bb\eta} = 0.4 \cdot g_{bbh}$$

| $m_\eta$ | 100 | 130 | 200 | 285 |
|---|---|---|---|---|
| $\Gamma_{\gamma\gamma}$[keV] | 0.15 | 0.27 | 1.1 | 3.6 |



# $T$ parity and Dark Matter

Cheng/Low, 2003; Hubisz/Meade, 2005

- $T$ parity: $T^a \to T^a, \quad X^a \to -X^a$, automorphism of coset space
  analogous to $R$ parity in SUSY, KK parity in extra dimensions
- Bounds on $F$ MUCH relaxed, $F \sim 1$ TeV
  *but:* Pair production!, typical cascade decays
- Lightest $T$-odd particle (LTP) $\Rightarrow$ Candidate for Cold Dark Matter

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Littlest Higgs: $A'$ LTP

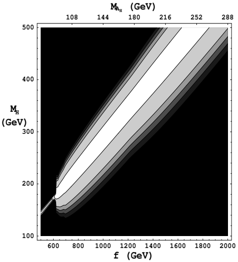
$W', Z' \sim$ 650 GeV, $\Phi \sim$ 1 TeV

$T, T' \sim$ 0.7-1 TeV

Annihilation: $A'A' \to h \to WW, ZZ, hh$

Hubisz/Meade, 2005

0/10/50/70/100



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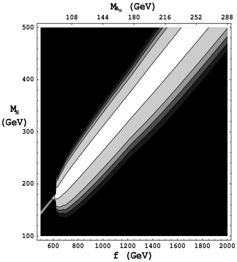


- $T$ parity Simplest LH: Pseudo-Axion $\eta$ LTP
  $Z'$ remains odd: good or bad (?) Kilian/Rainwater/JR/Schmaltz
- $T$ parity might be anomalous (???) Hill/Hill, 2007

# Outline


Hierarchy Problem
- Higgs as Pseudo-Nambu-Goldstone Boson (PNGB)
- The Little Higgs mechanism

Generic properties – Examples of Models

Phenomenology
- Effective Field Theories
- Electroweak Precision Observables
- Neutrino masses
- LHC pheno – Heavy Quark States
- LHC pheno – Heavy Vectors
- LHC pheno – Heavy Scalars
- Reconstruction of Little Higgs Models

Pseudo-Axions in Little Higgs Models
- ZH eta coupling as a discriminator
- $T$ parity and Dark Matter

Summary and Conclusions

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Little Higgs: Global Symmetry structure stabilizes EW scale

New heavy gauge bosons, scalars, quarks (same spin)

EW precision observables:
Higgs is generically heavy in LHM (Little Big Higgs)

Inclusion of Dark Matter: $T$-parity (anomalies?)

Open questions: UV embedding, GUTs, Flavour

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Little Higgs models generally have extra pseudoscalars

- Maybe the only observable states (before VLHC!)
- Discriminator between Product and Simple Group Models
- LHC has first option: gluon fusion, $T/Z'/W'$ decays
- ILC can cover all regions
- Possible “invisible” Higgs decays

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# Simplest Little Higgs (“$\mu$ Model”)

Schmaltz ’04, Kilian/Rainwater/JR ’04

Field content ($SU(3)_c \times SU(3)_w \times U(1)_X$ quantum numbers)

$$\begin{array}{lllllllll} \Phi_{1,2} & : & (1,3)_{-\frac{1}{3}} & \Psi_\ell & : & (1,3)_{-\frac{1}{3}} & {u_{1,2}}^c & : & (\bar{3},1)_{-\frac{2}{3}} \\ \Psi_Q & : & (3,3)_{\frac{1}{3}} & d^c & : & (\bar{3},1)_{\frac{1}{3}} & e^c, n^c & : & (1,1)_{1,0} \end{array}$$

Lagrangian $\mathcal{L} = \mathcal{L}_{\text{kin.}} + \mathcal{L}_{\text{Yuk.}} + \mathcal{L}_{\text{pot.}}$ $\quad \Psi_{Q,L} = (u,d,U)_L, \Psi_\ell = (\nu,\ell,N)_L$:

$$\mathcal{L}_{\text{Yuk.}} = -\lambda_1^u \overline{u}_{1,R} \Phi_1^\dagger \Psi_{T,L} - \lambda_2^u \overline{u}_{2,R} \Phi_2^\dagger \Psi_{T,L} - \frac{\lambda^d}{\Lambda} \epsilon^{ijk} \overline{d}_R^b \Phi_1^i \Phi_2^j \Psi_{T,L}^k$$

$$- \lambda^n \overline{n}_{1,R} \Phi_1^\dagger \Psi_{Q,L} - \frac{\lambda^e}{\Lambda} \epsilon^{ijk} \overline{e}_R \Phi_1^i \Phi_2^j \Psi_{Q,L}^k + \text{h.c.},$$

$$\mathcal{L}_{\text{pot.}} = \mu^2 {\Phi_1}^\dagger \Phi_2 + \text{h.c.}$$

Hypercharge embedding $\quad (\text{diag}(1,1,-2)/(2\sqrt{3}))$:

$$Y = X - T^8/\sqrt{3} \qquad D_\mu \Phi = (\partial_\mu - \frac{1}{3} g_X B_\mu^X \Phi + i g W_\mu^w) \Phi$$