Status of Little Higgs Models in 2013

Jürgen Reuter

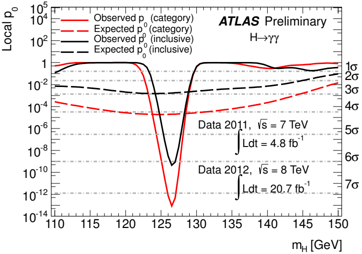
DESY

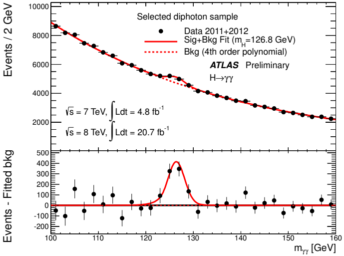
JRR/Tonini/de Vries, arXiv:1309.xxxx; arXiv:1307.5010; JRR/Tonini, JHEP **1302** (2013) 077; Kilian/JRR/Rainwater **PRD 74** (2006), 095003; **PRD 71** (2005), 015008; Kilian/JRR **PRD 70** (2004), 015004

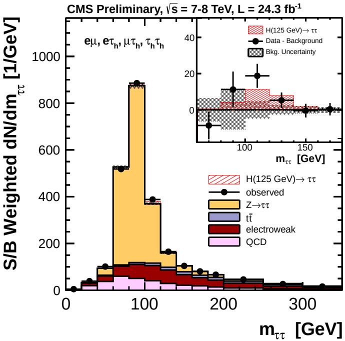
Seminar, U. of Pittsburgh, Pittsburgh, 17.9.2013

Standard Model Triumph:

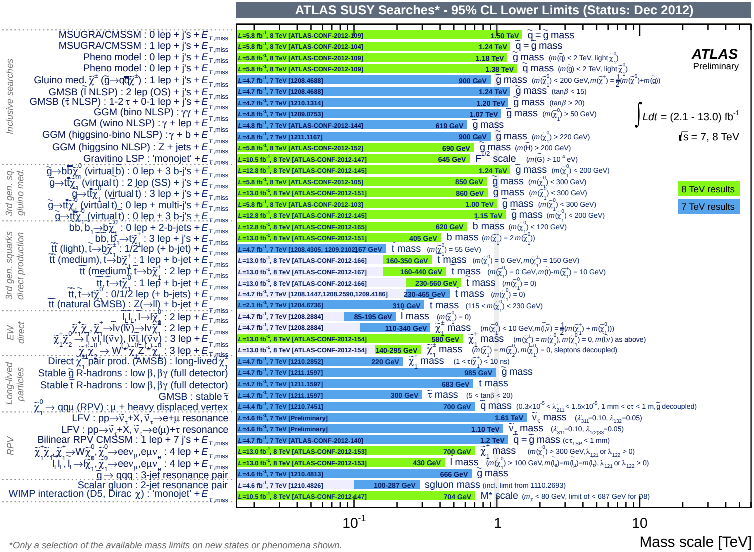
- 2012: Discovery of a Higgs boson





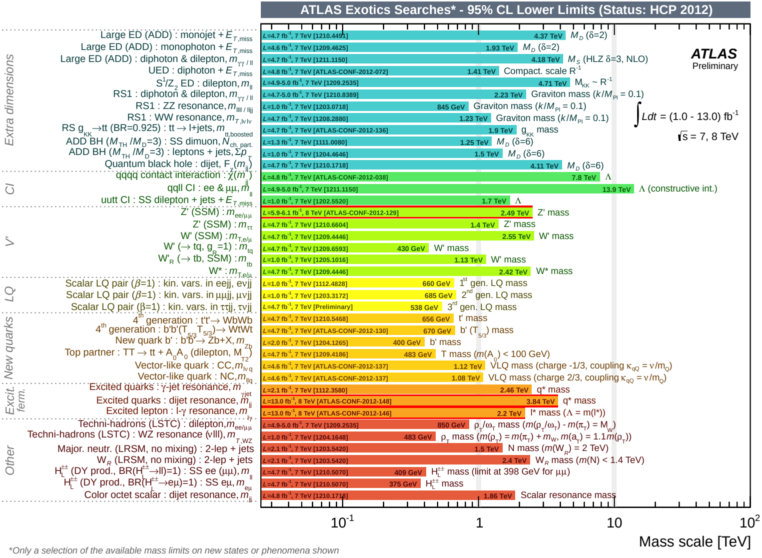


... and what now?



*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

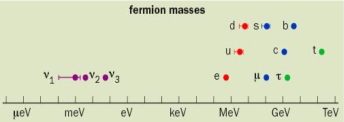
... and what now?


ATLAS Exotics Searches* - 95% CL Lower Limits (Status: HCP 2012)
ATLAS
Preliminary
∫Ldt = (1.0 - 13.0) fb^-1
√s = 7, 8 TeV
Extra dimensions
CI
V'
LQ
New quarks
Excit. ferm.
Other
Large ED (ADD) : monojet + E_T,miss | L=4.7 fb^-1, 7 TeV [1210.4491] | 4.37 TeV | M_D (δ=2)
Large ED (ADD) : monophoton + E_T,miss | L=4.6 fb^-1, 7 TeV [1209.4625] | 1.93 TeV | M_D (δ=2)
Large ED (ADD) : diphoton & dilepton, m_γγ / ll | L=4.7 fb^-1, 7 TeV [1211.1150] | 4.18 TeV | M_S (HLZ δ=3, NLO)
UED : diphoton + E_T,miss | L=4.8 fb^-1, 7 TeV [ATLAS-CONF-2012-072] | 1.41 TeV | Compact. scale R^-1
S^1/Z_2 ED : dilepton, m_ll | L=4.9-5.0 fb^-1, 7 TeV [1209.2535] | 4.71 TeV | M_KK ~ R^-1
RS1 : diphoton & dilepton, m_γγ / ll | L=4.7-5.0 fb^-1, 7 TeV [1210.8389] | 2.23 TeV | Graviton mass (k/M_Pl = 0.1)
RS1 : ZZ resonance, m_llll / lljj | L=1.0 fb^-1, 7 TeV [1203.0718] | 845 GeV | Graviton mass (k/M_Pl = 0.1)
RS1 : WW resonance, m_T,lνlν | L=4.7 fb^-1, 7 TeV [1208.2880] | 1.23 TeV | Graviton mass (k/M_Pl = 0.1)
RS g_KK → tt (BR=0.925) : tt → l+jets, m_tt,boosted | L=4.7 fb^-1, 7 TeV [ATLAS-CONF-2012-136] | 1.9 TeV | g_KK mass
ADD BH (M_TH /M_D=3) : SS dimuon, N_ch. part. | L=1.3 fb^-1, 7 TeV [1111.0080] | 1.25 TeV | M_D (δ=6)
ADD BH (M_TH /M_D=3) : leptons + jets, Σp_T | L=1.0 fb^-1, 7 TeV [1204.4646] | 1.5 TeV | M_D (δ=6)
Quantum black hole : dijet, F_χ(m_jj) | L=4.7 fb^-1, 7 TeV [1210.1718] | 4.11 TeV | M_D (δ=6)
qqqq contact interaction : χ(m_jj) | L=4.8 fb^-1, 7 TeV [ATLAS-CONF-2012-038] | 7.8 TeV | Λ
qqll CI : ee & μμ, m_ll | L=4.9-5.0 fb^-1, 7 TeV [1211.1150] | 13.9 TeV | Λ (constructive int.)
uutt CI : SS dilepton + jets + E_T,miss | L=1.0 fb^-1, 7 TeV [1202.5520] | 1.7 TeV | Λ
Z' (SSM) : m_ee/μμ | L=5.9-6.1 fb^-1, 8 TeV [ATLAS-CONF-2012-129] | 2.49 TeV | Z' mass
Z' (SSM) : m_ττ | L=4.7 fb^-1, 7 TeV [1210.6604] | 1.4 TeV | Z' mass
W' (SSM) : m_T,e/μ | L=4.7 fb^-1, 7 TeV [1209.4446] | 2.55 TeV | W' mass
W' (→ tq, g_R=1) : m_tq | L=4.7 fb^-1, 7 TeV [1209.6593] | 430 GeV | W' mass
W'_R (→ tb, SSM) : m_tb | L=1.0 fb^-1, 7 TeV [1205.1016] | 1.13 TeV | W' mass
W* : m_T,e/μ | L=4.7 fb^-1, 7 TeV [1209.4446] | 2.42 TeV | W* mass
Scalar LQ pair (β=1) : kin. vars. in eejj, eνjj | L=1.0 fb^-1, 7 TeV [1112.4828] | 660 GeV | 1st gen. LQ mass
Scalar LQ pair (β=1) : kin. vars. in μμjj, μνjj | L=1.0 fb^-1, 7 TeV [1203.3172] | 685 GeV | 2nd gen. LQ mass
Scalar LQ pair (β=1) : kin. vars. in ττjj, τνjj | L=4.7 fb^-1, 7 TeV [Preliminary] | 538 GeV | 3rd gen. LQ mass
4th generation : t't'→ WbWb | L=4.7 fb^-1, 7 TeV [1210.5468] | 656 GeV | t' mass
4th generation : b'b'(T_5/3 T_5/3)→ WtWt | L=4.7 fb^-1, 7 TeV [ATLAS-CONF-2012-130] | 670 GeV | b' (T_5/3) mass
New quark b' : b'b'→ Zb+X, m_Zb | L=2.0 fb^-1, 7 TeV [1204.1265] | 400 GeV | b' mass
Top partner : TT → tt + A_0A_0 (dilepton, M_T2) | L=4.7 fb^-1, 7 TeV [1209.4186] | 483 GeV | T mass (m(A_0) < 100 GeV)
Vector-like quark : CC, m_lνq | L=4.6 fb^-1, 7 TeV [ATLAS-CONF-2012-137] | 1.12 TeV | VLQ mass (charge -1/3, coupling κ_qQ = ν/m_Q)
Vector-like quark : NC, m_llq | L=4.6 fb^-1, 7 TeV [ATLAS-CONF-2012-137] | 1.08 TeV | VLQ mass (charge 2/3, coupling κ_qQ = ν/m_Q)
Excited quarks : γ-jet resonance, m_γjet | L=2.1 fb^-1, 7 TeV [1112.3580] | 2.46 TeV | q* mass
Excited quarks : dijet resonance, m_jj | L=13.0 fb^-1, 8 TeV [ATLAS-CONF-2012-148] | 3.84 TeV | q* mass
Excited lepton : l-γ resonance, m_lγ | L=13.0 fb^-1, 8 TeV [ATLAS-CONF-2012-146] | 2.2 TeV | l* mass (Λ = m(l*))
Techni-hadrons (LSTC) : dilepton, m_ee/μμ | L=4.9-5.0 fb^-1, 7 TeV [1209.2535] | 850 GeV | ρ_T/ω_T mass (m(ρ_T/ω_T) - m(π_T) = M_W)
Techni-hadrons (LSTC) : WZ resonance (νlll), m_T,WZ | L=1.0 fb^-1, 7 TeV [1204.1648] | 483 GeV | ρ_T mass (m(ρ_T) = m(π_T) + m_W, m(a_T) = 1.1m(ρ_T))
Major. neutr. (LRSM, no mixing) : 2-lep + jets | L=2.1 fb^-1, 7 TeV [1203.5420] | 1.5 TeV | N mass (m(W_R) = 2 TeV)
W_R (LRSM, no mixing) : 2-lep + jets | L=2.1 fb^-1, 7 TeV [1203.5420] | 2.4 TeV | W_R mass (m(N) < 1.4 TeV)
H_L^±± (DY prod., BR(H_L^±±→ll)=1) : SS ee (μμ), m_ll | L=4.7 fb^-1, 7 TeV [1210.5070] | 409 GeV | H_L^±± mass (limit at 398 GeV for μμ)
H_L^±± (DY prod., BR(H_L^±±→eμ)=1) : SS eμ, m_eμ | L=4.7 fb^-1, 7 TeV [1210.5070] | 375 GeV | H_L^±± mass
Color octet scalar : dijet resonance, m_jj | L=4.8 fb^-1, 7 TeV [1210.1718] | 1.86 TeV | Scalar resonance mass
10^-1
1
10
10^2
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena shown

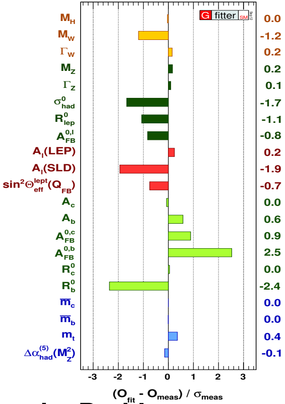
Doubts on the Standardmodel

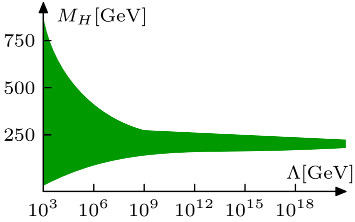
– describes microcosm (too good?)

– 28 free parameters



– Higgs ?, form of Higgs potential ?





Hierarchy Problem

chiral symmetry: $\delta m_f \propto v \ln(\Lambda^2/v^2)$

no symmetry for quantum corrections to Higgs mass

$$\delta M_H^2 \propto \Lambda^2 \sim M_{\text{Planck}}^2 = (10^{19})^2\ \text{GeV}^2$$

$(125\ \text{GeV})^2$ = (1000000000000000000000000000000020000 –

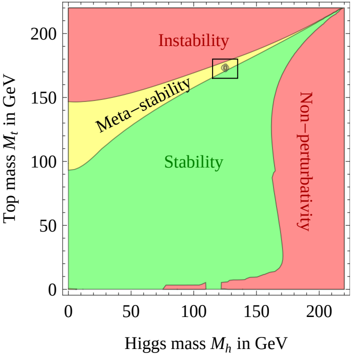
1000000000000000000000000000000000000) GeV^2

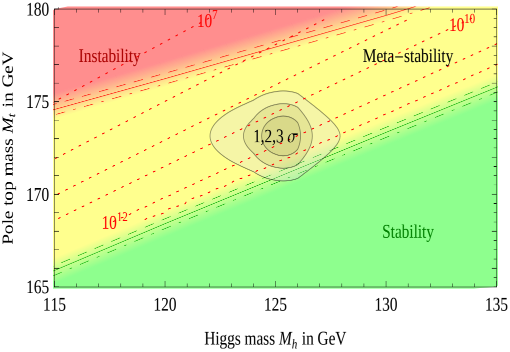
Electroweak vacuum stability

- Most recent analysis: Metastable vacuum with lifetime longer than the age of the universe Degrassi et al., arXiv:1205.6497

Electroweak vacuum stability

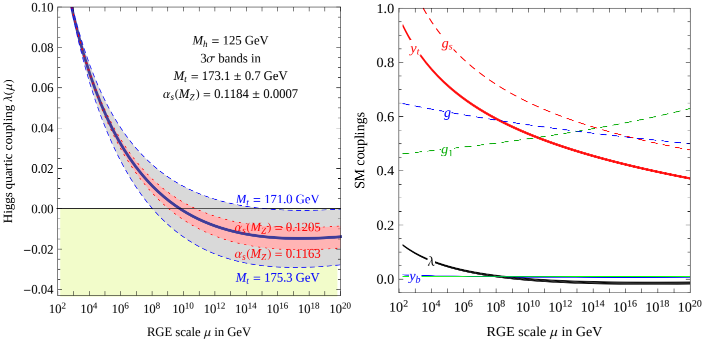
- Most recent analysis: Metastable vacuum with lifetime longer than the age of the universe Degrassi et al., arXiv:1205.6497





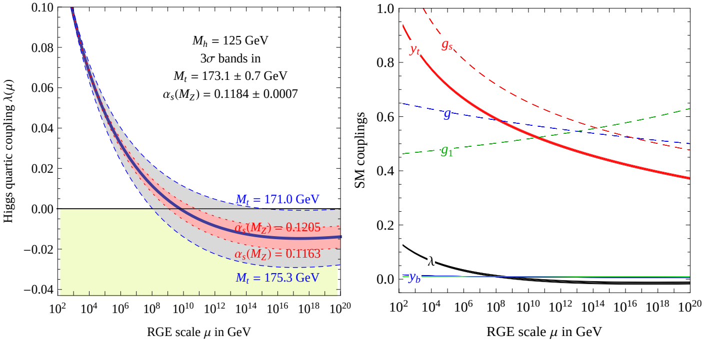
Electroweak vacuum stability

- Most recent analysis: Metastable vacuum with lifetime longer than the age of the universe Degrassi et al., arXiv:1205.6497



Electroweak vacuum stability

- Most recent analysis: Metastable vacuum with lifetime longer than the age of the universe   Degrassi et al., arXiv:1205.6497



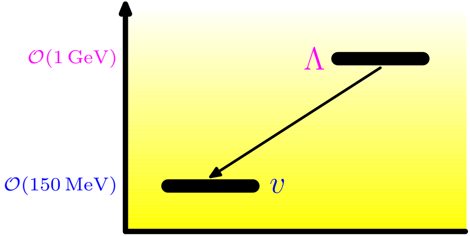
- Could the Higgs field ever have fallen in the correct vacuum?
  Hertzberg, arXiv:1210.3624

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



Analogous: QCD

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

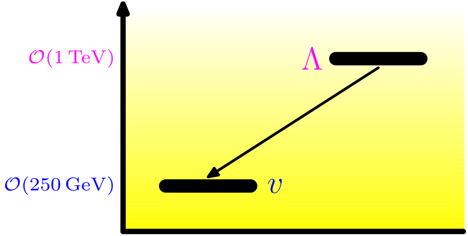
Scale v: pions, kaons, . . .

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



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

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

Without Fine-Tuning: experimentally excluded

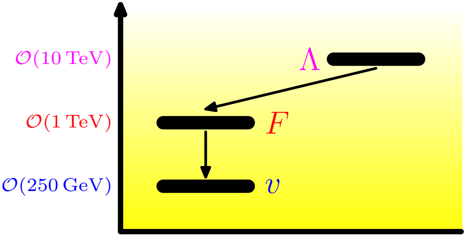
Collective symmetry breaking and 3-scale models

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

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

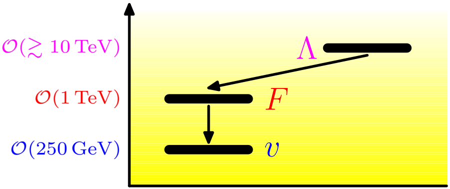


Scale Λ: global SB, new IA

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

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

Characteristics and Spectra

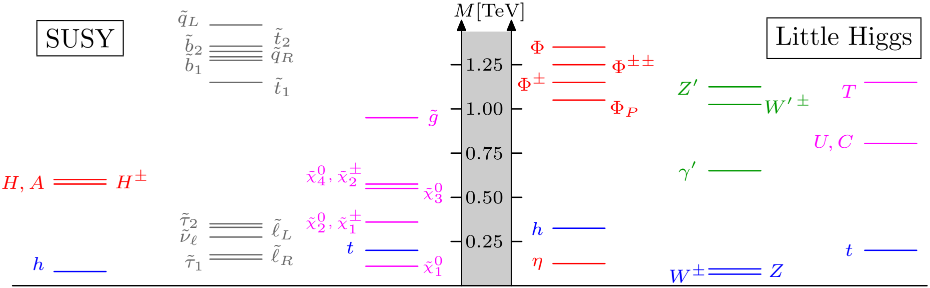


Scale Λ: "hidden sector", symmetry breaking

Scale F: new particles

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

Terascale: new particles to stabilize the hierarchy

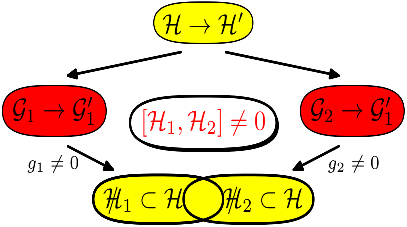


Generic properties of Little-Higgs models

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

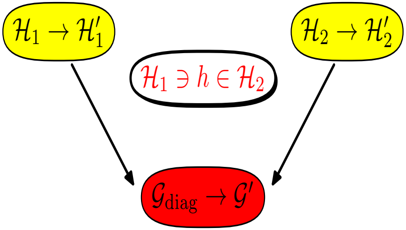
Product Group Models

(e.g. Littlest Higgs)



Simple Group Models

(e.g. Simplest Little Higgs)



- discrete T(TeV) parity: pair production, cascades, DM

Generic properties of Little-Higgs models

– Extended global symmetry (extended scalar sector)

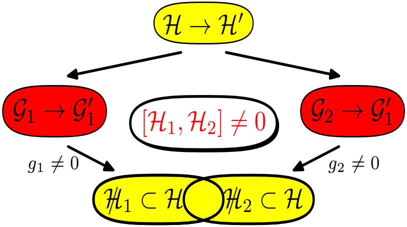
– Specific functional form of the potential

– Extended gauge symmetry: $\gamma' \equiv A_H, Z' \equiv Z_H, W'^{\pm} \equiv W_H$

– New heavy fermions: T, but also $U, C, \ldots$

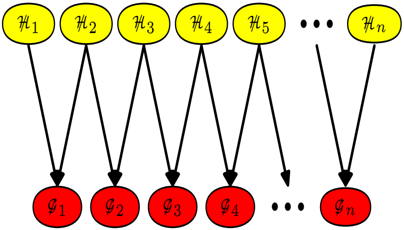
Product Group Models

(e.g. Littlest Higgs)



Moose Models

(e.g. Minimal Moose Model)



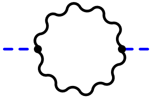
- discrete T(TeV) parity: pair production, cascades, DM

Prime Example: Simple Group Model

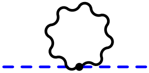
- enlarged gauge group: $SU(3) \times U(1)$; globally $U(3) \to U(2)$
- **Two** nonlinear Φ representations $\boxed{\mathcal{L} = |D_\mu \Phi_1|^2 + |D_\mu \Phi_2|^2}$

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

Coleman-Weinberg mechanism: Radiative generation of potential



$+$



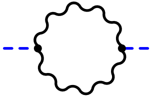
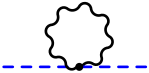
$$= \frac{g^2}{16\pi^2} \Lambda^2 \left(|\Phi_1|^2 + |\Phi_2|^2 \right) \sim \frac{g^2}{16\pi^2} f^2$$

Prime Example: Simple Group Model

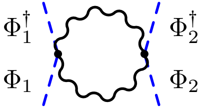
- enlarged gauge group: $SU(3) \times U(1)$; globally $U(3) \to U(2)$
- **Two** nonlinear Φ representations $\boxed{\mathcal{L} = |D_\mu \Phi_1|^2 + |D_\mu \Phi_2|^2}$

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

Coleman-Weinberg mechanism: Radiative generation of potential

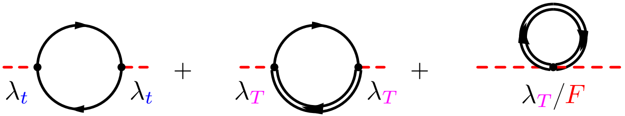
 $+$ 

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

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

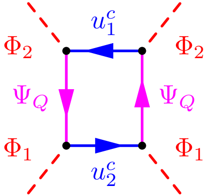


$$\propto \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2(k^2-m_T^2)} \left\{ \lambda_t^2 (k^2 - m_T^2) + k^2 \lambda_T^2 - \frac{m_T}{F} \lambda_T k^2 \right\}$$

Little Higgs global symmetry imposes relation

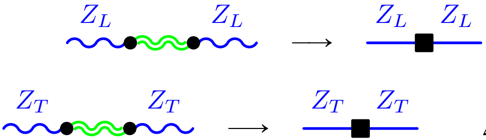
$$\frac{m_T}{F} = \frac{\lambda_t^2 + \lambda_T^2}{\lambda_T} \quad \Longrightarrow \quad \textbf{Quadratic divergence cancels}$$

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



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

Constraints from Oblique Corrections: S, T, U



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

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

◇ All low-energy effects order v^2/F^2 (Wilson coefficients)

ΔS, ΔT 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/JRR, 2003

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

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

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

Motivation

How to constrain a generic model in *HEP*?

- direct searches of resonances
- electroweak precision tests
- flavour constraints
- nowadays: Higgs sector

Higgs sector is the key to understand EW-scale physics (and beyond?)

Statistical analysis

We considered the three most popular Little Higgs models:

- Simplest Little Higgs (*SLH*) [Schmaltz]
- Littlest Higgs (L^2H) [Arkani-Hamed et al.]
- Littlest Higgs with *T*-parity (*LHT*) [Low et al.]

and realized a χ^2 analysis on their parameter spaces, taking into account the whole set of 7+8 TeV Higgs searches by *ATLAS* and *CMS*, and by fitting 21 different *EW* Precision Observables:

$$\chi^2 = \sum_i \frac{\left(\mathcal{O}_i - \mathcal{O}_i^{\text{exp}}\right)^2}{\sigma_i^2}$$

where $\mathcal{O}_i$ depends on the free parameters of the model considered.

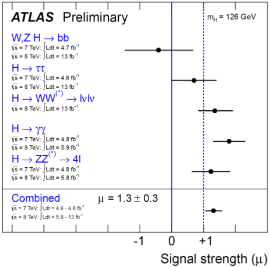
Data used: Higgs sector

the Higgs results are expressed in terms of a *signal strength modifier*

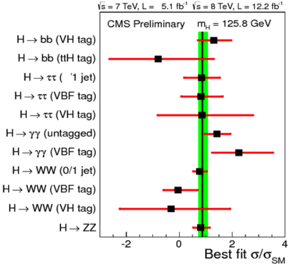
$$\mu_i = \frac{\sum_p {\epsilon^p}_i \, \sigma_p}{\sum_p {\epsilon^p}_i \, \sigma_p^{SM}} \cdot \frac{BR(h \to X_i X_i)}{BR(h \to X_i X_i)_{SM}}$$

we included in our χ^2 analysis the best-fit values of μ_i reported by the Collaborations for all the different 7+8 TeV channels i:

Best–fit Higgs mass m_H :
126.0 ± 0.4 (stat) ± 0.4 (syst) GeV



- M=125.8 ±0.4 (stat) ± 0.4 (syst) GeV



- σ/σ_{SM}=0.88±0.21

Data used: *EWPD*

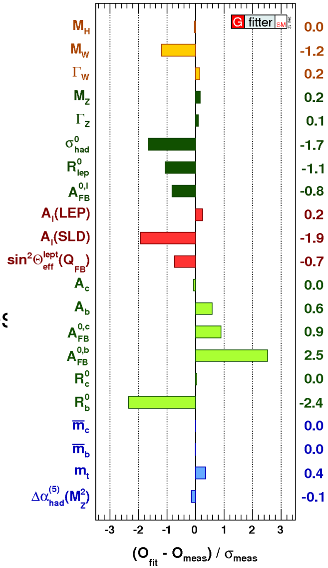
every extension of *SM* has to satisfy at least the precision constraints of the electroweak sector:

- low-energy observables

  e.g. ν-scattering, parity violation observables

- Z-pole observables

  e.g. m_Z, Γ_Z, Z-pole asymmetries...



LH Smoking guns

Where do the *LH* corrections to the *SM* quantities come from?

- new decay channels of the Higgs, e.g. $h \to A_H A_H$ in *LHT*
- modified Higgs couplings with *SM* fermions and vector bosons

$$\text{e.g.} \quad 2\,\frac{m_W^2}{v} y_W \, h \, W^+ W^-, \quad y_W = \begin{cases} 1 & SM \\ 1 + \mathcal{O}\left(v^2/f^2\right) & LH \end{cases}$$

- interaction terms of Higgs with new fermions/vector bosons

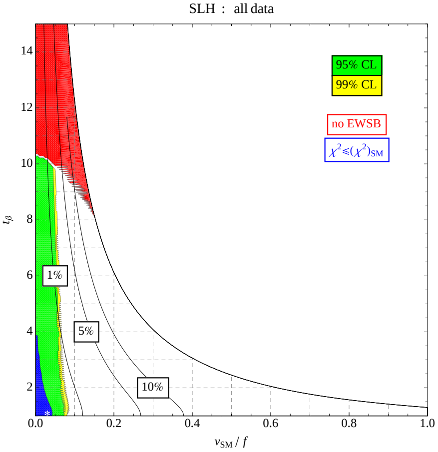
$$\text{e.g.} \quad \frac{m_T}{v} y_T \, h \, \bar{T} \, T \qquad m_T \sim f, \; y_T \sim \mathcal{O}\left(v^2/f^2\right)$$

- modified neutral- and charged-currents

$$\text{e.g.} \quad \frac{g}{c_W} \sum_f \bar{f} \gamma^\mu \Big((g_L^{SM} + \delta g_L) P_L + (g_R^{SM} + \delta g_R) P_R \Big) f \, Z_\mu$$

SLH results

JRR/Tonini, JHEP 1302 (2013) 077



$$\chi^2_{\text{min}}/\text{d.o.f.} = 1.043$$
$$\chi^2_{\text{SM}}/\text{d.o.f.} = 1.048$$

- free parameters: f *SSB* scale, t_β ratio of *vevs* of scalar fields $\phi_{1,2}$
- $f^{99\%}_{\text{min}} = 2.88$ TeV, translates into lower bounds on new states' masses, e.g.

$$m_{W'} \gtrsim 1.35 \text{ TeV}$$
$$m_T \gtrsim 2.81 \text{ TeV}$$

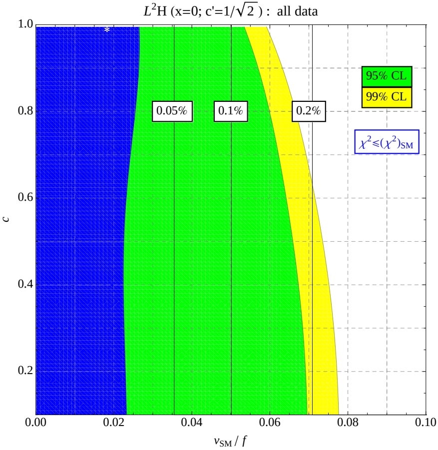
- min. required fine tuning: $\sim 1\%$, defined as

$$\Delta = \frac{|\delta\mu^2|}{\mu^2_{\text{obs}}}$$

- results mainly driven by *EWPD*

L^2H results

JRR/Tonini, JHEP 1302 (2013) 077



$$\chi^2_{\text{min}}/\text{d.o.f.} = 1.048$$
$$\chi^2_{\text{SM}}/\text{d.o.f.} = 1.049$$

- free parameters: f *SSB* scale, c mixing angle in gauge sector
- $f^{99\%}_{\text{min}} = 3.20$ TeV, translates into lower bounds on new states' masses, e.g.

$$m_{W'} \gtrsim 2.13 \text{ TeV}$$
$$m_T \gtrsim 4.50 \text{ TeV}$$

- min. required fine tuning: $\sim 0.1\%$, defined as

$$\Delta = \frac{|\delta\mu^2|}{\mu^2_{\text{obs}}}$$

- results mainly driven by *EWPD*

Partial decay widths in *LH*

- 1-loop decays

$$\Gamma(h \to gg)_{LH} \sim \frac{\alpha_s^2 m_h^3}{32\pi^3 v^2} \left| \sum_{\text{f,col}} -\frac{1}{2} F_{\frac{1}{2}}(x_f)\, y_f \right|^2$$

$$\Gamma(h \to \gamma\gamma)_{LH} \sim \frac{\alpha^2 m_h^2}{256\pi^3 v^2} \left| \sum_{\text{f,ch}} \frac{4}{2} F_{\frac{1}{2}}(x_f)\, y_f + \sum_{\text{v,ch}} F_1(x_v)\, y_v + \sum_{\text{s,ch}} F_0(x_s)\, y_s \right|^2$$

where $x_i = \frac{4m_i^2}{m_h^2}$, $F_i(x_i)$ are loop functions, y_i the modified Yuk. coupl.

$\Rightarrow$ narrow-width approximation: $\frac{\sigma_{LH}}{\sigma_{SM}}(gg \to h) = \frac{\Gamma(h \to gg)_{LH}}{\Gamma(h \to gg)_{SM}}$

- tree-level decays

$$\Gamma(h \to VV)_{LH} \sim \Gamma(h \to VV)_{SM} \left(\frac{g_{hVV}}{g_{hVV}^{SM}} \right)^2$$

$$\Gamma(h \to f\bar{f})_{LH} \sim \Gamma(h \to f\bar{f})_{SM} \left(\frac{g_{hff}}{g_{hff}^{SM}} \right)^2$$

where $g_{hVV} = \frac{m_V^2}{v} y_V$ and $g_{hff} = \frac{m_f}{v} y_f$

LHT: Littlest Higgs with T parity

- Goldstone boson matrix:

$$\Sigma = e^{2\,i\,\Pi/f} \qquad \Pi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & H & \sqrt{2}\Phi \\ H^\dagger & 0 & H^t \\ \sqrt{2}\Phi^\dagger & H^* & 0 \end{pmatrix} \qquad \Phi \propto \begin{pmatrix} \sqrt{2}\phi^{++} & \phi^+ \\ \phi^+ & \phi^0 + i\,\phi^P \end{pmatrix}$$

- Discrete T parity:

$$T: \quad \Pi \to -\Omega\,\Pi\,\Omega \qquad \Omega = \text{diag}(1,1,-1,1,1)$$

$$V_{CW} = \lambda_{\phi^2} f^2\,\text{Tr}(\phi^\dagger\phi) + i\lambda_{h\phi h} f\left(H\phi^\dagger H^t - H^*\phi H^\dagger\right) - \mu^2 HH^\dagger + \lambda_{h^4}(HH^\dagger)^2 +$$
$$+ \lambda_{h\phi\phi h}\,H\phi^\dagger\phi H^\dagger + \lambda_{h^2\phi^2}\,HH^\dagger\text{Tr}(\phi^\dagger\phi) + \lambda_{\phi^2\phi^2}\left[\text{Tr}(\phi^\dagger\phi)\right]^2 + \lambda_{\phi^4}\,\text{Tr}(\phi^\dagger\phi\phi^\dagger\phi).$$

$$\lambda_{\phi^2} = 2(g^2 + g'^2) + 8\lambda_1^2 \qquad \lambda_{h^4} = \tfrac{1}{4}\lambda_{\phi^2} \qquad \lambda_{h\phi h} = -\tfrac{4}{3}\lambda_{\phi^2}$$
$$\lambda_{h^2\phi^2} = -16\,\lambda_1^2 \qquad \lambda_{\phi^4} = -\tfrac{8}{3}(g^2 + g'^2) + \tfrac{16}{3}\lambda_1^2$$

- Yukawa couplings $\qquad k, R \equiv \lambda_1/\lambda_2$

$$\mathcal{L}_k = -\,kf\left(\bar\Psi_2\xi\Psi_c + \bar\Psi_1\langle\Sigma\rangle\Omega\xi^\dagger\Omega\Psi_c\right) - m_q\,\bar u'_c\,u_c - m_q\,\bar d'_c\,d_c - m_\chi\,\bar\chi'_c\,\chi_c + \text{h.c.}$$

$$\mathcal{L}_t = -\,\frac{\lambda_1 f}{2\sqrt{2}}\,\epsilon_{ijk}\,\epsilon_{xy}\left[\left(\bar\Psi_{1,t}\right)_i\Sigma_{jx}\Sigma_{ky} - \left(\bar\Psi_{2,t}\langle\Sigma\rangle\right)_i\Sigma'_{jx}\Sigma'_{ky}\right]t'_R - \lambda_2 f\left(\bar T_{L_1}T_{R_1} + \bar T_{L_2}T_{R_2}\right)$$

T parity and Dark Matter Cheng/Low, 2003; Hubisz/Meade, 2005; Wang/Yang/Zhu, 2013

- 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, $F \sim 0.5 - 1$ TeV
  but: Pair production!, typical cascade decays
- Lightest T-odd particle (LTP) $\Rightarrow$ Candidate for Cold Dark Matter

T parity and Dark Matter

Cheng/Low, 2003; Hubisz/Meade, 2005; Wang/Yang/Zhu, 2013

- 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, $F \sim 0.5 - 1$ TeV
  but: Pair production!, typical cascade decays
- Lightest T-odd particle (LTP) $\Rightarrow$ Candidate for Cold Dark Matter

Littlest Higgs: A' LTP

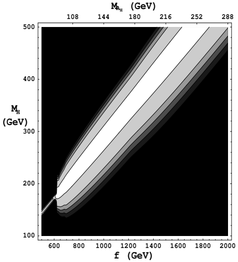
$W', Z' \sim$ 650 GeV, $\Phi \sim$ 1 TeV

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

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

Hubisz/Meade, 2005

0/10/50/70/100



T parity and Dark Matter Cheng/Low, 2003; Hubisz/Meade, 2005; Wang/Yang/Zhu, 2013

- 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, $F \sim 0.5 - 1$ TeV
  but: Pair production!, typical cascade decays
- Lightest T-odd particle (LTP) $\Rightarrow$ Candidate for Cold Dark Matter

Littlest Higgs: A' LTP

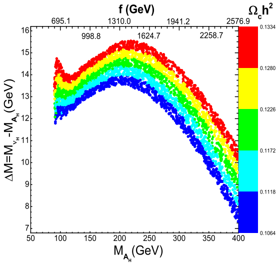
$W', Z' \sim$ 650 GeV, $\Phi \sim$ 1 TeV

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

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

Wang/Yang/Zhu, 2013

Relic density/SI cross section



T parity and Dark Matter

Cheng/Low, 2003; Hubisz/Meade, 2005; Wang/Yang/Zhu, 2013

- 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, $F \sim 0.5 - 1$ TeV
  but: Pair production!, typical cascade decays
- Lightest T-odd particle (LTP) $\Rightarrow$ Candidate for Cold Dark Matter

Littlest Higgs: A' LTP

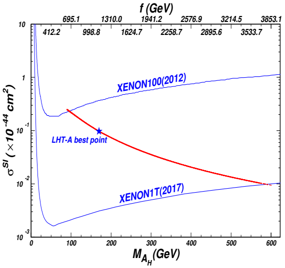
$W', Z' \sim$ 650 GeV, $\Phi \sim$ 1 TeV

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

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

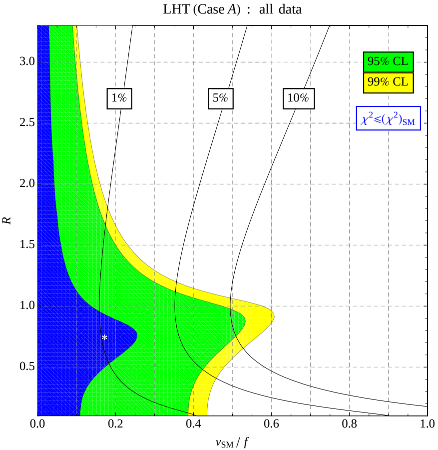
Wang/Yang/Zhu, 2013

Relic density/SI cross section



- T parity Simplest LH: Pseudo-Axion η LTP
  Z' remains odd: good or bad (?) Martin, 2006; JRR/Tonini, in prep.
- T parity might be anomalous (???) Hill/Hill, 2007

LHT results



$$\chi^2_{\text{min}}/\text{d.o.f.} = 1.048$$
$$\chi^2_{\text{SM}}/\text{d.o.f.} = 1.053$$

- free parameters: f *SSB* scale, R ratio of Yukawa couplings in top sector
- $f^{99\%}_{\text{min}} = 405.9$ GeV, translates into lower bounds on new states' masses, e.g.

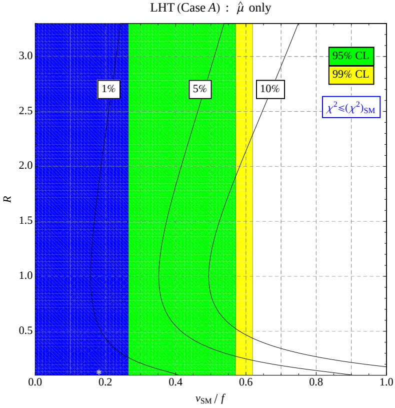
$$m_{W'} \gtrsim 269.6 \text{ GeV}$$
$$m_T \gtrsim 553.6 \text{ GeV}$$

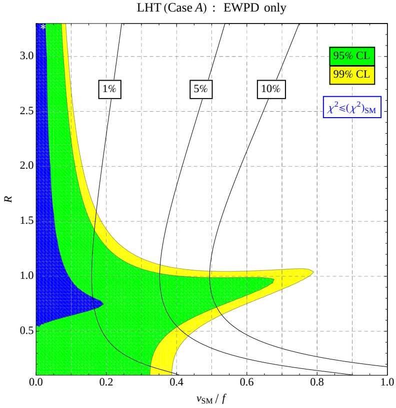
- min. required fine tuning: $\sim 10\%$, defined as

$$\Delta = \frac{|\delta\mu^2|}{\mu^2_{\text{obs}}}$$

- results mainly driven by *EWPD* (see next slide)

Higgs data vs. *EWPD*



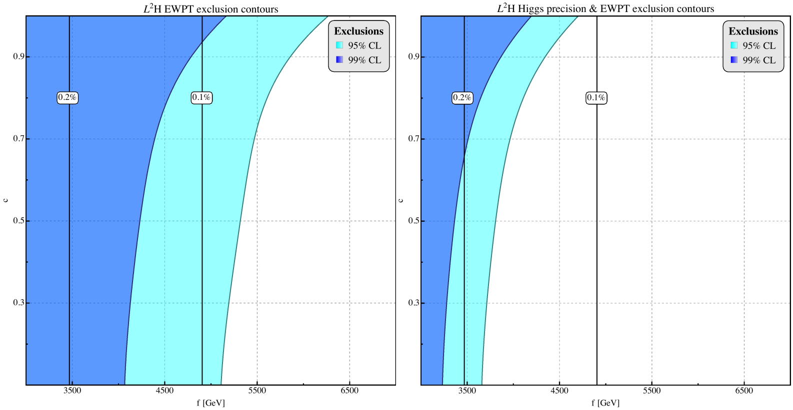


- the shape of the combined result is driven by the *EW* constraints (much smaller uncertainties)
- Higgs data only: for $v/f \gtrsim 0.6$ decay $h \to A_H A_H$ open and dominant
- Higgs data only: subdominant dependence on R w.r.t. f is a consequence of the Collective Symmetry Breaking mechanism

New Results (incl. Moriond ’13)

JRR/Tonini/de Vries, 1307.5010

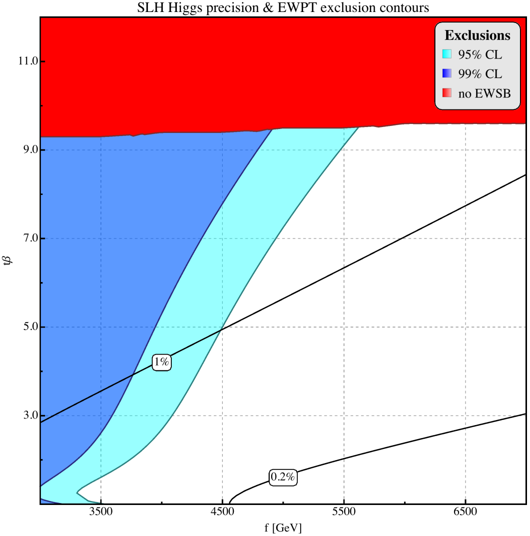
Littlest Higgs Model



New Results (incl. Moriond ’13)

JRR/Tonini/de Vries, 1307.5010

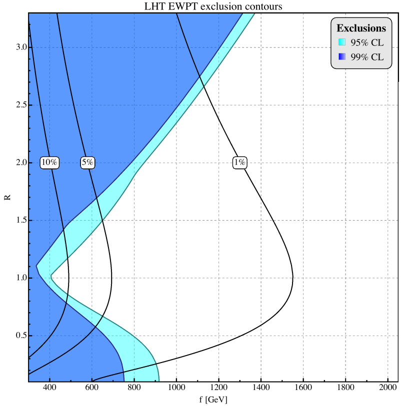
Simplest Little Higgs



New Results (incl. Moriond '13)

JRR/Tonini/de Vries, 1307.5010

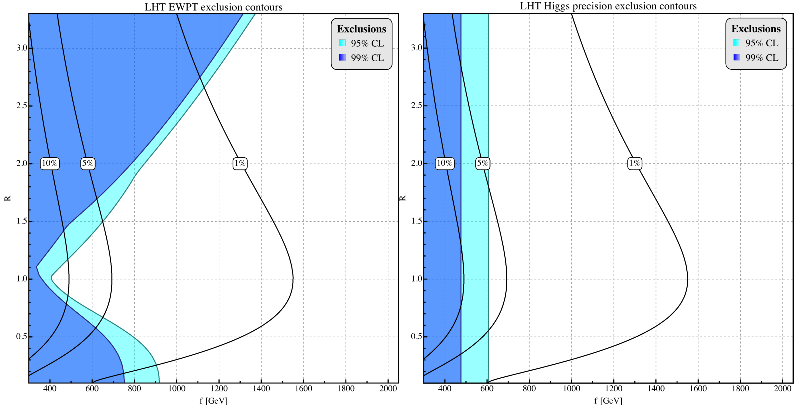
Littlest Higgs with T Parity



New Results (incl. Moriond ’13)

JRR/Tonini/de Vries, 1307.5010

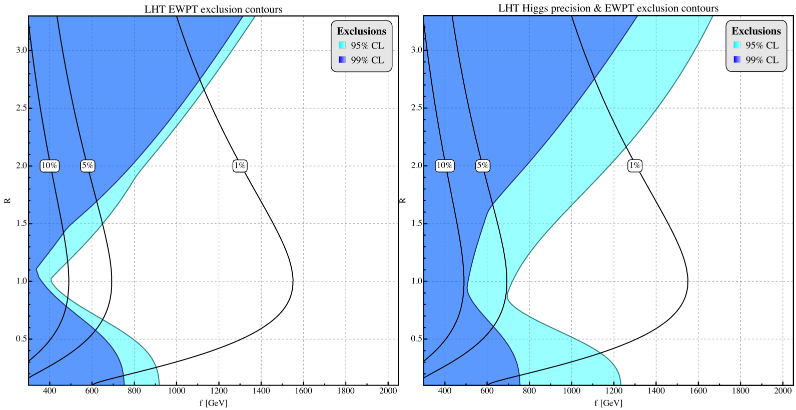
Littlest Higgs with T Parity



New Results (incl. Moriond ’13)

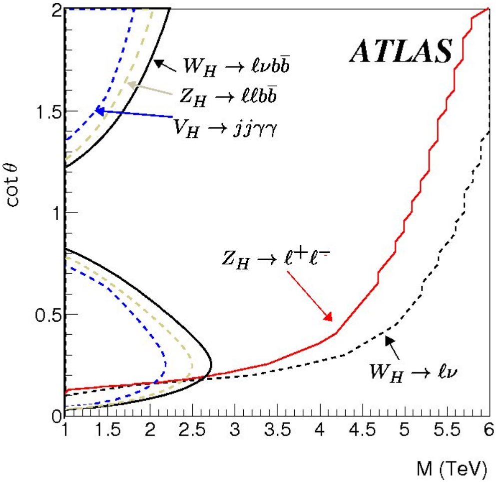
JRR/Tonini/de Vries, 1307.5010

Littlest Higgs with T Parity



- EWPT and Higgs data $\Rightarrow$ $f \gtrsim 694$ GeV

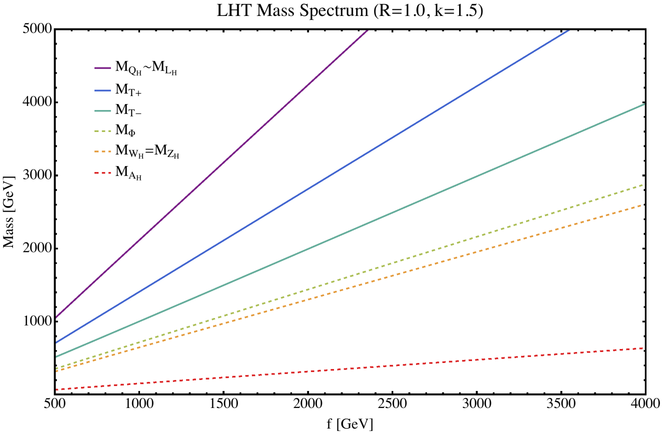
Direct searches: Drell-Yan mainly



Reach in the gauge boson sector: depends on mixing angle

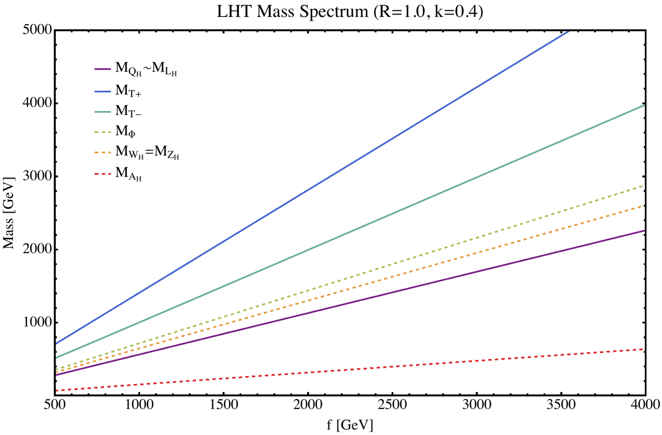
Direct Searches: Focus on LHT

- Defining two benchmark scenarios: 1. heavy quarks



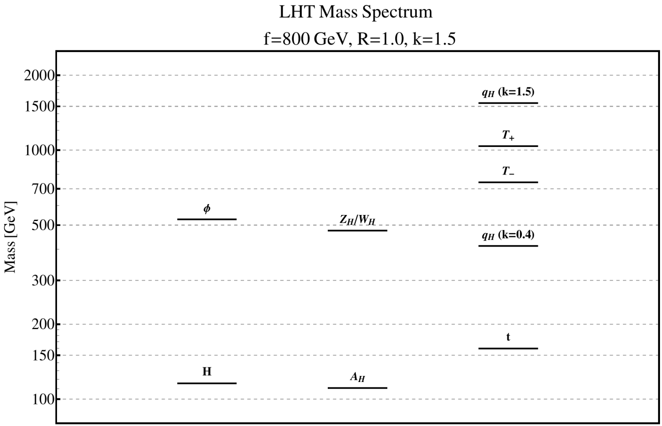
Direct Searches: Focus on LHT

- Defining two benchmark scenarios: 2. heavy top/vectors



Direct Searches: Focus on LHT

- Defining two benchmark scenarios: 1. $k = 1.5$, 2. $k = 0.4$



Branching Ratios

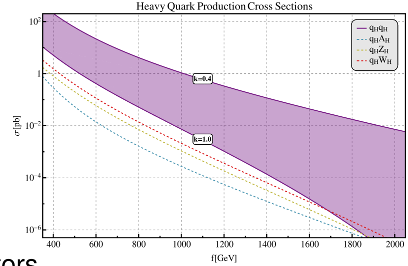
- Decay patterns:

Particle	Decay	$\mathrm{BR}_{k=1.0}$	$\mathrm{BR}_{k=0.4}$
$l_H^\pm$	$W_H^\pm\ \nu$	62%	0%
	$Z_H\, l^\pm$	31%	0%
	$A_H\, l^\pm$	6%	100%
$\nu_H^\pm$	$W_H^\pm\ l^\mp$	61%	0%
	$Z_H\, \nu$	30%	0%
	$A_H\, \nu$	9%	100%
T_H^+	$W^+\ b$	46%	45%
	$Z\ t$	22%	22%
	$H\ t$	21%	21%
	$T_H^-\ A_H$	11%	11%
A_H	stable		
Z_H	$A_H\, H$	100%	2%
	$d_H\, d$	0%	41%
	$u_H\, u$	0%	30%
	$l_H^\pm\ l^\mp$	0%	14%
	$\nu_H\, \nu$	0%	14%

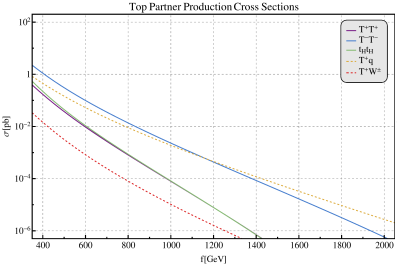
Particle	Decay	$\mathrm{BR}_{k=1.0}$	$\mathrm{BR}_{k=0.4}$
d_H	$W_H^-\ u$	62%	0%
	$Z_H\, d$	30%	0%
	$A_H\, d$	6%	100%
u_H	$W_H^+\ d$	58%	0%
	$Z_H\, u$	30%	0%
	$A_H\, u$	9%	100%
T_H^-	$A_H\ t$	100%	100%
	$Z_H\ t$	0%	0%
$\Phi^{0/P}$	$A_H\, H$	100%	100%
$\Phi^\pm$	$A_H\, W^\pm$	100%	100%
$\Phi^{\pm\pm}$	$A_H\, (W^\pm)^2$	100%	96%
$W_H^\pm$	$A_H\, W^\pm$	100%	2%
	$u_H\, d$	0%	44%
	$d_H\, u$	0%	27%
	$l_H^\pm\ \nu$	0%	16.5%
	$\nu_H\, l^\pm$	0%	16.5%

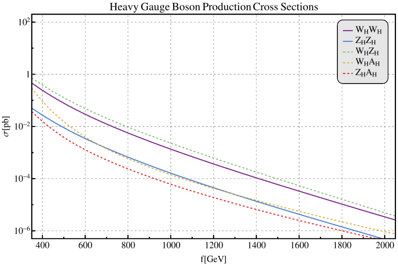
Cross Sections (I)

- Heavy Quarks



- Heavy Top and Vectors





Channels and signatures: Parameters

final state			modes	params
leptons	# jets	$\not{E}_T$		
0	1	✓	$q_H A_H$	f, k
0	2	✓	$q_H q_H$	f, k
0	3	✓	$q_H W_H^\pm$	f, k
0	4	✓	$q_H q_H$ $W_H^\pm W_H^\mp$ $W_H^\pm Z_H$ $Z_H Z_H$	f, k f, k f, k f, k
0	4	✗	$T^+ q$	f, k, R
0	5	✓	$q_H W_H^\pm$	f, k
0	6	✓	$q_H q_H$ $T^- T^-$	f, k f, k, R

final state			modes	params
leptons	# jets	$\not{E}_T$		
$l^\pm$	2	✓	$W_H^\pm W_H^\mp$ $W_H^\pm Z_H$ $q_H q_H$	f, k f, k f, k
$l^\pm$	3	✓	$q_H W_H^\pm$ $T^+ q$	f, k f, k, R
$l^\pm$	4	✓	$q_H q_H$ $T^- T^-$	f, k f, k, R
$l^+ l^-$	0	✓	$W_H^\pm W_H^\mp$	f, k
$l^+ l^-$	1	✓	$q_H W_H^\pm$	f, k
$l^+ l^-$	2	✓	$q_H q_H$ $T^- T^-$	f, k f, k, R
$l^\pm l^\pm$	2	✓	$q_H q_H$	f, k

Channels and signatures (I)

final state			production	$\sigma_{8\text{ TeV}} \times \text{Br (fb)}$		$\sigma_{14\text{ TeV}} \times \text{Br (fb)}$	
$\# l^{\pm}$	# jets	$\not{E}_T$	modes	$k = 1.0$	$k = 0.4$	$k = 1.0$	$k = 0.4$
0	1	✓	$q_H A_H$	0.24	1.1×10^2	2.1	4.5×10^2
0	2	✓	$q_H q_H$	0.56	5.6×10^3	5.2	3.2×10^4
0	3	✓	$q_H W_H^{\pm}$ $q_H Z_H$	0.73 0.76	14 8.6	8.0 8.0	77 49
0	4	✓	$q_H q_H$ $W_H^{\pm} W_H^{\mp}$ $W_H^{\pm} Z_H$ $Z_H Z_H$	4.0 1.9 4.8 0.56	9.1×10^2 low low low	35 9.1 23 3.0	5.6×10^3 low low low
0	4	✗	$T^+ q$	2.0	2.0	17	17
0	5	✓	$q_H W_H^{\pm}$ $q_H Z_H$	5.1 4.1	✗ ✗	54 44	✗ ✗
0	6	✓	$q_H q_H$ $T^- T^-$	1.6 2.5	9.7×10^2 2.5	1.7×10^2 25	6.0×10^3 25

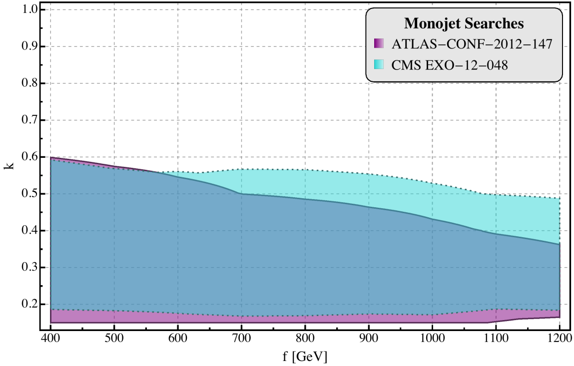
Channels and signatures (II)

final state			production	$\sigma_{8\text{ TeV}} \times \text{Br (fb)}$		$\sigma_{14\text{ TeV}} \times \text{Br (fb)}$	
$\# l^\pm$	# jets	$\not{E}_T$	modes	$k = 1.0$	$k = 0.4$	$k = 1.0$	$k = 0.4$
$l^\pm$	2	✓	$q_H q_H$ $W_H^\pm W_H^\mp$ $W_H^\pm Z_H$ $T^+ q$	0.058 0.77 2.1 1.3	9.0×10^2 low low 1.2	1.1 3.9 10 10	5.6×10^3 low low 10
$l^\pm$	3	✓	$q_H W_H^\pm$ $q_H Z_H$	3.5 0.99	✗ ✗	37 11	✗ ✗
$l^\pm$	4	✓	$q_H q_H$ $T^- T^-$	7.4 2.2	9.7×10^2 2.2	82 21	6.0×10^3 21
$l^+ l^-$	0	✓	$W_H^\pm W_H^\mp$	0.32	low	1.7	low
$l^+ l^-$	1	✓	$q_H W_H^\pm$	0.54	✗	5.8	✗
$l^+ l^-$	2	✓	$q_H q_H$ $T^- T^-$	1.1 0.47	✗ 0.47	11 4.6	✗ 4.6
$l^\pm l^\pm$	2	✓	$q_H q_H$	0.37	✗	2.7	✗

Recasting results

JRR/Tonini/deVries,2013

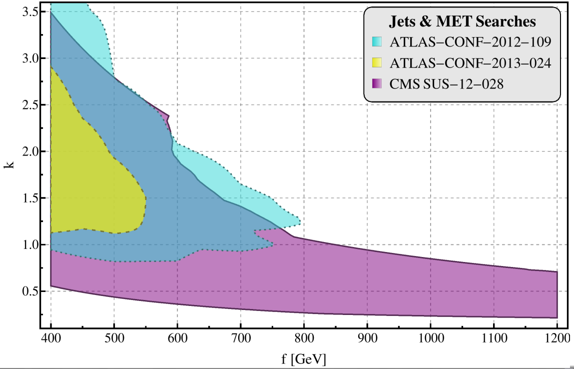
- 95% CL from Monojets + $\not{E}_T$ from LHC8
- 1 hard jet, $\not{E}_T$, no leptons, 2nd jet w. $p_T > 30$ GeV
  signal regions: ATLAS $(p_T, \not{E}_T) >$ 120/220/350/500 GeV, CMS: $\not{E}_T >$ 250/300/350/400/450/500/550 GeV
- Dijet suppression: ATLAS $\Delta\phi(\not{E}_T, j_2) > 0.5$, CMS $\Delta\phi(j_1, j_2) < 2.5$
- $pp \to q_H q_H$, $pp \to q_H A_H$



Recasting results

JRR/Tonini/deVries,2013

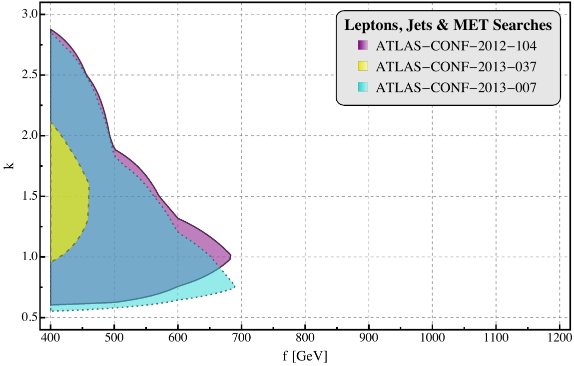
- 95% CL from Jets + $\not\!\!E_T$ from LHC8
- $\geqslant 2$ hard jets, $\not\!\!E_T$, no leptons
- signal regions: ATLAS $\not\!\!E_T > 200/300/350$ GeV, CMS:
  $(N_j, N_b) = (2-3, 0); (2-3, 1-2); (\geqslant 4, 1-2); (\geqslant 4, 0); (\geqslant 4, \geqslant 2)$
- QCD suppression: ATLAS $\Delta\phi(\not\!\!E_T, j_2) > 0.5$, $\not\!\!E_T/m_{eff}$, CMS $\Delta\phi(j_1, j_2) < 2.5$
- $pp \to q_H q_H \to (jA_H)(jA_H)$



Recasting results

JRR/Tonini/deVries,2013

- 95% CL from Leptons + Jets + $\not{E}_T$ from LHC8
- single isolated lepton, $\geqslant 2$ hard jets, $\not{E}_T$,
- signal regions: ATLAS $\not{E}_T >$ 200/300/350 GeV
- Cuts: $\not{E}_T > 250\,\text{GeV}$, $m_T(l, \not{E}_T) > 250\,\text{GeV}$, $\not{E}_T/m_{\text{eff}} > 0.2$, $m_{\text{eff}}^{\text{inc}} > 800\,\text{GeV}$
- $pp \to q_H q_H$ with $q_H \to W_H q, Z_H q, t_H \to t A_H, Z_H \to H A_H$

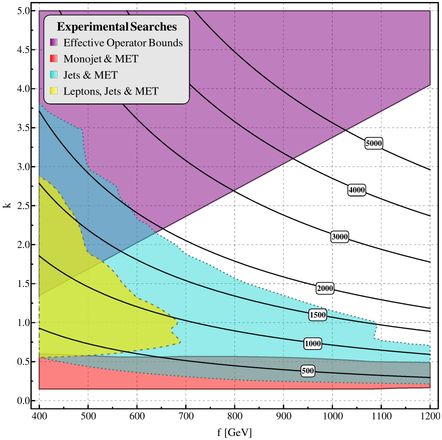


Combined analysis

JRR/Tonini/deVries,2013

- Operator bounds: $\mathcal{O}_{4\text{-f}} = -\frac{k^2}{128\,\pi^2 f^2} \bar{\psi}_L \gamma^\mu \psi_L \bar{\psi}'_L \gamma_\mu \psi'_L + O\left(\frac{g}{k}\right)$

  Hubisz/Meade/Noble/Perelstein, 2005



- Bound from combined analysis: $f \gtrsim 638\text{GeV}$

Conclusions

- *Little Higgs* models are an appealing solution to the hierarchy problem, alternative to weakly coupled solutions like *SUSY*
- most of the parameter space of three popular *Little Higgs* models is still compatible at $\sim 99\%$ *CL* with the early results of the 7+8 TeV Higgs searches
- electroweak precision data represent still the most severe constraints
- fine-tuning as a guideline to understand the naturalness of a model: *Little Higgs* models require a minimum level of $\sim 10\%$ of fine tuning
- Limits on the LHT:
  1. EWPO: $f \gtrsim 405$ GeV@95% CL

Conclusions

- *Little Higgs* models are an appealing solution to the hierarchy problem, alternative to weakly coupled solutions like *SUSY*
- most of the parameter space of three popular *Little Higgs* models is still compatible at $\sim 99\%$ *CL* with the early results of the 7+8 TeV Higgs searches
- electroweak precision data represent still the most severe constraints
- fine-tuning as a guideline to understand the naturalness of a model: *Little Higgs* models require a minimum level of $\sim 10\%$ of fine tuning
- Limits on the LHT:
  1. EWPO: $\boxed{f \gtrsim 405 \text{ GeV@}95\% \text{ CL}}$
  2. Higgs: $\boxed{f \gtrsim 607 \text{ GeV@}95\% \text{ CL}}$

Conclusions

- *Little Higgs* models are an appealing solution to the hierarchy problem, alternative to weakly coupled solutions like *SUSY*
- most of the parameter space of three popular *Little Higgs* models is still compatible at $\sim 99\%$ *CL* with the early results of the 7+8 TeV Higgs searches
- electroweak precision data represent still the most severe constraints
- fine-tuning as a guideline to understand the naturalness of a model: *Little Higgs* models require a minimum level of $\sim 10\%$ of fine tuning
- Limits on the LHT:
  1. EWPO: $f \gtrsim 405$ GeV@95% CL
  2. Higgs: $f \gtrsim 607$ GeV@95% CL
  3. Higgs+EWPO: $f \gtrsim 694$ GeV@95% CL

Conclusions

- *Little Higgs* models are an appealing solution to the hierarchy problem, alternative to weakly coupled solutions like *SUSY*
- most of the parameter space of three popular *Little Higgs* models is still compatible at $\sim 99\%$ *CL* with the early results of the 7+8 TeV Higgs searches
- electroweak precision data represent still the most severe constraints
- fine-tuning as a guideline to understand the naturalness of a model: *Little Higgs* models require a minimum level of $\sim 10\%$ of fine tuning
- Limits on the LHT:
  1. EWPO: $f \gtrsim 405$ GeV@95% CL
  2. Higgs: $f \gtrsim 607$ GeV@95% CL
  3. Higgs+EWPO: $f \gtrsim 694$ GeV@95% CL
  4. Direct searches: $f \gtrsim 638$ GeV@95% CL

Conclusions

- *Little Higgs* models are an appealing solution to the hierarchy problem, alternative to weakly coupled solutions like *SUSY*
- most of the parameter space of three popular *Little Higgs* models is still compatible at $\sim 99\%$ *CL* with the early results of the 7+8 TeV Higgs searches
- electroweak precision data represent still the most severe constraints
- fine-tuning as a guideline to understand the naturalness of a model: *Little Higgs* models require a minimum level of $\sim 10\%$ of fine tuning
- Limits on the LHT:
  1. EWPO: $f \gtrsim 405$ GeV@95% CL
  2. Higgs: $f \gtrsim 607$ GeV@95% CL
  3. Higgs+EWPO: $f \gtrsim 694$ GeV@95% CL
  4. Direct searches: $f \gtrsim 638$ GeV@95% CL
- We need more data!

Lessons from Lepton Photon 2013 ...

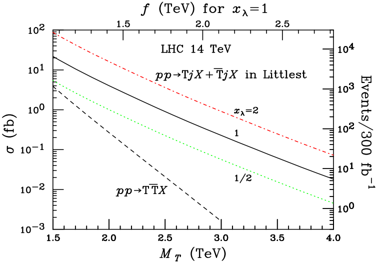
There are either colored exotics ...

Lessons from Lepton Photon 2013 ...

... or the world is fine tuned

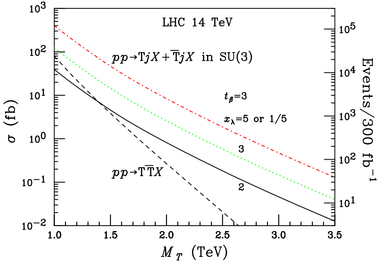
Direct Searches – Heavy Quark States

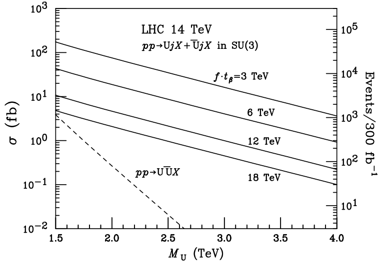
- EW single dominates QCD pair production: Perelstein/Peskin/Pierce, ’03



Direct Searches – Heavy Quark States

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





- Characteristic branching ratios :

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

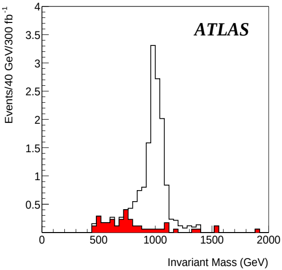
- Proof of T as EW singlet; but: $T \to Z'T, W'b, t\eta$!

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

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

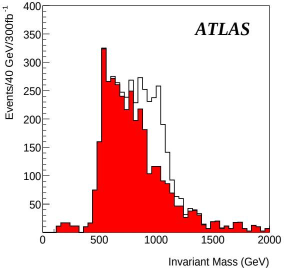
$T \to Zt \to \ell^+\ell^-\ell\nu b$ SN-ATLAS-2004-038

- $\not{E}_T > 100$ 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



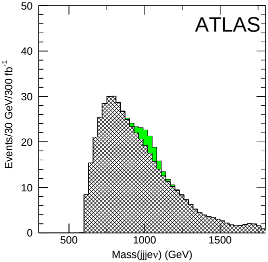
$T \to Wb \to \ell\nu b$ SN-ATLAS-2004-038

- $\not{E}_T > 100$ 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



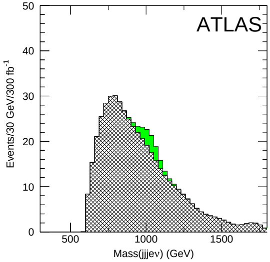
$T \to th \to \ell\nu bbb$ SN-ATLAS-2004-038

- $\ell, p_T > 100$ 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



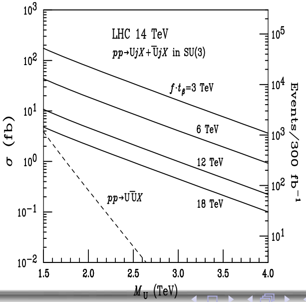
$T \to th \to \ell\nu bbb$ SN-ATLAS-2004-038

- $\ell, p_T > 100$ 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

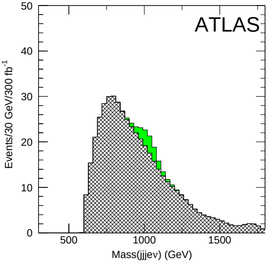


Additional heavy quarks (Simple Group Models): U, C or D, S Han et al., 05

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



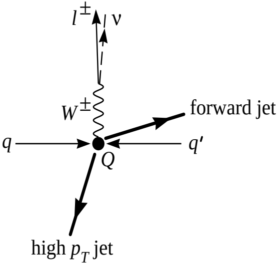
$T \to th \to \ell\nu bbb$ SN-ATLAS-2004-038



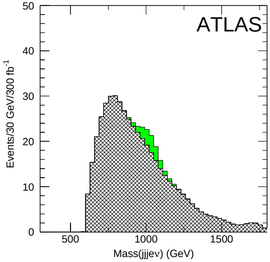
- $\ell, p_T > 100$ GeV, $jjj, p_T > 130$ GeV, at least 1 b-tag
- Bkgd.: $t\bar{t}, Wb\bar{b}$, single t
- Observation for $M_T \lesssim 2.5$ TeV

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 ℓ charge asymmetry
- Good mass reconstruction



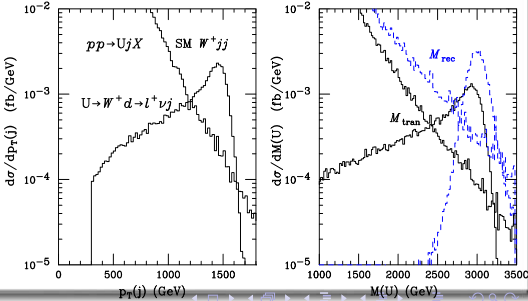
$T \to th \to \ell\nu bbb$ SN-ATLAS-2004-038



- $\ell, p_T > 100$ 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

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

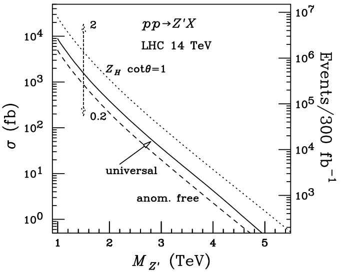
- Large cross section: u or d PDF
- Huge final state ℓ charge asymmetry
- Good mass reconstruction



Direct Searches – Heavy Vectors

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

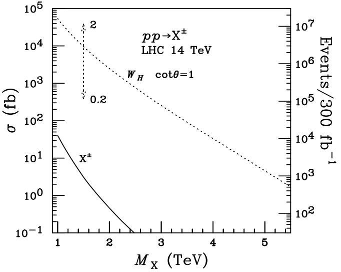
- Dominant decays:
  Product group: $Z' \to Zh, WW$,
  $W' \to Wh, WZ$
  Simple group: $Z' \to qq, \quad X \to fF$



Direct Searches – Heavy Vectors

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

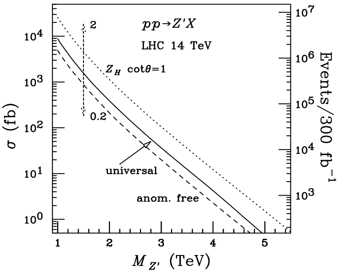
- Dominant decays:
  Product group: $Z' \to Zh, WW$,
  $W' \to Wh, WZ$
  Simple group: $Z' \to qq, \quad X \to fF$



Direct Searches – Heavy Vectors

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

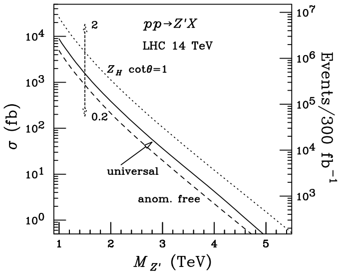
- Dominant decays:
  Product group: $Z' \to Zh, WW$,
  $W' \to Wh, WZ$
  Simple group: $Z' \to qq, \quad X \to fF$
- Discovery channel: $Z' \to \ell\ell$, $W' \to \ell\nu$
- $\Gamma_{Z'} \sim 10 - 50$ GeV, $\Gamma_X \sim 0.1 - 10$ GeV

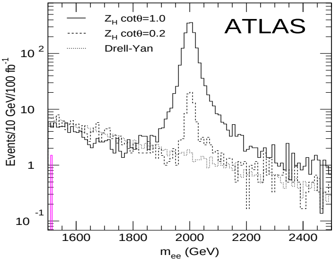


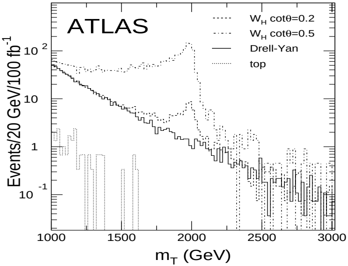
Direct Searches – Heavy Vectors

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

- Dominant decays:
  Product group: $Z' \to Zh, WW$,
  $W' \to Wh, WZ$
  Simple group: $Z' \to qq$, $X \to fF$
- Discovery channel: $Z' \to \ell\ell$, $W' \to \ell\nu$
- $\Gamma_{Z'} \sim 10 - 50$ GeV, $\Gamma_X \sim 0.1 - 10$ GeV





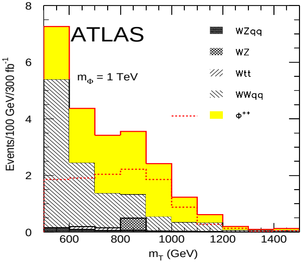


Direct Searches – Heavy Scalars

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



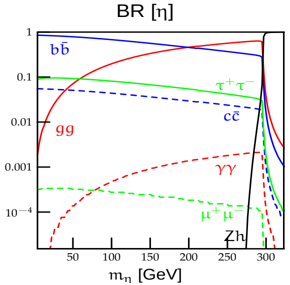
Alternative: Model-Independent search in WW fusion:

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

LHC: Alboteanu/Kilian/JRR, 2008; Kilian/JRR/Sekulla, 2013

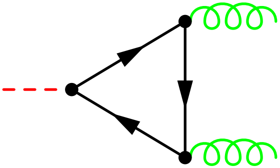
Pseudo-Axions in Little Higgs

Kilian/Rainwater/JRR, 2004, 2006; JRR, 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 $U(1)$:



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

- $U(1)$ 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/JRR, 2006

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

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

- Use special structure of covariant derivatives:

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

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

- 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

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

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

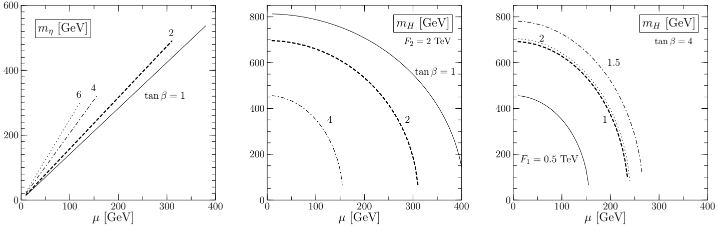
$$\mathbb{V}_\mu + \frac{i}{F}[\Sigma, \mathbb{V}_\mu] - \frac{1}{2F^2}[\Sigma,[\Sigma,\mathbb{V}_\mu]] + \ldots$$
$$= \begin{pmatrix} \mathbb{W}_\mu & 0 \\ 0 & 0 \end{pmatrix} + \frac{i}{F}\begin{pmatrix} 0 & -\mathbb{W}_\mu h \\ h^\dagger \mathbb{W}_\mu & 0 \end{pmatrix} - \frac{1}{2F^2}\begin{pmatrix}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

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

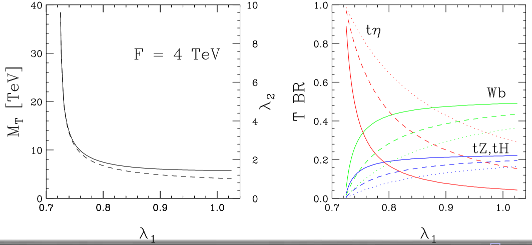
$$(\partial^\mu\eta)h^\dagger\mathbb{W}_\mu h \sim vHZ_\mu\partial^\mu\eta .$$

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/JRR, 2006



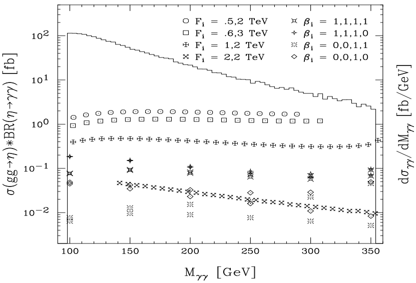
Discovery of Pseudo-axions

Kilian/Rainwater/JRR, 2004, 2006

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

LHC: $T \to t\eta$

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



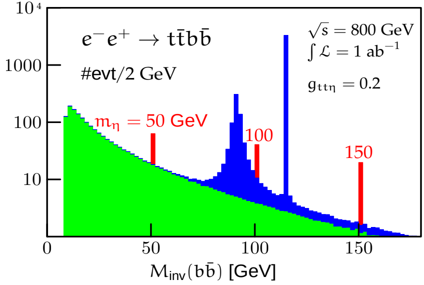
Discovery of Pseudo-axions

Kilian/Rainwater/JRR, 2004, 2006

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

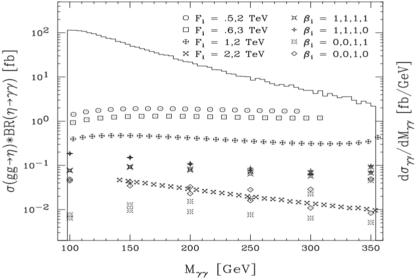
LHC: $T \to t\eta$

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



Discovery of Pseudo-axions

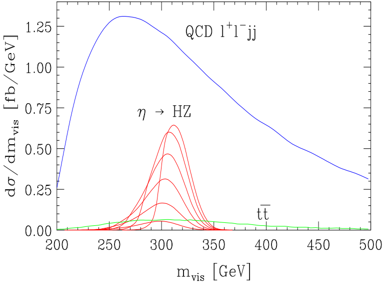
Kilian/Rainwater/JRR, 2004, 2006



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

LHC: $T \to t\eta$

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



$ZH\eta$ coupling

forbidden in Product Group Models

Discriminator of diff. model classes

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

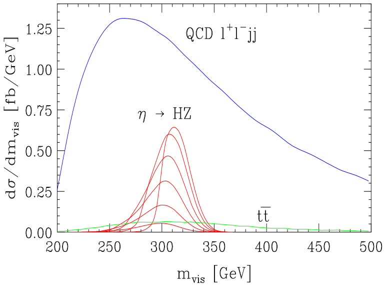
Discovery of Pseudo-axions

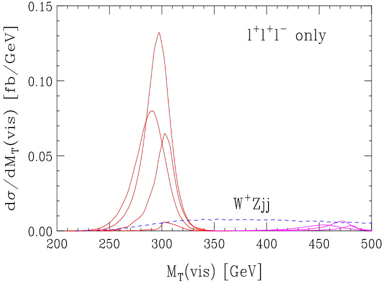
Kilian/Rainwater/JRR, 2004, 2006

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

LHC: $T \to t\eta$

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





$ZH\eta$ coupling

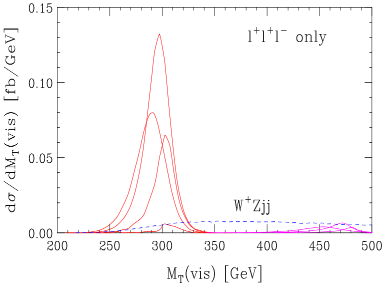
forbidden in Product Group Models

Discriminator of diff. model classes

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

Discovery of Pseudo-axions

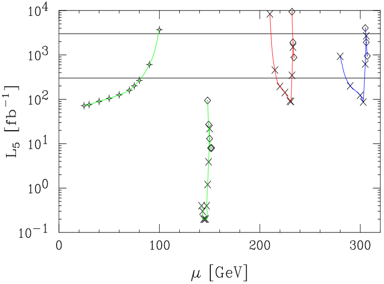
Kilian/Rainwater/JRR, 2004, 2006



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

LHC: $T \to t\eta$

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



$ZH\eta$ coupling

forbidden in Product Group Models

Discriminator of diff. model classes

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

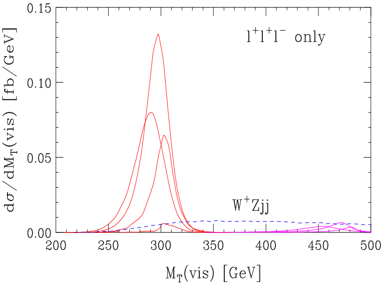
Discovery of Pseudo-axions

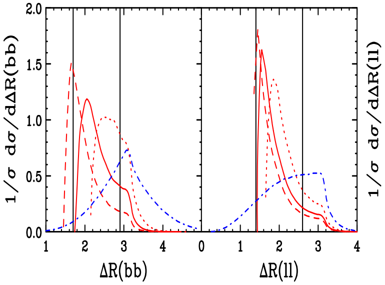
Kilian/Rainwater/JRR, 2004, 2006

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

LHC: $T \to t\eta$

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





$ZH\eta$ coupling

forbidden in Product Group Models

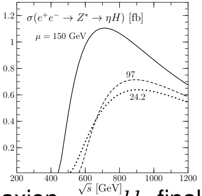
Discriminator of diff. model classes

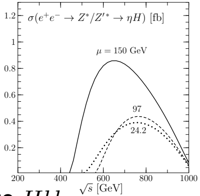
$$gg \to \left\{ \begin{array}{lll} H \to Z\eta & \to \ell\ell bb \\ \eta \to ZH & \to \ell\ell bb, \ell\ell\ell jj \end{array} \right\}$$

η pheno at ILC

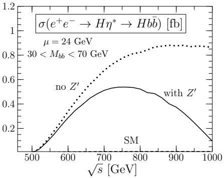
Kilian/Rainwater/JRR, 2006

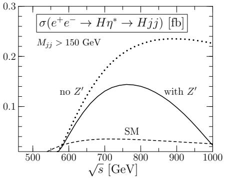
If $ZH\eta$ coupling present: $H\eta$ production in analogy to HA:

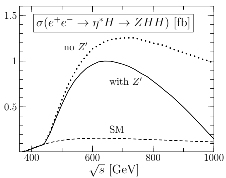




- Light pseudoaxion, $\eta \to bb$, final state Hbb
- Intermediate range, $\eta \to gg$, final state Hjj
- $\eta \to ZH$: ZHH final state





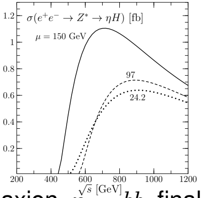


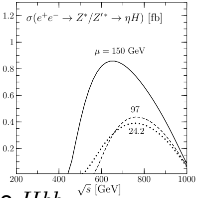
More detailed insights from photon collider option

η pheno at ILC

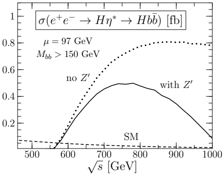
Kilian/Rainwater/JRR, 2006

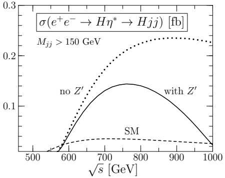
If $ZH\eta$ coupling present: $H\eta$ production in analogy to HA:

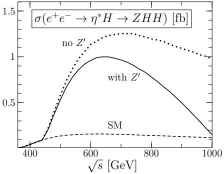




- Light pseudoaxion, $\eta \to bb$, final state Hbb
- Intermediate range, $\eta \to gg$, final state Hjj
- $\eta \to ZH$: ZHH final state



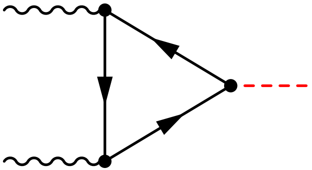




More detailed insights from photon collider option

Pseudo Axions at the Photon Collider

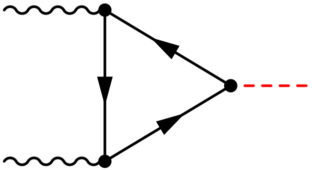
- Photon Collider as precision machine for Higgs physics (s channel resonance, anomaly coupling)



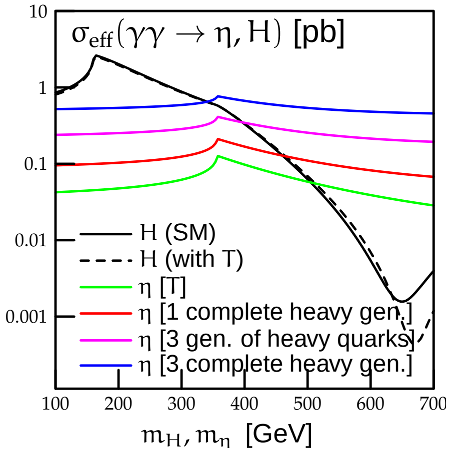
- S/B analogous to LC
- η in the μ model with (almost) identical parameters as A in MSSM
  ($\hookrightarrow$ Mühlleitner et al. (2001))

Pseudo Axions at the Photon Collider

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

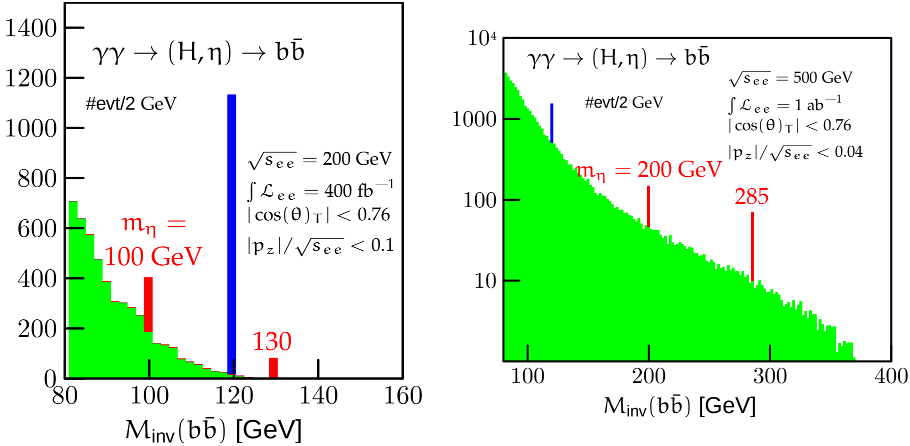


- S/B analogous to LC
- η in the μ model with (almost) identical parameters as A in MSSM
  ($\hookrightarrow$ Mühlleitner et al. (2001))



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

m_η	100	130	200	285
$\Gamma_{\gamma\gamma}$[keV]	0.15	0.27	1.1	3.6



Simplest Little Higgs ("μ Model")

Schmaltz '04, Kilian/Rainwater/JRR '04

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

$$\Phi_{1,2} : (1,3)_{-\frac{1}{3}} \qquad \Psi_\ell : (1,3)_{-\frac{1}{3}} \qquad {u_{1,2}}^c : (\bar{3},1)_{-\frac{2}{3}}$$

$$\Psi_Q : (3,3)_{\frac{1}{3}} \qquad d^c : (\bar{3},1)_{\frac{1}{3}} \qquad e^c, n^c : (1,1)_{1,0}$$

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

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