The Big Deal with the Little Higgs

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The Higgs boson: pros and cons

Electroweak interactions mediated by massive gauge bosons:
($SU(2) \times U(1)$ gauge theory)

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- **Formal Solution:** Introduction of a field which *makes Lagrangian gauge-invariant:* $\Rightarrow$ Higgs field
- Spontaneous symmetry breaking: Higgs gets a Vacuum Expectation value $v \sim 250$ GeV
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- Data prefers a weakly interacting theory at the TeV scale $\Rightarrow$ Higgs field corresponds to light Higgs particle ($m_h < 300\,$GeV)
- **Fine-tuning/Hierarchy problem:** quantum corrections $\boxed{\delta m_h^2 \propto \Lambda^2}$
  Λ new physics scale
- **Solution:** Symmetry cancels quantum corrections, broken at lower scale $F \sim 1\,$TeV

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

Light Higgs as Pseudo-Goldstone boson $\Leftrightarrow$ spontaneously broken (approximate) *global* symmetry

- w/o Fine-Tuning: $v \sim \Lambda/4\pi$

Collective Symmetry Breaking and 3 Scale-Models

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

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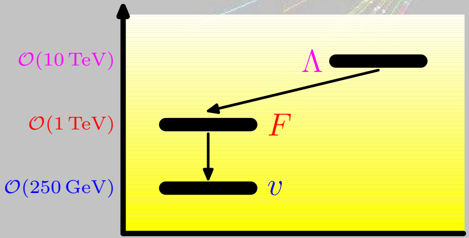

- Scale Λ: global SB, new dynamics
- Scale F: Pseudo-Goldstone bosons, new vectors/fermions
- Scale v: Higgs, W/Z, $\ell^{\pm}$, . . .

Generic properties of Little Higgs Models

- Extended scalar (Higgs-) sector

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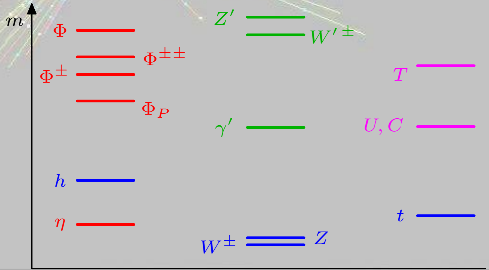
- **Extended Gauge Sector:** $\gamma', Z', W'^{\pm}$
- Extended fermion sector: new heavy top: T, maybe also $U, C, \ldots$

Example: Littlest Higgs

Arkani-Hamed/Cohen/
Katz/Nelson, 2002



Phenomenology of Little Higgs Models

Questions:

- Constraints from past/present experiments?
- What can future experiments do?
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- Experimental precision @ ‰ level consistent with truncation of expansion at order v^2/F^2
- ◇ **Little Higgs Effective Field Theory:** SM + Dimension 6 Operators

Constraints from contact interactions (SLC/LEP): $F \gtrsim c^2 \times (4.5\,\text{TeV})$

◇ **Constraints evaded** $\Longleftrightarrow$ $c \ll 1$

$\gamma', Z', W'^{,\pm}$ superheavy ($\mathcal{O}(\Lambda)$) *decouple from fermions*

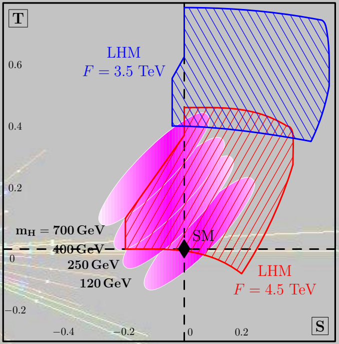
More Phenomenology

ΔS, ΔT in the Littlest Higgs model

Csáki et al./Hewett et al., 2002; Han et al.; Kilian/JR, 2003

- Mixing of (Z, γ', Z'), $(W^\pm, W'^\pm)$

$$\Delta S/8\pi \to 0 \qquad \alpha \Delta T \sim \frac{v^2}{F^2}$$



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Heavier Higgs compensates ΔT.

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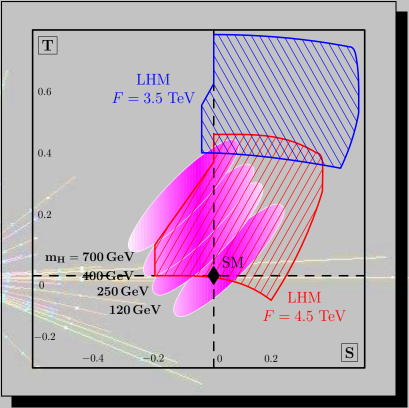

Neutrino masses

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

Lepton-number violating interactions can generate **neutrino masses**

Direct Searches

- **Heavy Gauge Bosons:** Resonance in $e^+e^- \to f\bar{f}$

Drell-Yan: $pp/p\bar{p} \to \ell^+\ell^- \Rightarrow$ Tevatron: $M_{\gamma'} \gtrsim 650$ GeV

$\mathcal{O}(10^2)$ lepton events @ LHC *Determination of* $\boldsymbol{F}$, $\boldsymbol{c}$

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Forward-Backward-Asymmetry Rosner et al., 1984; Han/Kilian/JR

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- **Heavy Scalars:** very difficult (CLIC?)

- **Heavy Top:** T production @ LHC: $bq \to Tq'$
  $T \to W^+b, th, tZ$ Perelstein/Peskin/Pierce, 2003

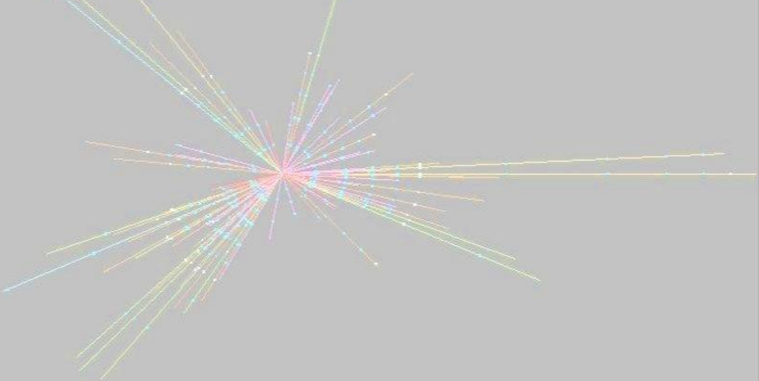
Determination of $\boldsymbol{M_T}$, Yukawa coupling

Reconstruction of Little Higgs

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

How to unravel the structure of LHM @ colliders?

- Symmetry structure
  $\Rightarrow$ **Quantum Corr. Cancell.**
- **Nonlinear Goldstone boson structure**



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- *Anom.* Higgs Coupl.: $H(H)WW$, $H(H)ZZ$
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- Direct Search (LHC) $M_{\gamma'/Z'} \sim 5$ TeV, c
- ILC: Contact Terms: $M_{\gamma'/Z'} \sim 10$ TeV
- Check from Triple Gauge Coupl. (ILC: per mil precision), GigaZ

Scalars:

- Higgsstr., WW fusion $\Rightarrow$ Higgs couplings
- Higgs decays $\Rightarrow$ Evidence for nonlinear Goldstone nature

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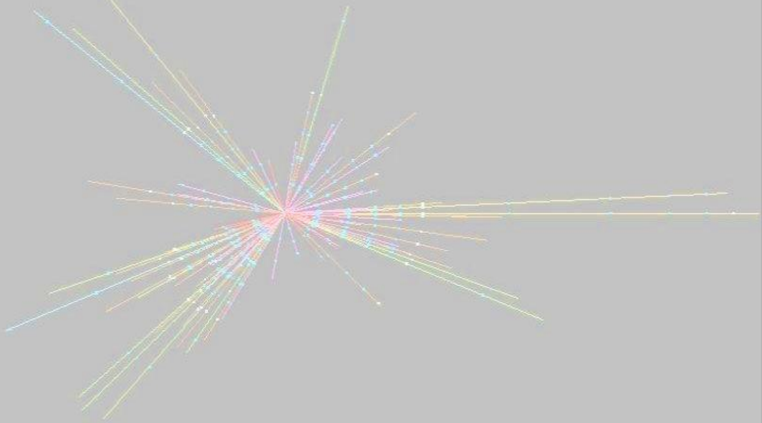
Include all observables in a combined fit if Little Higgs signals are found (sufficient data from LHC and ILC)

Pseudo Axions in Little Higgs Models

Kilian/Rainwater/JR, 2004

- Generically: $U(1)$ gauged: Z'



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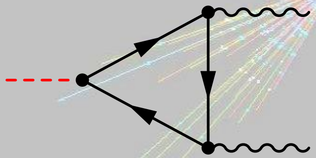
- Generically: $U(1)$ gauged: Z' $\longleftrightarrow$ ungauged: η, $m_\eta \lesssim 300$ GeV
- broken diagonal generator: η in QCD; *couples to fermions as a pseudoscalar*, behaves as a axion

QCD-axion: $\mathcal{L}_{\text{Ax.}} \sim \frac{1}{\Lambda}\eta G_{\mu\nu} G_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma}$

Anomalous $U(1)_\eta$:



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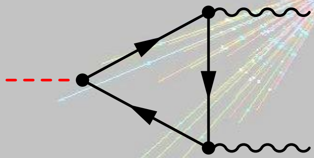

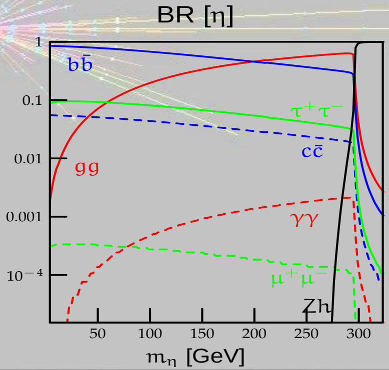

explicit symmetry breaking $\Rightarrow$ axion bounds *not applicable*

η EW singlet, couplings to SM particles v/F suppressed

Little Higgs Axions at Colliders

η changes decay rates of T: Branching ratio $T \to t\eta \sim 20 - 30\%$

new Higgs decays: ($H \to Z\eta$, $H \to \eta\eta$!)

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- LHC: **Gluon Fusion**, Peak in diphoton spectrum
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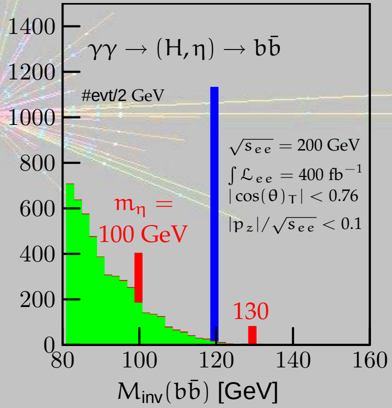
- Photon Collider as precision machine for Higgs physics (s channel resonance)



WHIZARD/OMEGA: Kilian/Ohl/JR

T parity and Dark Matter

- T parity: SM particles even, new ones odd
- analogous to R parity in SUSY, KK parity
- Bounds on f relaxed, *but:* pair production!
- Lightest T-odd particle (LTP) $\Rightarrow$ Candidate for Cold Dark Matter

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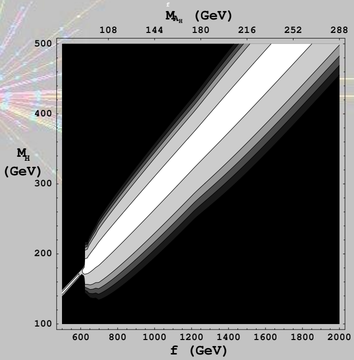
Littlest Higgs: γ' LTP

Cheng/Low, 2003; Hubisz/Meade, 2005

$W', Z' \sim$ 650 GeV
$\Phi \sim$ 1 TeV
$T, T' \sim$ 0.7-1 TeV

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

0/10/50/70/100



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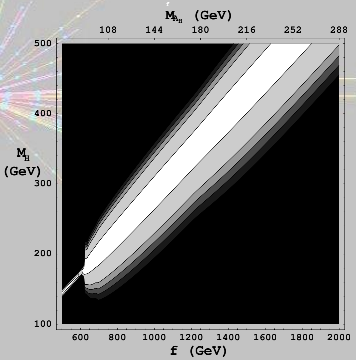

- T parity Simple Group model: Pseudo-Axion η LTP

Kilian/Rainwater/JR/Schmaltz

Conclusions

Little Higgs elegant alternative to SUSY
Global Symmetry structure stabilizes the Electroweak scale

- Generics: new heavy gauge bosons, scalars, quarks

Little Higgs *predicts higher Higgs masses* $M_H \sim 300 - 400$ GeV

UV embedding, GUT, Flavor ?

- New developments: Neutrino masses, T-parity, LH Dark Matter, Pseudo-Axions

Strategy for Reconstruction at **COLLIDER EXPERIMENTS**
direct search LHC (ILC) $\longleftrightarrow$ precision observables ILC (LHC)