



**The Abdus Salam
International Centre for Theoretical Physics**



2326-10

School on Strongly Coupled Physics Beyond the Standard Model

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Little Higgs Models - Lecture 1

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①

Three Lectures on Little Higgs

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Little Higgs vs.

- { Composite Higgs
- { Holographic Higgs
- { Gauge/Higgs Unification
- { Minimal Technicolor

Technicolor-like Strong Dynamics

$\Rightarrow$ Higgs as Pseudo Nambu-Goldstone Boson.

h^+h forbidden by $h \rightarrow h + \pi$
(then softly broken)

Little Higgs

$$v_{EW} \ll f_{\pi}$$



Due to special collective
symmetry breaking structure

Generic Composite Higgs

$$v_{EW} \lesssim f_{\pi}$$



Hierarchy would be
accidental.

②

These lectures : Emphasize $v \ll f_\pi$

Won't cover
very much

"Classical" Little Higgs Models

- Littlest Higgs
- Minimal Moose
- Simplest LH

Precision EW Bounds

Dark Matter & T-Parity

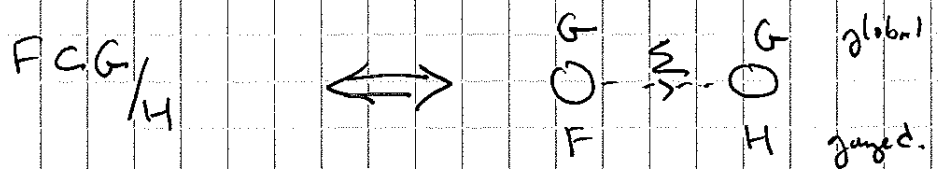
LH in AdS Space

LHC Signatures (a bit)

Will cover :

Little Technicolor (essential knowledge!)

↪ Hidden Local Symmetry... kind of



Quickest "derivation" of CCWZ formalism.

References :
(my own work)

hep-ph/0502175

Little Technicolor

0812.2477

Collective Quarks &
Dangerous Singlets
w/ M. Schmaltz

will use as
example
throughout

⇒ 1006.1356

Bestest LH
w/ M. Schmaltz &
D. Stolarski

Outline:

★ : Essential knowledge

Lecture 1:

- Basic Structure of Composite Higgs Models
- Collective Symmetry Breaking
- ★ - Collective Quarks & Dangerous Singlets

Lecture 2:

- Building a LH Model
- Collective Yukawas & Fermion Partners
- Collective Gauge Coupling & Gauge Partners
- (Little Higgs @ the LHC)

Lecture 3:

- ★ - Little Technicolor & CCWZ
- Holographic Interpretation
- Grand Summary

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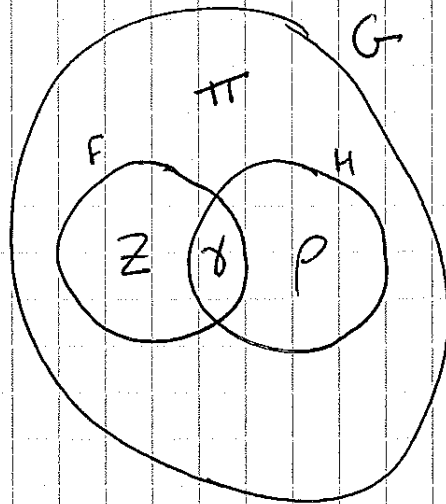
Note: I will be ahistorical, somewhat "reversed" in logic. See also hep-ph/0502182 for Schmaltz/Tucker-Smith Review; references to original literature

Basic Structure of Composite Higgs

Higgs as PNGB

$$F \subset G/H$$

In Language of Technicolor



Scales

$$f_\pi$$

$$m_Z \approx g f_\pi$$

$$m_P \approx \sqrt{4\pi} f_\pi$$

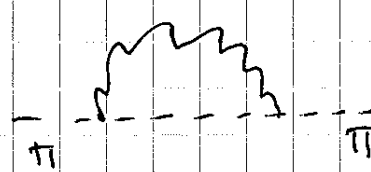
$$G/H \Rightarrow \pi = (P) \text{ NGB}$$

in F ?

Eaten by Higgs Mechanism (Z)

charged under F

Radiative mass from

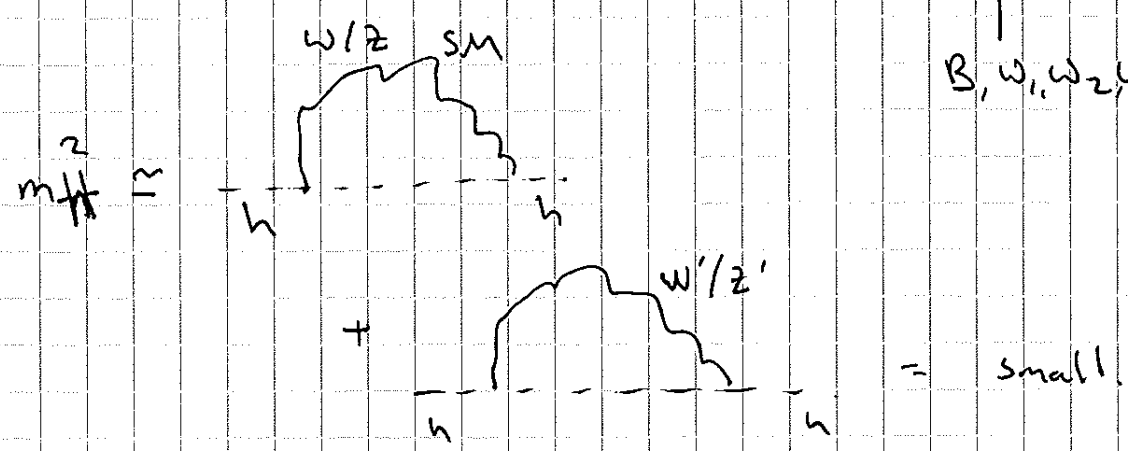
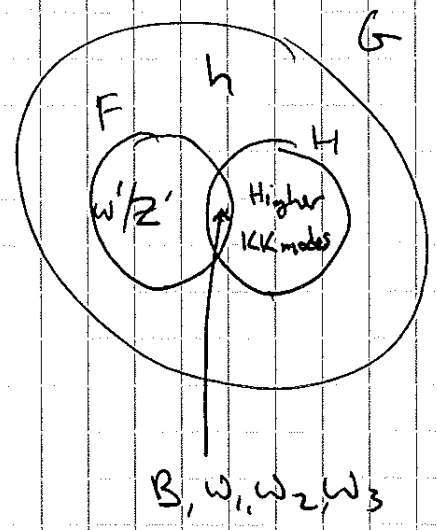


$$F \cap H \Rightarrow \gamma = \text{Unbroken gauge symmetry}$$

$$H \Rightarrow P = \text{Possible resonances from strong dynamics (more in lecture 3)}$$

Little Higgs

Higgs is a "pion"
Radiative potential
 protected by collective
 symmetries



Not sufficient!

$V \sim \text{small} \cdot \sin^2 \left(\frac{h}{f_\pi} \right)$

↑ doesn't matter how small ...

↑ $V_{EW} \approx f_\pi$ unless cancellation.

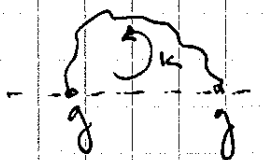
Indistinguishable from technicolor.

Composite Higgs: $V_{EW} \lesssim f_\pi$ by mild cancellation.
 Little Higgs: $V_{EW} \ll f_\pi$ by symmetries!

⑥

Collective Symmetry Breaking (reason for small potential)

$$\Delta m^2 \sim \frac{1}{16\pi^2} g^2 \Lambda^2$$



In Little Higgs, arrange couplings such that
 $h \rightarrow h + e$

persists when any 1 coupling is on, and shift
 symmetry is broken only by multiple couplings.

$$\Delta m^2 \simeq \frac{1}{16\pi^2} g^2 m_{2'}^2 \log\left(\frac{\Lambda^2}{m_{2'}^2}\right)$$

(Appears in many
 xdim scenarios,
 not unique to
 LH.)

More about this in Lecture 2

↳ usually with
 logarithmic
 sensitivity

Collective Quartic Coupling (reason for small v_{ew})

Key to LH models!

Symmetry such that

$$V \sim \text{small} \cdot h^\dagger h + \mathcal{O}(1) \cdot |h^\dagger h|^2$$

compared to
 f_π^2

$$\Rightarrow v_{ew} \ll f_\pi$$

Is this even possible?!

7

Symmetries that can forbid $h^\dagger h$ but allow $|h^\dagger h|^2$.

→ Supersymmetry (e.g. D-term potential)

→ Shift Symmetries. (in the presence of extra PNCBs)

$h \rightarrow h + \epsilon$ (forbids entire Higgs potential)

$\phi \rightarrow \phi \mp \frac{h\epsilon + \epsilon h}{f} \dots$ (allows "quartics")
(Explicitly breaks G)

$$V \sim \lambda_1 f_\pi^2 \left| \phi + \frac{h^2}{f} \dots \right|^2 + \lambda_2 f_\pi^2 \left| \phi - \frac{h^2}{f} \dots \right|^2$$

λ_1 : Not a quartic, just a mass for ϕ , no $\Delta m^2 \sim \frac{1}{16\pi^2} \lambda_1 \Lambda^2$

λ_2 : Not a quartic, just a mass for ϕ , no $\Delta m^2 \sim \frac{1}{16\pi^2} \lambda_2 \Lambda^2$

$\lambda_1 \& \lambda_2$: mass for ϕ , quartic for h , $\Delta m^2 \sim \frac{1}{16\pi^2} \lambda_{\text{eff}} \Lambda^2$
↑
more about this later...

Integrate out ϕ

$$V \sim \frac{4\lambda_1\lambda_2}{\lambda_1 + \lambda_2} |h^\dagger h|^2$$

↑
 λ_{eff}

This is the form of all LH quartics.

8

Requirements for a Collective Higgs Quartic

G/H : contains Higgs doublets & extra ϕ PNCB

Two Types of explicit breaking of G : Both give ϕ mass, neither gives quartic coupling, together yield quartic.

★ Subtlety : "Dangerous Singlets"
Must forbid ϕ tadpole
 $V \sim \left(\phi + \frac{h^2}{f} \right)^2$
↑ oops! Higgs mass.

Some group theory:

Quantum numbers of ϕ ?

Can forbid dangerous singlet tadpole even with a Z_2 symmetry.

In $su(2)$:

$$2 \otimes 2 = 3_S \oplus 1_A$$

$$2 \otimes \bar{2} = 3 \oplus 1$$

Want $\phi \propto \frac{h^2}{f}$

One Higgs Doublet

$$\epsilon_{ij} h^i h^j = 0$$

(no 1_A representation)

Used in
Littlest
Higgs

~~→~~ $h^i h^j \rightarrow \phi^{ij}$

(3_S , complex $su(2)$ triplet, hypercharge 1)

Not in
Literature!

~~→~~ $h^\dagger \tau^a h \rightarrow \phi^a$

(3 , real $su(2)$ triplet, hypercharge 0)

BAD

$$h^\dagger h \rightarrow \gamma$$

(1 , real singlet, hypercharge 0)

↑
no possible
symmetry

Two Higgs Doublets

BAD
Quartic is
wrong direction

$$\epsilon_{ij} h_1^i h_2^j \rightarrow \phi \quad (1_A, \text{complex singlet, hypercharge } 1)$$

Used in
Antisymmetric
Condensate
LH

$$h_1^\dagger h_2 \rightarrow \phi \quad (1, \text{complex singlet, hypercharge } 0)$$

Today
(Bestest)

~~→~~ $\text{Re}[h_1^\dagger h_2] \rightarrow \phi \quad (1, \text{real singlet, } \mathbb{Z}_2 \text{ symmetry})$

Bottom Line

(10)

One Higgs
Doublet
Models

$\Rightarrow$

$SU(2)$
Triplet

$\Downarrow$

Unless you
impose additional
symmetry

$\Downarrow$

Disfavored

$$V \approx \left| \phi_{ij} + \frac{h_i h_j}{f} \right|^2$$

$$\langle \phi_{ij} \rangle \neq 0$$

Large contribution
to T parameter.

Two Higgs
Doublet
Models

$\Rightarrow$

$SU(2)$
Triplet or Singlet

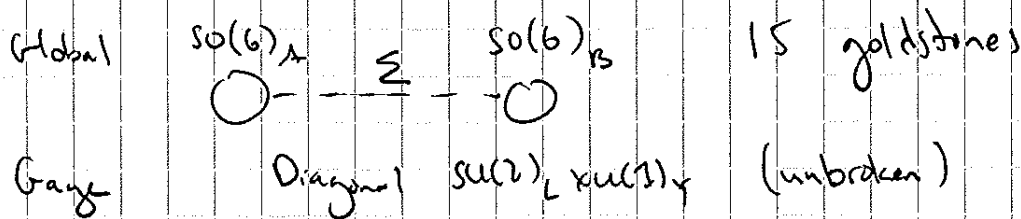
$$V \approx \left| \phi \pm h_1^\dagger h_2 \right|^2$$

NMSSM-like gauge
coupling.

Explicit Lagrangian $so(6)^2/so(6)$

(11)

Two Higgs Doublet Case



$$\Sigma \rightarrow G_A \Sigma G_B^T$$

$$\Sigma = e^{2i\pi_a T_a / f}$$

imaginary,
antisymmetric
matrices.

NLSM: $\mathcal{L} = \frac{f^2}{4} \text{Tr} |\partial_\mu \Sigma|^2$

$$2i\pi_a T_a = \begin{pmatrix} \begin{matrix} \text{SO(4)} \\ \text{6 extra goldstones} \end{matrix} & & \\ \begin{matrix} Q & & \\ & Q & \\ & & Q \end{matrix} & \begin{matrix} | h_1 | \\ | h_2 | \end{matrix} & \\ \hline & & \begin{matrix} \sigma \\ \frac{1}{\sqrt{2}} \end{matrix} \end{pmatrix}$$

has automatic
custodial
Symmetry
 $so(4) \Rightarrow su(2)_L \times su(2)_R$

Explicit
Breaking
(By Hand)

$$V = \frac{1}{4} \lambda_{65} f^4 \Sigma_{65}^2 + \frac{1}{4} \lambda_{56} f^4 \Sigma_{56}^2$$

$$\left(\sigma - \frac{h_1^T h_2}{\sqrt{2}} \right)^2 \quad \left(\sigma + \frac{h_1^T h_2}{\sqrt{2}} \right)^2$$

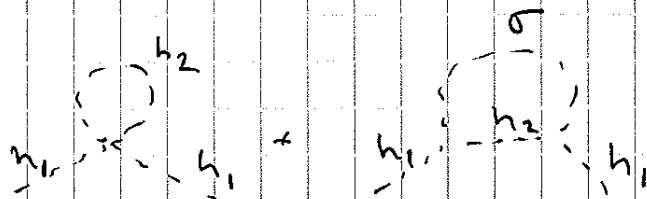
Z_2 symmetry forbids Σ_{65} , Σ_{56} alone.

(12)

$$m_\sigma^2 = (\lambda_{65} + \lambda_{56}) f^2$$

$$\lambda_{\text{eff}} = 2 \frac{\lambda_{56} \lambda_{65}}{\lambda_{65} + \lambda_{56}}$$

One-loop



$$\Rightarrow \Delta m_{1,2}^2 = \frac{\lambda_{\text{eff}} m_\sigma^2}{16\pi^2} \log \left(\frac{\Lambda^2}{m_\sigma^2} \right)$$

Subtleties : Need to break EWSB, requires B-terms,
 $\checkmark > \sum_{65} + \sum_{56}$
 $\uparrow$ adding single terms

Discussion Question:

At the end of the day, no symmetry forbids $h_1^T h_1 + h_2^T h_2$ mass term.

To what extent can it be considered small?

Good point, but we usually ok with technically natural stability.
 "Spurion analysis"

Next time:

Extend Collective Symmetry Breaking
to Yukawas & Gauge Interactions

↳ Very similar to ordinary
composite Higgs model building
(unlike quarks which is LH specific)

For Lecture 3:

Surprise for collective gauge coupling

$$F \subset G/H \quad \Leftrightarrow \quad F \times H \subset G \times G/G$$