Electroweak Symmetry Breaking From Theory Space

Jay G. Wacker

U.C. Berkeley / Harvard

ICHEP 02

With
N. Arkani-Hamed
A. Cohen
T. Gregoire
E. Katz
A. Nelson

hep-ph/0202089
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Experimental Results of Past Decade:

The chiral Lagrangian describing EWSB works to 1 loop accuracy.

$$\mathcal{L}_{\substack{\text{eff} \\ \text{S.B.}}} = v^2 \, \mathrm{Tr} \, |D_\mu \omega|^2$$

$\omega^\dagger \omega = \mathbb{1}$

$\omega \to g_2 \, \omega \, g_1^\dagger$

Non Renormalizable operators

$|D_\mu \omega|^4$, $|D_\mu \omega|^2 W_{\mu\nu}^2$, etc

are suppressed by a scale $\Lambda \gg 1 \, \mathrm{TeV}$

Perturbative Physics at 1 TeV

$\rightarrow$ Physical higgs boson

$$H = \frac{(h^0 + v)}{\sqrt{2}} \, \omega$$

Hierarchy Problem $\longrightarrow$ description is Incomplete

Take Conservative Point of View

Want effective Valid to $\Lambda \gg 1\,\text{TeV} \sim 10\text{-}30\,\text{TeV}$

Higgs VeV is stable relative to this Scale

Old Idea: Higgs is Pseudo Goldstone Boson

Georgi-Pais '74

Dimopoulos-Georgi-Kaplan '84

Problem: Higgs doesn't look much like a pion

Overview

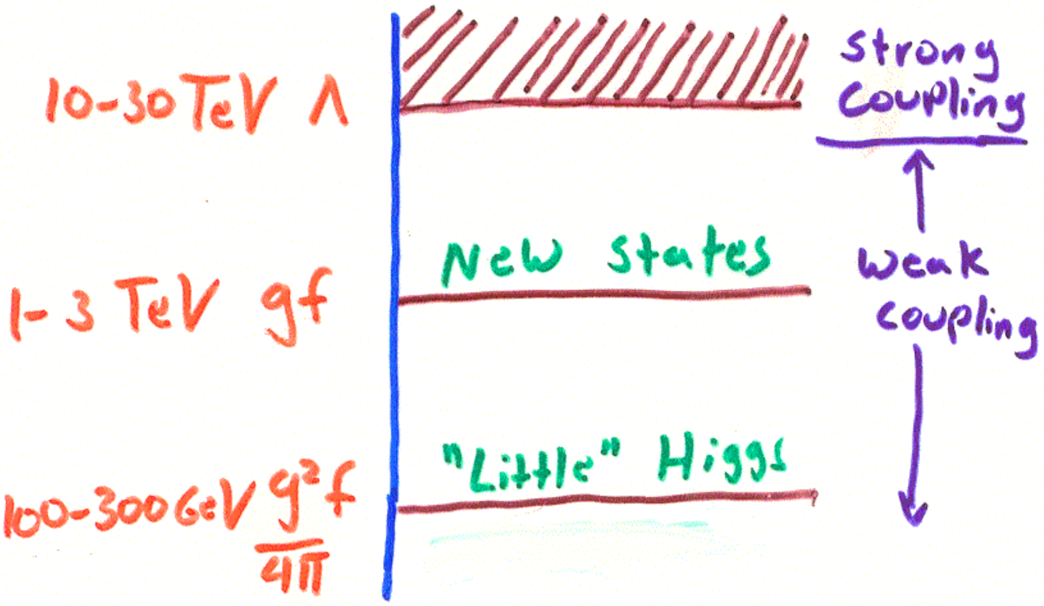
Higgs is a Pseudo GoldStone boson

$$\Sigma = \exp(i\sigma/f) \qquad \Lambda \sim 4\pi f$$

hep-ph/0105189
Arkani-Hamed-Cohen-Georgi

Approximate chiral symmetries keep Higgs Light $\quad m_h^2 \ll \Lambda^2$

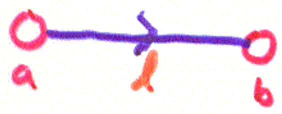
$\Sigma \to L \Sigma R^\dagger$ broken by couplings



Theory Space

Defines a gauged non-linear sigma model

Point — Gauge Group



Line — nonlinear σ model field

$$\Sigma_l \to g_a \Sigma_l g_b^\dagger$$

face — Potential

$$V = -\lambda \, \mathrm{Tr}\, \Sigma_1 \Sigma_2 \Sigma_3 + h.c.$$

Defines a Gauged non-linear Sigma Model

$$\mathcal{L} = \mathcal{L}_{Gauge} + \mathcal{L}_{\substack{norm \\ Kin}} + \mathcal{L}_{Plaquette}$$

Seperate States → Classically Massless — Light d.o.f.

Seperate States → Classically Massive
↳ Integrate out

hep-ph/0206023
Gregoire, JW

Radiative Corrections and Chiral Symmetries

In limit of vanishing couplings
nlσm fields become exact Goldstones

$\Sigma \to L \Sigma R^{\dagger} \Rightarrow$ Little Higgs massless

Couplings break chiral symmetries.

Need to communicate symmetry breaking to generate masses for Little Higgs.

Will require 2 couplings to communicate sufficient Chiral Symmetry Breaking

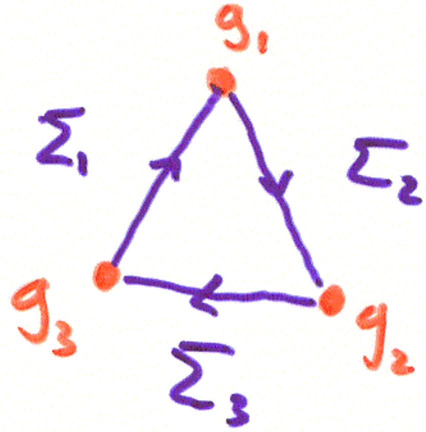
Ultraviolet physics is analytic in couplings.

$$\Rightarrow \delta m_{LH}^2 = \left(\frac{g^2}{16\pi^2}\right)^N \Lambda^2$$

N is # of couplings needed to communicate sufficient symmetry breaking

IE in "circle"

$$\mathcal{O} = |\mathrm{Tr}\, \Sigma_1 \Sigma_2 \Sigma_3|^2$$



$$\delta m_{LH}^2 \sim \left(\frac{g_1}{4\pi}\right)^2 \left(\frac{g_2}{4\pi}\right)^2 \left(\frac{g_3}{4\pi}\right)^2 \Lambda^2$$

if any $g_i \to 0$ $\quad \delta m_{LH}^2 \to 0$

2 Facts about Radiative Corrections In Theory Space

1. If all nlσm fields are bi-fundamentals

No 1 loop Λ^2 div from Gauge Sector

2. If no Plaquette contains any nlσm more than once

1 loop Λ^2 div only renormalize Plaquettes

(does not give mass to anything classically massless)

Finite Radiative Corrections.

Rule of thumb:

Low energy Λ^2 div. to Little Higgs Mass cut off at Mass of first Heavy Mode

$$\delta m_{LH}^2 \sim \frac{g^2}{16\pi^2} M_{Heavy}^2 \qquad M_{Heavy} \sim gf$$

$$= \frac{g^2}{16\pi^2} g^2 f^2 = \boxed{\left(\frac{g^2}{16\pi^2}\right)^2 \Lambda^2}$$

Same Size as 2 loop Λ^2 div

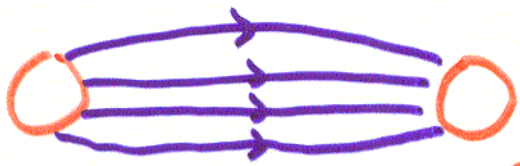
$\Rightarrow$ No Parametric gain in removing More than 1 loop Λ^2 div

Still allows for Seperation of Scales

$$M_{LH} \ll M_{Heavy}$$

$\Rightarrow$ What's stabilizing EW Scale Invisible to ~ 1 TeV!

The Minimal Moose



$$\mathcal{L} = \mathcal{L}_{Gauge} + \mathcal{L}_{\substack{nlsm \\ Kin}} - V(X_i)$$

$$V(X_i) = -\lambda_1 f^4 \, \mathrm{Tr}\, X_1 X_2^\dagger X_3 X_4^\dagger$$
$$- \lambda_2 f^4 \, \mathrm{Tr}\, X_2 X_3^\dagger X_4 X_1^\dagger \quad + \text{h.c.}$$

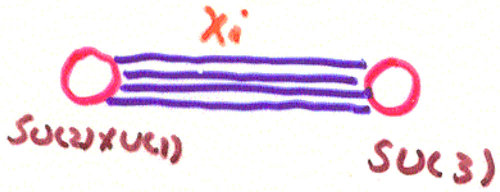
Expanding $X_i = e^{i\sigma/f}$ in Mass eigenstates U, V, W

$$V = \lambda_1 (f W - i[U,V])^2$$
$$+ \lambda_2 (f W + i[U,V])^2 + \ldots$$

W massive → integrate out

$$V_{eff} = \lambda_{eff} \, \mathrm{Tr}\, [U,V]^2 \qquad \frac{1}{\lambda_{eff}} = \frac{1}{\lambda_1} + \frac{1}{\lambda_2}$$

Apply to EWSB



$X_i \sim 3\times 3$ Special Unitary Matrices.

$X_i \to g_{2,1} X_i g_3^\dagger$ under Gauge Transformation.

$$g_{2,1} = \left(\begin{array}{c|c} g_2 & 0 \\ \hline 0 & 1 \end{array}\right) \times e^{i T_8 \theta/6}$$

$$T_8 = \begin{pmatrix} 1 & & \\ & 1 & \\ & & -2 \end{pmatrix}$$

Breaks $SU(3) \times [SU(2) \times U(1)] \to [SU(2) \times U(1)]_{Diag}$

EW gauge symmetry

$$8 \to 3_0 + 1_0 + 2_{\frac{1}{3}}$$

W	B	V	Vectors
φ	η	h	Scalars

States

Massless	Gauge	W, B	EW Gauge
Massive	Gauge	W, B, V	
Massless	Scalar	2φ, 2η, $2h$	SM Higgs
Massive	Scalar	φ, η, h	

Higgs Potential

Low energy Scalar Potential

$$V_{LE} = \lambda_{eff} \, Tr[U, V]^2 + \ldots$$

In terms of doublets $h_{1,2} = h_U \pm i h_V$

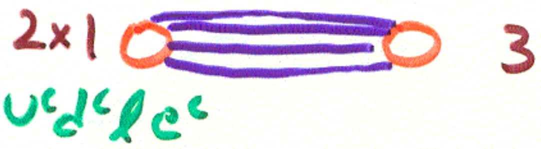
$$V_{LE} = \lambda_{eff} \left(|h_1|^2 - |h_2|^2 \right)^2$$

MSSM Higgs Potential...

but λ_{eff} is Undetermined

was $\sim (g^2 + g'^2)$ in MSSM

Yukawa couplings



$Q = \begin{pmatrix} q \\ 0 \end{pmatrix} \quad U^c = \begin{pmatrix} 0 \\ 0 \\ u^c \end{pmatrix} \quad D^c = \begin{pmatrix} 0 \\ 0 \\ d^c \end{pmatrix} \quad \cdots\cdots$

$$\mathcal{L}_{yuk.} = y_u \, Q^T [X_1 X_2^+] U^c + y_d \, Q^T [X_1 X_2^+]^T D^c$$

$U(3)^5$ Flavour Symmetry only Broken by Yukawa couplings

These are 1 loop Λ^2 div.

but $\frac{y^2}{16\pi^2}\Lambda^2$ is Tiny for every thing

except the top

$$y_t \sim O(1)$$

Top Sector

Extend top sector with an addition fermion

$$Q = \begin{pmatrix} q \\ \tilde{u} \end{pmatrix} \quad \tilde{U}^c$$

full SU(3) symmetry now

$$\mathcal{L}_{top} = y_{top} f \, Q X_1 X_2^\dagger P_1 U^c + m_{\tilde{u}} \tilde{U} \tilde{U}^c$$

1 loop Λ^2 div

$$V_{eff} = \Lambda^2 \, Tr M^\dagger M \sim Tr \, X_1 X_2^\dagger P_1 X_2 X_1^\dagger \sim Const$$

Independent of Background field.

1 loop Log div. is negative and drives EWSB!

Gauge & Scalar 1 loop Log div Gives Positive mass^2 to all other Scalars

Where do Plaquettes come from?

$-\lambda f^4 \mathrm{Tr}\, X_1 X_2^\dagger X_3 X_4^\dagger$ looks strange

In general this is a question about UV physics (what generates this model?)

Sometimes the low energy theory requires/generates plaquettes.

Consider Yukawa

$$\mathcal{L} = y f \, \Psi (X_1 X_2^\dagger + X_4 X_3^\dagger) \psi^c$$

1 loop Λ^2 div gives

$$\mathcal{L}_{eff} = \frac{y^2 f^2}{16\pi^2} \Lambda^2 \left(\text{const.} + \mathrm{Tr}\, X_1 X_2^\dagger X_3 X_4^\dagger + \text{h.c.} \right)$$

$y^2 f^4 = O(1) f^4$ if $y^2 \sim O(1)$!

Minimal Signals

100-300 GeV

2 Higgs doublets
either Type I or II models
2 ϕ 2 η
Can be lifted to
TeV scale

1 - 3 TeV

Coloured Dirac Fermion
Cancels Top 1 loop Λ^2 div

W' B' V
Cancels $SU(2) \times U(1)$ Λ^2 div
optional

ϕ η h
Cancels h^4 Λ^2 div

10 - 30 TeV

New Physics

Susy? Another Moose

ETC has flavour
Problems to $\Lambda \sim 100$ TeV

Out look

- 1 Higgs doublet models or
  2 Higgs doublet models w/o MSSM Potential

SU(5)/SO(5)
1 HDM
hep-ph/0206021
Arkani-Hamed, Cohen, Katz, Nelson

SU(6)/SP(6)
2 HDM w/o MSSM Potential
hep-ph/0207243
Low, Skiba, Smith

- Constraints on models
  hep-ph/0204193
  Chivukula, Evan, Simmons

- Understanding $\sin^2\theta_w$ from TeV Scale physics
  hep-ph/0201148
  hep-ph/0203001
  Dimopolous, D.E. Kaplan

- UV completions
  ETC still difficult
  Susy completions
  Mooses in Mooses
  ⋮

  hep-ph/0204193
  Chivukula, Evans, Simmons

- Detailed experimental signatures
  hep-ph/0202089
  Arkani-Hamed, Cohen, Gregoire, Jw