A Little Higgs at the Linear Collider

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American Linear Collider Workshop, Cornell
July 2003

- How to make a light Higgs (without SUSY)
- Status of Models
- Linear Collider Phenomenology

Electroweak symmetry breaking (beyond the SM):

- Dynamics responsible for the electroweak scale?

  $v = 246\ \mathrm{GeV} \approx 10^{-17} M_{\mathrm{Planck}}$

  – Perturbative field theory: unnatural

  $\Rightarrow$ Non-perturbative origin

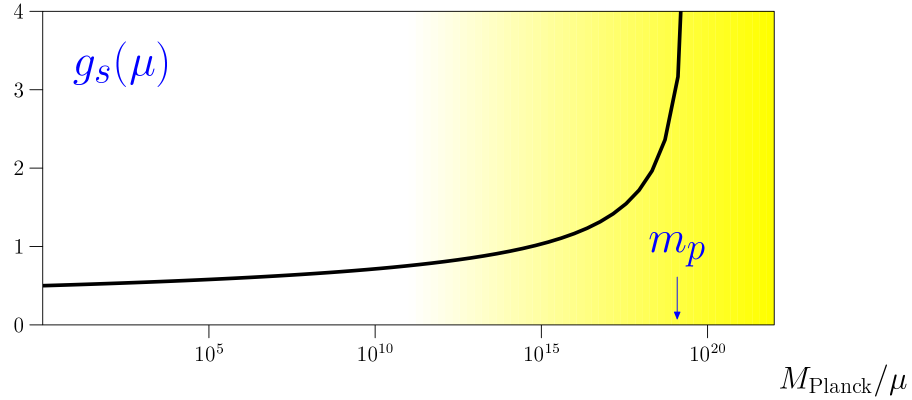
  – Geometrical: gravitational background = extra dimensions

  – Field-theoretical = non-perturbative field condensation

- Dynamical scale generation in 4D: QCD

  $\Rightarrow$ The proton mass is natural

  $\Rightarrow$ W mass, t mass, . . . ?



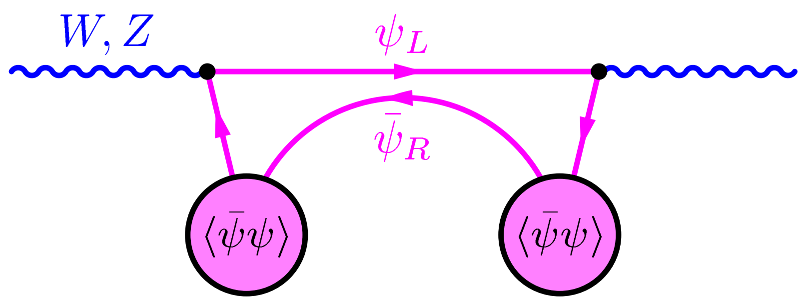
Dynamical scale generation:

Susskind/Weinberg 1979

Simplest model: Technicolor

⇒ Compositeness (of $W, Z, \ldots$)

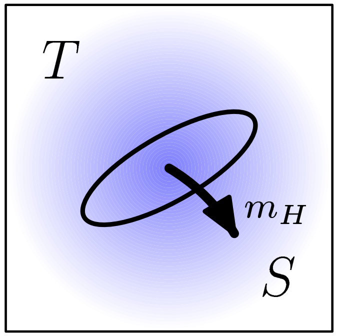
⇒ EWSB due to chiral symmetry breaking



This is elegant, but . . .

- EW precision data
- Flavor Physics

suggest:



⇒ TeV-scale physics is weakly interacting

⇒ Strongly interacting physics (if any) is beyond $10\ \mathrm{TeV}$ and/or decoupled

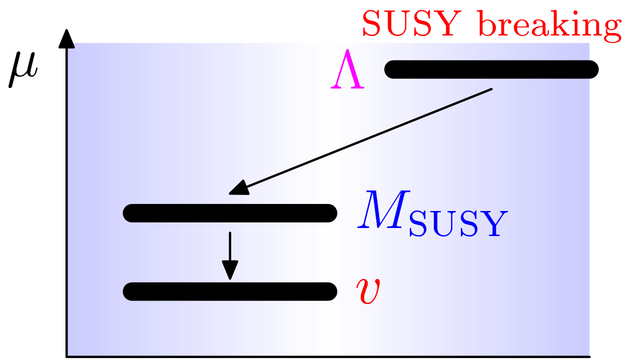
⇒ There is a $\sim 100\ \mathrm{GeV}$ scalar: The Higgs boson

Possible solution: Indirect (dynamical) scale generation

Supersymmetric Models:

- SUSY + hidden sector

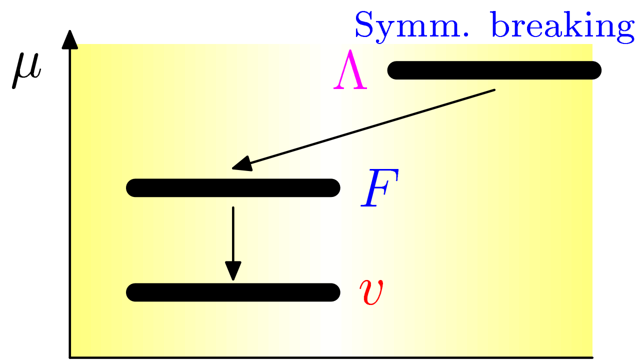
  $\Rightarrow$ (dynamical) SUSY breaking $\Rightarrow$ Scale generation
- Light scalars because of SUSY
- Higgs potential by radiative corrections



Little Higgs Models:

- New global symmetry

  $\Rightarrow$ (dynamical) symmetry breaking $\Rightarrow$ Scale generation
- Light scalars because of Goldstone theorem
- Higgs potential by radiative correctons



Higgs = Pseudo-Goldstone boson: Georgi/Pais 1974, Georgi/Dimopoulos/Kaplan 1984, ...

Problem: Without fine-tuning

$\Rightarrow$ two-scale model $\Rightarrow$ compositeness in TeV range

Little-Higgs Models: Three scales Arkani-Hamed/Cohen/Georgi 2001, ...

$m_H \sim v \longrightarrow F \sim 4\pi v \longrightarrow \Lambda \sim 4\pi F$

- Scale Λ:

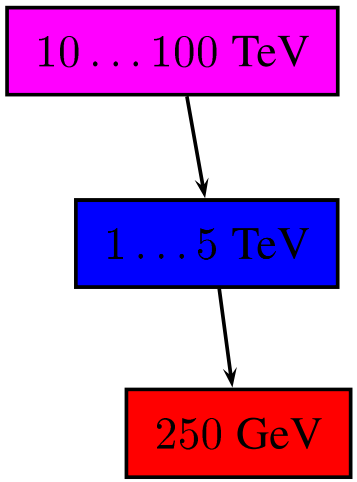
  Compositeness, new dynamics

- Scale F:

  Pseudo-Goldstone scalars, extra vector bosons, extra fermions

- Scale v:

  Higgs bosons, known vector bosons and fermions



How to make a Little Higgs Model:

(1) Extended gauge theory: $\mathcal{G}_{\rm new} \to \mathrm{SM}$

Compare: Z' models, MSSM with GMSB

(2) Enlarged global symmetry: $\mathcal{G}_{\rm new}$ embedded in $\mathcal{H}$

Compare: SM custodial symmetry

(3) Extended top sector: New vector-like quark(s)

Compare: See-saw topcolor models

(1) Extended Gauge Theory: $\mathcal{G}_{\text{new}} \to \text{SM}$

$\mathcal{G}_{\text{new}}$ has two gauge couplings g_1, g_2 (or more):

$$\frac{1}{g^2} = \frac{1}{g_1^2} + \frac{1}{g_2^2}$$

Canonical choice:

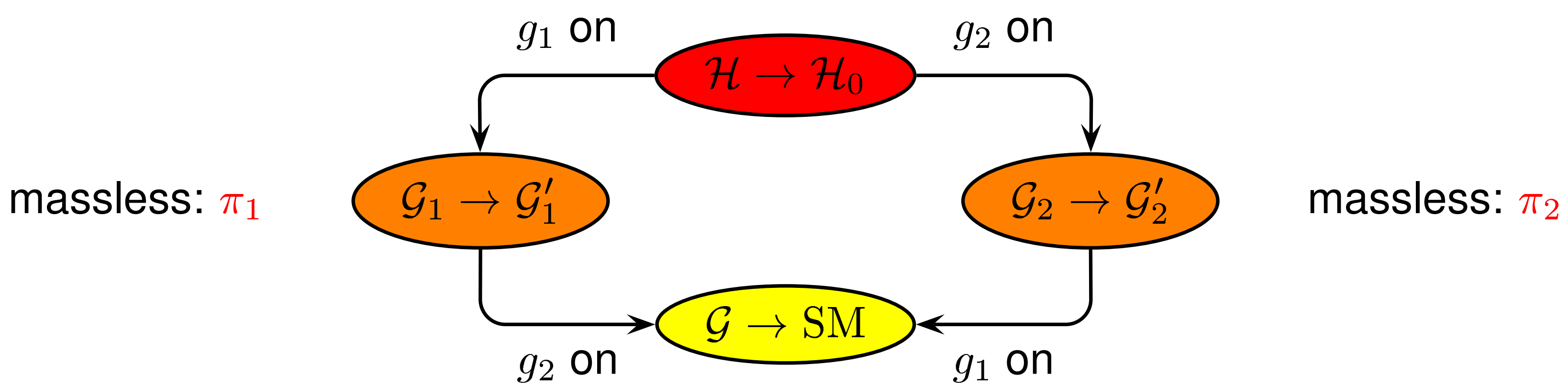
$$\begin{array}{ccc} (SU(2) \otimes U(1))_1 & \otimes & (SU(2) \otimes U(1))_2 \\ (g_1, g_1') & & (g_2, g_2') \end{array}$$

$$\begin{array}{cc} \to & (SU(2) \otimes U(1))_{\text{SM}} \\ & (g, g') \end{array}$$

$\Rightarrow$ Four heavy vector bosons: $\boxed{W^{\pm\prime},\ Z' \text{ and } B'}$

(2) Enlarged global symmetry

Embed the gauge group $\mathcal{G}_1 \otimes \mathcal{G}_2$ in a larger global symmetry $\mathcal{H}$



Switch on gauge couplings g_1, g_2:

- Some Goldstone bosons are eaten $\Rightarrow$ TeV-mass vectors
- Some become heavy $(M/\Lambda \sim g/4\pi)$ $\Rightarrow$ TeV-mass scalars
- Some become light $(M/\Lambda \sim g_1 g_2/16\pi^2)$ $\Rightarrow$ Higgs boson candidates $\pi_1 \cap \pi_2$

Radiatively generated Higgs potential

Heavy scalars: H

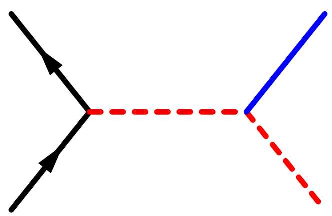
Light scalars: h (includes W_L, Z_L)

Coleman-Weinberg potential (1 loop):

$$V(h, H) = aF^2H^2 + bF(hHh) + ch^4 + \dots$$

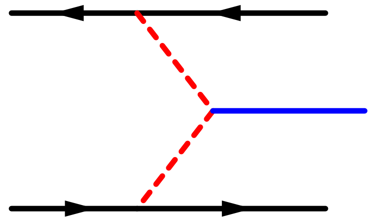
- h is massless to one-loop order
- Trilinear couplings Hhh

  $\Rightarrow$ H contains triplets and/or singlets



- positive m^2 generated at subleading order

$\Rightarrow$ EWSB?



(3) Extended top quark sector:

Extra massive fermion(s) (vectorlike): $t'_{L,R}$ with Yukawa couplings (λ_1) and mass term ($\lambda_2 F$)

$\Rightarrow$ Top Yukawa coupling $\frac{1}{\lambda_t} = \frac{1}{\lambda_1} + \frac{1}{\lambda_2}$

$\Rightarrow$ negative Higgs mass squared (1 loop)

$$V(h) = -a\frac{\lambda_1\lambda_2 F^2}{16\pi^2}h^2$$

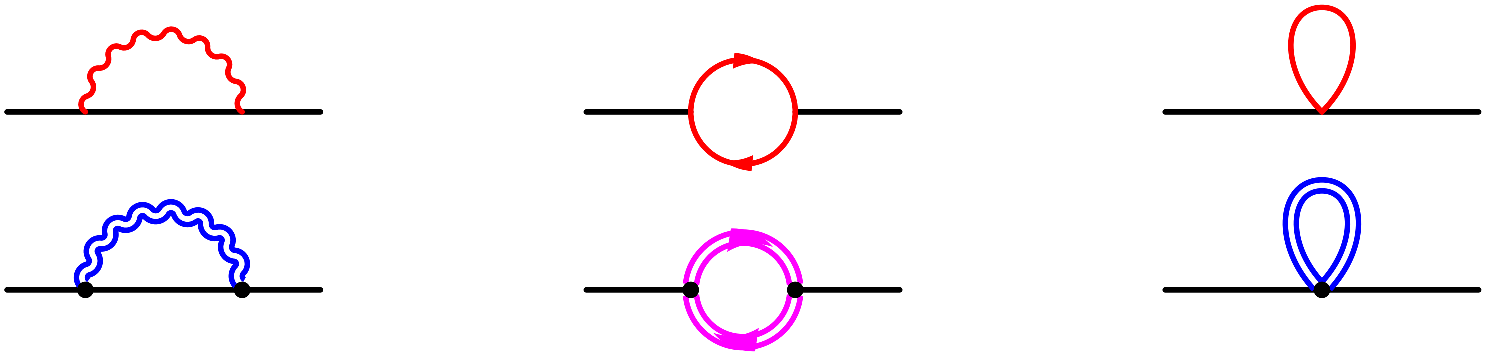
$\Rightarrow$ Higgs VEV $\langle h\rangle = v$

$\Rightarrow$ top mass $m_t = \lambda_t v$ and top' mass $m_{t'} \approx \lambda_2 F$

Summary: LHM particle content

- Light Higgs doublet(s), possibly extra light scalar multiplets
- Heavy Higgs multiplets, coupled to Higgs/Goldstone pairs, decoupled from fermions
- Heavy vector bosons, coupled to SM fermions,
- Heavy vectorlike quark(s)

Effective theory above F: cancellation of quadratic divergences in Higgs self-energy

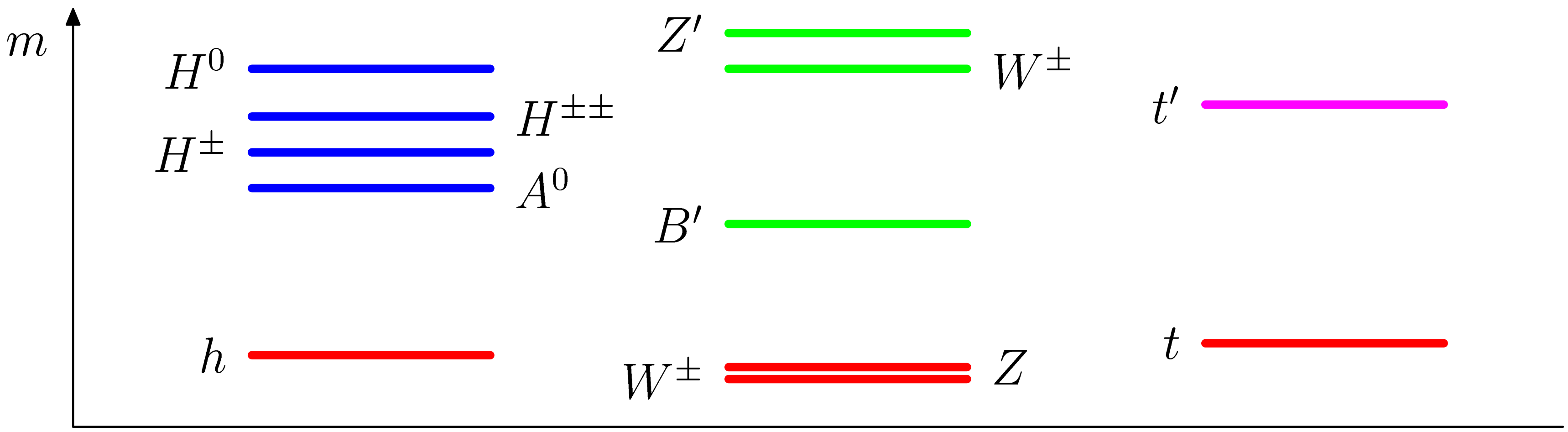


$\Rightarrow$ Higgs mass corrections $F^2/16\pi^2 \sim v^2$ *natural*

The Littlest Higgs: Arkani-Hamed/Cohen/Katz/Nelson 2002

- Global symmetry breaking $SU(5) \to SO(5) \quad \Rightarrow \quad 14$ Goldstone bosons
- Gauge symmetry breaking $(SU(2) \otimes U(1))^2 \to SU(2) \otimes U(1) \quad \Rightarrow \quad W_L^{\pm\prime}, Z_L', B_L'$
- 10 scalars remain:
  - Complex doublet (light) $\Rightarrow$ Higgs boson h and $W_L^{\pm}, Z_L$ with $\langle h \rangle = v$
  - Complex triplet (heavy) $\Rightarrow$ $H, A, H^{\pm}, H^{\pm\pm}$ with $\langle H \rangle \sim v^2/F$

Spectrum (not to scale):



Some variations of the Littlest Higgs:

- $SU(5)/SO(5)$: Arkani-Hamed/Cohen/Katz/Nelson 2002

  Low Energy: Minimal SM

- $SU(6)/Sp(6)$: Low/Skiba/Smith 2002

  Low Energy: 2HDM

- $SU(4)^4/SU(3)$: Kaplan/Schmaltz 2003

  Low Energy: 2HDM + 2 singlets

- $SU(3)^8/SU(3)$: Arkani-Hamed/Cohen/Katz/Nelson/Gregoire/Wacker 2002

  Low Energy: 2HDM + 2 scalar triplets + 2 singlets

- $SO(5)^8/SO(5)$: Chang/Wacker 2003

  Low Energy: 2HDM + 2 scalar triplets + 6 singlets

- $SO(9)/SO(5) \times SO(4)$: Chang 2003

  Low Energy: Minimal SM

Present limits: indirect effects ($M_{\rm new} \gtrsim 1$ TeV)

- New vectors $\Rightarrow$ contact interactions
  - Limits from 2-fermion production
- Violation of custodial $SU(2)$: B' vector boson, heavy Higgs triplets, extended top sector
  - Limits from the ρ parameter ($\equiv T$)
  - Higgs mass limited by S and T parameters

$\Rightarrow$ Constraints, generically:

$$F \gtrsim 3 \text{ TeV} \quad \Rightarrow \qquad M_{B'} \gtrsim 700 \text{ GeV} \quad \text{and} \quad M_{W'} \gtrsim 3 \text{ TeV}$$

Hewett/Petriello/Rizzo 2002, Csaki/Hubisz/Kribs/Meade/Terning 2002, Han/Logan/McElrath/Wang 2003

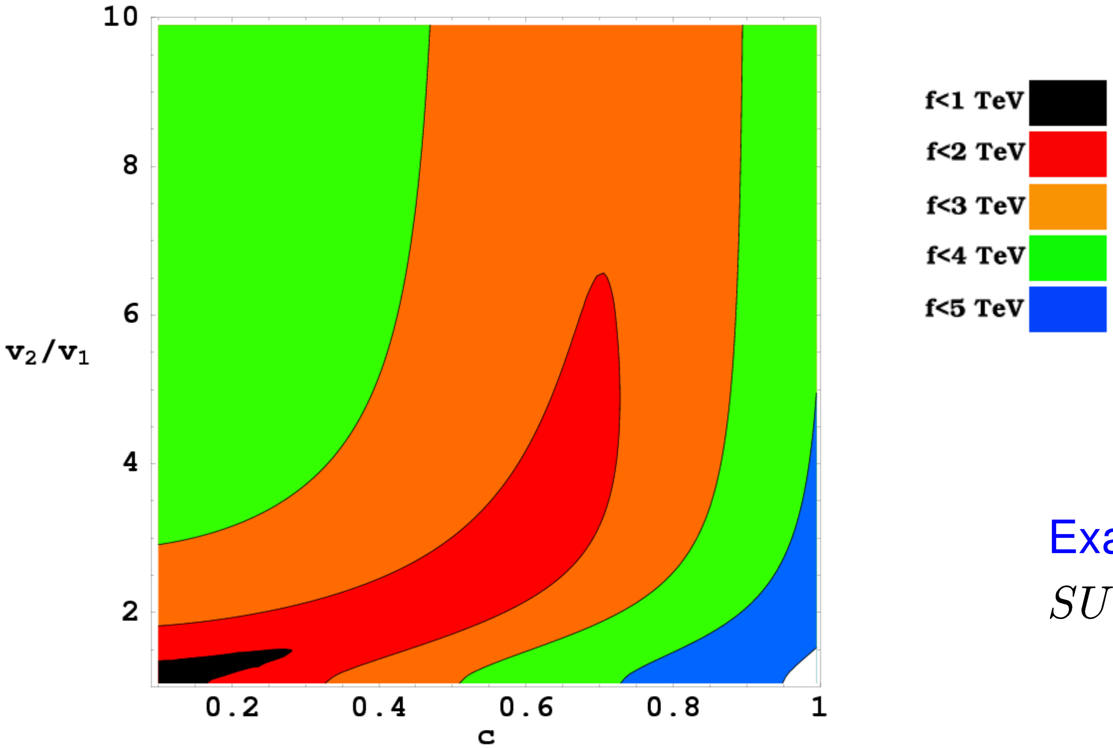
Way out?

1. avoid B', Higgs triplets
2. manifest custodial $SU(2)_c$ $\Rightarrow$ extra $W_r^\pm$, more triplets

Constraints:

Csaki/Hubisz/Kribs/Meade/Terning 2003

- EW precision data favor $F \gtrsim 3\ \text{TeV}$
  (expected: $F \sim 4\pi v \sim 3\ \text{TeV}$)
- Some fine-tuning required for small Higgs mass



Example:

$SU(6)/Sp(6)$ with only one $U(1)$

What can we learn at the LHC?

⇒ discover new states: heavy quarks, some vectors and scalars

- reduces parameter space

$*$ difficult:

- complete spectrum (heavy states, colorless scalars)?
- absolute values of couplings (symmetry structure)?

⇒ **Linear Collider?**

What will a Linear Collider contribute?

⇒ Spectrum

- How many Higgs doublets are there? (distinguish from MSSM)
- Are there extra singlets? (distinguish from radion / NMSSM)
- Are there extra triplets?

⇒ Measurement of Higgs and W, Z couplings

- constrain heavy states via anomalous couplings (e.g. Z')
- need:
  - $*$ absolute values of Higgs couplings (BRs unaffected)
  - $*$ total Higgs width

⇒ Measurement of the Higgs potential (trilinear couplings)

- reconstruct non-linear structure of Goldstone interactions

Conclusions:

- Little Higgs Models = indirect EW scale generation
- Phenomenology:
  - Light Higgs boson (multiple light states possible)
  - Heavy scalar states
  - Heavy vector bosons: recurrences of W, Z, γ (and others)
  - Heavy quarks mixed with 3rd generation
- Significant sensitivity of precision observables, even if no new states accessible
- LHC likely to discover new states
- . . . but Linear Collider needed for model determination