Little Higgs Models

Theory & Phenomenology

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- How to make a light Higgs (without SUSY)
- Minimal models: The Littlest Higgs and the Minimal Moose
- Phenomenology

Electroweak symmetry breaking (beyond the SM):

- Dynamics responsible for the electroweak scale?

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

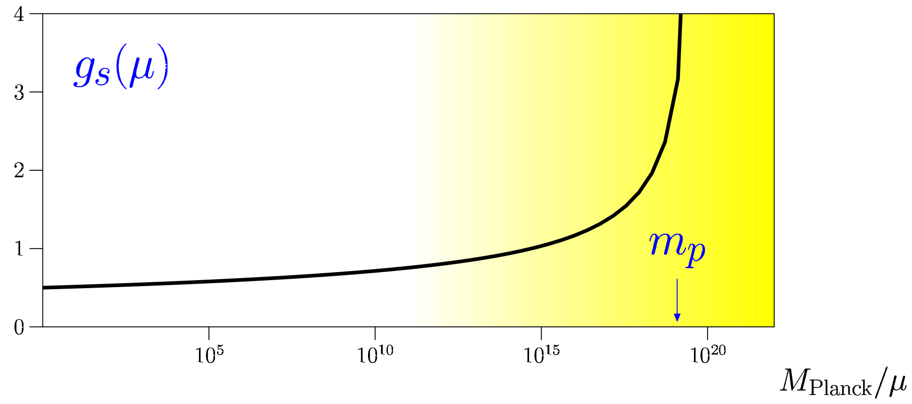
  - New idea (and very old): geometrical origin = extra dimensions
  - Old idea: field-theoretical origin = renormalization-group running and field condensation

- Why would we like dynamical scale generation?
  - We see it at work (QCD):

    $\langle GG \rangle \sim \langle qq \rangle \sim 1\ \text{GeV} \approx 10^{-19} M_{\text{Planck}}$

    without GUT: $g_s(M_{\text{Planck}}) \approx 1/2$

  $\Rightarrow$ The proton mass is natural



Dynamical scale generation:

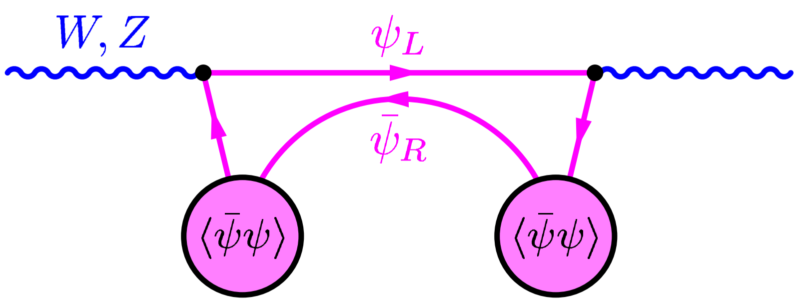
Why not simply copy QCD?

Susskind/Weinberg (1979)

- New QCD' (Technicolor), $\Lambda \sim 3\ \mathrm{TeV} = 4\pi v$

⇒ Compositeness (of $W, Z, \ldots$)

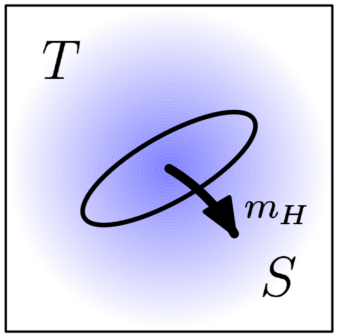
⇒ Resonances in the TeV range



This is elegant, but . . .

- EW precision data
- Flavor Physics

suggest:



⇒ TeV-scale physics is weakly interacting

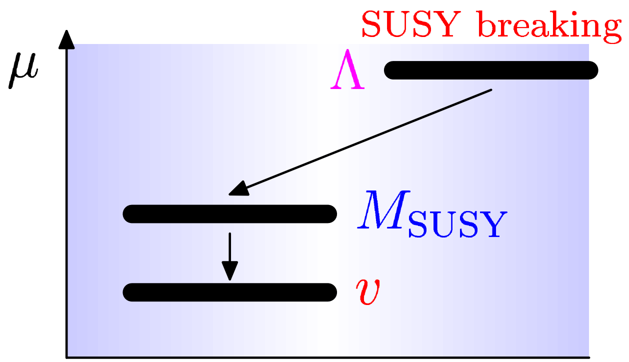
⇒ Strongly interacting physics (if any) is beyond $10\ \mathrm{TeV}$ and/or decoupled

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

Possible solution: Indirect (dynamical) scale generation

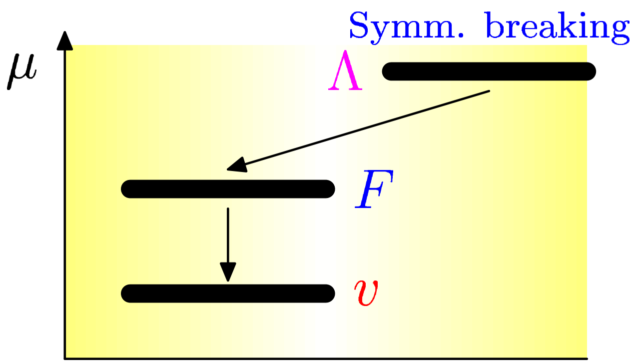
Supersymmetric Models:

- Field condensation in new (hidden) sector with SUSY
  ⇒ SUSY breaking ⇒ Scale generation
- Scalars are present because of SUSY
- Scalar potential by radiative corrections
- Top sector triggers EWSB



Little Higgs Models:

- Field condensation in new sector with global symmetry
  ⇒ spontaneous symmetry breaking ⇒ Scale generation
- Scalars are present because of Goldstone theorem
- Scalar potential by radiative correctons
- Top sector triggers EWSB



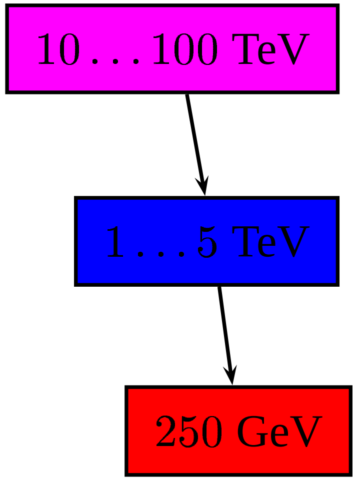
Higgs = Pseudo-Goldstone boson: Georgi, Pais (1974); Georgi, Dimopoulos, Kaplan (1984); . . .

Problem: Without fine-tuning, $v = F \sim \Lambda/4\pi$

$\Rightarrow$ two-scale model (like technicolor)

Three-scale models: Arkani-Hamed, Cohen, Georgi (2001); . . .

$v \sim F/4\pi$ and $F \sim \Lambda/4\pi \Rightarrow$ *little Higgs*



- 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:

- Extended gauge theory: $\mathrm{SM}' \otimes \mathcal{G}_{\mathrm{new}} \to \mathrm{SM}$

  Compare: GMSB-type SUSY, Z' models

- Enlarged global symmetry: $\mathrm{SM}' \otimes \mathcal{G}_{\mathrm{new}}$ embedded in $\mathcal{H}$

  Compare: SM custodial symmetry

- Extended top sector: New vector-like quark(s) coupled to both SM' and $\mathcal{G}_{\mathrm{new}}$

  Compare: See-saw topcolor models

LHM = Extended Gauge Theory:

Generic symmetry breaking pattern:

$$\mathrm{SM}' \quad \otimes \quad \mathcal{G}_{\mathrm{new}} \qquad \to \quad \mathrm{SM}$$

Fermions: Charged under SM and SM', neutral under $\mathcal{G}_{\mathrm{new}}$

Minimal version:

$$\underset{(g_1, g_1')}{(SU(2) \otimes U(1))_1} \quad \otimes \quad \underset{(g_2, g_2')}{(SU(2) \otimes U(1))_2}$$

$$\to \quad \underset{(g, g')}{(SU(2) \otimes U(1))_{\mathrm{SM}}}$$

$\Rightarrow$ Four heavy vector bosons (at least): $W^{\pm\prime}$, Z' and B'

Vector bosons: $W^{\pm\prime}$, Z' and B'

Mass scale: $F \sim 4\pi v \Rightarrow$ TeV range

Couplings:

$$\frac{1}{g^2} = \frac{1}{g_1^2} + \frac{1}{g_2^2} \qquad \text{and} \qquad \frac{1}{g'^2} = \frac{1}{g_1'^{\,2}} + \frac{1}{g_2'^{\,2}}$$

$\Rightarrow$ Both g_1 and g_2 are $> g$

Limits:

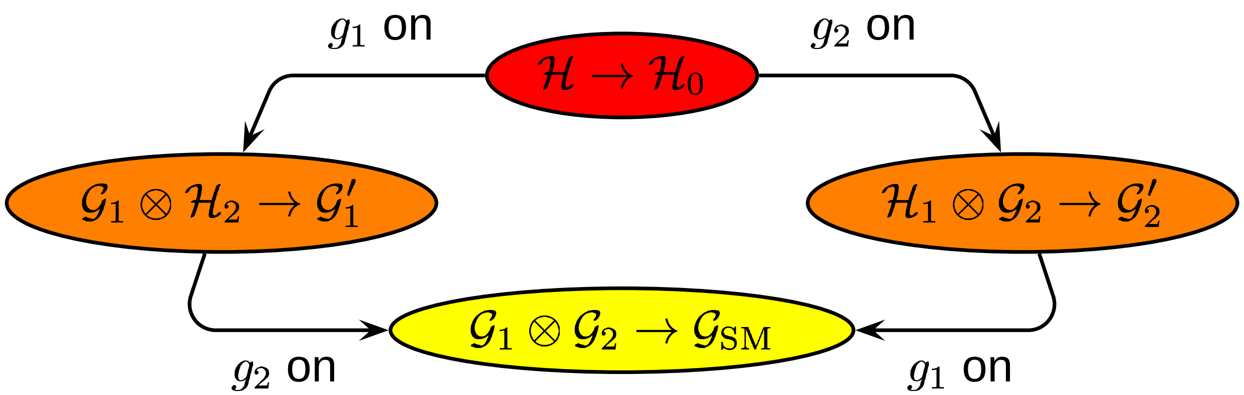
- $g_1 \gg g_2 \quad \Rightarrow \quad W', Z'$ superheavy and strongly coupled to fermions
- $g_1 \approx g_2 \quad \Rightarrow \quad W', Z'$ masses of order F, standard fermion couplings
- $g_1 \ll g_2 \quad \Rightarrow \quad W', Z'$ superheavy and decouple from fermions (fermiophobic)

Larger gauge symmetry: Additional heavy vectors, e.g.

$\mathcal{G}_2 = SU(3) \quad \Rightarrow \quad$ complex $SU(2)$ doublet $V^{\pm}$, V^0, $\bar{V}^0$

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: Symmetry is reduced

- Some Goldstone bosons of $\mathcal{H} \to \mathcal{H}_0$ are eaten $\quad \Rightarrow \quad W'_L, Z'_L, B'_L$
- Some become heavy (mass of order $F \sim \Lambda/4\pi$) $\quad \Rightarrow \quad$ TeV-scale scalars
- Some become light (mass of order $v = g_1 g_2 \Lambda/16\pi^2$) $\quad \Rightarrow \quad$ Higgs boson candidates

  Requirement: $\mathcal{H}_1$ and $\mathcal{H}_2$ don't commute

Radiatively generated Higgs potential

Heavy scalars: H

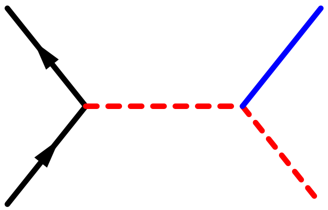
Light scalars: h (includes Goldstone bosons W_L, Z_L)

1-loop Coleman-Weinberg potential for H and h: determined by symmetry pattern

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

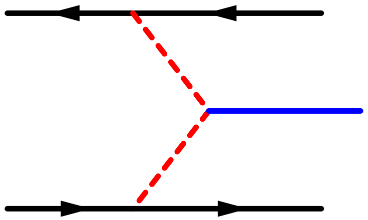
Integrate out the H fields:

$$V(h) = c' h^4 + \ldots$$



- $\Rightarrow$ h is massless to one-loop order
- $\Rightarrow$ Positive mass^2 at two-loop order
- $\Rightarrow$ Trilinear couplings Hhh:

  production and decay channels for heavy scalars



Extended top quark sector:

Extra massive singlet fermion(s) with top quantum numbers: $t'_{L,R}$

Yukawa coupling (model dependent):

$$\lambda_1 F\ \mathrm{Tr}[(\bar{t}_L\ \bar{b}_L\ \bar{t}'_L) \times \Sigma(H,h)]\, t_R + \lambda_2 F\ \bar{t}'_L t'_R$$

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

t, t' loop correction $\quad\Rightarrow\quad$ negative Higgs mass squared

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

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

$\Rightarrow$ Top mass $m_t = \lambda_t v$

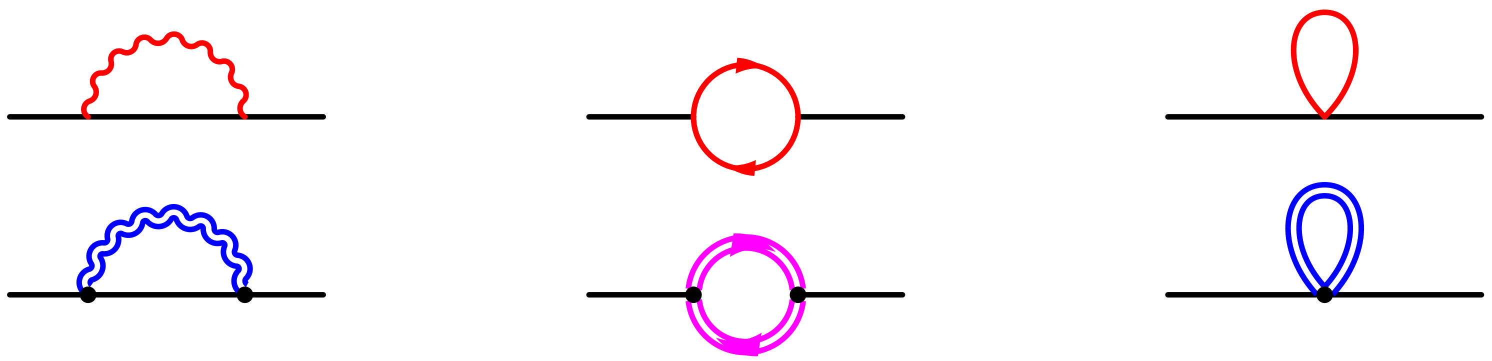
$\Rightarrow$ Top' mass $m_{t'} = \lambda_2 F$

Yukawa couplings of heavy scalars H: suppressed by v/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, mixed with light Higgses (mixing angle $\sim v/F$)
- Heavy vector bosons:
  $W^{\pm\prime}, Z', B'$ coupled to SM fermions, mixed with $W^{\pm}, Z$ (mixing angle $\sim v/F$)
- Heavy up-type quark(s): t'

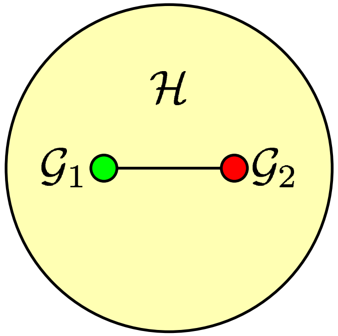
Effective theory above F: cancellation of quadratic divergences in Higgs self-energy



Two classes of LHM have been proposed:

Simple group:

Extended gauge symmetry $\mathcal{G}_1 \otimes \mathcal{G}_2$ embedded in simple group $\mathcal{H}$



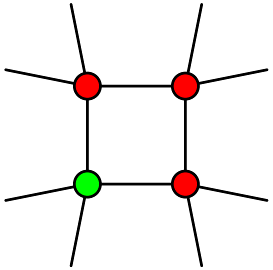
$\Rightarrow$ exotic Higgs representations,

$\Rightarrow$ low-energy effective theory can be the minimal SM

Minimal version: $(SU(2) \otimes U(1))^2$ embedded in $SU(5)$

Theory space (Moose Models):

Extended gauge symmetry $(\mathcal{G}_{\rm SM})^n$ embedded in semisimple group $\mathcal{G}^{4n}$



$\Rightarrow$ many copies of scalar (and vector) multiplets

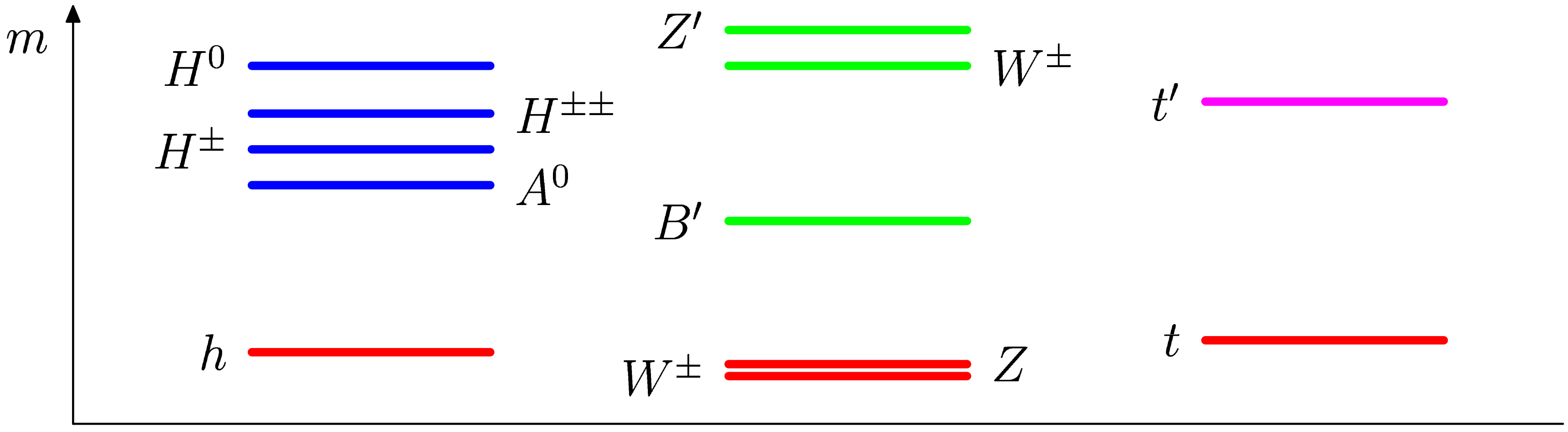
$\Rightarrow$ low-energy effective theory contains at least two Higgs doublets

Minimal version: $(SU(2) \otimes U(1))^2$ embedded in $SU(3)^8$

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

- Global symmetry breaking $SU(5) \to SO(5) \quad \Rightarrow \quad 24 - 10 = 14$ 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 (example):



Heavy vectors

Vector bosons with TeV scale masses:

$*$ B' significantly lighter than W', Z', production at LC 800?

$\Rightarrow$ Resonance in $e^+e^- \to f\bar{f}$ and $qq \to qq$ $\quad$ ($\to$ Tevatron Run 2)

$\Rightarrow$ Fermion couplings suppressed if $g_1' < g_2'$, enhanced if $g_1' > g_2'$

$\Rightarrow$ Hypercharge boson: coupling to W^+W^- suppressed

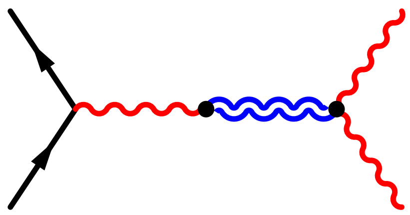
$\Rightarrow$ Measurements of mass, width and BRs determine scale F, quantum numbers and gauge sector parameters

$*$ $W'^{\pm}$ and Z' are heavier

$\Rightarrow$ Indirect constraints from contact interactions

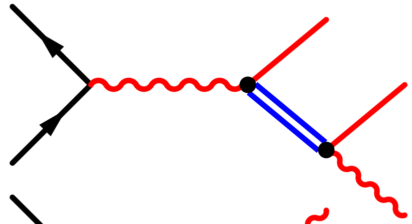
$\Rightarrow$ Effect on triple gauge couplings

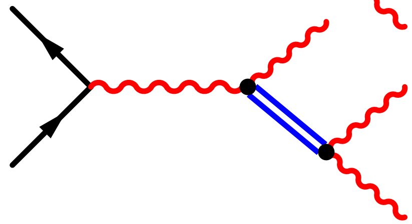
$\Rightarrow$ GigaZ



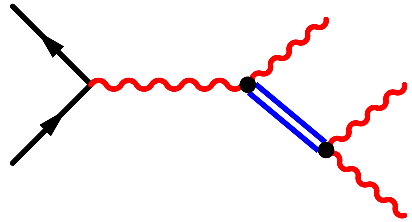
Heavy scalars

Scalars with TeV scale masses, unsuppressed couplings to light Higgs and Goldstones:





- $\ast$ A^0 could be the lightest state
  - $\Rightarrow$ Associated production $e^+e^- \to Ah$
  - $\Rightarrow$ Fermion couplings suppressed $\Rightarrow$ decay into hZ_L
- $\ast$ Charged Higgs $H^\pm$
  - $\Rightarrow$ Single production in $e^+e^- \to H^+W_L^-$, decay into W_LZ_L
- $\ast$ Doubly charged Higgs $H^{\pm\pm}$
  - $\Rightarrow$ Single production in $e^-e^- \to \nu\nu H^{--}$, decay into $W_L^-W_L^-$
- $\ast$ Heavy Higgs H^0
  - $\Rightarrow$ Higgs-strahlung $e^+e^- \to Z_LH$
  - $\Rightarrow$ Decay into Z_LZ_L and hh, but not W^+W^-



. . . but they may be too heavy $\Rightarrow$ indirect constraints from Higgs, Z and W observables

Light scalars

Higgs boson h mixes with heavy scalar H, mixing angle $\sim v/F$:

$\Rightarrow$ Light Higgs h mass significantly decreased

$\Rightarrow$ Yukawa couplings slightly decreased

$\Rightarrow$ Anomalous hVV and hhh couplings

Precise measurements of all Higgs couplings very important!

Heavy quarks

Top quark t mixes with heavy fermion t'

* t' production at LHC?
* Decay into bW_L and th

Linear collider: Precise measurements of t quark couplings!

Precision observables

Violation of the custodial $SU(2)_C$ symmetry $\Rightarrow$ contributions to the ρ parameter $O(v^2/F^2)$

* extra hypercharge boson B'
* Higgs triplet
* extended top quark sector
* $[m_h > 100\ \mathrm{GeV}]$

Light hypercharge boson B'

* Limits from Drell-Yan processes / contact terms at Tevatron, LEP2

Extra t'

* Contributions to t, b couplings and R_b

Present limits:

Csaki/Hubisz/Kribs/Meade/Terning (2002)

$$M_{B'} > 650 \text{ GeV} \qquad \text{and} \qquad M_{W'} > 2.7 \text{ TeV}$$

Caveat: Top sector neglected

Hewett/Petriello/Rizzo (2002)

$$F > 3.5 \text{ TeV} \qquad \text{and} \qquad m_{t'} > 10 \text{ TeV}$$

Caveat: Scalar sector neglected

$\Rightarrow$ Need to take into account all contributions (cancellations!)

$\Rightarrow$ Favored: Models with

- Different hypercharge embedding: B' heavier
- Custodial $SU(2)$ symmetry: $SU(2) \otimes SU(2) \subset \mathcal{G}_2$?
- Fermiophobic vector bosons

Han/Logan/McElrath/Wang (2003)

The Minimal Moose Model: Arkani-Hamed/Cohen/Katz/Nelson/Gregoire/Wacker (2002)

- Global symmetry breaking:

$$(SU(3) \otimes SU(3))^4 \to SU(3)^4$$

with four independent scalar multiplets $\Rightarrow$ 32 Goldstone bosons

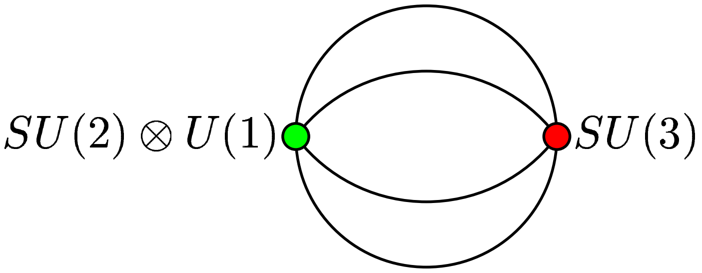
- Gauge symmetry breaking:

$$SU(3) \otimes SU(2) \otimes U(1) \to SU(2) \otimes U(1)$$

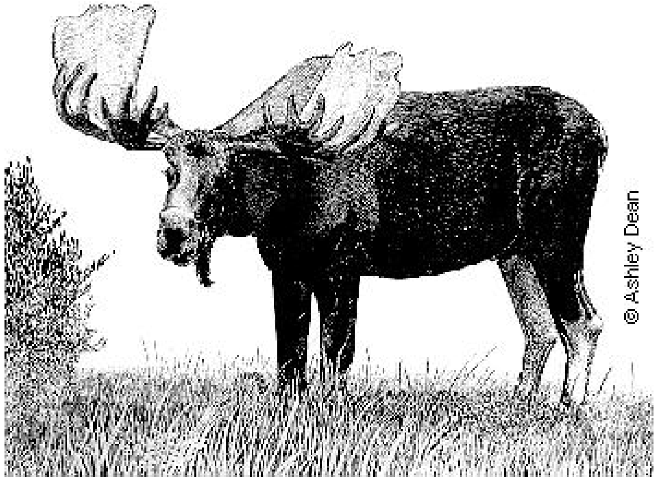
$\Rightarrow$ Heavy vectors $W^{\pm\prime}, Z', B'$ and $V^{\pm}, V^0, \bar{V}^0$

- Light scalars: 2 Higgs doublets, 2 real triplets, 2 real singlets

- Heavy scalars: 1 singlet, 1 doublet, 1 triplet



- Top sector: Vector-like heavy fermion(s)



Phenomenology of the Minimal Moose:

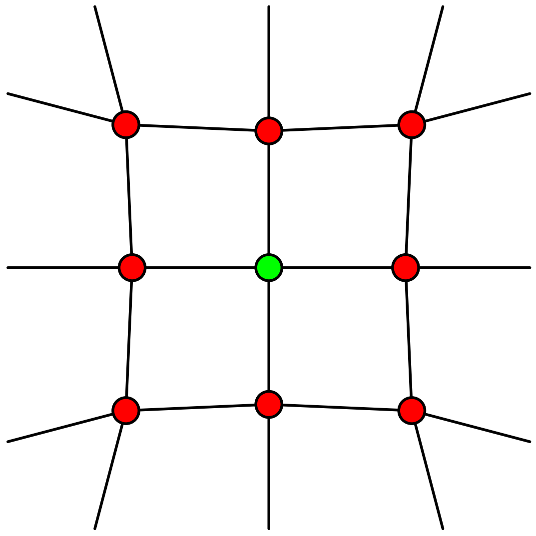
- B' is candidate for the lightest new vector boson
- Rich low-energy Higgs phenomenology ($100 \ldots 1000$ GeV)
  - Two Higgs doublets: $h, H, A^0, H^\pm$
  - Scalar triplet $\phi^\pm, \phi^0$ and singlet η^0 bosons (no VEV)
- Additional heavy Higgs states (mixing with light Higgs)
- Anomalous top sector

Theory space

Multiple gauge groups: *sites*

Goldstone multiplets, charged under two gauge groups: *links*

Spontaneous symmetry breaking in the Goldstone sectors $\Rightarrow$ breaking of $\mathcal{G}^n \to \mathrm{SM}$



Little Higgs Models:

- Extra links $\Rightarrow$ closed cycles
- Two-dimensional lattice $\Rightarrow$ unsuppressed quartic couplings $\Rightarrow$ EWSB by Goldstone VEV

$\Rightarrow$ Many multiplets of scalars and vector bosons

$\Rightarrow$ Spectrum and interactions similar to 6D extra-dimension model
(Scalars = 5-6 components of 6D gauge fields)

What should we look for?

Direct observation

- LHC/LC: Light Higgs boson?
- LHC: Heavy vector bosons, heavy colored fermions
- LHC/LC: Uncover Higgs sector completely (how many sub-TeV scalars are there?)

Precision observables

- Tevatron/LHC/LC: Contact terms $\Rightarrow$ constrain four-fermion operators
- LHC/LC: Triple gauge couplings (fermiophobic vector bosons)
- LHC/LC: Quartic gauge couplings (vector bosons and heavy scalars)

  $\Rightarrow$ Analysis similar to strong-WW scattering, but in the presence of light Higgs
- LC: Higgs self-coupling(s), quartic Higgs-vector boson couplings

More phenomenology:

- Grand Unification:
  - The SM $SU(2) \otimes U(1)$ symmetry is continued above the TeV scale. If the extra $\mathcal{G}_2$ symmetry is strongly coupled, the shifts in the SM couplings are small
  - $\Rightarrow$ The SM mismatch in unification could be a consequence of $\mathcal{G}_2$
  - $\Rightarrow$ Coupling sum rule: The GUT scale is lowered . . . unless $SU(3)_{\rm QCD}$ is also affected.
- Dark Matter:
  - If there is an unbroken discrete symmetry in the LHM, there will be a dark matter candidate. (Not in the minimal model.)
  - $\Rightarrow$ Heavy neutral scalar?
- Supersymmetry:
  - LHM symmetry structure could come with SUSY breaking in the $10\ \mathrm{TeV}$ range
  - $\Rightarrow$ Superpartners much more heavy?

Conclusions:

- Little Higgs Models = indirect EW scale generation: symmetry breaking in new sector (analogous to SUSY models)
- Special role of top quark
- . . . but no solution to flavor problem   Chivukula/Evans/Simmons (2002)
- 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
  $\Rightarrow$ get a complete and consistent picture of all Higgs and vector boson couplings!