The Bestest Little Higgs

Daniel Stolarski

Martin Schmaltz, DS, Jesse Thaler
JHEP 1009 (2010) 018
[arXiv:1006.1356 [hep-ph]].

University of Maryland 1856
The Johns Hopkins University · Baltimore · 1876

Little Higgs History

- Arkani Hamed, Cohen, Georgi, "Electroweak Symmetry Breaking From Dimensional Deconstruction" (2001)
- Arkani-Hamed, Cohen, Gregoire, Wacker, first use of "Little Higgs" (2002)
- Arkani-Hamed, Cohen, Katz, Nelson, Gregoire, Wacker, "The Minimal Moose for a Little Higgs" (2002)

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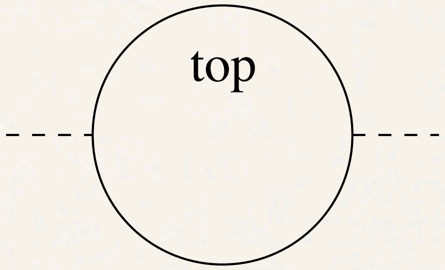
- "Bestest Little Higgs"
    - "Worstest title ever"
      -- Cliff Cheung

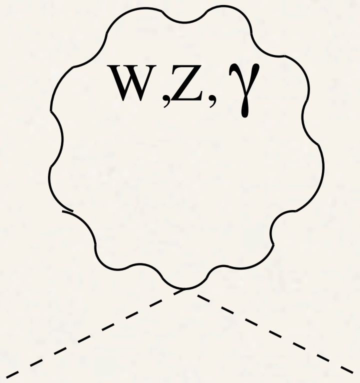
Outline

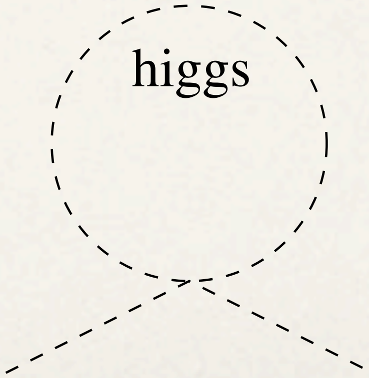
- SM hierarchy and little hierarchy problems
- Higgs and pseudo--Nambu--Goldstone boson and little Higgs
- Problems with little Higgs models
- A model with a simple quartic
- A modular gauge sector
- Bestest fermion sector
- Constraints and collider phenomenology

Hierarchy Problem

- Standard Model very successful
- Quadratic divergences, need new physics to prevent fine-tuning
  - Top: $\Lambda \lesssim 2\,\text{TeV}$
  - Gauge: $\Lambda \lesssim 5\,\text{TeV}$
  - Quartic: $\Lambda \lesssim 10\,\text{TeV}$



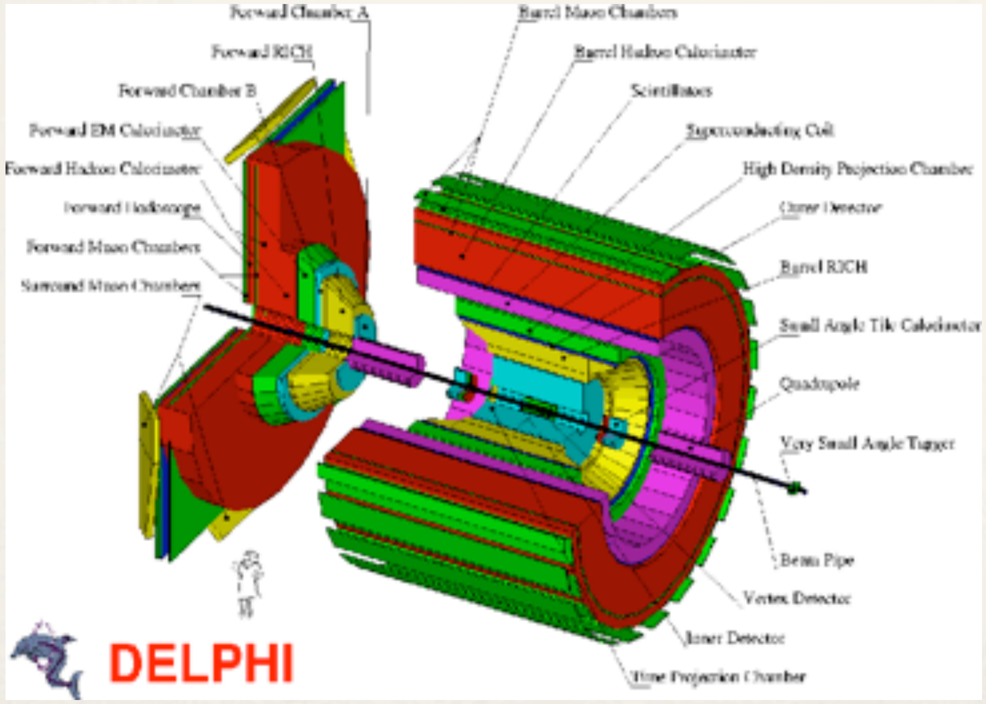




Little Hierarchy Problem

- Precise measurements of SM gauge sector

- No deviations from SM, stringent bounds



- Custodial symmetry violation

$$\frac{1}{\Lambda^2}|h^\dagger D_\mu h|^2$$

$$\Lambda \gtrsim 5\,\mathrm{TeV}$$

- Four fermion operators

$$\frac{1}{2\Lambda^2}(\bar{l}\gamma^\mu\sigma^a l)(\bar{l}\gamma_\mu\sigma^a l)$$

$$\Lambda \gtrsim 7\,\mathrm{TeV}$$

Higgs as a PNGB

- Make the Higgs pseudo--Nambu--Goldstone Boson (PNGB)

  Kaplan, Georgi, Dimopoulos, 1984; Dugan, Georgi, Kaplan, 1985.

- Break a global symmetry, Higgs is one of the broken generators

- Explicitly break the global symmetry

- Tree level potential for Higgs vanishes, one loop contribution generates mass and self interactions

Little Higgs

- PNGB Higgs doesn't solve little hierarchy problem
  - Potential will be quadratically divergent, proportional to explicit breaking
  - Have to fine-tune two terms

- Little Higgs: *collective* symmetry breaking
  - Explicitly break global symmetry with two different operators
  - Each operator preserves enough symmetry
  - Radiative corrections proportional to 2 couplings, only *log* divergent at one loop

Simple(st) Model

- SU(3)/SU(2) toy model with two Σ fields

$$\mathcal{L} = \sum_{i=1}^{2} \mathrm{tr}(\partial_\mu \Sigma_i^\dagger \partial^\mu \Sigma_i)$$

- Parameterize Goldstones

$$\Sigma_1 = e^{i\pi_1/f} \left(\begin{array}{c} 0 \\ f \end{array} \right)$$

$$\Sigma_2 = e^{i\pi_2/f} \left(\begin{array}{c} 0 \\ f \end{array} \right)$$

- Gauge diagonal $SU(3)$, explicitly break $SU(3)^2$

- Symmetry is broken collectively: both Σ_1 and Σ_2 must have gauge interactions

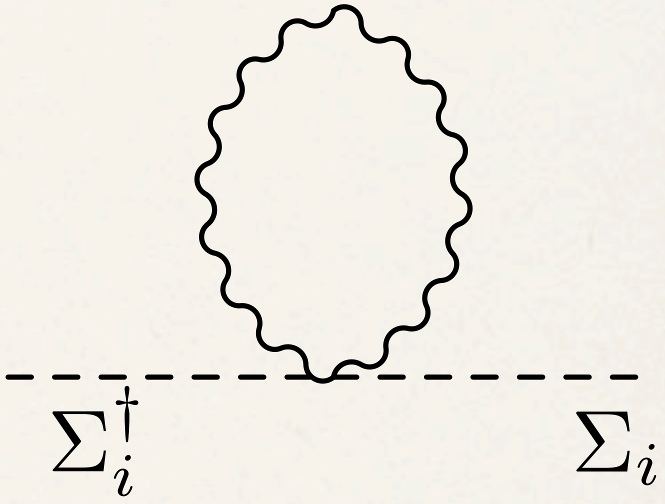
Schmaltz, Tucker-Smith, hep-ph/0502182

Collective Symmetry in Action

- Quadratic divergence generates

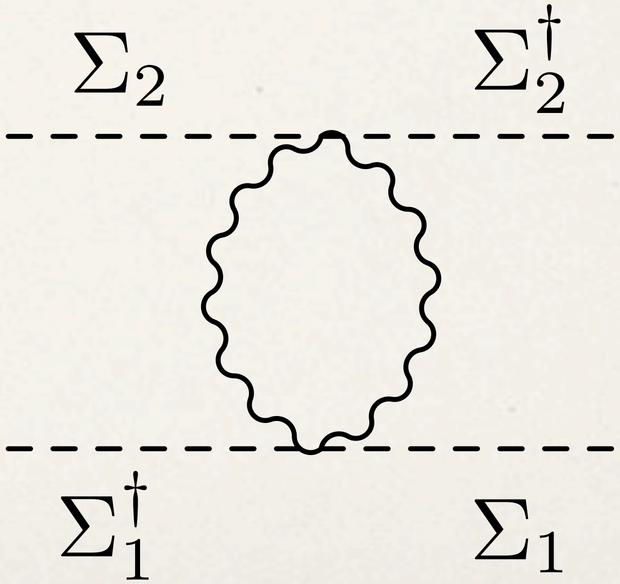
  $$\frac{g^2\Lambda^2}{16\pi^2}(\Sigma_1^\dagger\Sigma_1+\Sigma_2^\dagger\Sigma_2)$$

  which does not generate a potential for π_i

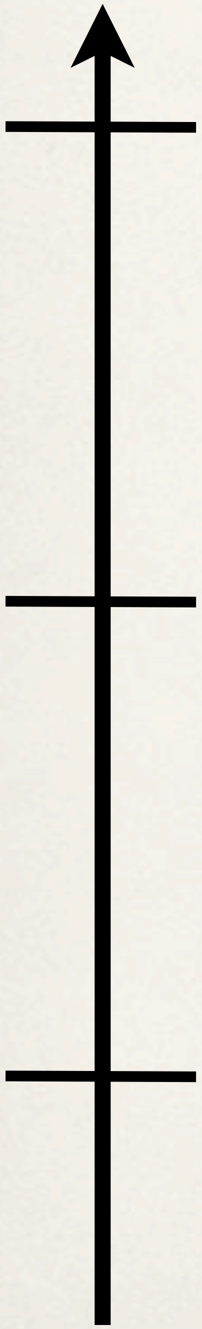


- Log divergence can generate potential for π_i

  $$\frac{g^4}{16\pi^2}\log\Lambda^2\,|\Sigma_1^\dagger\Sigma_2|^2\sim\frac{g^4 f^2}{16\pi^2}\log\Lambda^2\,h^\dagger h$$



Scales of the Theory

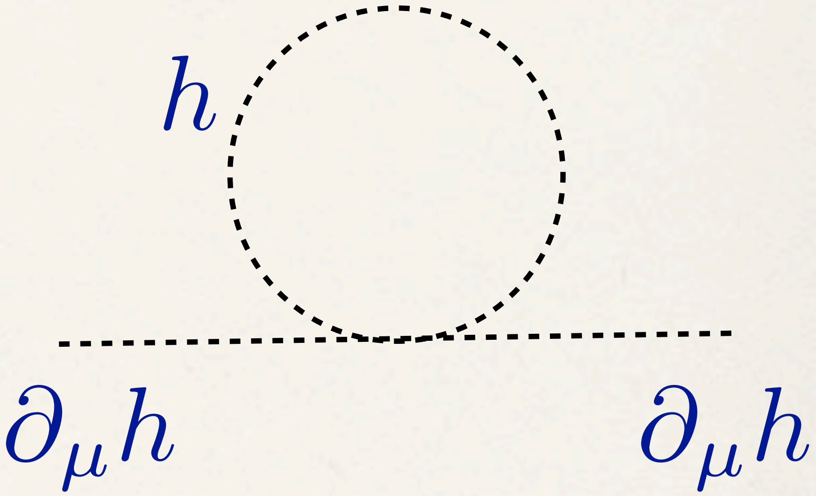


$$\Lambda \sim 4\pi f \sim 10\,\mathrm{TeV}$$

$$\langle \Sigma \rangle \sim f \sim 1\,\mathrm{TeV}$$

$$\Sigma = e^{2\,i\,\pi/f}$$

$$v_{\mathrm{EW}} \sim m_h \sim \frac{f}{4\pi}$$



$$\sim \frac{1}{f^2}\frac{\Lambda^2}{16\pi^2}$$

Recipe for a Little Higgs

- Spontaneously break global symmetry. Some PNGBs = SM Higgs
- Parameterize PNGBs with nlσm, cutoff at $\Lambda \simeq 4\pi f$
- Collectively break symmetries to generate gauge, Yukawa, and Higgs self interactions
- Enlarged symmetry means extra particles
- Explicit breaking for small couplings, ie light quark Yukawa’s

Problems with LH models

- Fine tuning in top sector $\Lambda \lesssim 2\,\text{TeV}$
- Precision electroweak constraints $\Lambda \gtrsim 5\,\text{TeV}$
  - Allow some fine tuning
  - Implement T-parity to reduce PEW corrections

    Cheng and Low, hep-ph/0308199
  - Separate scales control top Yukawa and gauge sectors
- Preserve custodial symmetry before and after electroweak symmetry breaking

Difficulty with Quartic

- Collective Higgs quartic

$$\lambda_+|\sigma + h\,h|^2 + \lambda_-|\sigma - h\,h|^2$$

- No dangerous singlets, must forbid: $(\sigma \pm h\,h)$

  Schmaltz and Thaler, 0812.2477 [hep-ph]

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  Dangerous Singlet

  Schmaltz and Thaler, 0812.2477 [hep-ph]

Difficulty with Quartic

- Collective Higgs quartic

$$\lambda_+ |\sigma + h\, h|^2 + \lambda_- |\sigma - h\, h|^2$$

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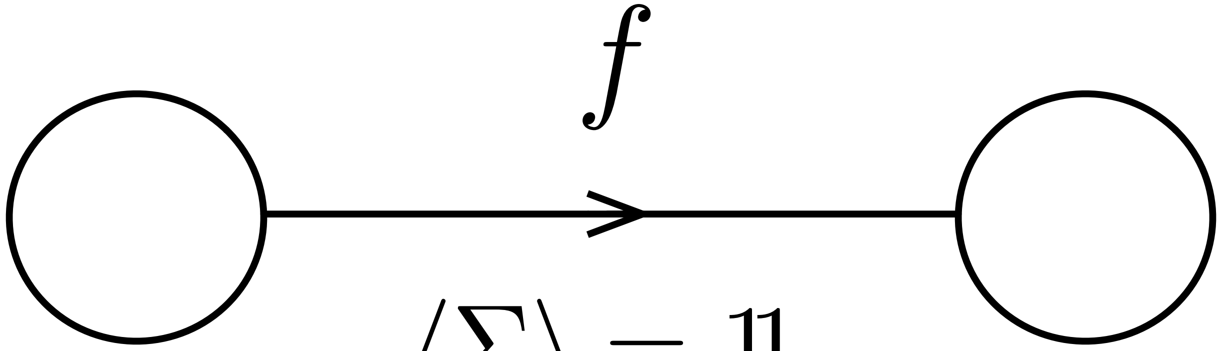
- Ugly in other models

Minimal Moose:
$\mathrm{tr}(\Sigma_1\Sigma_2^\dagger\Sigma_3\Sigma_4^\dagger + \Sigma_1\Sigma_4^\dagger\Sigma_3\Sigma_2^\dagger)$

Littlest Higgs:
$\varepsilon^{wx}\varepsilon_{yz}\varepsilon^{ijk}\varepsilon_{kmn}\Sigma_{iw}\Sigma_{jx}\Sigma^{*my}\Sigma^{*nz}$

Symmetry Structure



Global: $SO(6)_A$ $SO(6)_B$

f

$\langle \Sigma \rangle = \mathbb{1}$

Gauged: $SU(2) \times U(1)$

Non-linear sigma model

$$\Pi_h = i \overset{\underline{SO(6)}}{\left(\begin{array}{c|c|c} SO(4) & h_1 & h_2 \\ \hline -h_1^T & & \\ \hline -h_2^T & & \end{array}\right)}$$

$$SO(4) = SU(2)_L \times SU(2)_R$$

$$\Pi = i \begin{pmatrix} \phi_i + \eta_i & 0 & 0 \\ 0 & 0 & \sigma/\sqrt{2} \\ 0 & -\sigma/\sqrt{2} & 0 \end{pmatrix}$$

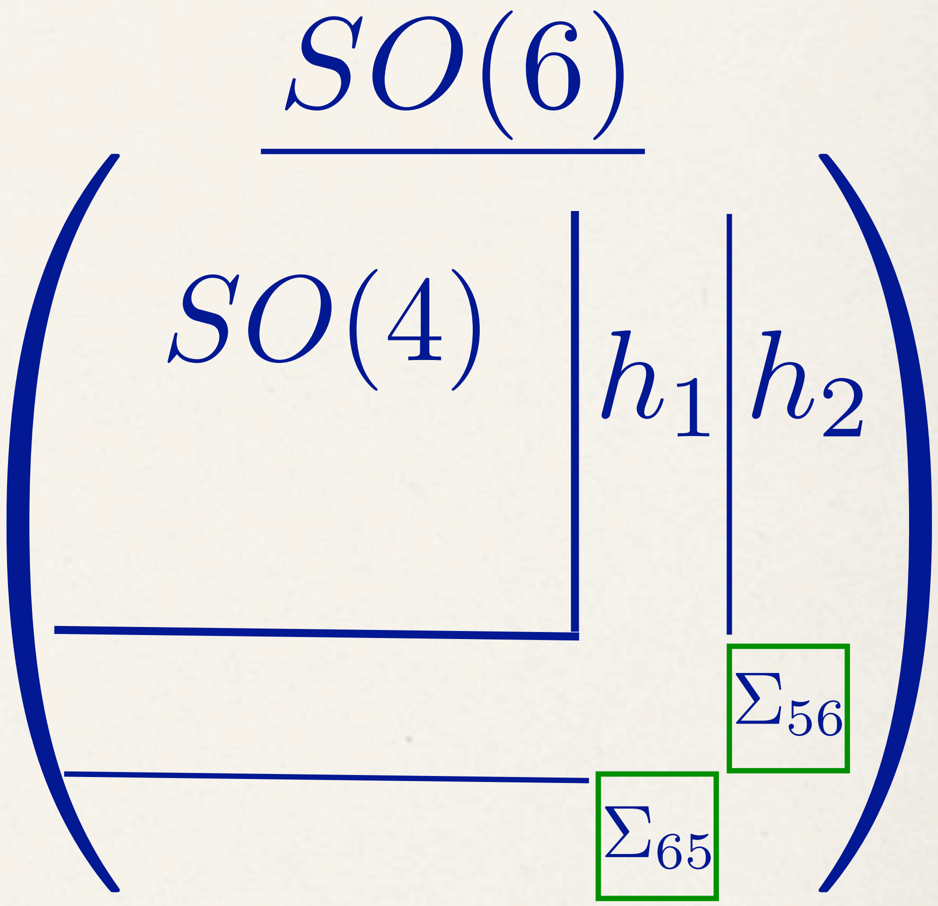
Collective Quartic

- $\lambda_{65}|\Sigma_{65}|^2 + \lambda_{56}|\Sigma_{56}|^2$
- $\Sigma \rightarrow g_A \Sigma\, g_B^\dagger$
- λ_{65} operator breaks

  $SO(6)_A \times SO(6)_B \rightarrow SO(5)_6 \times SO(5)_5$
- λ_{56} operator breaks

  $SO(6)_A \times SO(6)_B \rightarrow SO(5)_5 \times SO(5)_6$
- Two operators combined break

  $SO(6)_A \times SO(6)_B \rightarrow SO(4) \times SO(4)$



Expanding in terms of Π

Σ_{65} Σ_{56}

$$\lambda_{65}\left(f\,\sigma - h_1^T h_2 + \ldots\right)^2 + \lambda_{56}\left(f\,\sigma + h_1^T h_2 + \ldots\right)^2$$

Integrate out σ and plug back in to get $\dfrac{\lambda_{56}\lambda_{65}}{\lambda_{56}+\lambda_{65}}(h_1^T h_2)^2$

which is collective

No h mass generated

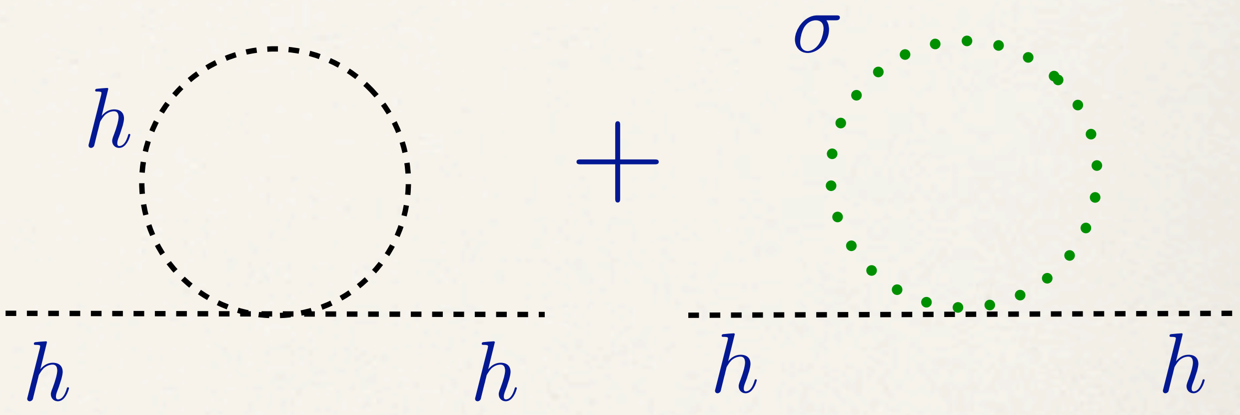
σ transforms under a symmetry, $\sigma \to -\sigma,\; h_2 \to -h_2$

Not a dangerous singlet!

Radiative Corrections

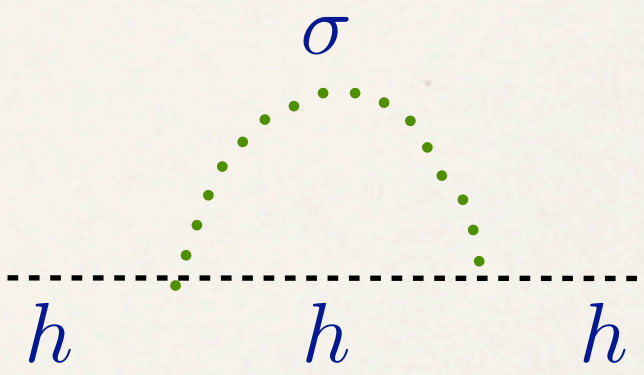
- Quadratic divergence

$$-\frac{3f^2\Lambda^2}{16\pi^2}\left(\lambda_{65}|\Sigma_{65}|^2+\lambda_{56}|\Sigma_{56}|^2\right)$$



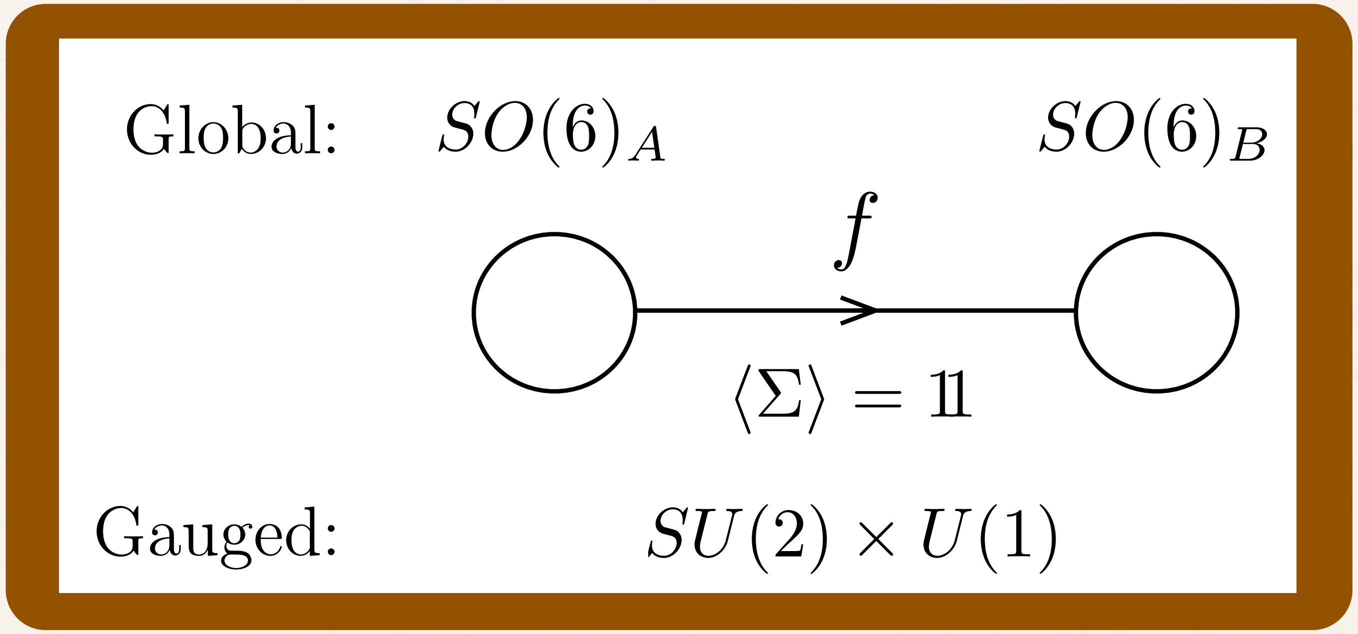
- Log divergence

$$\frac{\lambda_{65}\lambda_{56}f^2}{16\pi^2}\log\left(\frac{\Lambda^2}{m_\sigma^2}\right)\left(h_1^T h_1+h_2^T h_2\right)$$



- Right order of magnitude for natural EWSB

Gauge Sector



Global: $SO(6)_A$ $SO(6)_B$

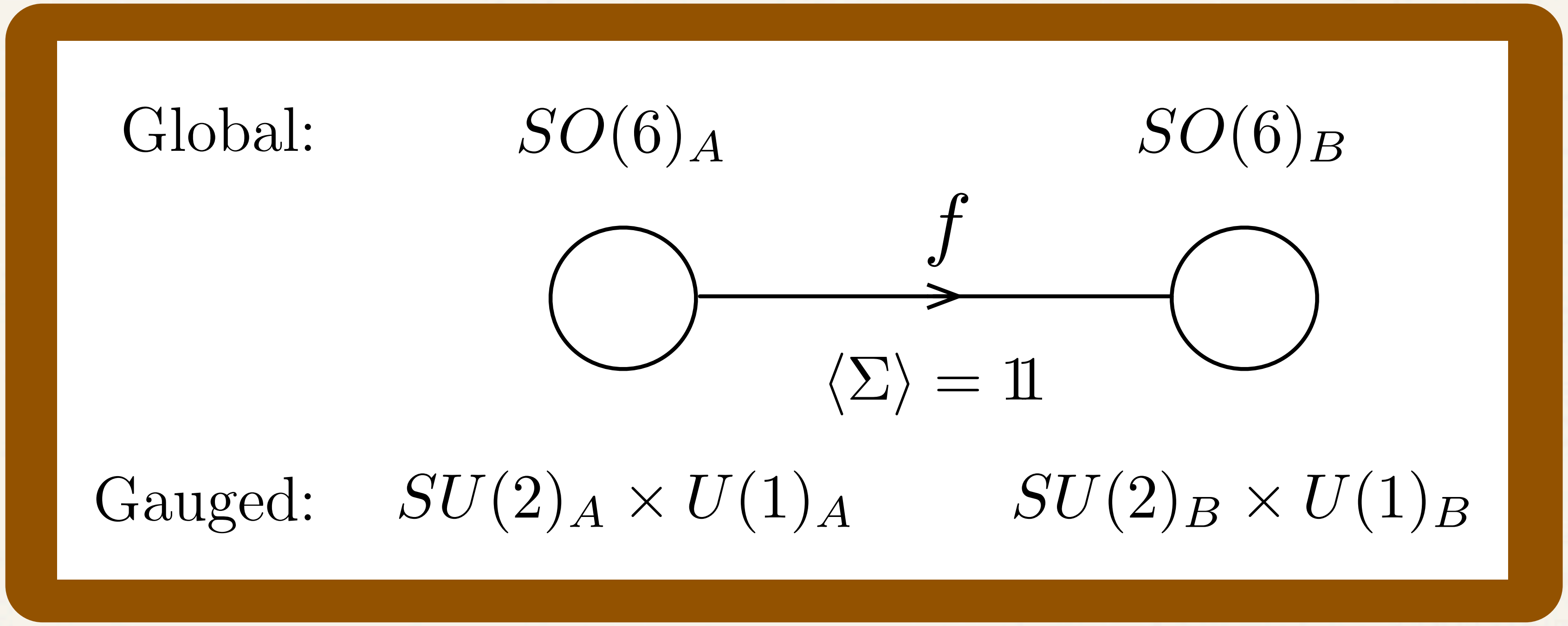
f

$\langle\Sigma\rangle = \mathbb{1}$

Gauged: $SU(2)\times U(1)$

$$\frac{9\, g_{\rm EW}^2 \Lambda^2}{128\pi^2}\left(h_1^T h_1 + h_2^T h_2\right)$$

Gauge Sector



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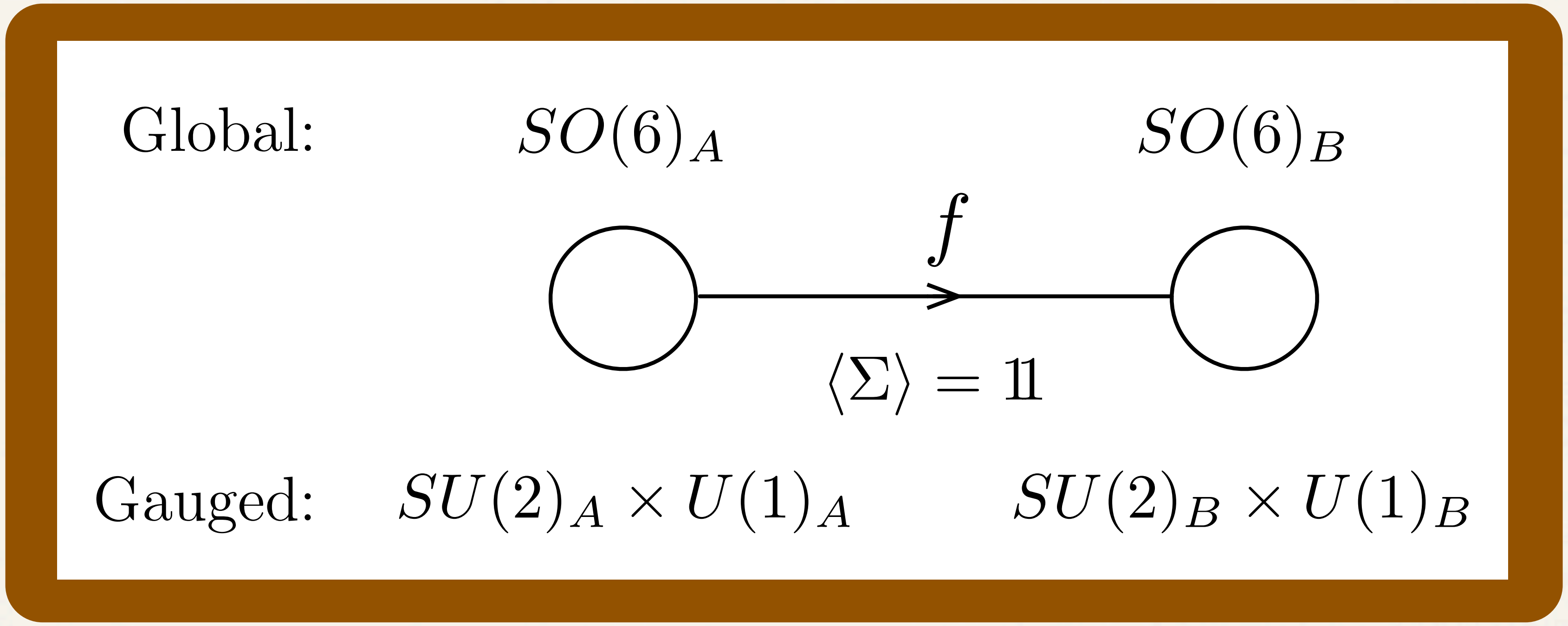
$\langle\Sigma\rangle = \mathbb{1}$

Gauged: $SU(2)_A \times U(1)_A$ $SU(2)_B \times U(1)_B$

- Collective symmetry breaking, $g_i \to 0$ then full $SO(6)$ is preserved

Gauge Sector



Global: $SO(6)_A$ $SO(6)_B$

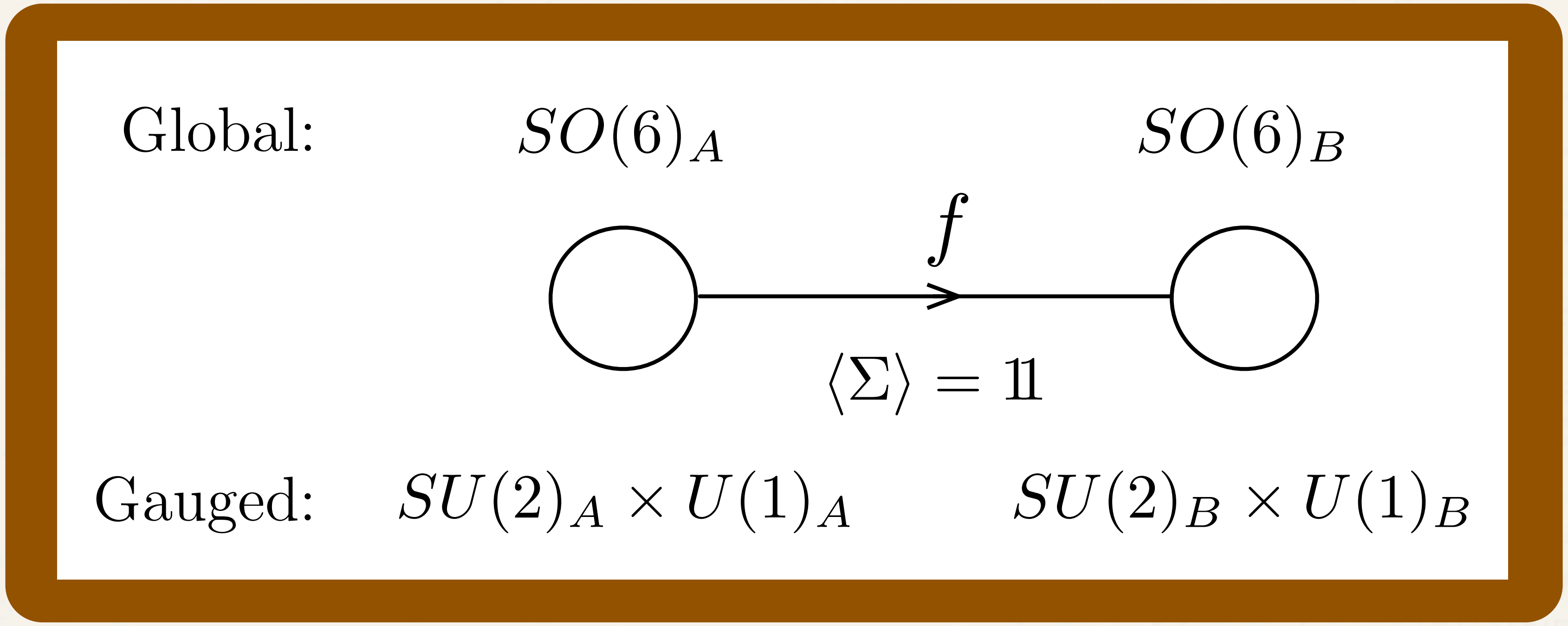
f

$\langle \Sigma \rangle = \mathbb{1}$

Gauged: $SU(2)_A \times U(1)_A$ $SU(2)_B \times U(1)_B$

- Collective symmetry breaking, $g_i \to 0$ then full $SO(6)$ is preserved
- Gauge and top partner masses controlled by f

Gauge Sector



Global: $SO(6)_A$ $SO(6)_B$

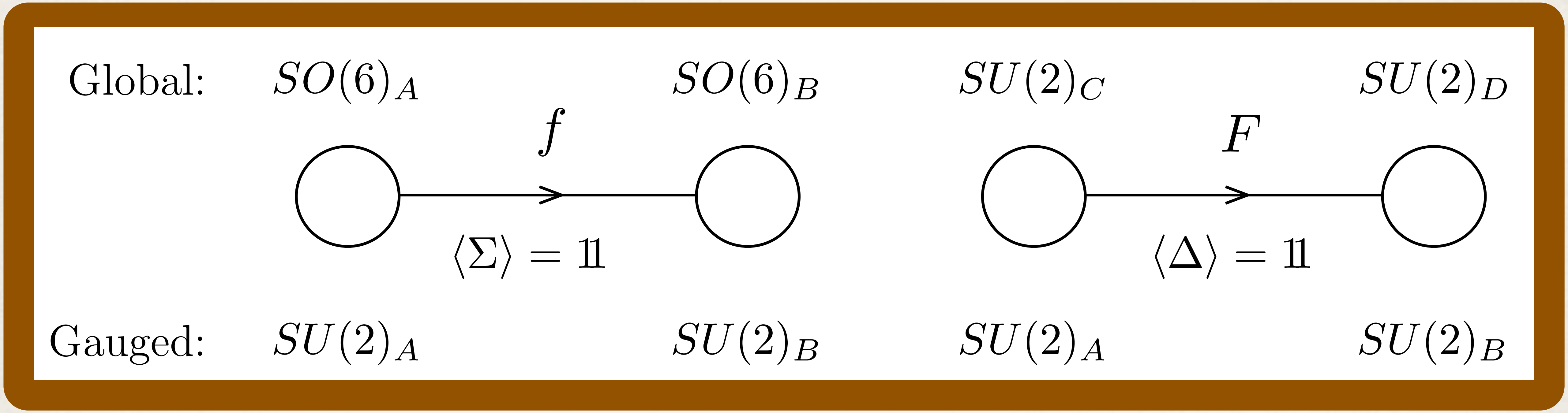
$$\xrightarrow{f}$$

$\langle\Sigma\rangle = \mathbb{1}$

Gauged: $SU(2)_A \times U(1)_A$ $SU(2)_B \times U(1)_B$

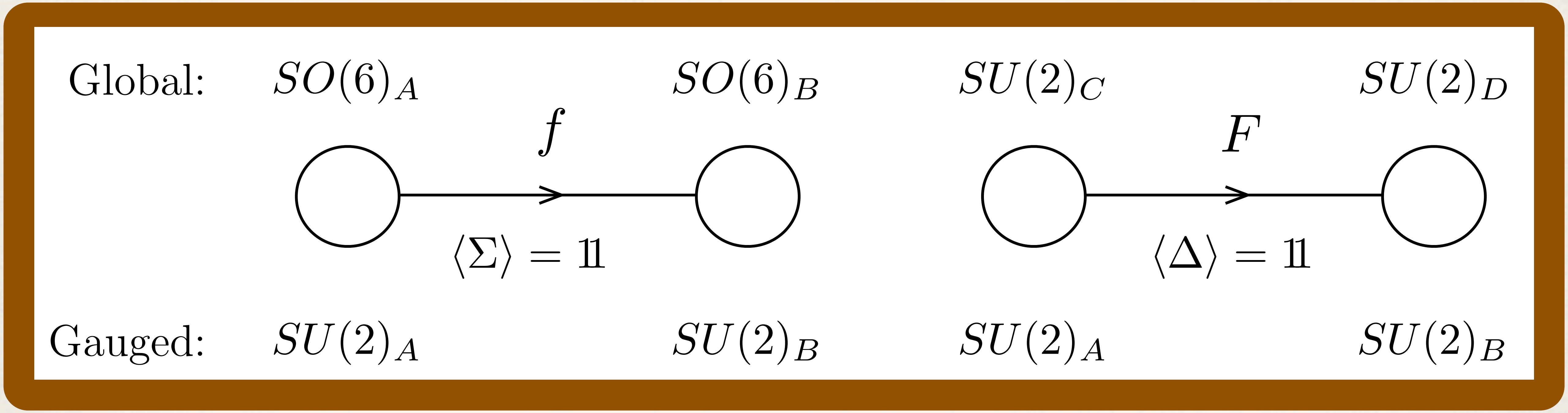
- Collective symmetry breaking, $g_i \to 0$ then full $SO(6)$ is preserved
- Gauge and top partner masses controlled by f
- Situation worse because $\dfrac{m_T}{m_{W'}} \simeq \dfrac{m_{\text{top}}}{m_W} \simeq 2$

Modular Gauge Sector



- Add a gauge breaking module, Δ that has a decay constant F
- Δ is a singlet under $SO(6)$ global symmetries
- Make $F > f$, gauge partner mass ~ $g\,F$ while top partners mass $\sim \lambda_t f$

Reduction to Initial Model

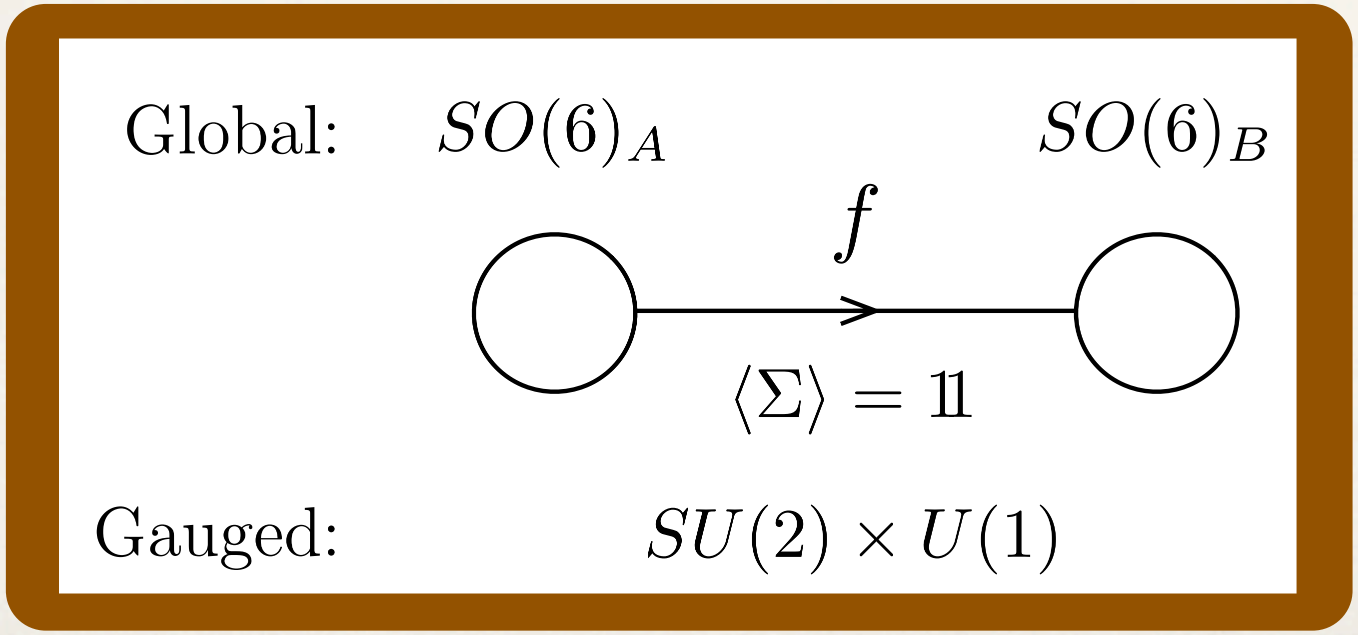


Global: $SO(6)_A$ $SO(6)_B$ $SU(2)_C$ $SU(2)_D$

f F

$\langle\Sigma\rangle = \mathbb{1}$ $\langle\Delta\rangle = \mathbb{1}$

Gauged: $SU(2)_A$ $SU(2)_B$ $SU(2)_A$ $SU(2)_B$



Global: $SO(6)_A$ $SO(6)_B$

f

$\langle\Sigma\rangle = \mathbb{1}$

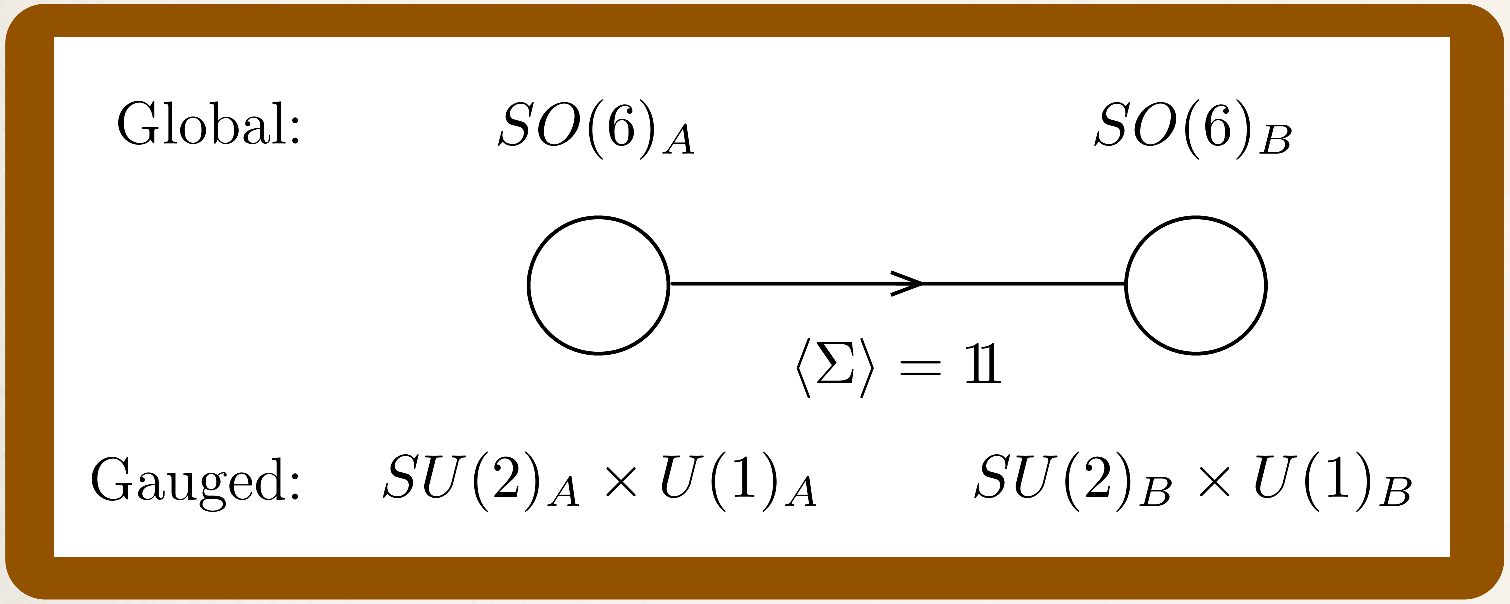
Gauged: $SU(2) \times U(1)$

$$m_{W'}^2 \simeq f^2 + F^2$$

A Generic Tool

- While LH quartic is difficult, this shows that putting in gauge sector is easy
- This tool is very generic, can be used by LH model builders again

Consequences



Global: $SO(6)_A$ $SO(6)_B$

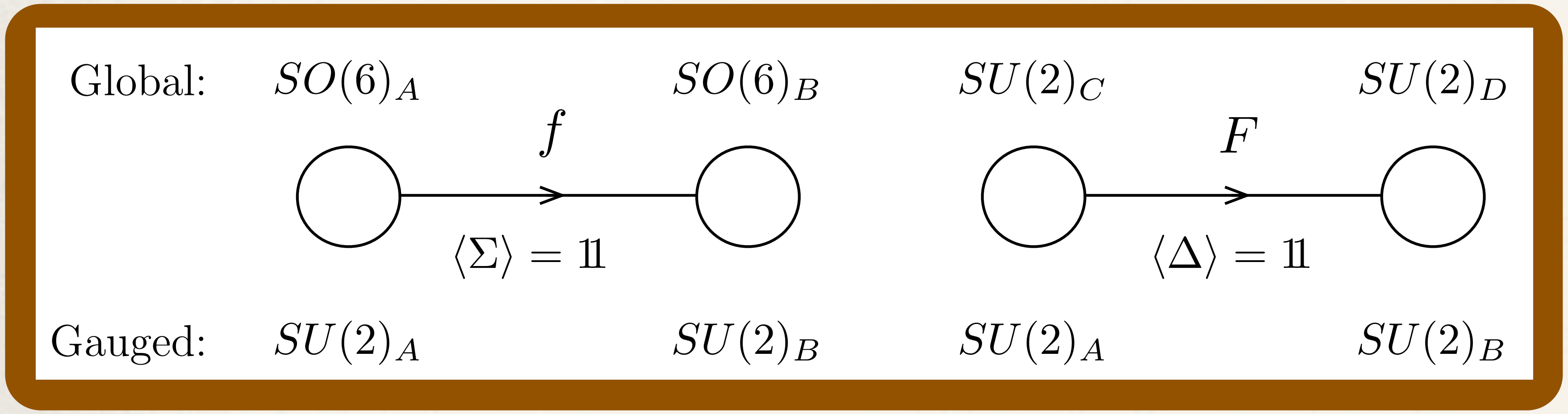
$\langle \Sigma \rangle = \mathbb{1}$

Gauged: $SU(2)_A \times U(1)_A$ $SU(2)_B \times U(1)_B$

$$i \begin{pmatrix} \phi + \eta & 0 & 0 \\ 0 & 0 & \sigma/\sqrt{2} \\ 0 & -\sigma/\sqrt{2} & 0 \end{pmatrix}$$

- Traditional LH models: ϕ is eaten

Consequences



Global: $SO(6)_A$ $\xrightarrow{f}$ $SO(6)_B$ $SU(2)_C$ $\xrightarrow{F}$ $SU(2)_D$

$\langle\Sigma\rangle = \mathbb{1}$ $\langle\Delta\rangle = \mathbb{1}$

Gauged: $SU(2)_A$ $SU(2)_B$ $SU(2)_A$ $SU(2)_B$

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- Δ means more PNGB's, ϕ remains in the spectrum

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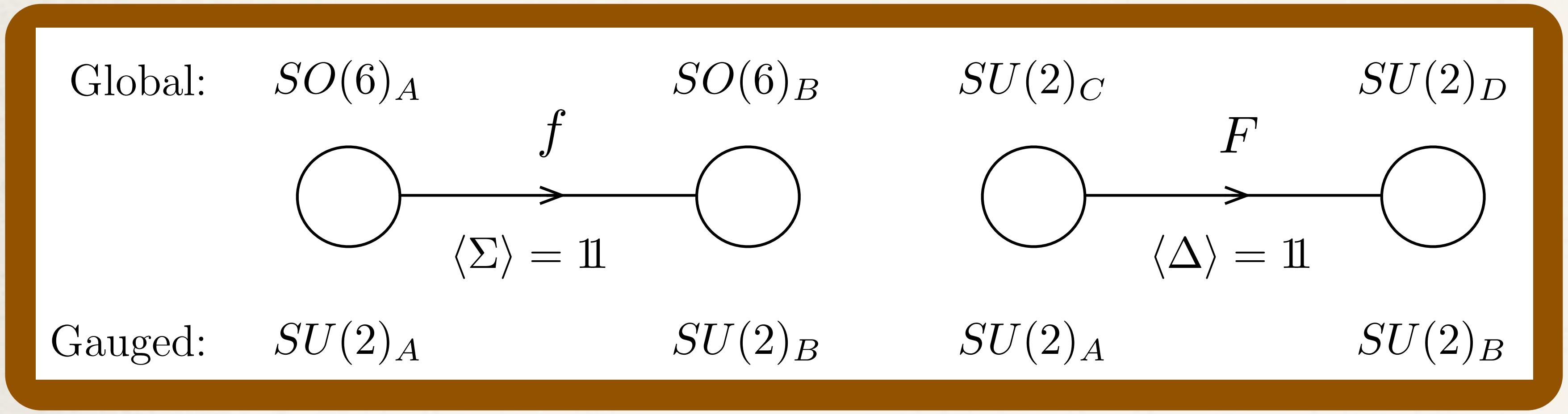


$$\begin{pmatrix} \phi+\eta & 0 & 0 \\ 0 & 0 & \sigma/\sqrt{2} \\ 0 & -\sigma/\sqrt{2} & 0 \end{pmatrix}$$

- Traditional LH models: ϕ is eaten
- Δ means more PNGB's, ϕ remains in the spectrum
- Custodial symmetry unbroken without hypercharge

Top Yukawa Coupling

- Want to minimize fine tuning and partner masses
- Use three different symmetry breaking operators

$$\mathcal{L} = y_1\mathcal{O}_1 + y_2\mathcal{O}_2 + y_3\mathcal{O}_3$$

- Each operator and each pair leaves enough symmetries unbroken
- One loop radiative corrections proportional to 3 couplings -> finite
- Each operator increases top Yukawa coupling for fixed partner mass

$SO(6)$ Fermions

- $SO(6)$ fundamentals: Q and U^c

$$\mathbf{6} = \left(\psi_a \quad \psi_b \quad \psi_5 \quad \psi_6 \right)$$

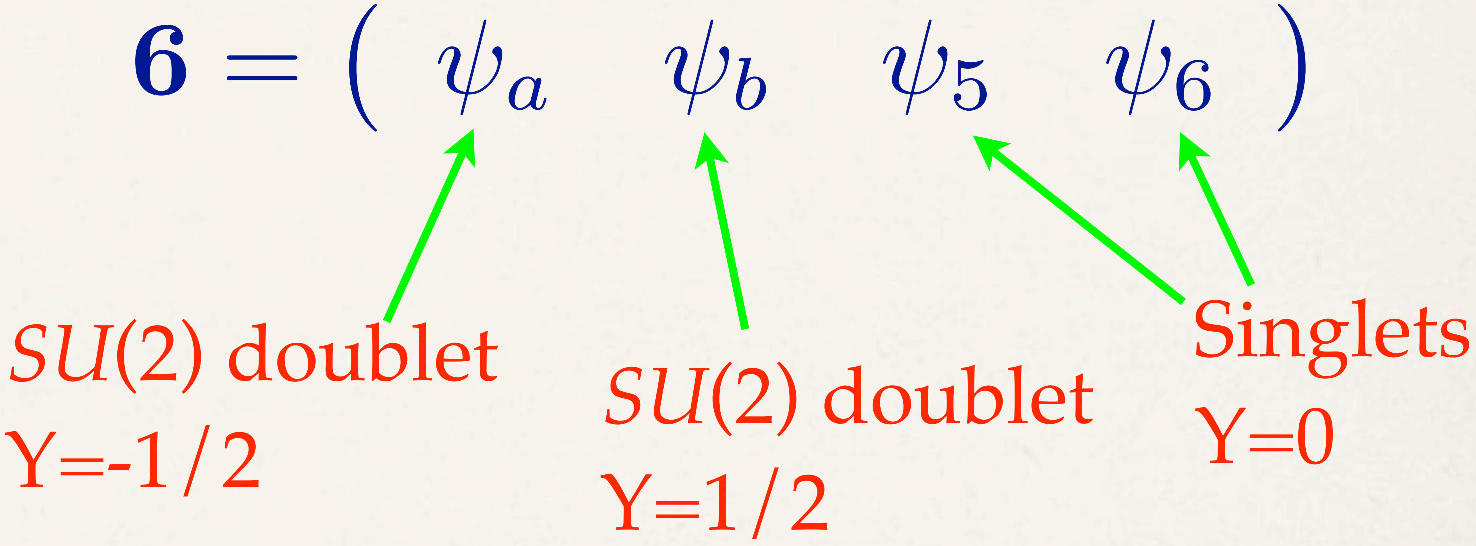
$SU(2)$ doublet
Y=-1/2

$SU(2)$ doublet
Y=1/2

Singlets
Y=0

$SO(6)$ Fermions

- $SO(6)$ fundamentals: Q and U^c
- $SO(6)$ incomplete multiplets: Q'_a and U'^{c}_{5}



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Y=-1/2

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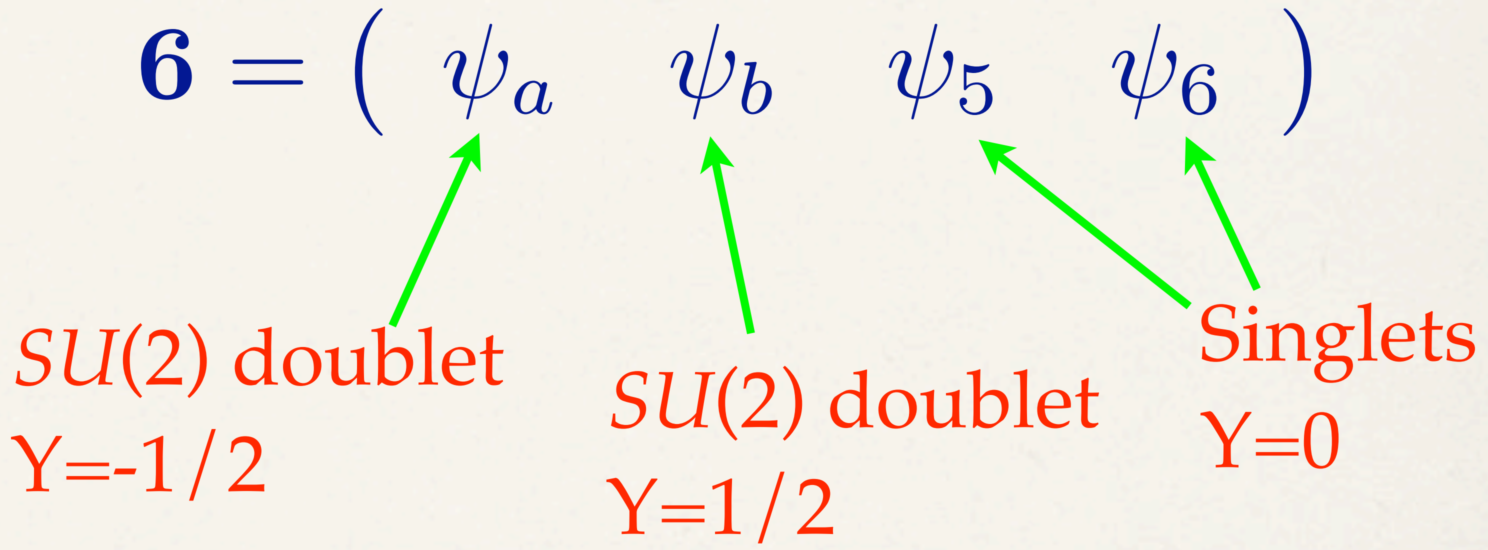
Singlets
Y=0

	$SO(6)_A$	$SO(6)_B$	$SU(3)_C$
Q	$\mathbf{6}$	$-$	$\mathbf{3}$
Q'_a	$\mathbf{2}^{(*)}$	$-$	$\mathbf{3}$
U^c	$-$	$\mathbf{6}$	$\overline{\mathbf{3}}$
U'^{c}_{5}	$-$	$\mathbf{1}^{(*)}$	$\overline{\mathbf{3}}$

$SO(6)$ Fermions

- $SO(6)$ fundamentals: Q and U^c
- $SO(6)$ incomplete multiplets: Q'_a and U'^{c}_5
- Additional gauge generator for hypercharge

$$\mathbf{6} = \left(\ \psi_a \quad \psi_b \quad \psi_5 \quad \psi_6\ \right)$$



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$SU(2)$ doublet
Y=1/2

Singlets
Y=0

	$SO(6)_A$	$SO(6)_B$	$SU(3)_C$	$U(1)_X$
Q	$\mathbf{6}$	$-$	$\mathbf{3}$	$2/3$
Q'_a	$\mathbf{2}^{(*)}$	$-$	$\mathbf{3}$	$2/3$
U^c	$-$	$\mathbf{6}$	$\overline{\mathbf{3}}$	$-2/3$
U'^{c}_5	$-$	$\mathbf{1}^{(*)}$	$\overline{\mathbf{3}}$	$-2/3$

Top Yukawa Operator 1

$$\mathcal{L} = y_1\mathcal{O}_1 + y_2\mathcal{O}_2 + y_3\mathcal{O}_3$$

$$\mathcal{O}_1 = Q^T S\,\Sigma\,S\,U^c$$

$$S = \mathrm{diag}(1,1,1,1,-1,-1)$$

	$SO(6)_A$	$SO(6)_B$
Q	$\mathbf{6}$	$-$
${Q'}_a$	$\mathbf{2}^{(*)}$	$-$
U^c	$-$	$\mathbf{6}$
${U'}^c_5$	$-$	$\mathbf{1}^{(*)}$

Top Yukawa Operator 1

$$\mathcal{L} = y_1 \mathcal{O}_1 + y_2 \mathcal{O}_2 + y_3 \mathcal{O}_3$$

$$\mathcal{O}_1 = Q^T S\,\Sigma\,S\,U^c$$

$$S = \mathrm{diag}(1,1,1,1,-1,-1)$$

Can do a field redefinition:

$Q^T \to Q_L^T S$ and $U^c \to S\,U^c$

	$SO(6)_A$	$SO(6)_B$
Q	$\mathbf{6}$	$-$
Q'_a	$\mathbf{2}^{(*)}$	$-$
U^c	$-$	$\mathbf{6}$
U'^c_5	$-$	$\mathbf{1}^{(*)}$

Top Yukawa Operator 1

$$\mathcal{L} = y_1 \mathcal{O}_1 + y_2 \mathcal{O}_2 + y_3 \mathcal{O}_3$$

	$SO(6)_A$	$SO(6)_B$
Q	$\mathbf{6}$	$-$
Q'_a	$\mathbf{2}^{(*)}$	$-$
U^c	$-$	$\mathbf{6}$
$U_5'^c$	$-$	$\mathbf{1}^{(*)}$

$$\mathcal{O}_1 = Q^T S \, \Sigma \, S \, U^c$$
$$S = \mathrm{diag}(1,1,1,1,-1,-1)$$

Can do a field redefinition:
$Q^T \rightarrow Q_L^T S$ and $U^c \rightarrow S\, U^c$

No global symmetries are broken by $\mathcal{O}_1$

Top Yukawa Operators 1 and 2

$$\mathcal{L} = y_1 \mathcal{O}_1 + y_2 \mathcal{O}_2 + y_3 \mathcal{O}_3$$

$$\mathcal{O}_1 = Q^T S\,\Sigma\,S\,U^c$$

$$\mathcal{O}_2 = {Q'_a}^T \Sigma\,U^c$$

	$SO(6)_A$	$SO(6)_B$
Q	$\mathbf{6}$	$-$
Q'_a	$\mathbf{2}^{(*)}$	$-$
U^c	$-$	$\mathbf{6}$
U'^c_5	$-$	$\mathbf{1}^{(*)}$

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$$\mathcal{L} = y_1\mathcal{O}_1 + y_2\mathcal{O}_2 + y_3\mathcal{O}_3$$

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$$\mathcal{O}_2 = {Q'_a}^T \Sigma\,U^c$$

	$SO(6)_A$	$SO(6)_B$
Q	$\mathbf{6}$	$-$
${Q'}_a$	$\mathbf{2}^{(*)}$	$-$
U^c	$-$	$\mathbf{6}$
U'^c_5	$-$	$\mathbf{1}^{(*)}$

Can do more complicated field redefinition:

$U^c \to \Sigma\,U^c$ and $Q_L^T \to Q_L^T S\Sigma S\Sigma^T$

which gives $Q^T U^c + {Q'_a}^T U^c$ and doesn't generate a potential for the PNGB's.

Top Yukawa Operators 2 and 3

$$\mathcal{L} = y_1 \mathcal{O}_1 + y_2 \mathcal{O}_2 + y_3 \mathcal{O}_3$$

$$\mathcal{O}_2 = {Q'_a}^T \Sigma U^c$$

$$\mathcal{O}_3 = Q^T \Sigma {U'_5}^c$$

	$SO(6)_A$	$SO(6)_B$
Q	$\mathbf{6}$	$-$
Q'_a	$\mathbf{2}^{(*)}$	$-$
U^c	$-$	$\mathbf{6}$
${U'_5}^c$	$-$	$\mathbf{1}^{(*)}$

Top Yukawa Operators 2 and 3

$$\mathcal{L} = y_1\mathcal{O}_1 + y_2\mathcal{O}_2 + y_3\mathcal{O}_3$$

$$\mathcal{O}_2 = {Q'_a}^T \Sigma U^c$$

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Q	$\mathbf{6}$	$-$
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U^c	$-$	$\mathbf{6}$
${U'_5}^c$	$-$	$\mathbf{1}^{(*)}$

Can do another field redefinition:

$U^c \to \Sigma U^c$ and $Q_L^T \to Q_L^T \Sigma$

which eliminates Σ from $\mathcal{O}_2$ and $\mathcal{O}_3$.

Top Yukawa Operators 2 and 3

$$\mathcal{L} = y_1\mathcal{O}_1 + y_2\mathcal{O}_2 + y_3\mathcal{O}_3$$

$$\mathcal{O}_2 = {Q'_a}^T \Sigma U^c$$

$$\mathcal{O}_3 = Q^T \Sigma {U'_5}^c$$

	$SO(6)_A$	$SO(6)_B$
Q	$\mathbf{6}$	$-$
Q'_a	$\mathbf{2}^{(*)}$	$-$
U^c	$-$	$\mathbf{6}$
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Can do another field redefinition:

$U^c \to \Sigma U^c$ and $Q_L^T \to Q_L^T \Sigma$

which eliminates Σ from $\mathcal{O}_2$ and $\mathcal{O}_3$.

Need all three operators to generate potential.

Top and Partner Spectrum

- Mass spectrum for top Yukawa operators
  - 6 colored Dirac fermions with mass ~ $y_t f$
  - 3 massless Weyl fermions; SM top

	$SO(6)_A$	$SO(6)_B$
Q	$\mathbf{6}$	$-$
Q'_a	$\mathbf{2}^{(*)}$	$-$
U^c	$-$	$\mathbf{6}$
$U_5'^c$	$-$	$\mathbf{1}^{(*)}$

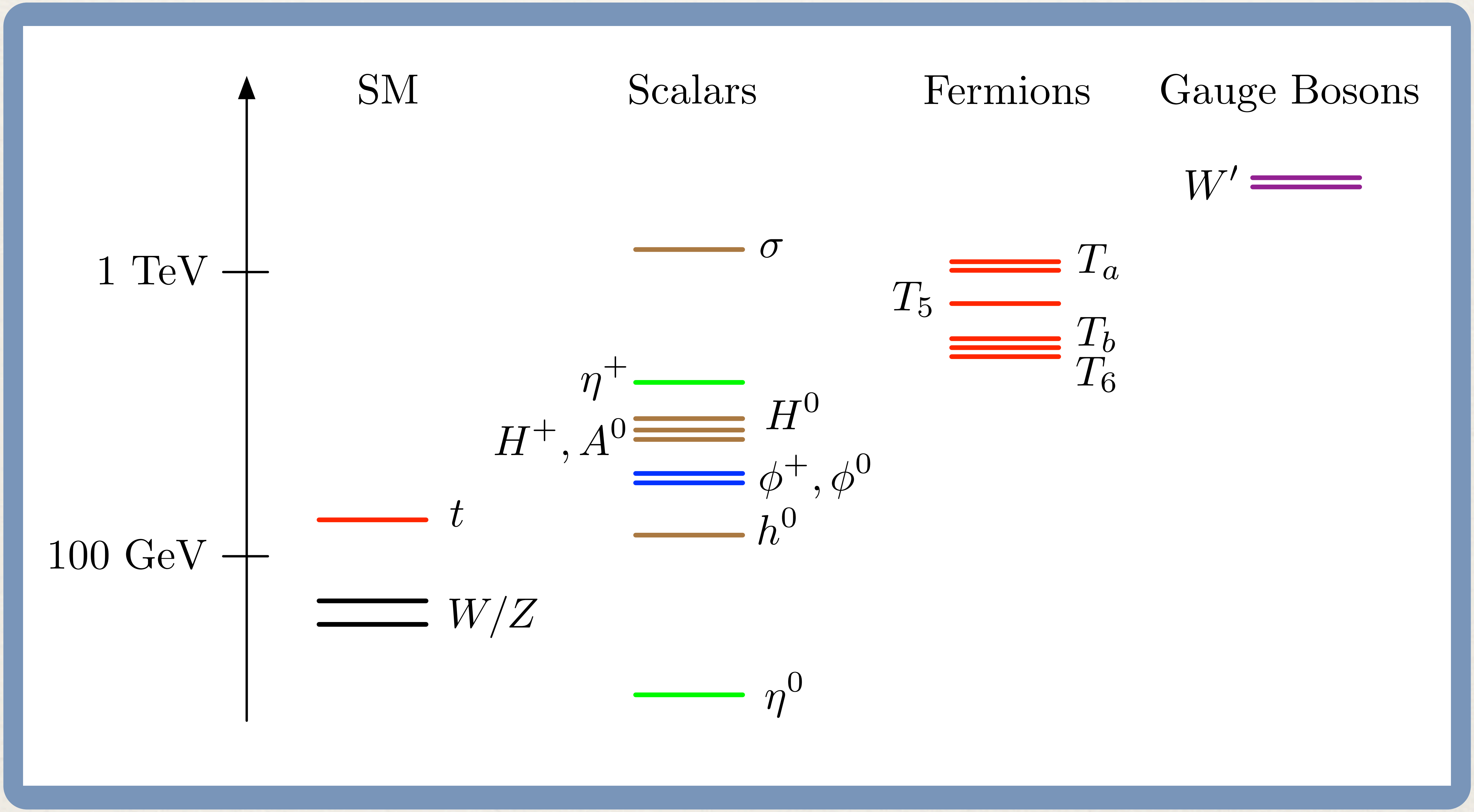
- Coupling to Higgs: $y_t\, q\, h_1 u$

$$y_t = 3\frac{y_1 y_2 y_3}{\sqrt{(|y_1|^2+|y_2|^2)(|y_1|^2+|y_3|^2)}}$$

- One loop Coleman--Weinberg potential

$$-\frac{3\, m_t^2}{8\pi^2 v_1^2}\,\frac{m_T^2\, m_U^2}{m_T^2 - m_U^2}\log\left(\frac{m_T^2}{m_U^2}\right) h_1^T h_1$$

Spectrum


SM
Scalars
Fermions
Gauge Bosons
W'
σ
1 TeV
T_a
T_5
T_b
T_6
η^+
H^0
H^+, A^0
ϕ^+, ϕ^0
t
h^0
100 GeV
W/Z
η^0

Sweet Spot for f

- Masses of top partners and (most) scalars controlled by f
- For $f \sim 1$ TeV, evade all direct bounds
- Indirect constraints fall like $1/F$
- Choosing f now dictated by naturalness

Constraint: Triplet VEV

- Electroweak measurements require:

$$\langle \phi \rangle \ll \langle h_i \rangle$$

- $\langle \phi \rangle$ generated through

$$h^\dagger \phi \, h$$

- Forbidden by symmetries
- Symmetries broken by combination of $SU(2)$ and hypercharge gauge couplings
- VEV is only generated at 2 loops, so no constraint

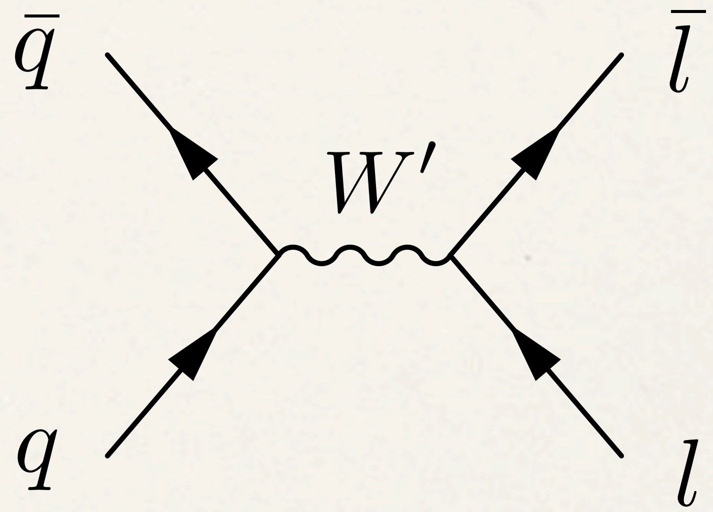
Constraints from Heavy Particles

- Use effective field theory analysis of Han and Skiba, hep-ph/0412166

- Dangerous operators generated only by heavy gauge bosons

$$\frac{1}{\Lambda^2}(\bar{q}\gamma^\mu\sigma^a q)(\bar{l}\gamma_\mu\sigma^a l)$$

$$\frac{i}{\Lambda^2}(h^\dagger\sigma^a D^\mu h)(\bar{q}\gamma_\mu\sigma^a q)$$



- Bound *F*, but *f* is unaffected

Light Quarks and Leptons

- Yukawa couplings for light quarks:

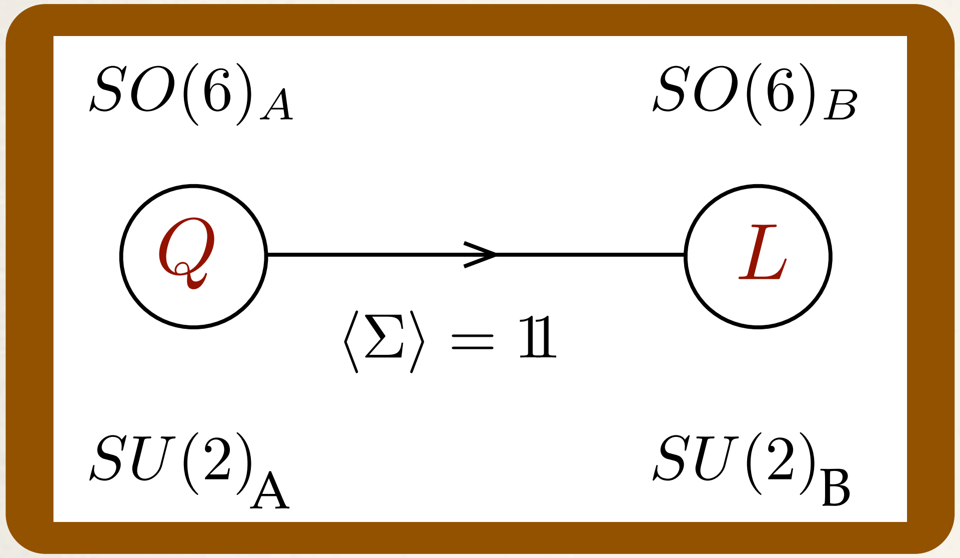
$$y_c\, c_L\, \Sigma_h\, c_R \qquad\qquad y_b\, Q_L\, \varepsilon\Sigma_h^*\, b_R$$

- Can leptons in a different way:

$$y_e\, e\, \varepsilon\Sigma_h^*\, L$$

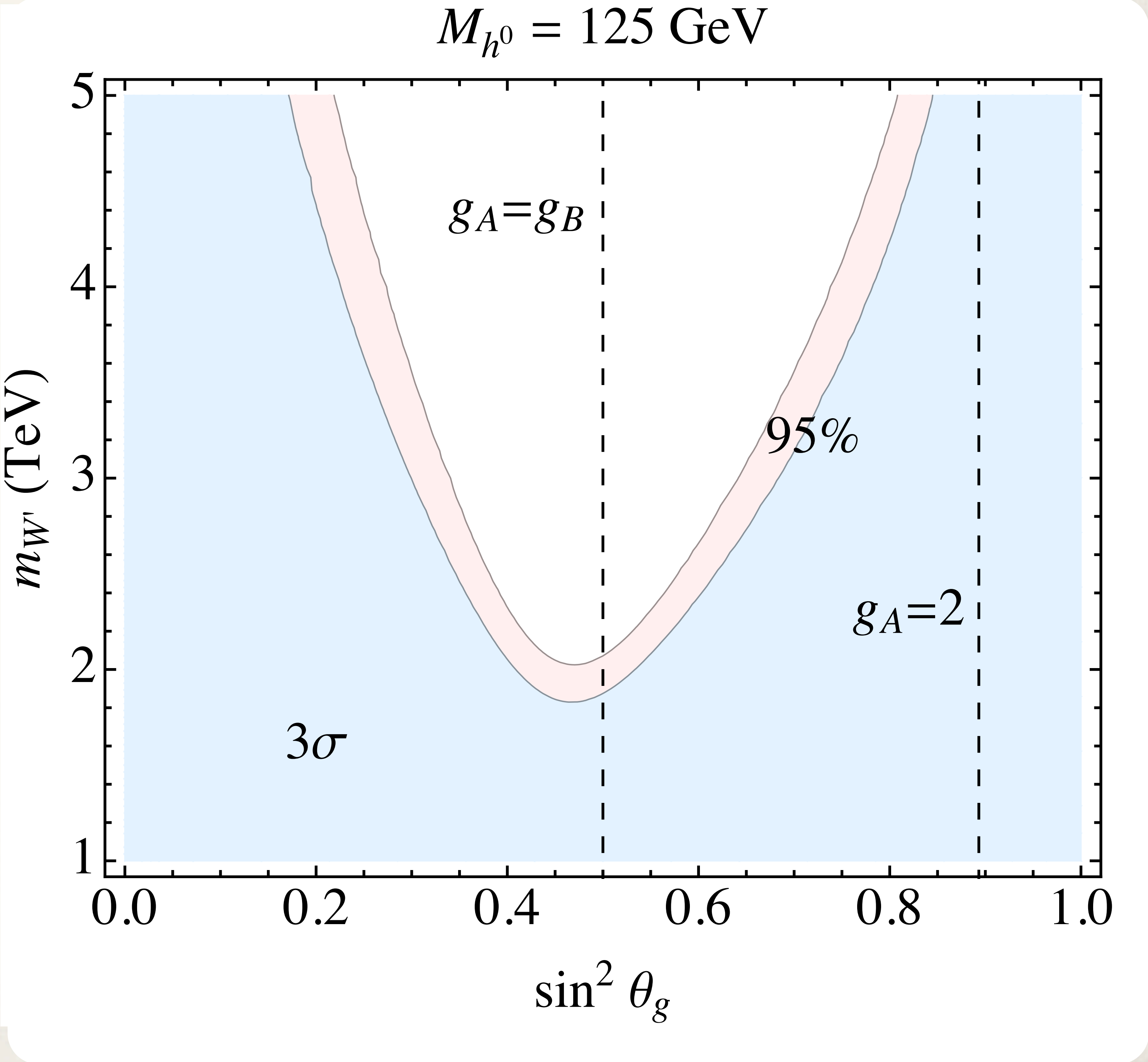
- Couple all fermions to h_1 (but don't have to)

Bounds on Heavy Gauge Bosons



- Can get better fit than SM

- Top partners are always lighter, $O(1\ \text{TeV})$

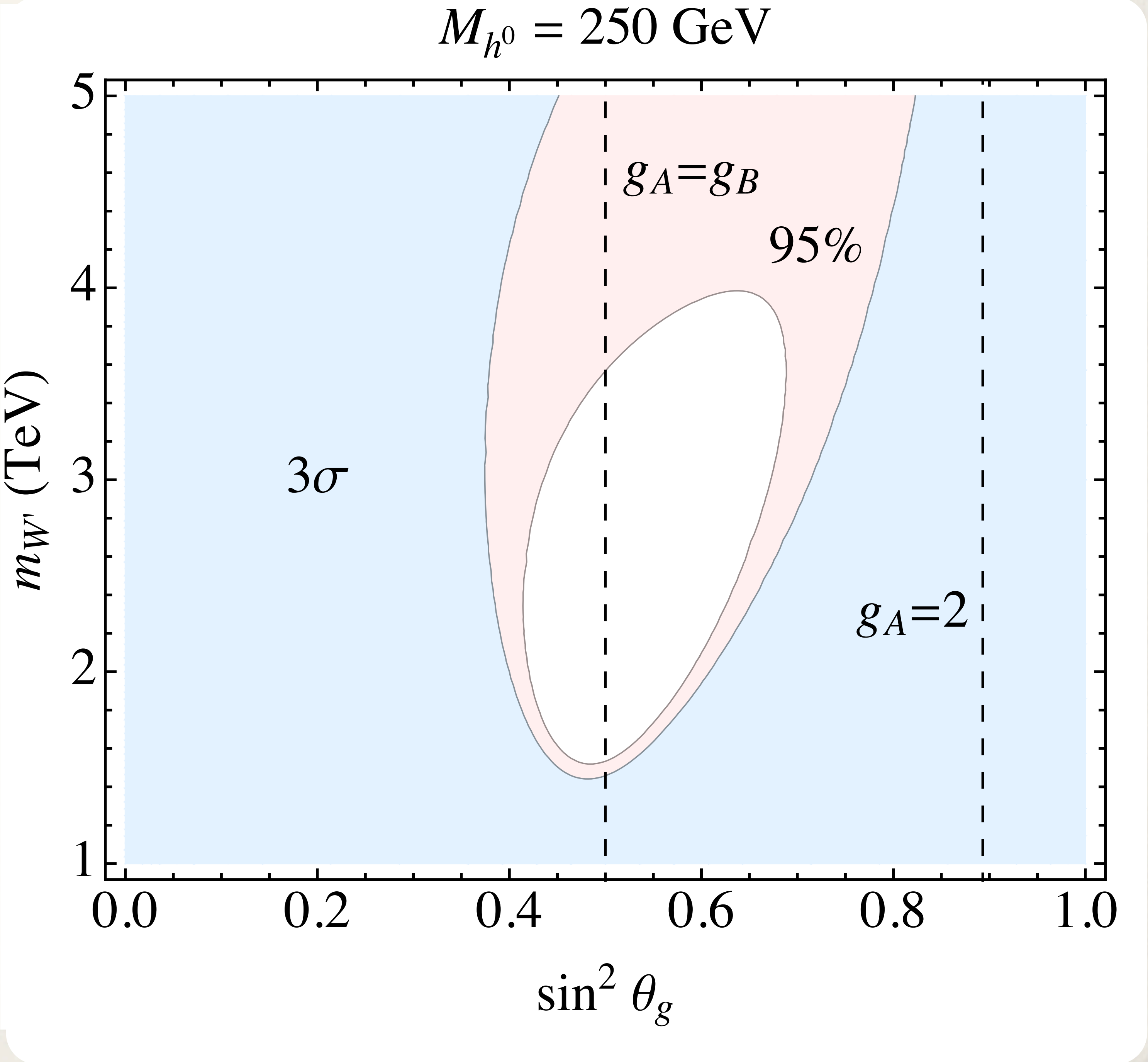


Reduce Fine Tuning

- Fine tuning ~ $\dfrac{\delta m_h^2}{m_h^2}$

- Change electroweak fit, heavier Higgs is allowed

- Can make gauge partners even lighter



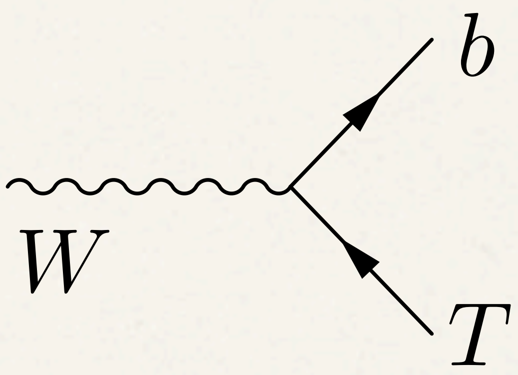
Collider Phenomenology

- Biggest difference: heavy gauge partners (lighter fermions)
- Gauge partner pheno similar to other LH models
- Can be discovered at the LHC if mass $\lesssim 5\ \mathrm{TeV}$

Collider Phenomenology II

- 6 new colored Dirac fermions with masses 600 GeV to 1 TeV

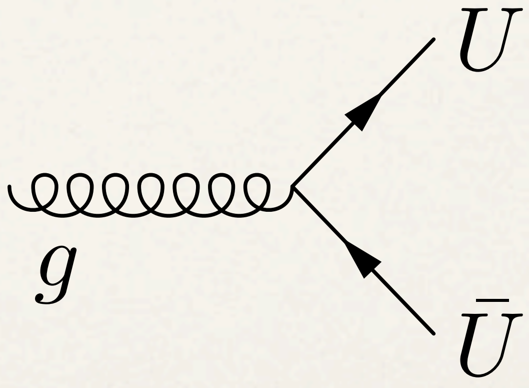
- Can singly produce T doublet with *Wb* or *Wt*



$\sigma \sim 1\,\text{pb}$

@ 14 TeV LHC

- All can be pair produced, three lightest will dominate



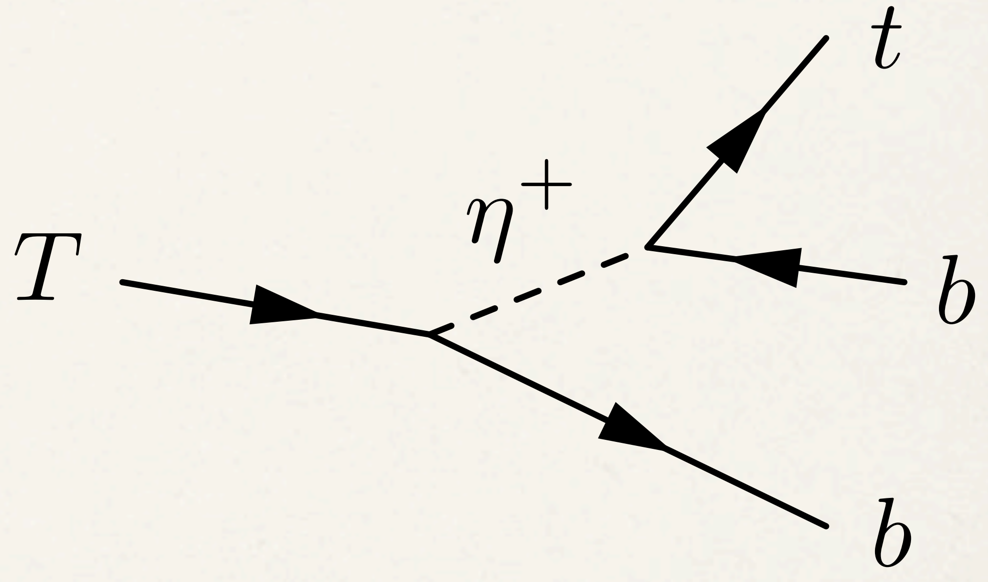
Lots of b's and t's

- Have would be eaten Goldstones η and ϕ, largest coupling via Yukawa coupling

$$\frac{m_f}{f}\,\eta\,\bar{f}\gamma^5 f$$

- Top partners often decay to t or b and η or ϕ

- Scalars tend to decay to third generation quarks also



Single production events have 4 third gen. quarks

Pair production events have 6 third gen. quarks

Light Pseudoscalar (Axion)

- This model (and other LH models) contains a light pseudo η^0
- No gauge charges or direct coupling to Higgs
- Couples to massive fermions $\frac{m_f}{f}\,\eta\,\bar{f}\gamma^5 f$
- Easiest place to find is events with tops
- Phenomenological study underway with Jesse Thaler

Conclusions

- Other LH models try to solve the hierarchy problem, but break cust. symmetry, have ugly quartics, and are still more than 10% fine-tuned
- We have built the first model which has a natural Higgs potential with no fine-tuning in the scalar, gauge, or fermion sector

Traditional LH:

$$\frac{m_T}{m_{W'}} \simeq \frac{m_{\rm top}}{m_W} \simeq 2$$

Bestest LH

$$\frac{m_T}{m_{W'}} \simeq \frac{y_t f}{g_{\rm EW} F} \simeq \frac{1}{2}$$

- Our modular gauge sector can be implemented in many LH models
- Collider signatures with copious top/bottom production
- Looking for triplet could provide smoking gun

Thank You

Hypercharge?

- Could use modular trick again with Δ' to cut off divergence
- Hypercharge coupling is small, so just gauge diagonal T_R^3 of $SO(6)$
- One loop corrections given by

$$\frac{3g_Y^2\Lambda^2}{32\pi^2}\left[\eta_1^2+\eta_2^2+\frac{1}{4}(h_1^T h_1+h_2^T h_2)\right]$$

- η_3 is neutral and light
- Fine-tuning is small, and heavy hypercharge boson are among biggest problems from precision electroweak

Masses of Particles

- Heavy gauge bosons: $m_A^2 = \frac{1}{4}(g_1^2 + g_2^2)(f^2 + F^2)$

$$m_A \gtrsim 3\,\mathrm{TeV}$$

- One loop Coleman--Weinberg, only log divergent and finite pieces

$$\frac{3\,g_{\mathrm{EW}}^2 m_A^2}{16\pi^2} \log\left(\frac{\Lambda^2}{m_A^2}\right)\left(\frac{3}{8}h_1^T h_1 + \frac{3}{8}h_2^T h_2 + \phi_i\phi^i\right)$$

- Other scalars uncharged under *SU*(2)

Top and Partner Spectrum

- Take $\Sigma \to \langle \Sigma \rangle$ in the top Yukawa Lagrangian

$$y_1 f (U_a \cdot Q_b + Q_6 U_6)$$

T

$$\sqrt{|y_1|^2 + |y_2|^2}\, f \left(\frac{y_1}{\sqrt{|y_1|^2 + |y_2|^2}} Q_a + \frac{y_2}{\sqrt{|y_1|^2 + |y_2|^2}} q' \right) \cdot U_b$$

$$\sqrt{|y_1|^2 + |y_3|^2}\, f\, Q_5 \left(\frac{y_1}{\sqrt{|y_1|^2 + |y_3|^2}} U_5 + \frac{y_3}{\sqrt{|y_1|^2 + |y_3|^2}} t' \right)$$

U

- Remaining light particles are orthogonal linear combination:
    - $SU(2)$ doublet, Y=1/6
    - singlet, Y=-2/3

$SU(4)$ Language

$SO(6) \simeq SU(4)$

$$\begin{array}{c}\underline{SU(4)}\\ \left(\begin{array}{c|c} SU(2)_L & \\ \hline & SU(2)_R \end{array}\right)\end{array}$$

$SU(4)$ Language

$$SO(6) \simeq SU(4)$$

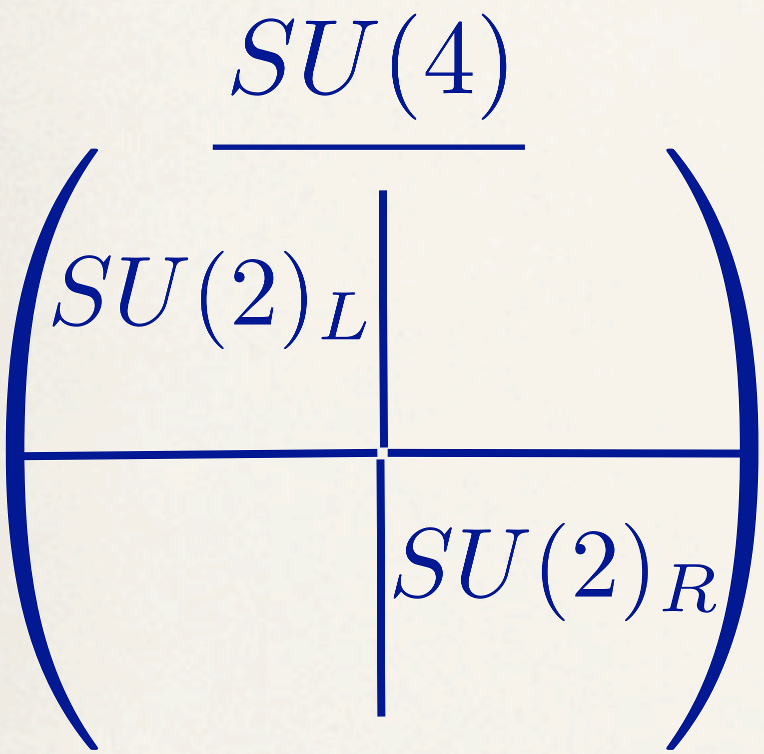
$$\overset{\underline{SU(4)}}{\left(\begin{array}{c|c} SU(2)_L & \\ \hline & SU(2)_R \end{array}\right)}$$

$$\begin{pmatrix} 0 & \tilde{H}_2^* - i\tilde{H}_1^* & H_2 - iH_1 \\ \tilde{H}_2{}^T + i\tilde{H}_1{}^T & 0 & 0 \\ H_2^\dagger + iH_1^\dagger & 0 & 0 \end{pmatrix}$$

$$\tilde{H} = i\tau^2 H$$

$SU(4)$ Language

$SO(6) \simeq SU(4)$



$SU(4)$

$SU(2)_L$

$SU(2)_R$

$$\begin{pmatrix} 0 & \tilde{H}_2^* - i\tilde{H}_1^* & H_2 - iH_1 \\ \tilde{H_2}^T + i\tilde{H_1}^T & 0 & 0 \\ H_2^\dagger + iH_1^\dagger & 0 & 0 \end{pmatrix}$$

$$\tilde{H} = i\tau^2 H$$

$$\begin{pmatrix} \phi_i\tau^i + \frac{\sigma}{\sqrt{2}}\mathbb{1} & 0 \\ 0 & \eta_i\tau^i - \frac{\sigma}{\sqrt{2}}\mathbb{1} \end{pmatrix}$$

Old and New Particles

- Light quarks do not couple to top partners (except b_L)
- Light quark coupling to other scalars at dimension > 4
- Minimal flavor bounds on third generation (only $Z \to b\bar{b}$ which is small)
- Could have chosen to put down-type quarks or leptons in 6th component, changes little
- Radiative corrections do not generate new operators and are small

Higgs Potential

- Kinetic Term

  $f^2 \,\mathrm{tr}(D_\mu \Sigma^T D^\mu \Sigma)$

- Radiative corrections also generate small quartics

- Need to lift flat direction with operator $\mathrm{tr}(\Sigma)$ which gives small mass to all scalars

- Need to destabilize origin for EWSB with $\Sigma_{65} + \Sigma_{56}$ which has $-B\mu\, h_1^T h_2$

$$V_{\text{higgs}} = \frac{1}{2} m_1^2\, h_1^T h_1 + \frac{1}{2}\, m_2^2 h_2^T h_2 \\ -B\mu\, h_1^T h_2 + \frac{\lambda_0}{2} (h_1^T h_2)^2$$

- Easy to show that vacuum preserves global symmetry