Phenomenology and structure of UV complete Little Higgs

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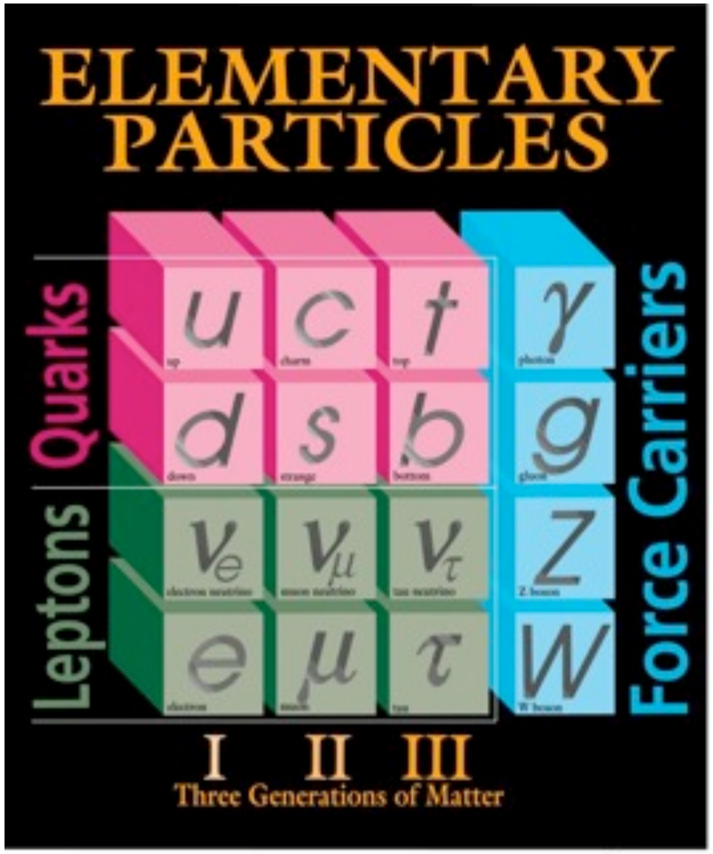
Standard Model



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$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

Electroweak symmetry breaking

$$SU(2)_L \times U(1)_Y \to U(1)_Q$$

condensate: vacuum not invariant

mechanism unknown

weak coupling	strong coupling
Higgs	Technicolor

Technicolor

Strong dynamics break the symmetry

Like QCD

$$q^\dagger D_\mu \sigma_\mu q + q^{c\dagger} D_\mu \sigma_\mu q^c$$

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

flavor symmetry

Low energy $E < \Lambda_{\mathrm{QCD}}$

$$\mathcal{L} = |\partial_\mu \Sigma|^2$$

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

$$\downarrow$$

$$\Sigma \to L \Sigma R^\dagger$$

$$f \sim \frac{\Lambda_{\mathrm{QCD}}}{4\pi}$$

derivative expansion:

$$\mathcal{L} = |\partial_\mu \Sigma|^2 + \frac{|\partial_\mu \Sigma|^4}{\Lambda_{\mathrm{QCD}}^2}$$

strong coupling: $E \sim \Lambda_{\mathrm{QCD}}$

Gauge: $SU(2)_L \times U(1)_Y$

$$\partial_\mu \Sigma \to D_\mu \Sigma$$

Electroweak symmetry is broken!

The scale is wrong $m_W \sim g f_{\text{QCD}}$

Originial Technicolor: scaled up QCD

quark $\longrightarrow$ techni-quark

$$SU(3)_C \to SU(3)_{\mathrm{TC}}$$

$$\Lambda_{\mathrm{QCD}} \to \Lambda_{\mathrm{TC}}$$

$$\Lambda_{\mathrm{TC}} \sim 1\mathrm{TeV}$$

Problems:

- Higher dimensional operators

$$\frac{\mathrm{Tr}\left(\Sigma^\dagger W_{\mu\nu} \Sigma B_{\mu\nu}\right)}{\Lambda^2}$$

contribute to the S parameter

coefficient can be infered from QCD

ruled out

- Fermion masses

$$\frac{Q\Psi_Q^\dagger \Psi_{u^c}^\dagger u^c}{\Lambda^2}$$

extended technicolor

danger of large FCNC

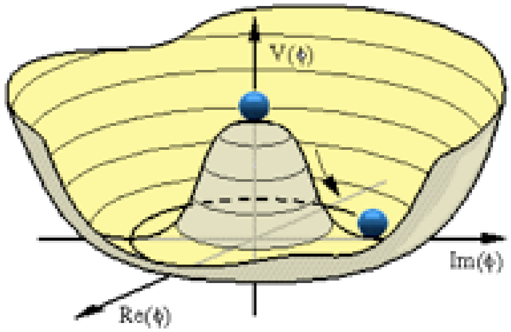
Solutions

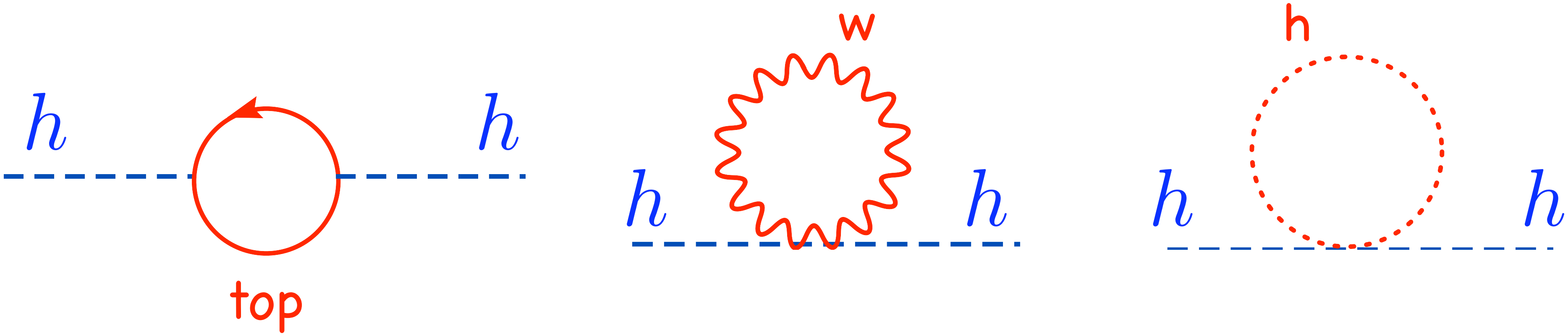
- S: Take a non-QCD-like theory and hope the coefficient of operator is small

- Fermion masses: Walking technicolor. Techni-quarks have non-trivial scaling dimension

Higgs

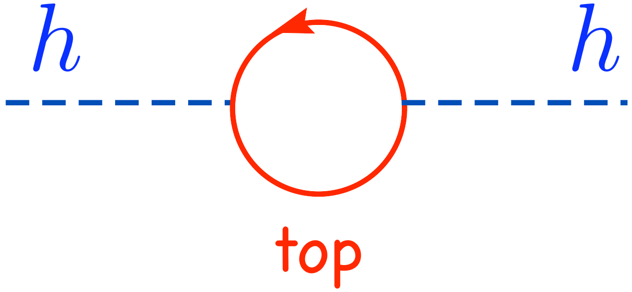
elementary scalar field





Divergent

cutoff Λ



$$m_h^2 = \frac{3}{8\pi^2}\Lambda^2 \;\sim (100\mathrm{GeV})^2$$

$$\Lambda \sim 1\mathrm{TeV}$$

new physics at Λ must cancel
quadratic divergences

Supersymmetry

Bosons ↔ Fermions

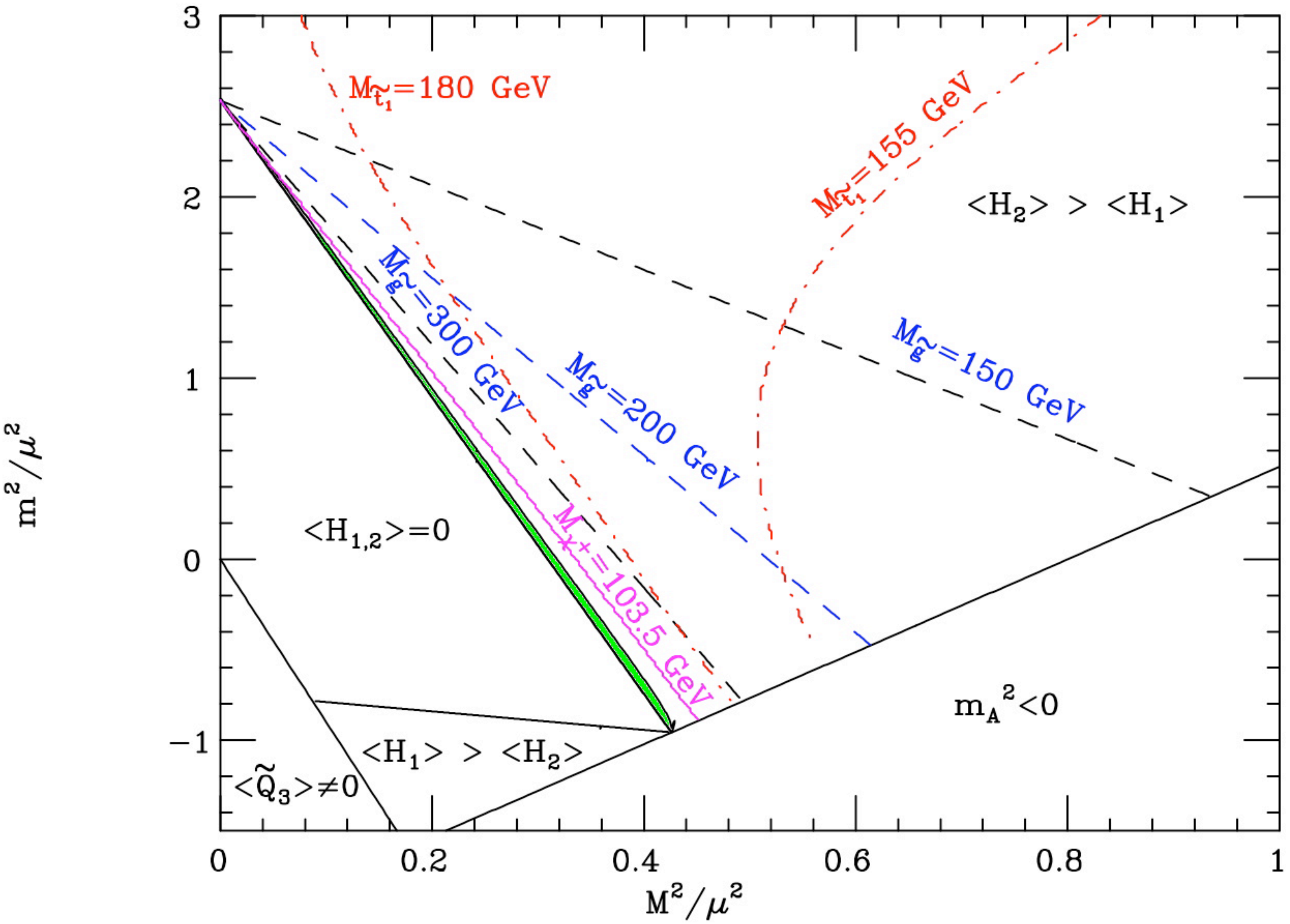
Higgs	h	→	$\tilde{h}$	Higgsino
gluon	g	→	$\tilde{g}$	gluino
selectron	$\tilde{e}$	←	e^-	electron
stop	$\tilde{t}$	←	t	top

etc...

quadratic divergences cancelled

$$m_h^2 \sim \frac{1}{16\pi^2} m_{\rm stop}^2 \log \Lambda^2$$

tuning in MSSM



Giudice,Rattazzi

LEP paradox

We expect new physics to explain electroweak symmetry breaking...

...but we haven't seen any

- precision measurement
- direct search

Little Higgs

Higgs is light because it's a Goldstone boson

(After all the only know light scalar in nature is a Goldstone boson)

Problem: the Higgs doesn't look anything like a Goldstone boson

- gauge couplings
- Yukawa couplings
- quartic couplings

Structure

- need a Goldstone boson

Global symmetry G/H

scale: $\Lambda \sim 10\mathrm{TeV}$ ← not dangerous for EWPO

- need couplings: e.g. gauge couplings

naive expectation: loop will give a mass to the Higgs

$$m_h^2 \sim \frac{g^2}{16\pi^2}\Lambda^2 \sim (1\mathrm{TeV})^2$$

Collective symmetry breaking

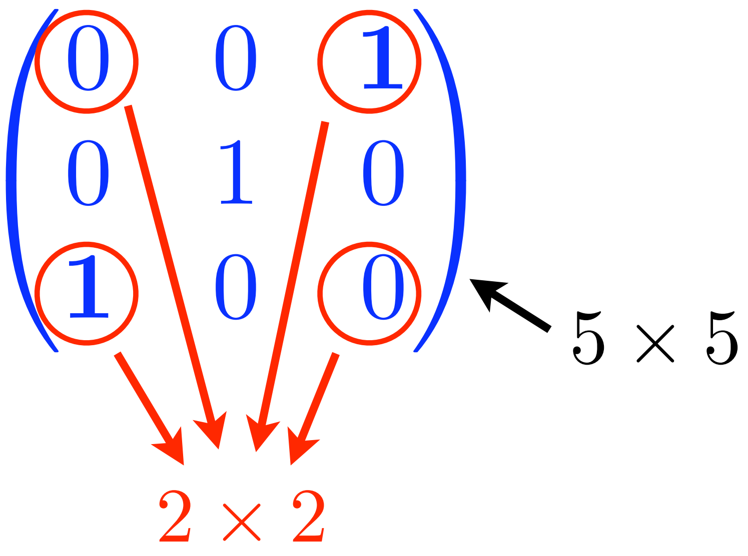
add couplings such that any one leave the
Higgs an exact Goldstone boson

example: littlest Higgs

$$SU(5)/SO(5)$$

$$\Sigma \to V \Sigma V^T$$

$$V \in SU(5)$$



$$\langle\Sigma\rangle = \Sigma_0 = \begin{pmatrix} \textcircled{0} & 0 & \textcircled{\textbf{1}} \\ 0 & 1 & 0 \\ \textcircled{\textbf{1}} & 0 & \textcircled{0} \end{pmatrix} \leftarrow 5\times 5$$

$$\Sigma = e^{i\pi/f}\Sigma_0 e^{i\pi^T/f}$$

$$\pi\Sigma_0 = \Sigma_0\pi^T$$

$$\pi = \begin{pmatrix} \alpha & h & \phi \\ h^\dagger & 0 & h^T \\ \phi^\dagger & h^* & \alpha^T \end{pmatrix}$$

gauge $SU(2)_1 \times SU(2)_2$

$$Q_1^a = \begin{pmatrix} \sigma^a & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad Q_2^a = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\sigma^{a\,*} \end{pmatrix}$$

Standard Model
$SU(2)$ →

$$SU(2)_{\text{diagonal}} \in SO(5)$$

$$g_1 \neq 0 \quad g_2 = 0$$

$$Q_1^a = \begin{pmatrix} \sigma^a & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$SU(3)$:Higgs is a Goldstone

estimate of the Higgs mass

$$m_h^2 \sim \frac{g_1^2}{16\pi^2}\frac{g_2^2}{16\pi^2}\Lambda^2$$

scalar couplings

$$c_1 f^2 \mathrm{Tr}\ \Sigma {Q_1^a}^T \Sigma^\dagger Q_1^a + c_2 f^2 \mathrm{Tr}\ \Sigma {Q_2^a}^T \Sigma^\dagger Q_2^a$$

$$c_1 f^2 \mathrm{Tr}\ \left|\phi - \frac{hh^\dagger}{f^2}\right|^2 + c_2 f^2 \mathrm{Tr}\ \left|\phi + \frac{hh^\dagger}{f^2}\right|^2$$

~ TeV mass for ϕ $\quad \sim 1$ quartic for h

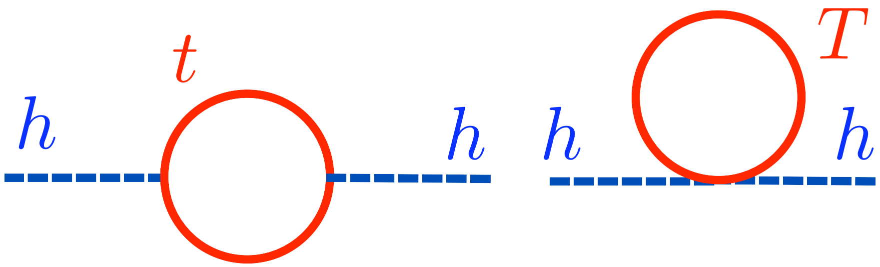
top Yukawa

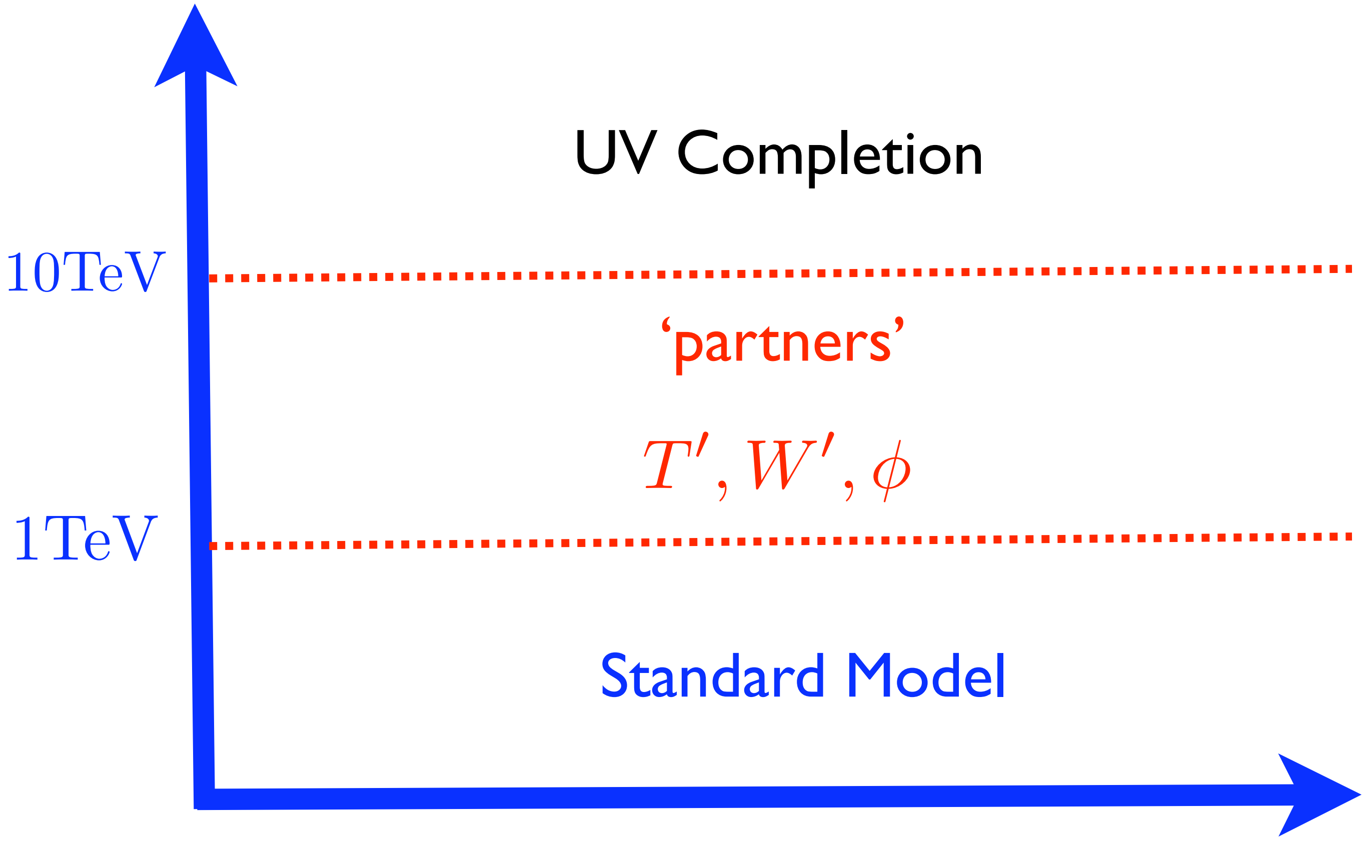
$$f\lambda_1\epsilon^{\overset{1,2,3}{\boxed{ijk}}}\epsilon^{\overset{4,5}{\boxed{xy}}}\underset{\begin{pmatrix}q\\T\\0\end{pmatrix}}{Q_i}\Sigma_{jx}\Sigma_{ky}u^c+\lambda_2 f\tilde{T}t^c$$

$$= f(\lambda_1 T+\lambda_2\tilde{T})t^c+\cdots$$

new TeV scale colored fermion

Quadratic divergences cancelled by 'partners' of the same spin




UV Completion

$10\mathrm{TeV}$

'partners'

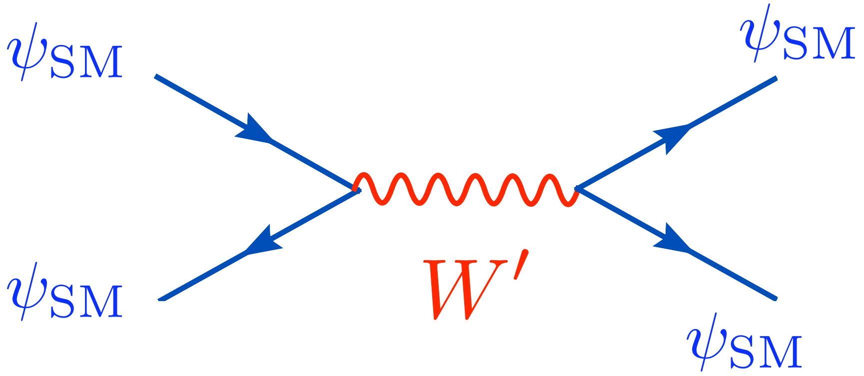
T', W', ϕ

$1\mathrm{TeV}$

Standard Model

Problems:

- Electroweak precision measurements



$$\frac{\Psi_{\rm SM}\Psi_{\rm SM}{\Psi_{\rm SM}}^\dagger{\Psi_{\rm SM}}^\dagger}{f^2}$$

others

Possible solution:

T-parity

$$\phi_{\rm SM} \to \phi_{\rm SM}$$

$$\phi_{\rm partner} \to -\phi_{\rm partner}$$

- Dark matter candidate
- LHC phenomenology more similar to SUSY

T-parity definition

$$\Sigma \to \Omega \Sigma^\dagger \Omega \qquad \Omega = \begin{pmatrix} 0 & 0 & \mathbf{1} \\ 0 & -1 & 0 \\ \mathbf{1} & 0 & 0 \end{pmatrix} \in SO(5)$$

$$A_\mu^1 \to A_2^\mu$$

$$W'_\mu \to -W'_\mu$$

$$\phi \to -\phi$$

$$W_{\mathrm{SM}\,\mu} \to W_{\mathrm{SM}\,\mu}$$

$$h \to h$$

UV completion?

- Strong dynamics
- Supersymmetry
- Another LH

two possible attitudes

- who cares, we will never access it directly
- specific UV completion might yield new light states

possible structure

Strong $SO(N)$

5 flavour charged under this $SO(N)$

$$\begin{pmatrix}\psi_2\\ \psi_0\\ \psi_2'\end{pmatrix} \longrightarrow \langle\Psi_5\Psi_5\rangle = \begin{pmatrix}\mathbf{0} & 0 & \mathbf{1}\\ 0 & 1 & 0\\ \mathbf{1} & 0 & \mathbf{0}\end{pmatrix}$$

What about the top?

Could be a composite too: a baryon

add 6 more flavour Ψ_3, Ψ_3^c

	ψ_5	ψ_3
ψ_5	‘gaugino’	top
ψ_3^c	top	‘gluino’

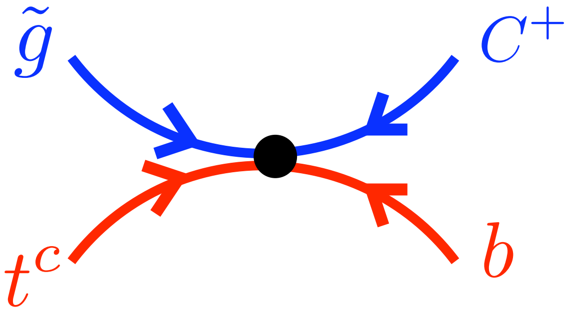
There is an R-parity $(-1)^{3B-L+2S}$

stable gaugino

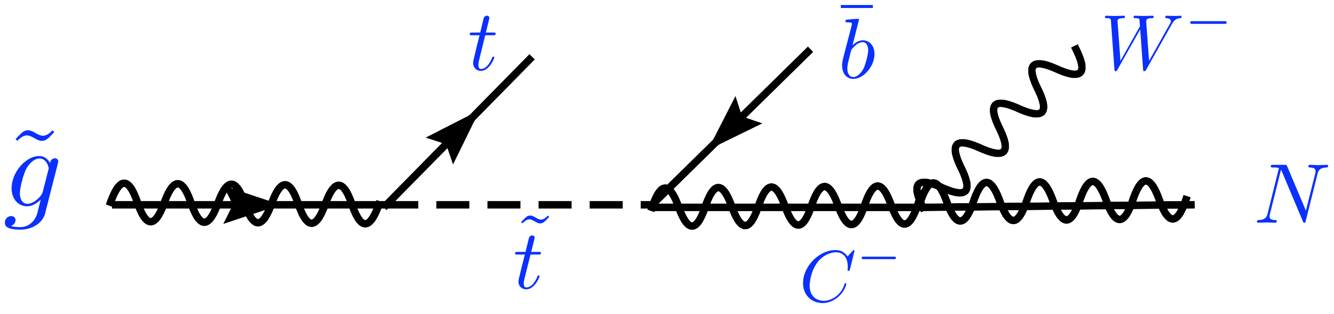
phenomenology could be confusing

gluino decay to top, bottom + missing energy

$$\frac{\tilde{g} C^{+} t^{c} b}{f^{2}}$$



Potentially very similar to SUSY decay



Can we impose T-parity in the UV completion?

$$\Sigma \rightarrow \Omega \Sigma^\dagger \Omega$$

⬇

$$\psi_2 \rightarrow {\psi'_2}^\dagger$$

$$\psi_0 \rightarrow -{\psi_0}^\dagger$$

not a symmetry

need $\mathbf{x} \rightarrow -\mathbf{x}$

Analogy to QCD

In the chiral Lagrangian $\Sigma \to \Sigma^\dagger$

$$\pi \longrightarrow -\pi$$

could be a symmetry

Not a symmetry of QCD

$$\pi F_{\mu\nu} \tilde{F}_{\mu\nu}$$

Similar terms exist in Little Higgs models

WZW terms: fixed by anomaly structure

Make the dark matter candidate unstable

Do not contribute to EWPO

problem is deeper: what symmetry to impose in the UV?

Possible solutions

Look for new UV completion

Look for a new definition of T-parity

Add a new field:

$$\Sigma_1 \to \Sigma_2$$

$$\Sigma_1 \to L\Sigma_1 L^T \qquad \Sigma_2 \to R^*\Sigma_2 R^\dagger$$

The number of fields is doubled: even and odd

Give mass to the unwanted combination:

$$\Lambda^2 f^2 \Sigma_1 \Sigma_2$$

break the enlarged gobal symmetry to the diagonal

Could come from 4-Fermi interactions in the UV theory, but might be hard to engineer.

Other possibility:

change global symmetry structure

we want: $A_1 \rightarrow A_2$

why not: $\psi_2 \rightarrow \psi_2'$?

2 of $SU(2)_1$ $\quad$ 2^* of $SU(2)$

$Y = \frac{1}{2}$ $\quad$ $Y = -\frac{1}{2}$

Add a new flavour

		$SU(2)_1$	$SU(2)_2$	$U(1)_Y$
	Ψ_2	2	1	0
$SU(6)$	Ψ_0	1	1	$1/2$
	Ψ'_0	1	1	$-1/2$
	Ψ'_2	1	2^*	0

$$\Psi_2 \rightarrow \epsilon \Psi_2'$$

$$\Psi_0 \rightarrow \Psi_0$$

$$\Psi_0' \rightarrow \Psi_0'$$

$$\Psi_2' \rightarrow -\epsilon \Psi_2$$

Global symmetry

$$SU(6)/Sp(6)$$

$$\Sigma_0 = \begin{pmatrix} \overset{\substack{2\times 2\\ \searrow}}{\mathbf{0}} & \overset{\substack{2\times 1\\ \downarrow}}{0} & \overset{\substack{2\times 1\\ \downarrow}}{0} & \overset{\substack{2\times 2\\ \swarrow}}{\mathbf{1}} \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ \underset{\substack{\nearrow\\ 2\times 2}}{-\mathbf{1}} & 0 & 0 & \underset{\substack{\nwarrow\\ 2\times 2}}{\mathbf{0}} \end{pmatrix}$$

$$Q_1^a = \begin{pmatrix} \sigma^a & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \qquad Q_2^a = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\sigma^{a*} \end{pmatrix}$$

$$Y = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1/2 & 0 & 0 \\ 0 & 0 & -1/2 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$\pi = \begin{pmatrix} \alpha - \eta/2 & h_1 & h_2 & s \\ h_1^\dagger & \eta & 0 & h_2^T \\ h_2^\dagger & 0 & \eta & h_1^T \\ s^\dagger & -h_2^* & h_1^* & \alpha^T - \eta/2 \end{pmatrix}$$

2 Higgs doublet

1 light real singlet

1 TeV complex singlet

top sector

$$\lambda_1 f Q \Sigma^\dagger Q^c$$

$$+\lambda_2 f (q_1^c K_1 q_3 + q_2^c K_2 q_3) + \lambda_3 u \tilde{u}^c$$

$$Q = \begin{pmatrix} q_1 \\ u \\ d \\ q_2 \end{pmatrix} \qquad Q^c = \begin{pmatrix} q_2^c \\ d^c \\ u^c \\ q_1^c \end{pmatrix}$$

1 even doublet

1 odd doublet

2 even singlets

Higgs sector

inert doublet model

$$\langle h_+ \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix} \qquad \langle h_- \rangle = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

$$m_{h_0} < m_{H_0} = m_{H^+} < m_A$$

Corrections to S and T from the 2 Higgs doublet model are small

The neutral, odd, CP even Higgs is the dark matter candidate

Conclusions

- Little Higgs model try to realize the Higgs as a pseudo-Goldstone boson
- UV completion change the phenomenology and structure of the low energy theory
- The SU(6)/Sp(6) model is well suited for a different implementation of T-parity