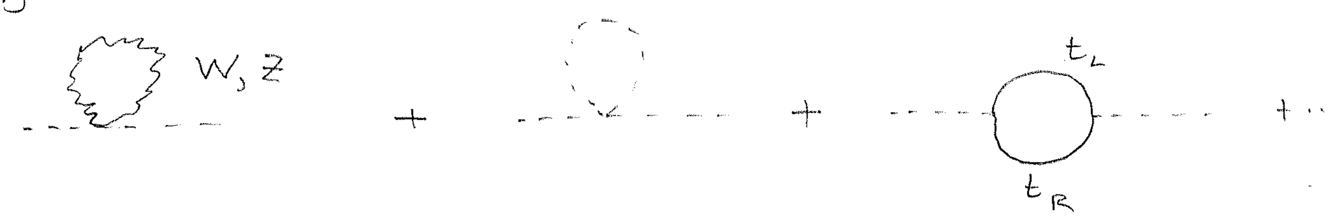
V. Compositeness, and precise EW constraints

Lone light scalars not natural (haven't seen!).

E.g. SM



$$\rightsquigarrow \quad \delta M_H^2 = \frac{G_F \Lambda^2}{4\sqrt{2}\,\pi^2}\left(6M_W^2 + 3M_Z^2 + M_H^2 - 12M_t^2\right) \qquad \text{(ex)}$$

$$\sim -\left(\frac{\Lambda}{.7\,\text{TeV}}\; 200\,\text{GeV}\right)^2$$

$\therefore \quad \Lambda \lesssim .7$ TeV to avoid fine tuning.

in particular: new colored states suggested (LHC ...)

"obvious" idea: Higgs = composite
(alternate: new symmetries - SUSY, etc.)

Example: Technicolor.

Begin w/

Imaginary world:

- no Higgs
- u, d quarks
- leptons
- $W^\pm$, Z ... massless

$\rightsquigarrow$ $SU(2)_L \times SU(2)_R$ symm (compare QCD chiral sym.)
here just u, d, no s.

at Λ_{QCD}, QCD strong, breaks $\longrightarrow SU(2)_V$.

$$\langle u \bar{u} \rangle = \langle d \bar{d} \rangle \simeq \Lambda_{QCD}^3$$

$\pi^{\pm,0}$ = Goldstone bosos (exact, since $m_u, m_d = 0$)

also, $\underline{SU(2)_W \times U(1)_Y \text{ broken!}}$

Indeed, EFT: $\Sigma = e^{2i\Pi/f_\pi}$ $\quad \Pi = \pi^a T^a$

$$\longrightarrow \underset{SU(2)_L}{U_L} \, \Sigma \, \underset{\substack{SU(2)_R \\ U(1)_Y}}{U_R^{+}}$$

$$\rightsquigarrow \mathcal{L}_{eff} = -\frac{f_\pi^2}{4} \operatorname{Tr} |D_\mu \Sigma|^2 + \dots$$

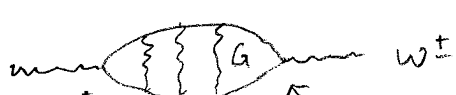
min coupling to A^a, B

e.g. see from argument for Goldstone's thm:

$$\langle 0 | J^a_{A\mu}(x) | \pi^b(p) \rangle = i \delta^{ab} f_\pi p_\mu e^{ip\cdot x}$$

$$\mathcal{L}_{SU(2)} = \dots + i \frac{g_2}{2} A^a_\mu J^{a\mu}_L$$

pictures:



$f_\pi \frac{g_2}{2} A^a_\mu \partial^\mu \pi^a$

So $\langle \Sigma \rangle = 1 \rightsquigarrow$ breaks $SU(2) \times U(1) \to U(1)$

$\therefore$ Σ_π plays exactly same role as Σ in chiral weak lag.

 $\rightsquigarrow M_W = \frac{g_2 f_\pi}{2} \simeq 30\ \text{MeV}.$

Technicolor proper: (color, the sequel)

SM ferms, + another strong force, $SU(N)_{TC}$, w/

technifermions $F = \underbrace{\begin{pmatrix} U \\ D \end{pmatrix}_L \quad \bar{U}_R \quad \bar{D}_R}_{\text{in } N \text{ of } SU(N)_{TC}}$

If strong at Λ_{TC}; breaks

$SU(2)_L \times SU(2)_R \times U(1)_L \times U(1)_R$

$$\langle \bar{U} U \rangle = \langle \bar{D} D \rangle = \mathcal{O}(\Lambda_{TC}^3).$$

$M_W = \frac{g_2 F_\pi}{2} = 80\ \text{GeV} \Rightarrow F_\pi \simeq 250\ \text{GeV} \sim \Lambda_{TC}$

decay constant of technipion

$M_Z = \cdots$ (ex)

So: $\pi^{\pm,0}$ ... Goldstone bosos

analog of $\eta = u\bar{u} + d\bar{d}$ (isoscalar): $H_T = U\bar{U} + D\bar{D}$ replaces Higgs.

So to compare,

QCD	QTCD
$\frac{g_3^2}{4\pi}(1\,\text{GeV}) \sim 1$	$\frac{g_{TC}^2}{4\pi}(1\,\text{TeV}) \sim 1$
$f_\pi = 93\,\text{MeV}$	$F_\pi = 250\,\text{GeV}$
$M_W = 30\,\text{MeV}$	$M_W = 80\,\text{GeV}$
Hadrons $\sim 1\,\text{GeV}$	Technihadrons $\sim 1\,\text{TeV} \sim 4\pi F_\pi$

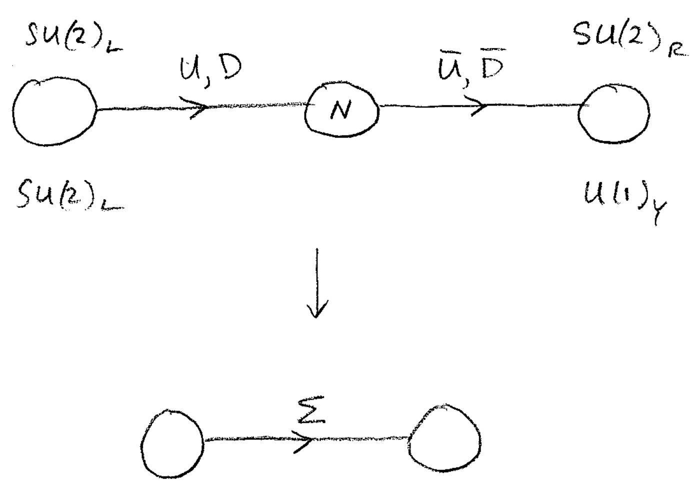
$\uparrow$ New physics

... elegant; $\rightsquigarrow$ retro physics ('70s again)

aside: Moose/Quiver notation

Global

Gauged



(same as SM Higgs)

useful way to organize SSB w/ multiple strong groups.

Hitch # 1

Fermion masses. $SU(2) \times U(1)$ broken, but

$$i\left(q^\dagger \not{D} q + \bar{u}^\dagger \not{D} \bar{u} + \bar{d}^\dagger \not{D} \bar{d}\right)$$

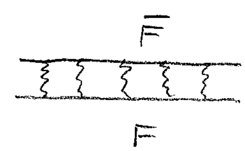
has chiral symms, e.g. $q \to e^{i\alpha} q$

$$\bar{u}, \bar{d} \to e^{-i\alpha}\, \bar{u}, \bar{d}.$$

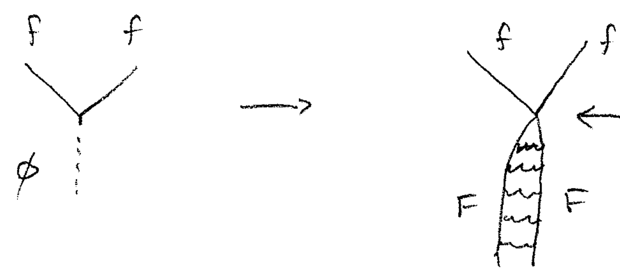
not broken $\Rightarrow$ no ferm masses.

In SM: $\phi\, q\, \bar{d}$, etc.

now $\phi \longleftrightarrow$

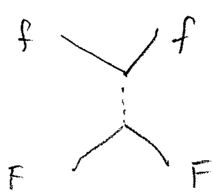


So:

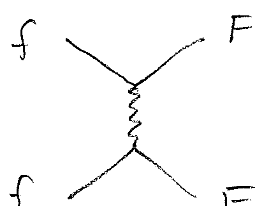


bad news!

now feeling like a bad rerun.



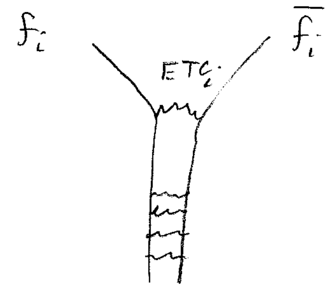
fund scalar ... trouble



extended technicolor

E.g. F's like SM: $Q, \bar{u}, \bar{D}, L, \bar{E}$

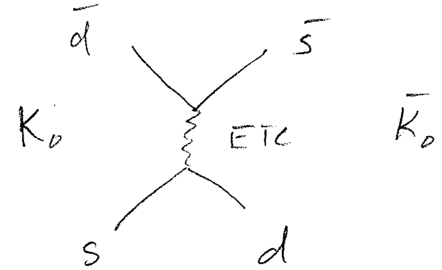
but • different Yukawas ⇒ different groups?



$$M_{f,i} \sim \frac{g^2_{ETC,i}}{M^2_{ETC,i}} \langle F\bar{F} \rangle$$

quickly baroque (many states, some stay light, ...)

• Flavor changing neutral currents



Maybe we're just not clever enough? (Many other versions...)

– 2/6/07

Hitch #2 Precise EW measurements

... strain many new physics scenarios, particularly technicolor, etc.

"LEP paradox"

Saw $\Lambda_{NP} \lesssim 700$ GeV for no fine tuning.

But, NP can enter in many higher dim ops. Some subject to test ... not seen

Bounds $\rightsquigarrow$ $\Lambda_{NP} \gtrsim$ few TeV.

E.g. if $\Lambda_{NP} \sim 6$ TeV, quad div $\Rightarrow$ 10^{-2} tuning.

"little hierarchy problem"

More detail: EW Chiral description

recall:

$$\mathcal{L}_\Sigma = \mathcal{L}_{GB} - \frac{f^2}{4} \mathrm{Tr}\left[(D_\mu \Sigma)^\dagger (D^\mu \Sigma)\right] + \underline{\text{higher dim}}$$

Recall useful combinations

$$T = \Sigma \tau_3 \Sigma^\dagger \quad \text{(cust. viol.)}$$
$$V_\mu = (D_\mu \Sigma)\Sigma^\dagger$$

$$+ \alpha_1 \frac{g_1 g_2}{2} B_{\mu\nu} \mathrm{Tr}(T \underset{\uparrow\, SU(2)}{F^{\mu\nu}}) + \underbrace{\beta_1 \frac{g_1^2 f^2}{4}\left[\mathrm{Tr}(T V_\mu)\right]^2}_{\text{Saw before}}$$

$$+ \alpha_8 \frac{g_1^2}{4}\left[\mathrm{Tr}(T F_{\mu\nu})\right]^2 + \cdots$$

(12 terms @ dim 4 — see Appelquist-Wu)
(CP invt)

These are determined by underlying EW breaking physics.

E.g.

$\Pi(q^2)$ ... self energy.

composite scenarios
Higgs

$\rightsquigarrow$ Structure
i.. $\Pi(q^2)$

In general,

$$W_+^\mu \Pi_{+-}(q^2) W_{-\mu} + W_3^\mu \Pi_{33}(q^2) W_{3\mu}$$
$$+ W_3^\mu \Pi_{3B}(q^2) B_\mu + B^\mu \Pi_{BB}(q^2) B_\mu$$

Certain new physics (e.g. technicolor, "higgsless," little Higgs) leading order corrns. only enter through these parameters ..
(Indeed, in technicolor this was the problem $\rightsquigarrow$ ETC.)
... "Oblique corrections"
Expand in q^2; typically sensitive to leading terms

e.g.

$$\boxed{' = d/dq^2}$$

$$S = -16\pi\, \Pi_{3B}'(0) = -16\pi \alpha_1$$

$$\alpha T = \frac{e^2}{c_W^2 s_W^2 M_Z^2}\left[\Pi_{+-}(0) - \Pi_{33}(0)\right] = 2g_1^2 \beta_1$$

$$U = 16\pi\left[\Pi_{+-}'(0) - \Pi_{33}'(0)\right] = -16\pi \alpha_8$$

chiral EW params

... "Peskin - Takeuchi" parameters

+ more (see e.g. Rattazzi)

Experimental sensitivity?

Some observables: (denote observables as opposed to lag. params. by ^)

$\hat{\alpha}$ EM scatt.

$\hat{G}_F$ μ decay

$\hat{M}_Z$ LEP - resonance

$\hat{m}_W$ " "

$\hat{A}^e_{LR}$ Z - decay

Specifically $$\hat{A}^f_{LR} = \frac{\Gamma(Z^0 \to f_L \bar{f}_R) - \Gamma(Z^0 \to f_R \bar{f}_L)}{\Gamma(Z^0 \to f_L \bar{f}_R) + \Gamma(Z^0 \to f_R \bar{f}_L)}$$

for $f = e$, at tree level,

$$A^e_{LR} = \frac{\left(\frac{1}{2} - s^2_W\right)^2 - s^4_W}{\left(\frac{1}{2} - s^2_W\right)^2 + s^4_W} \qquad \text{(ex)}$$

loop corrections, like the above, shift such relⁿs

Basic EW params - g_1, g_2, v : 3

> 5 observables

$\Rightarrow$ predicted relⁿs betw observables;

data tests whether other corrn's from new physics significantly modify these predictions

More specifically: $\hat{\alpha}, \hat{G}_F, \hat{m}_Z$ best observed

$\leadsto$ define weak angle

$$\sin 2\hat{\theta}_0 = \sqrt{\frac{4\pi\hat{\alpha}(m_Z^2)}{\sqrt{2}\,\hat{G}_F\,\hat{m}_Z^2}}$$

Then measure m_W $\leadsto$ $\dfrac{\hat{m}_W^2}{\hat{m}_Z^2} = \cos^2\hat{\theta}_W$

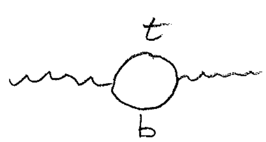
new observable

and $\hat{A}^e_{LR}$ $\leadsto$ $\sin^2\hat{\theta}_*$

$$\left.\begin{array}{l}\hat{s}_W^2 - \hat{s}_0^2 \\ \hat{s}_*^2 - \hat{s}_0^2\end{array}\right\} \text{ depend on}$$

(e.g. shift m_W; $Zf\bar{f}$ coupling, etc)
(details: Peskin & Schroeder)

e.g.



$\xrightarrow{\text{LEP}}$ $m_t = 169 \pm 24$ GeV

(otherwise corrn's too large)

later (1995) CDF/D0 found.

today: 174 ± 3 GeV not bad.

<u>Likewise sensitive to other new physics in propagator</u>

Present constraints: $S = -0.13 \pm 0.1$
$T = -0.13 \pm 0.1$ (PDG)
$U = 0.20 \pm 0.1$

expectations (can be more precisely checked)

$\alpha_1, \beta_1 \propto v^2$ (e.g. w/ Higgs, $\propto \phi^2$)

but dim.less $\Rightarrow$ e.g. $\alpha_1 \sim \frac{v^2}{\Lambda^2}$; $\therefore$ $S \sim -16\pi \frac{v^2}{\Lambda^2}$

So: $\Lambda \gtrsim \sqrt{\frac{16\pi \cdot (250\,GeV)^2}{.13}} \sim 5\,TeV$

too high. (?) (Fine tuning needed).

2/8/07

A proposed scheme to evade:

<u>Little Higgs</u>

various models, will describe "littlest:"

Consider $SU(5) \xrightarrow[\Sigma]{} SO(5)$

Σ = NLSM of type we've seen, here

$$\Sigma \to U \Sigma U^T \quad \text{under } SU(5).$$

(e.g. more fundamentally, $\Sigma_{ij} \sim \langle \psi_i \psi_j \rangle$)

five Weyl ferms; SO(5) gauge symm ~ TC