Tumbling

* Seen that SM described by a spontaneously broken non-abelian gauge theory

* In SM this breaking is achieved via elementary Higgs (scalar) field.

* Theories of scalar fields are generically thought of as "unnatural". The radiative corrections to the mass are quadratically divergent. Fine tuning is needed to achieve light mass relative to high scales

eg $(\Lambda_{GUT}/\Lambda_{EW})^2 \sim \delta m^2 \sim \underline{\underline{10^{26}}}$!

* One is motivated to find ~~natural~~ mechanisms of breaking EW (or GUT) symmetries without scalars (exception: SUSY where scalars can be light because of pairing with fermions)

$\Uparrow$

$\delta m \propto m$ because of chiral sym.

2nd problem (related ...)

SM contains many scales eg t quark mass, EW scale, electron mass et etc

* Where do these scales come from ?
* Can we find "natural" ways to break symmetries which automatically generate hierarchies of mass scale ?

Goal of Humbling Models — use strongly coupled gauge fermion dynamics to generate SSB

A remark: $\Lambda_{QCD} \ll \Lambda_{GUT} / \Lambda_{Planck}$ because "naturally"

$\Lambda_{QCD} / \Lambda_{GUT} \sim e^{+a/g^2}$ ie asymptotic freedom

ie log running ~~[illegible]~~ naturally allows scale where $\alpha \sim 1$ to be exp different from α small at Λ_{GUT}

If ~~fermion conden~~

In QCD $\alpha \sim 1 \to$ confinement & chirally symmetry breaking...

Can we use similar dynamics for SSB ?

Idea/.

Start with (chiral) gauge theory at high scales

where $\langle \bar{\psi}\psi \rangle = 0$

As go to I.R α grows. At some point may

trigger formation of a fermion condensate $\langle \bar{\psi}\psi \rangle$

Since theory is chiral this must break gauge

symmetry. Some fermions will pick up (large) mass

ie original symmetry breaks at exp diff mass scale

like QCD

The remaining gauge symmetry / light fermions

now define new theory with (maybe) small

α'. This will grow again in I.R — trigger

another condensate / symmetry at another

mass scale

etc etc. process can repeat many times..

$\boxed{\text{tumbling scenario}}$

Ingredients

just L handed fermions (Weyl)

(antiparticles must form in complex conjugate reps)

Lorentz scalars

$\epsilon^{ij}\,\psi_i\,\chi_j$ $\qquad$ i, j SU(2) spinor indices

bilinear must be symmetric under exchange of any gauge group indices

Most easily build such symmetric bilinears using antisymmetric reps

eg $\psi_{\alpha\beta} = N \otimes_A N$ $\qquad$ write $[2]_N$.

antisymmetric $N \times N$ matrix

in general $\psi_{\alpha_1 \dots \alpha_m} \equiv N \otimes_A N \otimes_A \dots$

$= [m]_N$

eg $[2]_5 = 10$ rep of $SU(5)$ ← complex

amusing fact $[m]_N = [N-m]_N$ conjugates

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$[m]_N \leftarrow$ antisymmetric product of m fundamental reps in $SU(N)$

Question: which bilinear will form?

Ansatz: consider $\boxed{\text{single gauge boson exchange}}$ between fermions in rep 1 & 2.

$$V \sim \frac{g^2}{r} T_1 \cdot T_2$$

generators in 1 & 2 rep!

$$T_1 \cdot T_2 = (T_1 + T_2)^2 - T_1^2 - T_2^2$$

composite

$$= C_{1+2} - C_1 - C_2 \leftarrow \text{quadratic Casimirs}$$

Assume potential between 2 fermions

$$\propto g^2(\mu)\left(C_{1+2} - C_1 - C_2\right)$$

work out all possible condensate reps/channels

$\hookrightarrow$ assume condenses in maximally attractive channel (MAC) — ASSUMPTION

where $C_{1+2} - C_1 - C_2$ most negative

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eg QCD

$SU(3)$, q, $\bar{q}$

when α_s becomes strong 4 possible condensates

n flavors

$SU(N) \times SU(N)$

global chiral symmetry

a) $q\bar{q} \to SU(3)$ singlet $C_{1+2} = 0$

b) $q\bar{q}$ octet $C_{1+2} = 3 = C_8$.

c) qq sextet $C_6 = 10/3$

d) qq antitriplet $C_{\bar{3}} = 4/3$

a) $V \sim g^2\left(0 - \frac{4}{3} - \frac{4}{3}\right) = -8/3\, g^2$

b) $V \sim g^2(C_8 - 8/3) = 1/3\, g^2$

c) $V \sim g^2(10/3 - 8/3) = 2/3\, g^2$

d) $V \sim g^2(4/3 - 4/3 - 4/3) = -4/3\, g^2$

thus MAC implies a color singlet as observed $\to$ does not break $SU(3)$ (singlet)

A more interesting example

$[2]_5 \sim 10 \qquad \psi_{\alpha\beta}$ like for SU(5) GUT

$[4]_5 \sim \bar{5} \qquad \chi_{\alpha\beta\gamma\delta}$

$\boxed{\text{anomaly free}}$

possible condensates

$$\{[2]_5 \oplus [4]_5\} \otimes \{[2]_5 \oplus [4]_5\}$$

$\boxed{\text{MAC turns out to be}}$:

$$[2]_5 \otimes [2]_5 \to [4]_5.$$

only option to contract indices is ϵ tensor

so $\phi_\sigma = \langle \psi_{\alpha\beta} \psi_{\gamma\delta} \epsilon_{\alpha\beta\gamma\delta\sigma} \rangle$

use SU(5) to rotate ϕ to put say 1^{st} comp non-zero

ie $\boxed{SU(5) \longrightarrow SU(4)}$

some scale M.

Any fermion participating in condensate become heavy $m_f \simeq M$. ie $10 \to 6 + 4$

$\psi_{\alpha\beta} \to \psi_{ab} + \psi_{a5} \qquad a,b = 1..4$

ψ_{ab}: $[2]_4$ & ψ_{a5}: $[1]_4$

$$\overset{\overline{5}}{X_{\alpha\beta\gamma\delta}} \to \overset{\overline{4}}{x_{abc5}} + \overset{1}{x_{abcd}}$$

$[3]_4$ 4 singlet $[0]_4$

(8)

note that (6)

$[2]_4$ state participates in condensate → gets mass $O(M)$

Now at lower energies

SU(4) theory has fermion content

$[1]_4 \oplus [3]_4 + [0]_4$

complex conj rep. singlet ~~interaction~~

again g_4 grows & a condensate forms at a new scale M'

like QCD $[1]_4 \otimes [3]_4 \to [0]_4$

i.e. massive Dirac particles from [1] + [3]

$\boxed{\text{no breaking of SU(4).}}$

more complicated models possible ....

SU(5N) → SU(M) → SU(M') etc

Criticism / Comments

* MAC is an ansatz : needs to be checked outside of pert. theory (strong coupling problem!)

[for QCD consistent with "breaking global symmetries to largest subgroup" eg

$$SU_V(N) \times SU_A(N) \to SU_V(N)$$]

Since it involves chiral gauge theories it is hard to test using eg lattice gauge theory

* Related (in spirit) to ideas for breaking EW symmetry using condensates of vector fermions

→ $\boxed{\text{technicolor models}}$

Technicolor – quick review

Another way to dispense with scalar fields

Hypothesize another (new) gauge interaction

couples to new (massless) (techni)fermions

Assume asymptotic freedom → confines

at EW scales (250 GeV)

Strong force spontaneously breaks

technifermion chiral symmetries a la QCD

If some of these chiral symmetries are

weakly gauged under SM → break EW

symmetry

→ dynamical Higgs mechanism

Simplest Model

Imagine single doublet of technifermions transforming according to some (complex) rep of $SU(N_T)$ eg fundamental.

Chiral symmetry $= SU_L(2) \times SU_R(2)$

breaks to $SU_V(2)$ (like QCD)

$T_L = \begin{pmatrix} U \\ D \end{pmatrix}_L$ $\quad$ U_R, D_R are $(1, -\frac{1}{2})$

$(2, 0)$ $\quad$ new gauge int. anomaly free.

3 would be Goldstone produced $\pi_T^{\pm}, \pi_T^{0}$

↪ supply 3 missing longitudinal "technipions" polarizations of W, Z

condensate $\langle \bar{U}_L U_R \rangle = \langle \bar{D}_L D_R \rangle = \Lambda^3$.

$M_W, M_Z \sim f_{\pi_T}$

scale of technicolor condensate

or. technicolor pion decay constant

What have we gained?

* mechanism is "natural" – stabilizes weak scale below Λ_{GUT} / M_P

  α_T grows logarithmically as μ decreases

* theory is non-trivial. β function negative – no Landau pole (like elementary Higgs)

  no triviality problem

* Higgs boson still possible – analog of σ in QCD.

  – not needed for breaking but like ρ_T etc will exist → technihadron spectrum

What is wrong

* No mechanism in simple technicolor for fermion masses (ETC – ugly...)

  FCNC – like SUSY.

* Where are the technihadrons?
  (LHC)

* What S, T parameters? Precision EW quantities sensitive to new physics ...

Extensions

(1) ETC ← coupling "walks" from high scales to Λ_{EW}

(2) Walking theories. Theories close to "conformal window" may possess light Higgs. Walking theories may help with EW precision. & may escape some of the problems with quark/lepton masses/ FCNC....

(3) Related. Put technifermions in reps other than the fundamental....