TECHNICOLOR & THE HEMC

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- OVERVIEW OF TECHNICOLOR
  - TC & EXTENDED TC (AKA ETC)
  - WALKING TC (WTC)
  - TOPCOLOR-ASSISTED TC (TC2)
- TC SIGNATURES AT AN HEMC
  - ρ_T^0 AND ω_T OF MINIMAL TC
  - Z' OF TC2
  - HIGHER-DIMENSIONAL FERMIONS OF TC2

TECHNICOLOR OVERVIEW

(WEINBERG, SUSSKIND -1979) **TC** = DYNAMICS OF $SU(2)\otimes U(1) \to U(1)_{EM}$
HIGGS MECHANISM WITHOUT
ELEMENTARY HIGGS BOSONS.

TC INSPIRED BY QCD PRECEDENT:

MASSLESS QUARKS ACQUIRE DYNAMICAL
"SOFT MASS" $m_Q \approx \Lambda_{QCD}$ — "SPONTANEOUSLY BREAKING"
CHIRAL SYMMETRY, PRODUCING MASSLESS
NAMBU-GOLDSTONE BOSONS $\pi, K, \eta, \ldots$
($N_f^2 - 1$ NGB'S)

"HARD MASS" **NOTE:** $(m_q) = (m_u, m_d, m_s, \ldots) \neq 0$
NEEDED FOR $M_\pi, M_K, M_\eta, \ldots \neq 0$

e.g. $f_\pi^2 M_\pi^2 = (m_u + m_d)\langle 0|\bar{q}q|0\rangle$

$\to f_\pi = 93\,\text{MeV} = O(\Lambda_{QCD})$

FOLLOWING THE QCD EXAMPLE

- $F_\pi \equiv 2^{-1/4} G_F^{-1/2} = 246\ \text{GeV} = O(\Lambda_{TC})$

  INDUCED BY STRONG GAUGE DYNAMICS AT

  $\Lambda_{TC} = 0.1 - 1.0\ \text{TeV}$

- <u>MASSLESS</u> TECHNIFERMIONS (T)

  INTERACT STRONGLY AT SCALE Λ_{TC},

  ACQUIRE DYNAMICAL MASS $= O(\Lambda_{TC})$,

  PRODUCE <u>MASSLESS</u> TECHNIPIONS π_T.

MINIMAL TC

- $T_L = \begin{pmatrix} T_U \\ T_D \end{pmatrix}_L$ & $SU(2)_{EW}$ DOUBLET

  T_{U_R}, T_{D_R} & $SU(2)_{EW}$ SINGLET

  $\Rightarrow$ $3\ \pi_T^{\pm,0}$ A.K.A. $W_L^\pm, Z_L^0$

  WITH $M_W^2 / M_Z^2 \cos^2\theta_W = 1$!!

- $N_D > 1$ TECHNIDOUBLETS $\Rightarrow$ $4N_D^2 - 4$ <u>EXTRA</u> π_T

  HOW DO THEY GET MASS??

EXTENDED TECHNICOLOR (ETC)

(DIMOPOULOS & SUSSKIND ; EICHTEN & K. LA 1979)

TC DOES NOT PROVIDE FOR "HARD MASSES"

- $m_q \neq 0$, $m_\ell \neq 0$.
- $m_T \neq 0$ — NEEDED FOR $M_{\pi_T} \neq 0$.

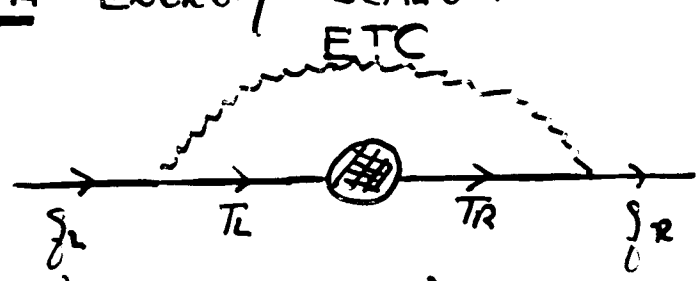
SOL'N: EMBED $TC \otimes COLOR \otimes FLAVOR \subset G_{ETC}$

$$(N_{ETC}) = \begin{pmatrix} 1_{TC} \\ 2_{TC} \\ \vdots \\ N_{TC} \\ 1_{QCD} \\ 2_{QCD} \\ 3_{QCD} \\ 1_F \\ 2_F \\ \vdots \\ N_F \end{pmatrix}$$

BREAK $G_{ETC} \to G_{TC} \otimes G_{QCD} \otimes G_F$

AT SOME <u>HIGH</u> ENERGY SCALE:

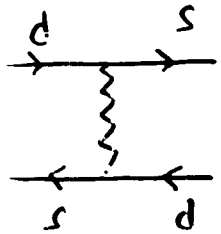
m_q (OR m_ℓ OR M_T) $\simeq$



$$\simeq \frac{g_{ETC}^2}{M_{ETC}^2} \langle 0 | \bar{T}_R T_L | 0 \rangle_{M_{ETC}}$$

BUT ... FCNC

e.g.



$$= \frac{g^2_{ETC}\,\theta^2_{sd}}{M^2_{ETC}}\,\bar{s}\gamma^\mu d\,\bar{s}\gamma_\mu d$$

$$\Rightarrow \quad \frac{M_{ETC}}{g_{ETC}\,\theta_{mix}} \gtrsim 500\text{-}1000\ \text{TeV}$$

Scaling $\langle\bar{T}T\rangle_{M_{ETC}}$ from QCD

$$\Rightarrow \quad m_q,\ m_\ell,\ m_T \sim \frac{g^2_{ETC}}{M^2_{ETC}}\langle\bar{T}T\rangle_{ETC} \lesssim \text{FEW MeV}$$

$$M_{\pi_T} \sim \left[\frac{g^2_{ETC}/M^2_{ETC}\,\langle\bar{T}T\bar{T}T\rangle_{ETC}}{F^2_{\pi_T}}\right]^{1/2} \lesssim \text{FEW GeV}$$

CATASTROPHE !

WALKING TECHNICOLOR (WTC

(HOLDOM 1981; APPELQUIST, et al. 1986; YAMAWAKI, et al.; AKIBA + YAMAGIDA, 1986.)

TC DYNAMICS ($\langle \bar{T}T \rangle_{M_{ETC}}$, e.g.) MUST NOT BE SCALED NAIVELY FROM QCD.
(c.f. TOM'S S-PARAMETER)

- PRECOCIOUS ASYMPTOTIC FREEDOM OF QCD

$$\Rightarrow \quad \langle \bar{T}T \rangle_{M_{ETC}} \approx \langle \bar{T}T \rangle_{\Lambda_{TC}} \simeq 4\pi F_{\pi_T}^3$$

- TC MUST APPROACH WEAK-COUPLING SLOWLY

i.e., WALK, NOT RUN:

$$\alpha_{TC}(M) \simeq \alpha_{TC}(\Lambda_{TC}) \quad \text{FOR } \Lambda_{TC} \lesssim M \lesssim M_{ETC}$$

$$\Rightarrow \quad \langle \bar{T}T \rangle_{M_{ETC}} \approx \frac{M_{ETC}}{\Lambda_{TC}} \langle \bar{T}T \rangle_{\Lambda_{TC}} \gg 4\pi F_{\pi_T}^3$$

$$\Rightarrow \quad m^{ETC}_{\gamma, \ell, T} \lesssim \text{FEW GeV}$$

$$M_{\pi_T} \lesssim \text{FEW 100 GeV}$$

[N.B. WTC AND PRECISION EW TESTS

* WHAT MAKES α_{TC} WALK? *

NEED TO MAKE $\beta(\alpha_{TC}) \approx 0$.
(NEAR AN IR FIXED POINT, e.g. ??)

INVOKE

(1) MANY T-FERMIONS IN N OF $SU(N)_{TC}$
(APPELQUIST, et al. 1987-88)

OR (2) FEW T-FERMIONS IN HIGHER IR OF SU(N).

OR (3) BOTH (E.E. + K.L., 1989; RAMANA + K.L. 1991)
(B. BALAJI - 1996
- WON'T WORK BECAUSE OF $b \to s\gamma$.)

(1) → LOW-SCALE TC, ACCESSIBLE AT TEVATRON, LHC, FIRST MUON COLLIDER

(2) → HIGH-SCALE TC, ACCESSIBLE AT LHC(?), VLHC, HEMC

TOPCOLOR-ASSISTED TECHNICOLOR

(TC2) (C.T. Hill, 1995)

$m_q^{ETC} \lesssim$ FEW GeV $\ll m_t = 175$ GeV

IF THERE'S AN ETC SCALE LOW ENOUGH (FEW TeV!!) TO GENERATE m_t

→ UNNATURAL FINE-TUNING OF g_{ETC}

→ TENDENCY FOR TROUBLE WITH $\rho = 1$.

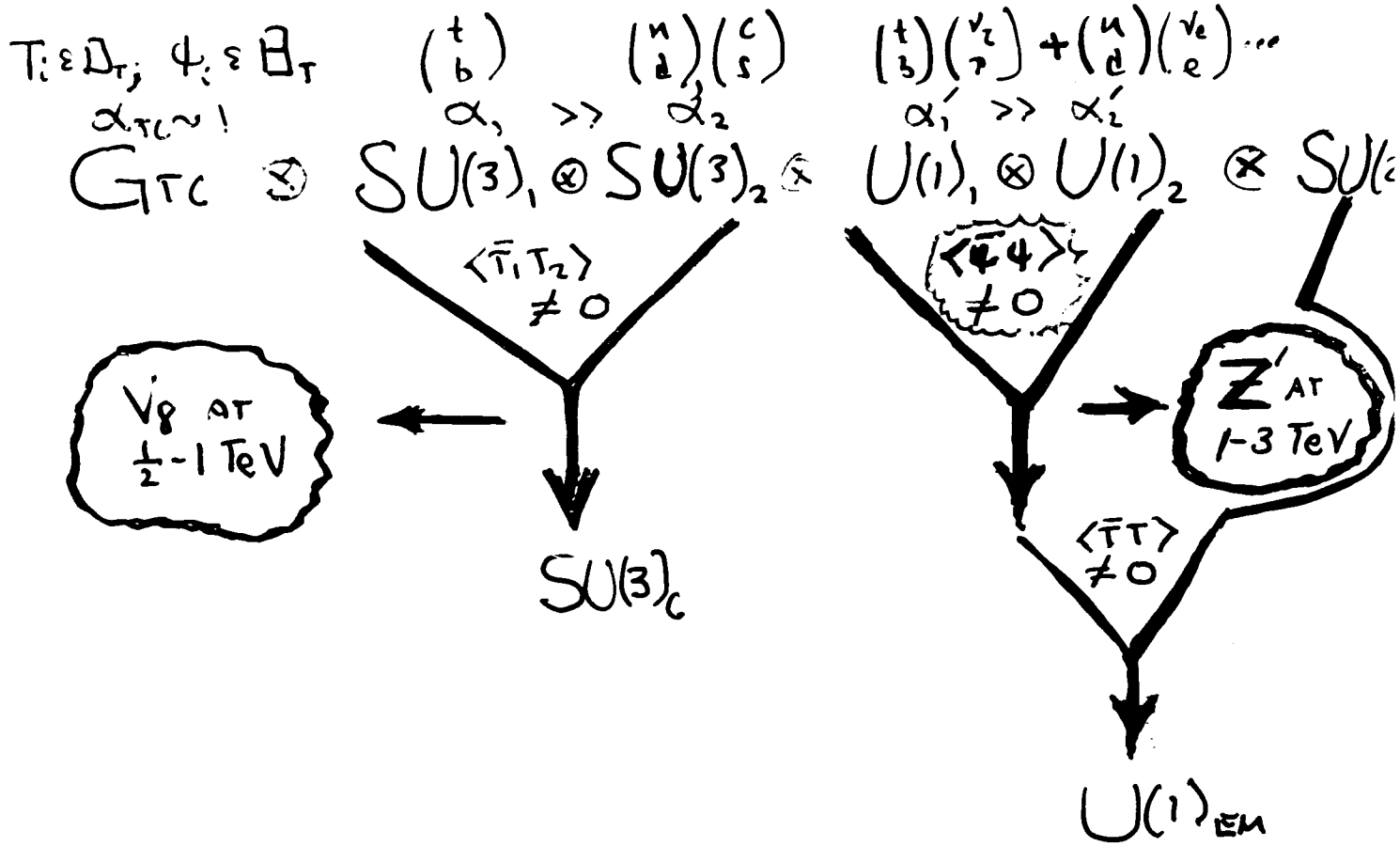
→ CONFLICT WITH $Z^0 \to b\bar{b}$

∴, INVOKE TOPCOLOR w/ $\Lambda_{top} \lesssim 1$ TeV TO GENERATE LARGE $\langle \bar{t}t \rangle$, m_t (NOT m_b!!

* WEAK-ISOSPIN ; $b \to c + \bar{X}$; $B_d^0 - \bar{B}_d^0$ MIXING ;..

➡ <u>MANY</u> T-FERMIONS NEEDED TO GIVE ETC MASSES + MIXINGS TO QUARKS + LEPTONS .... FOR EXAMPLE:

"SIMPLEST" TC2 SCHEME FOR $m_t \gg m_b$



LARGE m_t, BUT SMALL m_b, BECAUSE

- $SU(3)_1$ EQUALLY STRONG + <u>ATTRACTIVE</u> FOR t, b
- $U(1)_1$ STRONG + <u>ATTRACTIVE</u> FOR t, <u>REPULSIVE</u> FOR b.

AND THE "TOP SEE-SAW" SCHEME

(B. DOBRESCU + C. T. HILL; '98
R.S. CHIVUKULA, B. DOBRESCU, H. GEORGI, C. HILL '99)

MOTIVATION: TO REALIZE THE DREAM OF MAKING THE H^0 AN $\bar{F}F$-CONDENSATE.

IMPLICATIONS:

- GENERICALLY NEED Z', BUT AT ~ 5 TeV.

- F IS AN $SU(2)$-SINGLET QUARK WHICH MIXES (SEESAW) w/ t:

  $m_F \sim$ SEVERAL TeV

  $F \xrightarrow[\sim m_t/m_F]{\text{mix}} t \to Wb \; : \; \Gamma_F \simeq \frac{m_t}{m_F}\Gamma_t$.

MAIN LESSON FOR THE HEMC

TECHNICOLOR HAS HIGH-MASS SIGNALS AT THE REACH LIMIT, AND WELL ABOVE THE REACH, OF THE LHC ... A FORTIORI, NLC!

- ρ_T, ω_T AT 1-2 TeV IF MINIMAL TC
  PECULIAR SPECTRA BECAUSE T-FERMIONS ARE NON-FUNDAMENTAL, HAVE WTC DYNAMICS
- TC2 Z' AT 1-3 TeV
  OR ~ 5 TeV (IF TOP SEE-SAW)
- ELECTROWEAK SINGLET (OR VECTORIAL) ψ WHOSE CONDENSATION $\Rightarrow M_{Z'}$.
- $SU(2)$-SINGLET F OF TOP SEESAW. AT 2-5 TeV.

MINIMAL TC ρ_T, ω_T PHYSICS

* $\mu^+\mu^- \xrightarrow{\gamma, Z^0} \rho_T^0 \longrightarrow W_L^+ W_L^-$ (?)

  $\mu^+\mu^- \xrightarrow{\gamma, Z^0} \omega_T^0 \longrightarrow W_L^+ W_L^- Z_L^0$ (?)

  DETERMINE ρ_T, ω_T MASSES AND WIDTHS.

** LOOK FOR, MEASURE NON-STANDARD DECAY MODES.

*** STUDY $\rho_T^0 - \omega_T^0$ MIXING.

**** STUDY ρ_T, ω_T SPECTROSCOPY – IT CAN'T BE JUST QCD-LIKE!

TC2 Z' PHYSICS PROGRAM

* DETERMINE Z' MASS, WIDTH, COUPLINGS Y_{iL}, Y_{iR} TO QUARKS + LEPTONS.

$$\mu^+\mu^- \longrightarrow Z' \longrightarrow \bar{f}f, \bar{\ell}\ell, \ldots$$

** MEASURE $\Gamma(Z' \to \bar{T}_i T_i)$!

HOW WILL THESE DECAYS APPEAR?
AS $\pi_T \pi_T$? AS TECHNIBARYONS ??
AS TECHNI<u>JETS</u> ???

*** DISCOVER (THE ONLY WAY!) THE <u>HIGHER</u>-<u>DIMENSIONAL</u> <u>TECHNIFERMIONS</u> THAT GIVE MASS TO Z' (BUT NOT W, Z).

THESE NEED <u>HIGH</u> $\sqrt{s}$, <u>HIGH</u> $\int \mathcal{L}\, dt$, A <u>CLEAN</u> ENVIRONMENT. CAN THE HEMC PROVIDE ALL THAT?

TOP SEESAW SINGLET-F PHYSICS

* $\mu^+\mu^- \xrightarrow{\gamma, Z, Z'} \bar{F} F$

[$Q = 2/3$; $T = T_3 = 0$.

$F \longrightarrow t \longrightarrow W^+ b$, EACH W/ $E \gtrsim \frac{1}{2} m_F$

$\bar{F} \longrightarrow \bar{t} \longrightarrow W^- \bar{b}$ $\quad$? $\quad \gtrsim 1$ TeV!

** DETERMINE Q, Y, Y' OF F —
VERIFY $SU(2)$ - SINGLET

*** HOW DO WE SHOW THAT

$H^0 \simeq (\bar{F} F)$?