THE IMPORTANCE OF WALKING

Lattice Gauge Theory for the LHC

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I. **TECHNICOLOR and EXTENDED TECHNICOLOR**

- ELECTROWEAK SYMM. BREAKING:
  What **dynamics** are responsible for

$$SU(2)_{EW} \otimes U(1)_{EW} \longrightarrow U(1)_{EM} \quad ??$$

$\longrightarrow$ Technicolor (modeled on QCD and its chiral symmetry breaking)

- FLAVOR and FLAVOR SYMM. BRKNG:
  The **origin** of quark and lepton flavors?
  Why three identical generations?
  What is the **dynamical origin** of nontrivial quark and lepton masses and mixings?

$\longrightarrow$ Extended Technicolor (modeled on the the Higgs VEV as a T-fermion condensate)

TECHNICOLOR — NATURAL EWSB

TC = *asymptotically free gauge theory*
of *MASSLESS techni-fermions* T
with $\Lambda_{TC} \simeq 0.1 - 1.0\,\text{TeV}$.

Assume (e.g.) $T_{L,R\,i} = (U_i, D_i)_{L,R}$ form
N_D LH $SU(2)_{EW}$-doublets and $2N_D$ RH-singlets.

$\Longrightarrow$ *chiral* symmetry **and** χSB:

$$(SU(2) \otimes U(1))_{EW} \subset SU(2N_D)_L \otimes SU(2N_D)_R \longrightarrow SU(2N_D)_V$$

$$\langle \bar{U}_{Li} U_{Rj} \rangle = \langle \bar{D}_{Li} D_{Rj} \rangle = -\tfrac{1}{2}\delta_{ij}\Delta_T$$

$$\left(\Delta_T \simeq 4\pi F_T^3 \ \text{ where } \ F_T = 246\,\text{GeV}/\sqrt{N_D}\right)$$

$$\Longrightarrow (SU(2) \otimes U(1))_{EW} \longrightarrow U(1)_{EM}$$

with $M_W^2 = M_Z^2 \cos^2\theta_W = \frac{1}{2} g^2 N_D F_T^2$

NATURALNESS: *TC's GUIDING PRINCIPLE!*

$$\begin{aligned} \Lambda_{EW} &\equiv \Lambda_{\chi SB} \sim F_T \sim \Lambda_{TC} \sim M_{\text{technihadron}} \\ \text{at} &\;\; \alpha_{TC}(\Lambda_{TC}) = \mathcal{O}(1) \end{aligned}$$

EXTENDED TECHNICOLOR (ETC) SCENARIO FOR FLAVOR PHYSICS

- *WHY EXTENDED TECHNICOLOR?*

$\rightarrow$ Technicolor (and color) by itself leaves *too much* chiral symmetry unbroken.

$\rightarrow$ Explicit breaking of q, ℓ chiral symmetries required to give *"hard"* q, ℓ masses and avoid massless Goldstone bosons — $\pi, K, \eta, \ldots$

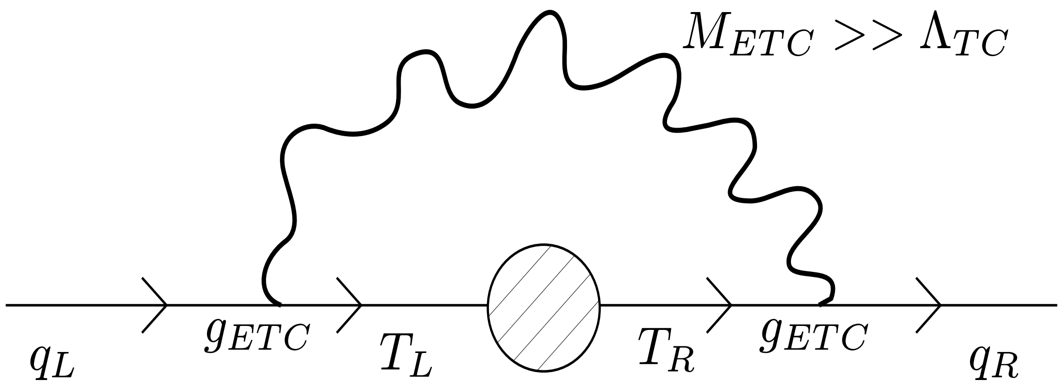
$\rightarrow$ Explicit breaking of technifermion chiral symmetries required to give *hard* masses to T_i and avoid massless technipions π_T — *"AXIONS"!*

• *THE STRUCTURE OF ETC:*

ETC = gauge interaction of *<u>massless</u>* T_i, q_a, ℓ_a — all together in a *<u>few</u>* ETC representations:

$$\underline{G_{ETC} \supset SU(N_{TC}) \otimes SU(3)_C \otimes \text{Flavor}}$$

$G_{ETC} \longrightarrow SU(N_{TC}) \otimes SU(3)_C$ at $M_{ETC} \gg \Lambda_{TC} \lesssim 1\,\text{TeV}$, *explicitly breaking* <u>**ALL**</u> global flavor symmetries.



$$m_{q,\ell}(M_{ETC}) \simeq \frac{g_{ETC}^2}{M_{ETC}^2}\langle \bar{T}T\rangle_{\boldsymbol{ETC}}$$

$$F_T^2 M_{\pi_T}^2 \simeq \frac{g_{ETC}^2}{2M_{ETC}^2}\langle \bar{T}T\bar{T}T\rangle_{\boldsymbol{ETC}}$$

$$\langle \bar{T}T\rangle_{\boldsymbol{ETC}} = \underbrace{\langle \bar{T}T\rangle_{\boldsymbol{TC}}}_{\sim\, \underline{\underline{4\pi F_T^3}}} \exp\left(\int_{\Lambda_{TC}}^{M_{ETC}} \frac{d\mu}{\mu}\,\gamma_m(\mu)\right)$$

$$\gamma_m(\mu) = \frac{3C_2(R)\,\alpha_{TC}(\mu)}{2\pi} + \cdots$$

II. TC and ETC SHOW–STOPPERS

FLAVOR-CHANGING NEUTRAL CURRENTS

Generic ETC models with *realistic* m_q-matrices have FCNC involving *mass eigenstate* q, ℓ. e.g.:

$$\left[q^\dagger T\,,\,T^\dagger q'\right] = q^\dagger q'$$

$$\Longrightarrow \mathcal{H}'_{\Delta|S|=2} = \frac{g^2_{ETC}\,\boldsymbol{V^2_{ds}}}{M^2_{ETC}}\;\bar{d}\Gamma^\mu s\;\bar{d}\Gamma'_\mu s + \text{h.c.}$$

$$|\Delta S| = 2 \text{ FCNC} \Longrightarrow \frac{M_{ETC}}{g_{ETC}\sqrt{\text{Re}(V^2_{ds})}} \gtrsim 1300\,\text{TeV}$$

Scaling $\langle\bar{T}T\rangle_{ETC}$ from QCD (for $\gamma_m \ll 1$) $\Longrightarrow$

$$m_{q,\ell}(M_{ETC}) \simeq \frac{g^2_{ETC}}{M^2_{ETC}}\langle\bar{T}T\rangle_{\boldsymbol{ETC}} \lesssim \frac{0.1\,\text{MeV}}{|V_{ds}|^2 N_D^{3/2}}$$

$$M_{\pi_T} \simeq \frac{g^2_{ETC}}{\sqrt{2}M^2_{ETC}}\frac{\langle\bar{T}T\rangle_{ETC}}{F_T} \lesssim \frac{0.4\,\text{GeV}}{|V_{ds}|\,N_D}$$

PRECISION ELECTROWEAK TESTS

<u>*ASSUMING*</u> all new physics scales such as Λ_{TC} are $\gg M_{W,Z}$, "Oblique" correction factor S is:

$$\begin{aligned} S &= 16\pi \frac{d}{dq^2}\left[\Pi_{33}(q^2) - \Pi_{3Q}(q^2)\right]_{q^2=0} \\ &= 4\pi \int \frac{dm^2}{m^4}\left[\rho_V^3(m^2) - \rho_A^3(m^2)\right] \\ &= -0.04 \pm 0.09 \text{ (PDG)} \end{aligned}$$

<u>ESTIMATES OF TC CONTRIBUTION TO S</u>

ASSUME THAT <u>**TC is QCD-like**</u>**:**
e.g., Peskin & Takeuchi: QCD as analog computer — spectral-function sum rules; VMD; scale from ρ, a_1 masses $\Longrightarrow$

$$S_{TC} = 4\pi \frac{N_D F_T^2}{M_{\rho_T}^2}\left(1 + \frac{M_{\rho_T}^2}{M_{a_T}^2}\right) \simeq 0.25 N_D \frac{N_{TC}}{3}$$

III. SAVING THE SHOW!

The KEY Equations of ETC — Again:

$$m_{q,\ell}(M_{ETC}) \simeq \frac{g_{ETC}^2}{M_{ETC}^2} \langle \bar{T}T \rangle_{\boldsymbol{ETC}}$$

$$F_T^2 M_{\pi_T}^2 \simeq \frac{g_{ETC}^2}{2M_{ETC}^2} \langle \bar{T}T\bar{T}T \rangle_{\boldsymbol{ETC}}$$

$$\langle \bar{T}T \rangle_{\boldsymbol{ETC}} = \langle \bar{T}T \rangle_{\boldsymbol{TC}} \exp\left(\int_{\Lambda_{TC}}^{M_{ETC}} \frac{d\mu}{\mu} \gamma_m(\mu) \right)$$

CAN γ_m *BE LARGE for a LARGE* μ-range — ENHANCING $\langle \bar{T}T \rangle_{\boldsymbol{ETC}} / \langle \bar{T}T \rangle_{\boldsymbol{TC}}$?

YES!

(Well... **<u>YOU</u>** need to demonstrate this!!)

HOW to keep γ_m LARGE?

Suppose $\alpha_{TC}(\mu) \simeq$ constant,i.e.,

$$\beta(\alpha_{TC}) = \frac{d\,\alpha_{TC}(\mu)}{d\,\log(\mu)} \simeq 0$$

Solution to the (approximate) equation for the anomalous dimension γ_m is

$$\Longrightarrow \gamma_m(\mu) = 1 - \sqrt{1 - \alpha_{TC}(\mu)/\alpha_{\chi SB}}$$

where $\alpha_{\chi SB} = \pi/3C_2(R)$ (in ladder approx'n).

This indicates that χSB occurs *iff*

$$\alpha_{TC} \geq \alpha_{\chi SB}.$$

And, at the χSB scale Λ_{TC}, $\gamma_m(\Lambda_{TC}) = 1$!

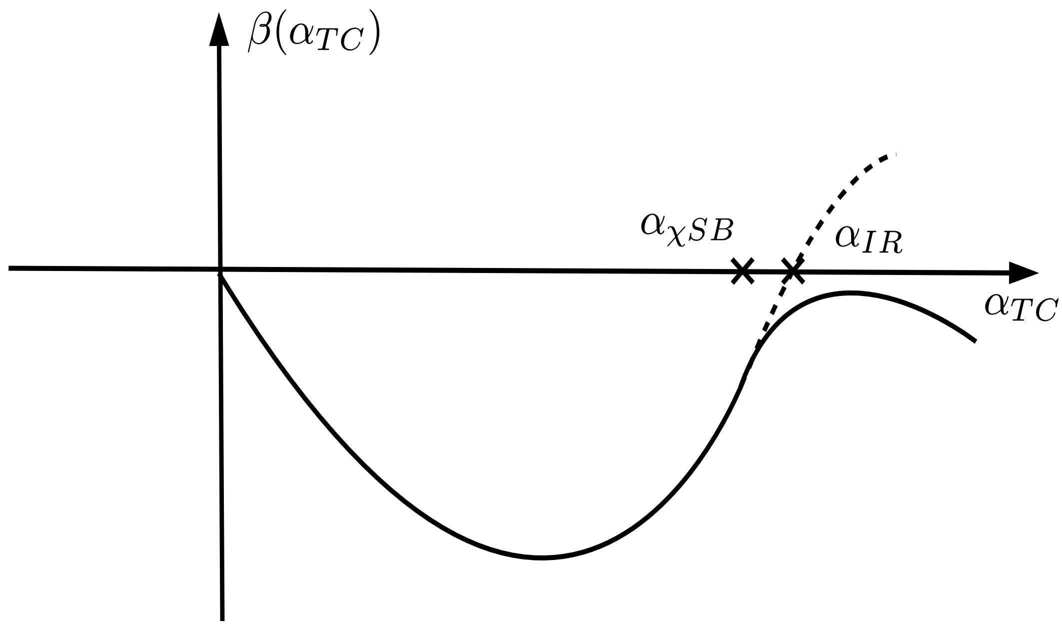
i.e., $\underline{\gamma_m = 1}$ <u>*is the signal for χSB !!*</u>

Again: to keep γ_m **large** for a **large** range of μ

$$\beta(\alpha_{TC}(\mu)) \simeq 0 \text{ for } \mu \simeq \Lambda_{TC} \longrightarrow \sim M_{ETC}$$

$$\Longrightarrow \alpha_{TC}(\mu) \simeq \alpha_{\chi SB} \Longrightarrow \gamma_m(\mu) \simeq 1$$

HOW? $\alpha_{\chi SB}$ lies *just below* an IR-fixed point:



i.e., TC must be a WALKING gauge theory!

CURING FCNC

Must have $M_{ETC}/(g_{ETC}|V_{ds}|) \sim 10^3$–$10^4$ TeV for the 1st two generations! The WTC enhancement of $\langle \bar{T}T \rangle_{\boldsymbol{ETC}}$ compensates $1/M^2_{ETC}$.

In the *extreme* walking limit, e.g.:

$$\langle \bar{T}T \rangle_{\boldsymbol{ETC}} \simeq \frac{M_{ETC}}{\Lambda_{TC}} \times \langle \bar{T}T \rangle_{\boldsymbol{TC}}$$

$$m_{q,\ell}(M_{ETC}) \simeq \frac{4\pi\alpha_{ETC}\langle \bar{T}T \rangle_{\boldsymbol{TC}}}{M_{ETC}\Lambda_{TC}} \simeq \frac{16\pi^2\alpha_{ETC}F_\pi^2 F_T}{N_D M_{ETC}\Lambda_{TC}}$$

$$\Rightarrow M_{ETC} = (140 \to 700{,}000\,\mathrm{TeV}) \left(\frac{10}{N_D}\frac{\alpha_{ETC}}{0.75}\frac{F_T}{\Lambda_{TC}}\right)$$

for $m_q = 5\,\mathrm{GeV} \to 1\,\mathrm{MeV}$

Furthermore...

$$M_{\pi_T} \simeq \underbrace{\sqrt{1.5\pi}4\pi F_\pi}_{7(!!)\ \mathrm{TeV}} \left(\frac{F_T}{\Lambda_{TC}}\right)\sqrt{\frac{\alpha_{ETC}}{0.75 N_D}}$$

...π_T may NOT be pseudo-Goldstone bosons!

<u>In any case, $\boldsymbol{M_{\pi_T}}$ **are significantly enhanced!**</u>

This has ENORMOUS implications for WTC phenomenology.

See Tulika's talk.

S in walking technicolor

WTC $\Longrightarrow$ spectral integrals

$$\int \frac{dm^2}{m^n}\left[\rho_V^3(m^2) - \rho_A^3(m^2)\right]$$

used in the S-calculation converge much slower than in QCD $\Longrightarrow$ integrals **are not** dominated by just the lowest-lying resonances.

- Spectrum of ρ_T, a_T **very different** from QCD.
- Cannot justify scaling arguments from QCD.
- Large-N_{TC} arguments may fail for large N_D.

Expect a *tower* of ρ_T, a_T??

$M_{a_T} \simeq M_{\rho_T}$ and $g_{a_T} \simeq g_{\rho_T}$ decrease $S \to 0$!

This talk needs a WOW FINISH!!

Either you'll provide it...or the LHC will.