LEPTON DIPOLE MOMENTS

WITH

DYNAMICAL ELECTROWEAK SYMMETRY BREAKING

Something utterly different

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DYNAMICAL ELECTROWEAK SYMMETRY BREAKING (TECHNICOLOR)

- New strong interactions at 1 TeV
  $SU(N)_{TC}$
  $\Lambda_{TC} \simeq 300$ GeV
- W_L, Z_L = Composite Nambu-Goldstone bosons
- New TeV-Scale Physics (Higgless)

QUARK AND CHARGED LEPTON MASSES (EXTENDED TECHNICOLOR)

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L \qquad \begin{pmatrix} U \\ D \end{pmatrix}_{L1} \quad \begin{pmatrix} U \\ D \end{pmatrix}_{L2}$$

$$u_R \quad c_R \quad t_R \qquad U_{R1} \quad U_{R2}$$

$$\leftarrow SU(2)_{TC} \rightarrow$$

$$(SSVZ)$$

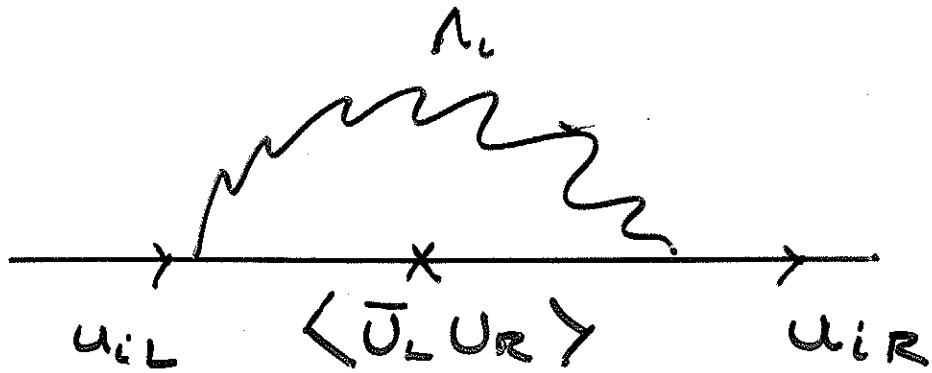
$$\leftarrow \qquad SU(5)_{ETC} \qquad \rightarrow$$

$$\Lambda_1 \qquad \Lambda_2 \qquad \Lambda_3$$

$$\simeq 10^3\,\text{TeV} \qquad \simeq 10^2\,\text{TeV} \qquad \simeq \text{Few TeV}$$

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

CONVENTIONAL FERMION MASS FORMULA



$$\boxed{M_{ii}^{(u)} \simeq \frac{8\pi}{3} \frac{\Lambda_{TC}^3}{\Lambda_i^2} \eta}$$

$$\exp\left\{ \int \frac{d\mu}{\mu} \gamma[\alpha_{TC}(\mu)] \right\}$$

$SU(2)_{TC} \rightarrow$ Walking to Λ_3!

$\boxed{\text{Very few parameters!}}$

CHALLENGES

(1) Precision Electroweak

S, T $(SU(2)_{TC})$

$Z \to b\bar{b}$

APS
ph/0308061

(2) Flavor-Changing Neutral Processes

Walking allows large ETC scales
APS

(3) Complete Theory?

Ingredients to break $ETC \to TC$
Intra-family mass splittings
Flavor Mixing
CP Violation
Neutrino Mass

CLASS OF MODELS

(Evolved from Terning + TA 1994)

$$SU(5)_{ETC} \times SU(2)_{HC} \times SU(3)_c \times SU(2)_L$$

q_L	$(5, 1, 3, 2)_{1/3}$	
u_R	$(5, 1, 3, 1)_{4/3}$	
d_R	$(\bar{5}, 1, 3, 1)_{-2/3}$	*
ℓ_L	$(\bar{5}, 1, 1, 2)_{-1}$	*
e_R	$(5, 1, 1, 1)_{-2}$	*
SM-Singlet → ψ_R	$(10, 1, 1, 1)_0$	
Neutrinos (Two below Λ_{TC}) ξ_R	$(10, 2, 1, 1)_0$	
ω_R	$2(1, 2, 1, 1)_0$	

Anomaly Free
Chiral ETC

IT "WORKS"

Attractive ETC + HC forces plausibly

$SU(5)_{ETC}$

$\Lambda_1 \simeq 2000$ TeV

$\langle \psi\psi \rangle$

$SU(4)_{ETC}$

$\Lambda_2 \simeq 100$ TeV

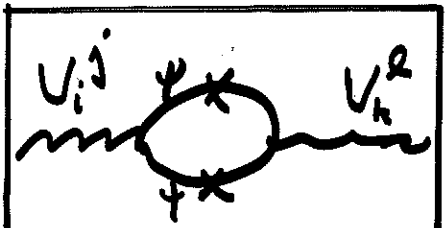
$\langle \xi\xi \rangle$

$SU(3)_{ETC}$

$\Lambda_3 \simeq 4$ TeV

$\langle \xi\xi \rangle \langle \omega\omega \rangle$

$SU(2)_{TC}$



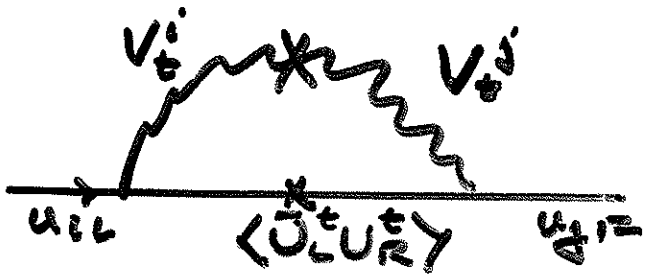
ETC Masses + Mixings

PHASES
- CALCULABLE
- FLAVOR DEPENDENT

QUARK AND LEPTON MASS MATRICES

- Up-quarks Diagonal $M_{ii}^{(u)}$ — Conventional ETC

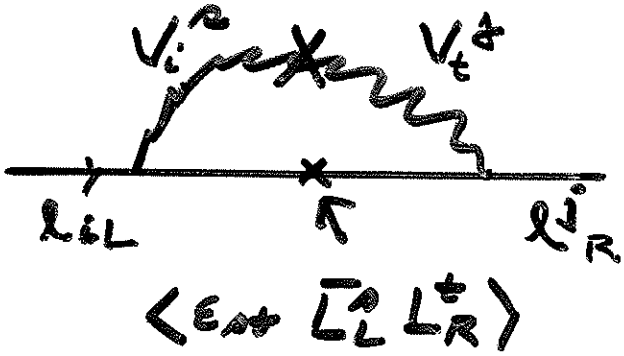
- Up-quarks OFF-diagonal $M_{ij}^{(u)}$



- Down-quarks Charged Leptons

Suppressed → $M_{ij}^{(\ell)}$

Complex Symmetric in models



- Dirac-Neutrino — Similar (2×3)

- Majorana-Neutrino SM-Singlet — Similar (2×2)

(SPONTANEOUS) RESULTS

(1) Reasonable t, c, u masses

(2) Suppressed down-quark and charged-lepton masses,

(3) Charged-current flavor mixing + CP violation

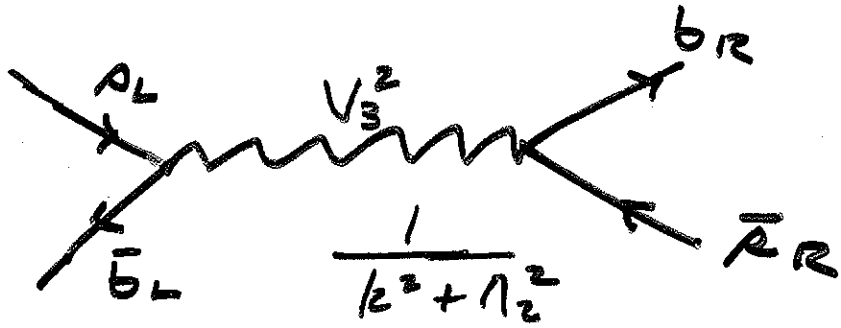
(4) Suppressed Dirac neutrino masses

(5) Larger Majorana M_R ($\rightarrow \sqrt{100}$ GeV) and a see-saw mechanism

<u>Not yet fully realistic</u>

MORE PHENOMENOLOGY

- Neutral Meson Systems



$$\Delta m_{B_d} \simeq 10^{-7}\ \text{MeV}$$
$$\Lambda_2 \simeq 100\,\text{TeV}$$

- (P)NGB's

$$U(1)_{q_L} \times U(1)_{u_R} \times U(1)_{d_R} \times U(1)_{l_L} \times U(1)_{e_R} \times U(1)_{\psi_R}$$

$$\longrightarrow U(1)_B + 5\ \text{NGB's}$$

- Dark Matter Candidates

1 Massive (ETC Inst's)
$\oplus$
1 Eaten by Z_0
$\oplus$
$\boxed{\text{3 Unacceptable NGB's}}$

EFFECTIVE THEORY BELOW Λ_{TC}

$\mathcal{L}_{EFF}$ = Standard Model Interactions (No Higgs)

+

Dimension-3 Mass Terms (Mass Matrices) for Quarks, Charged Leptons + neutrinos

+

Dimension-5 and higher operators - suppressed (Dipoles)

+

PNGB's

CP Violating Phases (Spontaneous)

Calculable in principle, Generically $O(1)$

K. Lane

(Vacuum Alignment)

STRONG CP PROBLEM

Quark Mass Terms

$$\mathcal{L} = \bar{u}_{Lj} M^{(u)}_{jk} u_{Rk} + h.c.$$
$$+ \bar{d}_{Lj} M^{(d)}_{jk} d_{Rk} + h.c$$

$$\boxed{\mathrm{Arg}\det M^{(u)} + \mathrm{Arg}\det M^{(d)} \leq 10^{-10}}$$

CHARGED LEPTON MASS MATRIX

- Mass Term

$$\mathcal{L}_{mass} = \bar{\ell}_{Lj} \, M^{(\ell)}_{jk} \, \ell_{Rk} + h.c.$$

- $\rightarrow$ Real Diagonal Form

$$U_L M^{(\ell)} U_R^{-1} = \begin{pmatrix} m_e & & \\ & m_\mu & \\ & & m_\tau \end{pmatrix}$$

$$\ell_L = U_L^{-1} \psi_L \qquad \ell_R = U_R^{-1} \psi_R$$

$$M = M^T \Rightarrow U_L = U_R^*$$

- ETC Estimate

$$\boxed{M^{(\ell)}_{jk} = \frac{8\pi \, \Lambda_{TC}^3 \, \Pi_{jk}}{3 \, \Lambda_j^2 \, \Lambda_k^2} \, \eta}$$

$$\Pi_{jk} = \text{mixing} < \min(\Lambda_j^2, \Lambda_k^2)$$

CHARGED LEPTON DIPOLE MATRIX

- Dimension-5 Dipole Term

$$\mathcal{L}_{dipole} = \bar{\ell}_{Lj}\, \tilde{D}_{jk}\, \sigma_{\mu\nu}\, \psi_{Rk}\, F^{\mu\nu}_{em} + h.c.$$

$$= \bar{\psi}\, D\, \sigma_{\mu\nu}\, \psi_R\, F^{\mu\nu}_{em} + h.c.$$

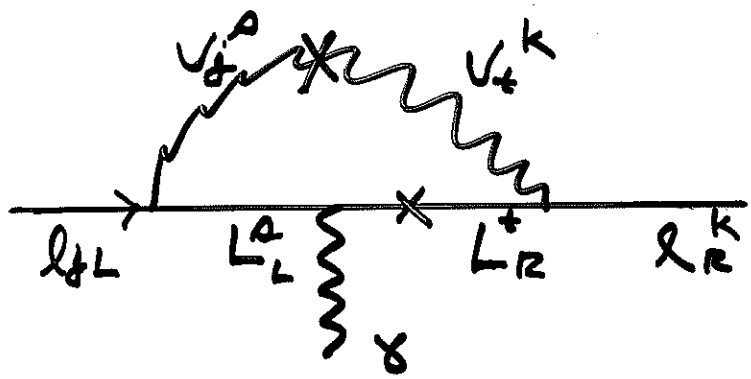
$$\boxed{D = U_L \tilde{D} U_R^{-1} = \text{complex non-diagonal}}$$

- $D = D_H + D_{AH}$

$$\mathcal{L}_{dipole} = \Big[\bar{\psi} \underset{\substack{\uparrow \\ \text{MDM}}}{D_H}\, \sigma_{\mu\nu}\, \psi + \bar{\psi} \underset{\substack{\uparrow \\ \text{EDM}}}{D_{AH}}\, \sigma_{\mu\nu}\, \gamma_5\, \psi\Big] F^{\mu\nu}_{em}$$

ESTIMATING $\tilde{D}$

- **ETC** graph



- Computation

Term $\sim 1/\Lambda^2$ vanishes

Result (from $k \sim \Lambda_{1,2,3}$):

$$\boxed{\tilde{D}_{jk} \simeq e\, M_{jk}^{(e)} / \Lambda_{jk}^2 \ll M_{jk}^{(e)}}$$

Cutoff Scale

Gen. of Gatnechi/ Marciano ph/0102122

$$\boxed{D = U_L \tilde{D} U_R = \text{complex non-diagonal}}$$

ELECTRON EDM

$$\boxed{\frac{d_e}{e} = \frac{-i}{e} D_{AH,11}}$$

In terms of lepton masses

$$\frac{D_{11}}{e} \simeq U_{L,1j} \left\{ \frac{\left[U_L^{-1} \begin{pmatrix} m_e & & \\ & m_\mu & \\ & & m_\tau \end{pmatrix} U_R \right]_{jk}}{\Lambda_{jk}^2} \right\} U^{-1}_{R,k1}$$

$$U_{L,\ell m} = e^{i\alpha_\ell^L} R(\theta_{23}) R(\theta_{13}) R(\theta_{12}) e^{i\beta_k^L}$$

Ratios of Λ_i's

Term proportional to m_τ / Λ_3^2
(small angles)

$$\frac{d_e}{e} \simeq \frac{m_\tau}{\Lambda_3^2} \theta_{13}^L \theta_{13}^R \, \mathrm{Im} \left\{ e^{i(\alpha_1 - \alpha_2)^L - (\alpha_1 - \alpha_3)^R} \right\}$$

+ other contributions

- Experimental bound

$$|d_e| < 1.6 \times 10^{-27} \text{ e-cm}$$

B. Regan et al
PRL 88, 071805 (2002)

$$\longrightarrow 10^{-30} \text{ e-cm}$$

Ongoing exp's
Dehmille
Kawall
Lamoreaux

- Generic (O(1)) phases $\Rightarrow$

$$|\theta_{13}^{L} \theta_{13}^{R}| \lesssim 10^{-6}$$

Natural?

OTHER CONSTRAINTS

- $\mu \to e\gamma$ (D_{21})

$$|\Theta_{13}^{L}\,\Theta_{23}^{R}| \lesssim 5\times 10^{-6}$$
$$|\Theta_{13}^{R}\,\Theta_{23}^{L}| \lesssim 5\times 10^{-6}$$

- Neutrino oscillations

Measured large mixing angles Θ_{23} + Θ_{12} due primarily to neutrino sector?

Large CP violation

- $\tau \to \mu\gamma$
  $\tau \to e\gamma$

- Muon $g-2$

$$\frac{a_\mu}{2m_\mu} \simeq \frac{m_\mu}{\Lambda_{22}} + \frac{m_\tau \,\mathrm{Re}\, F_{22,3}}{\Lambda_3^2}$$

$\Lambda_{22} = \Lambda_3 \to 10^{-9}$

SUMMARY

- ETC models with

  Ingredients for breaking → TC

  Generational hierarchy
  Intra-family splittings
  Flavor mixing
  Neutrino see-saw
  CP violation

- Features

  UV complete, All scales $\lesssim 1000$ TeV

  Not-yet-real-world mass matrices
  A few massless NGB's

- Needed

  New interactions at $E \gtrsim 1000$ TeV
  (Pati-Salam)

  More clever ETC models?

- CP Violation Lepton Sector

  Spontaneous, naturally $O(1)$

  Lepton mixing → electron EDM
  $\lesssim 1.6 \times 10^{-27}$ e-cm