Lattice 2019
武汉

TOWARDS COMPOSITE HIGGS & PARTIALLY COMPOSITE TOP QUARK

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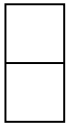
- The model: (Ferretti 1404.7137)
  - $\mathrm{SU}(4)$ gauge theory, quartet fermions and sextet fermions

COMPOSITE HIGGS

(Georgi & Kaplan 1984)

- $\mathrm{SU}(4)$ *hypercolor* gauge theory: new strong sector with scale $\Lambda_{\mathrm{HC}} \gg v$ ($5\ \mathrm{TeV}$ *vs* $246\ \mathrm{GeV}$)
- 5 Majorana fermions Q in sextet  rep $\Longrightarrow$ $\mathrm{SU}(5)$ global (chiral) symmetry
- Hypercolor theory breaks $\mathrm{SU}(5) \to \mathrm{SO}(5)$ (Peskin 1980)
  Goldstone bosons $\supset$ Higgs multiplet, so $m_h = 0$ and in fact $V(h) = 0$: *Goldstone Higgs* protected from Λ_{HC}
  [also $\mathrm{SO}(5) \supset \mathrm{SU}(2)_L \times \mathrm{U}(1)$ and $\mathrm{SU}(2)$ custodial symmetry]
- Couple to gauge bosons/fermions of SM, generate

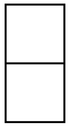
$$V_{\mathrm{eff}}(h) = -\alpha \cos^2(h/f) - \beta \sin^2(2h/f)$$

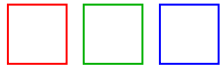
If $4\beta > \alpha$ then $h = 0$ is unstable $\Longrightarrow$ Higgs breaking of SM $\Longrightarrow$ mass for W, Z, H

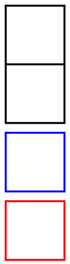
1st term ($+$ curvature): $\alpha = \frac{1}{2}(3g^2 + g'^2)C_{LR} +$ top loops*

2nd term ($-$ curvature): $\beta =$ top loops*

HYPERBARYONS for the TOP QUARK PARTNER (Kaplan 1991)

All HC singlets made of Q's  in SU(4) will be bosons (mesons, *diquarks*, etc.)

So add fund rep fermions q to the hypercolor theory. Give them 3 colors: 

Then Qqq  is a colored, fermionic hyperbaryon, ready to mix with the top quark.

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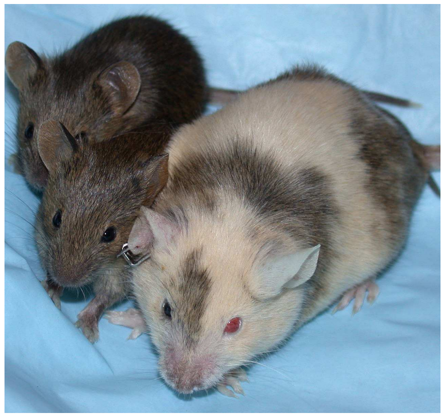
It's a CHIMERA:



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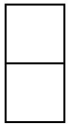
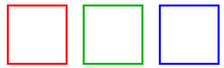
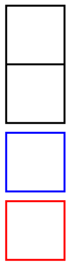
All HC singlets made of Q's  in SU(4) will be bosons (mesons, *diquarks*, etc.)

So add fund rep fermions q to the hypercolor theory. Give them 3 colors: 

Then Qqq  is a colored, fermionic hyperbaryon, ready to mix with the top quark.

MIXING with the top quark:

- Assume extended gauge sector at $\Lambda_{\rm EHC} \gg \Lambda_{\rm HC}$ to generate 4-fermion interaction $tQqq$

  — mix t quark with chimera, generate t mass via seesaw.

THE simplified LATTICE THEORY:

- SU(4) gauge theory
  $2\times$ sextet fermions Q (not 2.5)
  $2\times$ quartet fermions q (not 3)
- Wilson–clover fermions, nHYP smeared links, NDS gauge action

OLD RESULTS:

- $\bar{Q}Q$ & $\bar{q}q$ meson masses, 0^- and 1^-; decay constants
- q^4 & Q^6 baryons and Qqq chimera baryons
- scale t_0 from gradient flow $\Longrightarrow$ lattice spacing in physical units
- Fits to 2-rep χPT for chiral & continuum limits

NEW RESULTS:

- Matrix element for top mixing (TACO 1812.02727)
- C_{LR} — part of the Higgs potential (the gauge loop) (TACO 1903.02535)

MIXING WITH THE TOP QUARK

4-fermion interaction in the HC theory

$$V^{\rm HC}_{\rm top} = G_R \bar{t}_L B_R + G_L \bar{t}_R B_L + {\rm h.c.} \quad — \quad t \equiv \text{top quark}, B \equiv Qqq$$

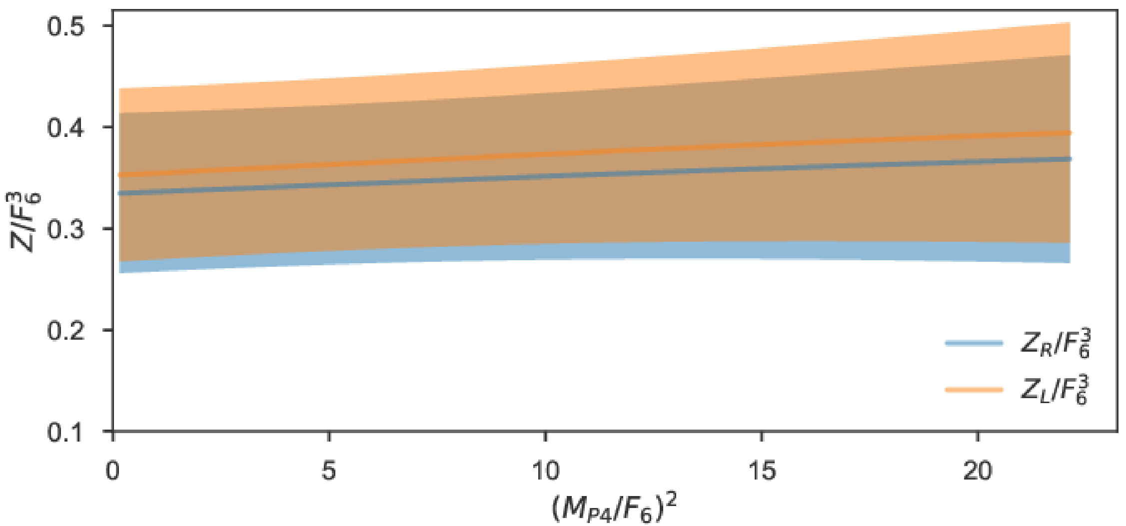
where $G_{L,R} \sim g^2_{\rm EHC}/\Lambda^2_{\rm EHC}$. Then $t \leftrightarrow B$ mixing $\Longrightarrow$

$$m_t \approx G_L G_R \frac{Z_L Z_R}{M_B} \frac{v}{F_6} \qquad (= y_t v)$$

where $Z_{L,R}$ are matrix elements (*cf. proton decay in QCD*)

$$\langle 0 \left| (Qqq)^\alpha_{L,R} \right| \text{Chimera} \rangle = Z_{L,R}\, u^\alpha$$

- F_6 is the scale (cf. Λ_{HC})
- Sextet chiral limit $m_6 \to 0$ (for Goldstone Higgs)
- continuum $a \to 0$
- m_4 is free parameter (alias meson mass M_{P4})



MIXING WITH THE TOP QUARK

Recap:

$$m_t \approx G_L G_R \frac{Z_L Z_R}{M_B} \frac{v}{F_6} \qquad (= y_t v)$$

$$G_{L,R} \sim g_{\rm EHC}^2 / \Lambda_{\rm EHC}^2$$

Result: $Z_L \simeq Z_R \equiv Z$ and

$Z/F_6^3 \simeq 0.35(8)$ Cf. QCD: $Z/f_\pi^3 \simeq 7$ — a factor of 20!

Rearrange:

$$y_t \approx \left(\frac{g_{\rm EHC} F_6}{\Lambda_{\rm EHC}}\right)^4 \left(\frac{Z}{F_6^3}\right)^2 \frac{F_6}{M_B} \simeq 0.01 \left(\frac{g_{\rm EHC} F_6}{\Lambda_{\rm EHC}}\right)^4$$

But $y_t \simeq 1$ and certainly $g_{\rm EHC} < 1$, so

$$\frac{F_6}{\Lambda_{\rm EHC}} \gtrsim 3$$

contradicting $\Lambda_{\rm EHC} \gg F_6$. BAD.

($\Longrightarrow$ large 4-fermi interactions at Λ_{HC}, etc.)

*** A *general problem*: Even if Z/F_6^3 comes out large, it's hard to push $\Lambda_{\rm EHC}$ very far.

Required: an enhancement (that recalls WALKING TECHNICOLOR).

Again

$$y_t \approx G_L G_R \frac{Z_L Z_R}{M_B} \frac{1}{F_6} \quad ,$$

$$G_{L,R} \sim g_{\rm EHC}^2/\Lambda_{\rm EHC}^2 \quad .$$

and we need a large $G_{L,R}$ — but at the $\rm HC$ scale where Z is measured:

$$G(\Lambda_{\rm HC}) = G(\Lambda_{\rm EHC}) \exp\left(- \int_{\Lambda_{\rm HC}}^{\Lambda_{\rm EHC}} \gamma_B(g_{\rm HC}(\mu)) \frac{d\mu}{\mu} \right)$$

where γ_B is the anomalous dimension of Qqq. This can be much bigger if γ_B is large (and < 0).

Is it?

Not in this theory — which resembles QCD (dynamically speaking).

[*NOTE*

1. The t mixes with B but also with excited states with same quantum numbers. The complete calculation is

$$\int d^4x \, \langle 0|B(x)\bar{B}(0)|0\rangle$$

— requires chiral valence fermions for the propagator. (We saturate the propagator with simple $|B\rangle\langle B|$.)

2. We calculated Z factors for 2 independent operators. There is one more.

** NO orders of magnitude will emerge from the complete treatment.]

WHAT HAPPENS IN OTHER MODELS?

Look for models with large γ_B AND large Z —

- E.g., add quartet flavors $\Longrightarrow$ approach conformality.
- Or . . . other models entirely (Franzosi & Ferretti 1905.08273)
  - e.g., $\mathrm{Sp}(4)$ gauge theory $\Longrightarrow$ $\mathrm{SU}(4)/\mathrm{Sp}(4)$ composite Higgs *and* top partner

    (E. Bennett, *et al.* 1712.04220 *et seq.*; Jong-Wan Lee, previous talk)

C_{LR}: THE GAUGE CONTRIBUTION IN THE COMPOSITE HIGGS POTENTIAL

$$C_{LR} = \int_0^\infty dq^2 q^2 \, \Pi_{LR}(q^2)$$

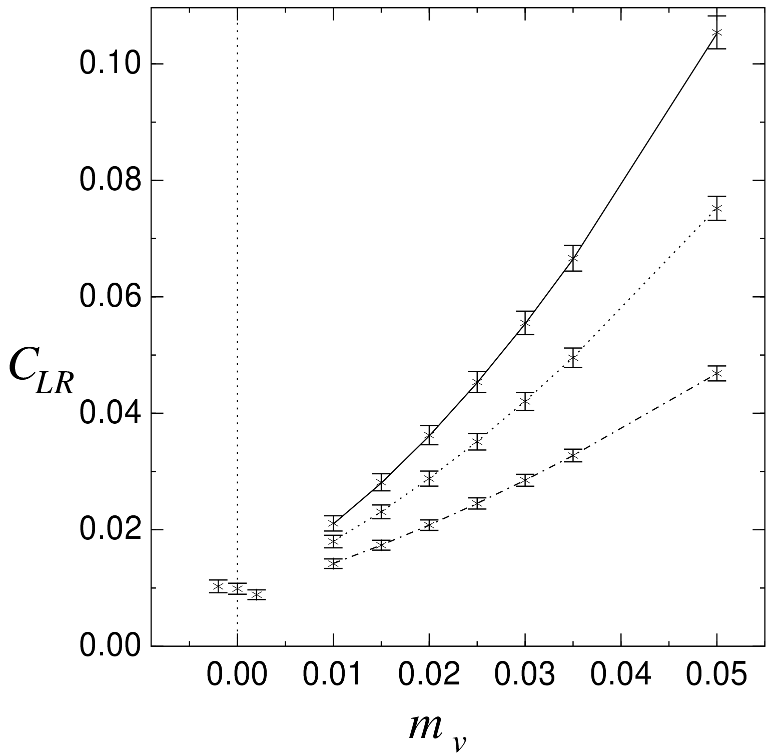
where

$$(q^2 \delta_{\mu\nu} - q_\mu q_\nu)\, \Pi_{LR}(q^2) = -\int d^4x \, e^{iqx} \, \langle J^L_\mu(x) J^R_\nu(0) \rangle \qquad \text{(current of } \mathbf{6} \text{ fermions)}$$

LATTICE:

Same ensembles $+$ smeared staggered valence fermions
(chiral symmetry needed to cancel UV divergence in $C_{LR}(m_v)$ at $m_v = 0$)

Single ensemble, 3 cutoffs:



CHIRAL & CONTINUUM LIMIT

m_6, $a \to 0$ [no discernible dependence on m_4]

RESULT:

$$\frac{C_{LR}}{F_6^4} = 29(8)(5)$$

Cf. QCD:

$$m_{\pi^\pm}^2 - m_{\pi^0}^2 = \frac{3\alpha}{4\pi}\frac{C_{LR}}{f_\pi^2} \quad \Longrightarrow \quad \frac{C_{LR}}{f_\pi^4} \approx 42$$

(Das, Guralnik, Mathur, Low, and Young 1967)

— not too different.

SUMMARY

1. Top quark mixing: Too small! Doesn't work!
2. Gauge loop $C_{LR} = \int_0^\infty dq^2 q^2 \, \Pi_{LR}(q^2) \Longrightarrow$ a piece of the Higgs potential. No surprises.

FUTURE

- Lots more models. Look for larger Z and/or large γ_B.
- Also need t loop coefficient $C_{\rm top}$ for the Higgs potential.