New strong dynamics beyond the standard model

Lecture 3 16 November 2017

Last time

- Light composite Higgs + heavy resonances $\Longrightarrow$ try to make Higgs a PNGB
- Conjecture strong symmetry breaking $\mathcal{G} \to \mathcal{H} \supseteq \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ at scale f
  with Higgs bidoublet $(2,2)$ among the NGBs in the coset $\mathcal{G}/\mathcal{H}$
- 'Minimal' $\mathrm{SO}(5) \to \mathrm{SO}(4)$ example of CCWZ construction $\longrightarrow v = f \sin\left(\frac{\langle h \rangle}{f}\right)$
- Recover SM in decoupling limit $f \to \infty$
  Deviations from SM vanish when $\xi = \frac{v^2}{f^2} = \sin^2\left(\frac{\langle h \rangle}{f}\right) \to 0$
- $\mathcal{G}$ explicitly (but weakly) broken by gauging electroweak $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$
  $\longrightarrow$ radiative PNGB Higgs potential $\overset{?}{\longrightarrow}$ correct EWSB vev, mass, interactions?
- Coleman–Weinberg Higgs potential $V(h) \simeq c_V \sin^2\left(\frac{h}{f}\right)$ $\qquad c_V \propto \int dQ^2\, \Pi_{U-B}(Q^2)$
  Witten's inequality: $c_V > 0 \Longrightarrow$ vev $\langle h \rangle = 0$, no EWSB
  If $c_V < 0$, minimizing potential gives $\xi = 1$ (i.e., $v = f$), experimentally ruled out

True Minimal (custodial) Composite Higgs model

- Most current work uses fermion–Higgs couplings (especially top quark)
  to generate viable EWSB potential with $\langle h \rangle \neq 0$ and $\xi \ll 1$
  (Until ~2003 the usual approach was to gauge $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathcal{G}_A \not\subseteq \mathcal{H}$)
- Quarks have QCD color and non-half-integer hypercharges $\Longrightarrow Y \neq T_R^3$
  $\Longrightarrow$ Need to extend model to $\mathcal{G} = \mathrm{SU}(3)_c \times \mathrm{SO}(5) \times \mathrm{U}(1)_X$
  breaking to $\mathcal{H} = \mathrm{SU}(3)_c \times \mathrm{SO}(4) \times \mathrm{U}(1)_X$, with $Y = T_R^3 + X$
- Previous work unaffected since Higgs, W and Z are color singlets with $X = 0$

Partial compositeness

(proposed 1991, rediscovered ~2002)

- Conjecture **linear mixing** between elementary fermions q_e and composite operators $\mathcal{O}_q$ arising from the new strong dynamics,
$$\mathcal{L} \supset \lambda_{q_L} \overline{q}_{eL} \mathcal{O}_q^L + \lambda_{q_R} \overline{q}_{eR} \mathcal{O}_q^R + \text{h.c.}$$
- To mix, $\mathcal{O}_q$ must have same quantum numbers as $q_e \longrightarrow$ **top partners**, etc.
- Mixing between elementary q_e and composite $\mathcal{O}_q$ produces "partially composite" physical mass eigenstates (observed q and heavier partner Q)
$$|\text{Observed } q\rangle = \cos\theta_q \,|\text{Elem. } q_e\rangle + \sin\theta_q \,|\text{Comp. } \mathcal{O}_q\rangle \qquad \sin\theta_q = \frac{\lambda_q}{\sqrt{g_*^2 + \lambda_q^2}}$$
$$|\text{Partner } Q\rangle = -\sin\theta_q \,|\text{Elem. } q_e\rangle + \cos\theta_q \,|\text{Comp. } \mathcal{O}_q\rangle$$
Yukawa coupling $y_q \simeq g_* \sin\theta_{q_L} \sin\theta_{q_R} = \frac{g_* \lambda_{q_L} \lambda_{q_R}}{\sqrt{g_*^2+\lambda_{q_L}^2}\sqrt{g_*^2+\lambda_{q_R}^2}}$
heavier quark $\longleftrightarrow$ more composite $\longrightarrow$ potentially lighter partner Q
(Note added: This is a qualitative illustration, which needs more care [cf. hep-ph/0612180] to demonstrate decoupling into light $m \sim [y + \mathcal{O}(\sqrt{\xi})]v$ and heavy $M \sim 4\pi f$)
- $\mathcal{O}_q$ must transform in complete rep(s) of $\mathcal{G}$
Elementary fermions q_e transform only in reps of $\text{SU}(2)_L \times \text{U}(1)_Y \subseteq \mathcal{H}$
$\Longrightarrow$ Another explicit breaking of $\mathcal{G}$, but now details depend on rep of $\mathcal{O}_q$

EWSB from partial compositeness

- Generic one-loop Coleman–Weinberg potential from (t_L, b_L) and t_R is
$$V(h) \simeq a\cos(h/f) + c_t \sin^2(h/f) + b\sin^4(h/f)$$
Still periodic in h/f as demanded by vacuum misalignment picture ✓
- Coefficients from model-dependent, analytically incalculable strong dynamics
Expect $|a| \sim |c_t| \sim |b|$, and their signs are not constrained by Witten's inequality
Parametrically proportional to $\lambda^2 \sim$ Yukawa coupling (so ignore lighter fermions) while gauge contribution $c_V \sim \alpha_2$ (so ignore that too, recalling $\alpha_2 \approx 0.03$)
- Two SO(5) $\to$ SO(4) examples that can be tuned to obtain $\xi \ll 1$:

MCHM$_5$ Fundamental rep: $\mathcal{O}_t = \mathbf{5}_{2/3} \longrightarrow \mathbf{2}_{7/6} + \mathbf{2}_{1/6} + \mathbf{1}_{2/3} = \mathbf{2}_{7/6} + Q_L + T_R$
$\mathcal{O}_b = \mathbf{5}_{-1/3} \longrightarrow \mathbf{2}_{-5/6} + \mathbf{2}_{1/6} + \mathbf{1}_{-1/3} = \mathbf{2}_{-5/6} + Q_L + B_R$
$a = 0$ and the potential is minimized at $\xi = \sin^2(\langle h\rangle/f) = -\dfrac{c_t}{2b} \geq 0$

MCHM$_4$ Spinorial rep: $\mathbf{4}_{1/6} \longrightarrow \mathbf{2}_{1/6} + \mathbf{1}_{2/3} + \mathbf{1}_{-1/3} = Q_L + T_R + B_R$
$b = 0$ and the minimum at $\cos(\langle h\rangle/f) = \dfrac{a}{2c_t} \Longrightarrow \xi = 1 - \left(\dfrac{a}{2c_t}\right)^2$

Also have $a = 0$ for adjoint (**10**) and two-index-symmetric traceless (**14**) reps

Higgs mass from partial compositeness

- For all SO(5)/SO(4) models, expanding around vev gives Higgs mass

$$M_H^2 \simeq \frac{3}{4\pi^2} y_t^2 M_T^2 \xi = \frac{3}{4\pi^2} m_t^2 \left(\frac{M_T}{f}\right)^2$$

  Roughly one-loop suppression ($\times \frac{1}{16\pi^2}$) of lightest (top) partner mass M_T^2,
  with y_t^2 the main source of $\mathcal{G}$ breaking and ξ from tuning coefficients of $V(h)$

- $M_T \propto f \Longrightarrow$ decoupling as expected

- Relatively light $M_T \lesssim 2.6f$ preferred (robust result despite approximations)

Revisit flavor problem from first lecture

- Rewrite $\mathcal{L} \supset \frac{y_q}{\Lambda_F^2} \overline{q}_L q_R \overline{Q}_R Q_L \longrightarrow \frac{y_q}{\Lambda_F^{d_S-1}} \overline{q}_L q_R \mathcal{O}_S + \text{h.c.}$ with $d_S \equiv [\mathcal{O}_S] = 3 - \gamma_S$
  Experiments prefer high flavor scale(s) $\Lambda_F \gg$ TeV, possibly $\Lambda_F \sim 10^{13}$ GeV

- The strong dynamics produce the **anomalous dimension** $\gamma_S(\mu) = -\frac{1}{\mathcal{O}_S(\mu)} \frac{d\mathcal{O}_S(\mu)}{d\log\mu}$
  Like β function, γ_S depends on both scale and renormalization scheme

- Approximating $\gamma_S \simeq$ const. for TeV $\lesssim \mu \lesssim \Lambda_F$ (i.e., near-conformality),
  we expect $m_q = y_q v \simeq v \left(\frac{\text{TeV}}{\Lambda_F}\right)^{d_S-1}$
  Experiments $\longrightarrow$ high scale $\Lambda_F \gg$ TeV $\longrightarrow$ quark mass too small $\longrightarrow$ problem

- Smaller $d_S \longleftrightarrow$ larger γ_S helps enhance quark mass (PRL **57**:957, 1987)
  Unitarity bound sets minimum $d_S > 1$ (maximum $\gamma_S < 2$) (Mack, 1975)
  but $d_S = 1 + \epsilon \Longrightarrow [\mathcal{O}_S \mathcal{O}_S] \simeq 2 + \mathcal{O}(\epsilon) \longrightarrow$ same naturalness problem as SM!
  (Note added: This **factorization** $[\mathcal{O}_A \mathcal{O}_B] \approx [\mathcal{O}_A] + [\mathcal{O}_B]$ is based on the large-N limit)

- Best balance seems to be $d_S \approx 2$ ($\gamma_S \approx 1$) so that $[\mathcal{O}_S \mathcal{O}_S] \simeq 4$
  Need different Λ_F for each generation ($\Lambda_1 \simeq 1000$ TeV, $\Lambda_2 \simeq 100$ TeV, $\Lambda_3 \simeq 4$ TeV)
  still some tension with experimental constraints

Flavor physics from partial compositeness

- Simplify by considering "$L = R$" $\longrightarrow \mathcal{L} \supset \frac{\lambda_q}{\Lambda_F^{d_q-5/2}} \overline{q}\mathcal{O}_q + \text{h.c.}$ with $d_q \equiv [\mathcal{O}_q]$
- This contribution to the mass is $m_q \simeq \lambda_q^2 v \simeq v \left(\frac{\text{TeV}}{\Lambda_F}\right)^{2d_q-5}$
- Now it's possible to decouple m_q from Λ_F via $d_q \simeq \frac{5}{2}$
  Safely above the unitarity bound $d_q > \frac{3}{2}$, with $[\mathcal{O}_q\mathcal{O}_q] \simeq 2d_q \simeq 5$ safely irrelevant
- Example: With a single flavor scale $\Lambda_F = 10^{13}$ GeV,

$$m_b \approx 4 \text{ GeV} \Longrightarrow d_b \approx 2.59 \qquad m_{u/d} \approx 4 \text{ MeV} \Longrightarrow d_{u/d} \approx 2.73$$

- Supplement: Can even have $d_q < \frac{5}{2}$ (e.g., for the top quark)
  Then no longer have factor of $\left(\frac{\text{TeV}}{\Lambda_F}\right)^{2d_q-5}$
  Instead $\frac{1}{\lambda_q}\frac{d\lambda_q}{d\log\mu} = -\left(\frac{5}{2} - d_q\right) + \frac{C}{16}\lambda_q^2 + \ldots$ with $C > 0$
  $\Longrightarrow \lambda_q$ can flow to IR fixed point, giving Λ_F-independent $m_q \simeq \lambda_q^2 v \simeq \frac{16}{C}\left(\frac{5}{2} - d_q\right) v$

"Minimal" UV completions

- As for QCD, want to understand the dynamics breaking $\mathcal{G} \to \mathcal{H}$
  Can help guide explorations of models and access energies $\gtrsim \Lambda_{\mathcal{G}\to\mathcal{H}} \simeq 4\pi f$
- SO(5)/SO(4) "minimal" models have no obvious (four-dim'l) UV completion
  (arXiv:1311.6562, arXiv:1312.5664, arXiv:1710.11206 attempt to construct possibilities)
- For F Dirac fermions ($\sim 2F$ Weyl fermions) expect (Peskin; Preskill; both 1980)

Complex:	$\text{SU}(F) \times \text{SU}(F) \to \text{SU}(F)$	with $F^2 - 1$ NGBs
Real:	$\text{SU}(2F) \to \text{SO}(2F)$	with $F(F+1)/2 - 1$ NGBs
Pseudoreal:	$\text{SU}(2F) \to \text{Sp}(2F)$	with $F(F-1)/2 - 1$ NGBs

  (Recall pseudoreal rep has $T_a^* = -U^{-1}T_aU$ for unitary trans. $U \neq \mathbb{I}$ — $U = \sigma_2$ for SU(2) fund.)

- Requiring Higgs bidoublet, corresponding "minimal" UV completions are
  1. $\text{SU}(N)$ gauge theory with $N \geq 3$ and $F = 4$ in fundamental rep
     Gives $[\text{SU}(4)]^2 \to \text{SU}(4)$ with 15 NGBs $\longrightarrow (3,1) + (1,3) + 2\times(2,2) + (1,1)$
  2. SU(4) gauge theory with $F = 2.5$ (5 Weyl) in 2-index-antisymmetric (AS2) rep
     Gives $\text{SU}(5) \to \text{SO}(5)$ with 14 NGBs $\longrightarrow (3,3) + (2,2) + (1,1)$
  3. SU(2) gauge theory with $F = 2$ in fundamental rep
     Gives $\text{SU}(4) \to \text{Sp}(4) \sim \text{SO}(6) \to \text{SO}(5)$ with 5 NGBs $\longrightarrow (2,2) + (1,1)$

  Widely studied cosets — composite 2HDM; Georgi–Kaplan coset; Next-to-MCHM
  ($\mathcal{H} = \text{SU}(3) \not\supseteq \text{SU}(2)_L \times \text{SU}(2)_R$, while $\text{SU}(4) \to \text{SO}(4)$ has all 9 NGBs in $(3,3)$ rep)

A partially composite UV completion

- Now also need ≥ 3 **fermionic** top parters $\mathcal{O}_t^a$ (one for each QCD 'color')
  Want small canonical dim. to enable $d_q \approx 5/2$ without huge anomalous dim.
  Best $\mathcal{O}_t$ is "baryon" of new strong SU(3) gauge group with fund.-rep fermions
  ($\mathcal{O} \sim \phi\psi$ needs susy to be natural; $\mathcal{O} \sim \sigma_{\mu\nu}\psi^A G^A_{\mu\nu}$ not asymptotically free for $F \geq 3$)

- Similarly requiring a weak doublet and a custodial doublet $\Longrightarrow F = 7$:

	$\mathrm{SU}(3)_{\mathrm{strong}}$	$\mathrm{SU}(3)_{\mathrm{QCD}}$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$
T	**3**	**3**	**1**	a
D	**3**	**1**	**2**	$\frac{1}{3} - \frac{1}{2}a$
S	**3**	**1**	**1**	$-\frac{1}{6} - \frac{1}{2}a$
C	**3**	**1**	**1**	$\frac{5}{6} - \frac{1}{2}a$

Table 1: Field content of the UV completion proposed by arXiv:1506.00623

$$Q_L \sim TDS \qquad T_R \sim TDD + TSC \qquad B_R \sim TSS$$

Appropriate hypercharge parameter 'a' avoids proton decay (many possible values)

- Family index on one of $\{T, D, S, C\}$ for other generations $\longrightarrow F = \{13, 11, 9, 9\}$
  Partially composite leptons imply either two more flavors or separate $\mathrm{SU}(3)'_{\mathrm{strong}}$

- At least $[\mathrm{SU}(7)]^2 \to \mathrm{SU}(7) \supset \mathrm{SU}(3)_{\mathrm{QCD}} \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_X$ with 48 NGBs

$$(8,1,1) + (3,2,1) + (\overline{3},2,1) + (3,1,2) + (\overline{3},1,2) + (1,3,1) + (1,1,3) + 2\times(1,2,2) + 2\times(1,1,1)$$

  Recover $[\mathrm{SU}(4)]^2 \to \mathrm{SU}(4)$ C2HDM if colored PNGBs heavier than others

Multi-rep partially composite UV completions

- To my knowledge, all other existing proposals have separate cosets for QCD & EW, which result from fermions ψ and χ in different reps of the new strong gauge group

- Example: Gauge group SU(4) with 5 Weyl ψ in AS2 rep and $F = 3$ χ in fund. rep
  The ψ give $\mathcal{G}_{\mathrm{EW}} = \mathrm{SU}(5) \times \mathrm{U}(1)_X \to \mathcal{H}_{\mathrm{EW}} = \mathrm{SO}(5) \times \mathrm{U}(1)_X$
  The χ give $\mathcal{G}_c = \mathrm{SU}(3) \times \mathrm{SU}(3) \times \mathrm{U}(1)' \to \mathcal{H}_c = \mathrm{SU}(3)_{\mathrm{QCD}} \times \mathrm{U}(1)'$
  Overall $\mathcal{G}_{\mathrm{EW}} \times \mathcal{G}_c \to \mathcal{H}_{\mathrm{EW}} \times \mathcal{H}_c$ with $14 + 8 = 22$ NGBs,

$$(8,1,1) + (1,3,3) + (1,2,2) + (1,1,1)$$

- The top partners Q_L and T_R are SU(4) "chimera baryons" $\sim \epsilon_{abcd}\chi_a\psi_{bc}\chi_d$
  QCD color comes from χ; EW comes from ψ
  (single-rep SU(4) 'baryons' are bosonic, $\sim \epsilon_{abcd}\psi_{ab}\psi_{cd}$ and $\sim \epsilon_{abcd}\chi_a\chi_b\chi_c\chi_d$)