New strong dynamics beyond the standard model

Lecture 1 2 November 2017

Course overview

- **Logistics:** 3 Thurs. lectures (2, 9, 16 Nov.), 5 Tues. (21, 28 Nov., 5, 12, 19 Dec.)
- **Main goal:** Introduction to large and evolving literature
  $\Longrightarrow$ Focus on big-picture context and concepts (few detailed calcs, limited rigor)
- **Background** exposure to quantum field theory & standard model useful,
  but should be able to take away main qualitative points & fill in details later
- (Flexible) **Plan:**
  1. "Behind the SM": Composite Higgs (5 lectures)
     —Context / Motivation
     —Representative model(s) via CCWZ construction
     —Partial compositeness and flavor physics
     —UV completions
     —Phenomenology (direct searches, indirect effects, probably not flavor)
     —Probably not holography
     —Lattice gauge theory basics and applications to composite Higgs
  2. "Beyond the SM": Composite dark matter (3 lectures)
     —Context / Motivation
     —Representative model(s)
     —Phenomenology (direct & indirect detection, collider searches)
     —Lattice gauge theory applications to composite dark matter

Resources

- **Web site:** `http://www.davidschaich.net/teaching/1718F_BSM/`
- **Reviews:**
  —Panico & Wulzer, *The Composite Nambu–Goldstone Higgs*, arXiv:1506.01961
  —Contino, *The Higgs as a Composite Nambu–Goldstone Boson*, arXiv:1005.4269
  —DeGrand, *Lattice tests of beyond Standard Model dynamics*, arXiv:1510.05018
  —Csaki, Grojean & Terning, *Alternatives to an Elementary Higgs*, arXiv:1512.00468
  (—Hill & Simmons, *Strong Dynamics and Electroweak Symmetry Breaking*, hep-ph/0203079)
  —Kribs & Neil, *Review of strongly-coupled composite dark matter…*, arXiv:1604.04627
  —Tulin & Yu, *Dark Matter Self-interactions and Small Scale Structure*, arXiv:1705.02358

Context: Standard Model as Effective Field Theory (EFT)

- The SM is an EFT, valid only up to some high-energy (UV) scale Λ_{SM}
  Expect $\Lambda_{SM} \lesssim M_{Pl} \equiv \sqrt{\frac{\hbar c}{G}} \simeq 10^{19}$ GeV where quantum gravity becomes strong
  Can have lower scale(s) for flavor, neutrino masses... or EW symmetry breaking

- For $E < \Lambda_{SM}$ fields are quarks, leptons, gauge bosons and elementary Higgs

- **EFT:** Lagrangian has all operators consistent with symmetries,
  with UV scale(s) providing the correct dimensionality $[\mathcal{L}] = 4$
  $$\mathcal{L} = \mathcal{L}_{SM} + \frac{c_i}{\Lambda_i}\mathcal{L}_5 + \frac{c_i}{\Lambda_i^2}\mathcal{L}_6 + \ldots$$
  Expect all c_i to be $\mathcal{O}(1)$ numbers, with $\Lambda_i \geq \Lambda_{SM}$

- Large Λ_{SM} suppresses higher-dimensional operators
  $\longrightarrow$ 'accidental' symmetries that can explain many SM phenomenological successes

- **Dim-5:** Schematically $\mathcal{L}_5 \sim \left(\overline{L} i\sigma_2 H\right)\left(H^\dagger i\sigma_2 L\right) \longrightarrow$ Majorana neutrino masses
  Here $H(x) = \frac{1}{\sqrt{2}} \exp\left[i\sigma_a \phi^a(x)/v\right] \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$ with $v = 246$ GeV, so $L_i = \begin{pmatrix} \nu_i \\ \ell_i^- \end{pmatrix}$
  $\Longrightarrow m_\nu \simeq \frac{v^2}{\Lambda_\nu}$ or $\Lambda_\nu \simeq \frac{v^2}{m_\nu} \simeq \frac{246^2}{10^{-10}}$ GeV $\simeq 10^{14}$ GeV for $m_\nu \simeq 0.1$ eV

- **Dimension-6** $\mathcal{L}_6$ has $\sim$80 operators (some redundant)
  Some contribute to proton decay; experimental bounds satisfied by $\Lambda_{\not{p}} \gtrsim 10^{16}$ GeV

BSM motivation from naturalness

- **Higgs sector:** $\mathcal{L}_{SM} \supset \mathcal{L}_H = \left(D_\mu H\right)^\dagger D^\mu H - V(H^\dagger H)$ with (all indices traced)
  $$D_\mu H = \left(\mathbb{I}\partial_\mu - ig_2 \frac{\sigma_a}{2} W_\mu^a - ig_1 \frac{\mathbb{I}}{2} B_\mu\right) H \qquad (1)$$
  $$V(H^\dagger H) = c_2 \Lambda_{SM}^2 H^\dagger H + c_4 \Lambda_{SM}^0 \left(H^\dagger H\right)^2 = -\mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2$$
  Minimum at $H^\dagger H = \mu^2/(2\lambda) = v^2/2$ with $\mu^2 = m_h^2/2 \approx (88\text{ GeV})^2$ and $\lambda \approx 0.13$
  $\longrightarrow$ Kinetic term produces masses $M_W = \frac{1}{2} g_2 v$ and $M_Z = \frac{M_W}{\cos\theta_W} = M_W \frac{\sqrt{g_2^2 + g_1^2}}{g_2}$
  ($M_W \approx 80$ GeV, $M_Z \approx 91$ GeV $\longrightarrow g_2 \approx 0.65$, $g_1 \approx 0.34$, $\cos\theta_W \approx 0.88$)

- **Dimensional analysis:** Expect $c_2 \simeq \mathcal{O}(1) \Longrightarrow \Lambda_{SM} \simeq 0.1$–$1$ TeV

- High $\Lambda_{SM} \gtrsim 10^{13}$ GeV as motivated above $\Longrightarrow c_2 \simeq \left(\frac{10^2}{\Lambda_{SM}}\right)^2 \lesssim 10^{-22}$
  "**unnatural**" breakdown of dimensional analysis

- Experiments currently constrain $\Lambda_{SM} \gtrsim 1$–10 TeV $\longrightarrow c_2 \lesssim 10^{-2}$–$10^{-4}$
  This "little hierarchy" could result from symmetry or from chance

New strong dynamics motivation

- EFT / Naturalness motivates new Higgs physics around TeV scale
  Why might such new physics be strongly coupled?
  1. All non-Higgs scalars arise via gauge–fermion dynamics (e.g., σ meson)
  2. Strong gauge–fermion dynamics can generate a scale
     Example: QCD chiral symmetry breaking scale $f \approx 86$ MeV (in massless limit)
     Typical scale of non-chiral QCD dynamics is $\Lambda_{QCD} \simeq 4\pi f \approx 1$ GeV
  3. This **dynamical scale** can be naturally suppressed compared to M_{Pl}
- **Dimensional transmutation:** Asymptotic freedom $g_s^2(\Lambda_{UV}) \to 0$ as $\Lambda_{UV} \to \infty$
  leads to exponentially separated scales $\Lambda_{IR} \ll \Lambda_{UV}$ hierarchy between
  Follows from small β function (near conformality) in UV

  $$\beta(g_s^2) \equiv \frac{d}{d\log\mu^2} g_s^2(\mu^2) = -\frac{b_1}{16\pi^2} g_s^4(\mu^2) - \mathcal{O}\left(g_s^6\right) \qquad b_1 = \frac{11}{3} C_2(G) - \frac{4}{3} N_F T(R)$$

  for gauge group G with N_F fermions transforming in representation R
  Both g_s and β function depend on scale and renormalization scheme
- Convenient to consider inverse coupling: $\displaystyle \frac{d}{d\log\mu^2}\frac{1}{g_s^2(\mu^2)} = -\frac{1}{g_s^4(\mu^2)}\beta(g_s^2) \simeq \frac{b_1}{16\pi^2}$
  Integrate down from high scale Λ_{UV},
  neglecting higher-order terms thanks to near conformality:

  $$\int_{\Lambda_{UV}}^{\Lambda_{IR}} d\frac{1}{g_s^2(\mu^2)} = \frac{b_1}{16\pi^2}\int_{\Lambda_{UV}}^{\Lambda_{IR}} d\log\mu^2 \Longrightarrow \frac{1}{g_s^2(\Lambda_{IR})} - \frac{1}{g_s^2(\Lambda_{UV})} = \frac{b_1}{8\pi^2}\log\left(\frac{\Lambda_{IR}}{\Lambda_{UV}}\right)$$

  Strong coupling $\displaystyle \frac{1}{g_s^2(\Lambda_{IR})} \simeq 0 \Longrightarrow \Lambda_{IR} \simeq \Lambda_{UV}\exp\left[-\frac{8\pi^2}{b_1 g_s^2(\Lambda_{UV})}\right]$
- Plug in $\Lambda_{UV} = M_Z \approx 90$ GeV, five-flavor $b_1 = \frac{23}{3}$
  and $\overline{\text{MS}}$-scheme $g_s(M_Z) \approx 1.22$ corresponding to $\alpha_s = \frac{g_s^2}{4\pi^2} \approx 0.12$
  Gives rough prediction $\Lambda_{QCD} \simeq 0.1$ GeV, right order of magnitude
  Exponential hierarchy: Three orders of magnitude scale separation
  results naturally from near-conformality

The meaning of "strong"

- "Weak coupling" means fields in lagrangian are in one-to-one correspondence
  with asymptotically non-interacting states in the S-matrix
- For strong coupling the connection is more complicated
- For QCD we know the strongly coupled fundamental (UV-complete) lagrangian
  and weakly coupled chiral effective field theory
  Let's compare symmetry breaking in the two descriptions

Electroweak symmetry breaking via QCD ('old strong dynamics')

- In gedanken worlds without a Higgs field, QCD dynamically breaks EW symmetry
- Without Higgs all quarks are massless
  Consider pure QCD (no EW yet) with $N_F = 2$ for simplicity:

$$\mathcal{L}_{QCD} = -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + \overline{Q}\left(\gamma^\mu D_\mu \otimes \mathbb{I}_{N_F}\right)Q \qquad Q = \begin{pmatrix} u \\ d \end{pmatrix}$$

$$G^a_{\mu\nu} = \partial_\nu G^a_\mu - \partial_\mu G^a_\nu + g_s f^{abc} G^b_\mu G^c_\nu \qquad D_\mu q = \left(\mathbb{I}_{N_c}\partial_\mu - i g_s T^a G^a_\mu\right) q$$

- Projecting $Q = \frac{1}{2}(1-\gamma_5)Q + \frac{1}{2}(1+\gamma_5)Q \equiv Q_L + Q_R$,
  massless lagrangian decomposes, $\mathcal{L}_{QCD} \supset \overline{Q}_L \not{D} Q_L + \overline{Q}_R \not{D} Q_R$
  Trivially invariant under independent $Q_L \to e^{-i\theta^a_L \sigma_a/2} Q_L$ and $Q_R \to e^{-i\theta^a_R \sigma_a/2} Q_R$
- Full global symmetries are $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_B$; axial $\mathrm{U}(1)_A$ is anomalous
- **Spontaneous chiral symmetry breaking:**
  Strong dynamics produces non-zero condensate $\langle \overline{Q}Q \rangle = \langle \overline{Q}_L Q_R + \overline{Q}_R Q_L \rangle \neq 0$
  Breaks $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \longrightarrow \mathrm{SU}(2)_V \Longrightarrow$ three Nambu–Goldstone bosons (NGBs)
- Since left- and right-handed quarks transform differently under $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$
  chiral symmetry breaking also breaks EW symmetry $\Longrightarrow$ pions should be eaten

Electroweak chiral lagrangian and scaled-up QCD

- Non-linear chiral effective lagrangian for three massless pions π^a:

$$\mathcal{L}_\chi = \frac{f^2}{4}\mathrm{Tr}\left[\partial_\mu \Sigma \partial^\mu \Sigma\right] + \mathrm{NLO} \qquad \Sigma(x) = \exp\left[i\sigma_a \pi^a(x)/f\right]$$

  These σ_a are the broken axial generators in $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R = \mathrm{SU}(2)_V \times \mathrm{SU}(2)_A$
- Under $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ the NGB matrix transforms as $\Sigma \to e^{-i\theta^a_L \sigma_a/2} \Sigma e^{i\theta^a_R \sigma_a/2}$
  or equivalently $\frac{\pi^a(x)}{f} \to \frac{\pi^a(x)}{f} - \frac{1}{2}\theta^a_L + \frac{1}{2}\theta^a_R$
  This **shift symmetry** forbids NGB potential, including mass term $\sim \pi^a \pi^a$
- Couple to electroweak $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \subset \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ by promoting

$$\frac{f^2}{4}\mathrm{Tr}\left[\partial_\mu \Sigma \partial^\mu \Sigma\right] \longrightarrow \frac{f^2}{4}\mathrm{Tr}\left[D_\mu \Sigma D^\mu \Sigma\right]$$

  with gauge-covariant derivative exactly the same as in Eq. 1
  $\Longrightarrow$ Schematically the same $M_W = \frac{1}{2}g_2 f \simeq 28$ MeV, $\quad M_Z = \frac{M_W}{\cos\theta_W} \simeq 32$ MeV
- **Custodial symmetry** $\mathrm{SU}(2)_R \supset \mathrm{U}(1)_Y$ or $\mathrm{SU}(2)_V \supset \mathrm{U}(1)_{em} \longrightarrow \rho \equiv \frac{M_W}{M_Z \cos\theta_W} = 1$
  In limit $g_1 \to 0$ we have $\cos\theta_W = \frac{g_2}{\sqrt{g_2^2 + g_1^2}} \to 1$ and $M_W = M_Z$
- **Scaled-up QCD:** Take $f \to v = 246$ GeV to restore observed M_W and M_Z

Need to go beyond scaled-up QCD

- Scaled-up QCD has three big problems, which ruled it out ∼25 years ago

  1. 1980s: Fermion masses vs. flavor-changing neutral currents
     Masses from $\frac{1}{\Lambda_{UV}^2}(\overline{q}_R q_L)(\overline{Q}_R Q_L)$, FCNCs from $\frac{1}{\Lambda_{UV}^2}(\overline{q}_R q_L)(\overline{q}_R q_L)$
     FCNCs lead to neutral meson mixing;
     D–$\overline{D}$ measurements generically prefer $\Lambda_{UV}^{(c)} \gtrsim 1500$ TeV $\Longrightarrow m_c \lesssim 1$ MeV

  2. 1990s: Electroweak precision tests (EWPT), especially the "S parameter"
     Parameterizes new physics effects in $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ vacuum polarizations
     Experimentally $S = 0.07(8)$ while scaled-up QCD predicts $S \gtrsim 0.4$

  3. 2010s: A relatively light Higgs boson, $m_H \approx \frac{1}{2}v$
     in contrast to the $m_\sigma \approx 450$ MeV $\simeq 5f$ of QCD

- Modern model building is designed to address these problems