The Relaxion in Composite Higgs Models

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Outline

Relaxion scanning mechanism

Composite Higgs

"Cartoon version" of our idea

$SU(3)_L \times SU(3)_R$ model — Work in progress!

Conclusion

The relaxion scanning mechanism: Introduction

- Novel solution to the SM Hierarchy Problem.
- Proposed by Graham, Kaplan and Rajendran [1504.07551]
- Exploits the interesting dynamics of a slow-rolling axion-like field to *dynamically stablise* a small Higgs mass.
- Illustrate idea with "minimal model" of Graham, *et al.*:

$$\mathcal{L} \supset -M(M - g\phi)|H|^2 - V(g\phi) + \frac{1}{16\pi^2}\frac{\phi}{f}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

  where $M \sim \mathcal{O}$(large cutoff) and g is an (exponentially) small dimensionless parameter. $\phi \equiv$ the "relaxion".
- Crucial to have source of dissipation to ensure slow roll of ϕ: e.g.,
  - a long period of low-scale inflation
  - particle production by the relaxion [1607.01786]

The relaxion scanning mechanism: Scalar dynamics

- After QCD confinement, and taking $V(g\phi) \sim -gM^3\phi + \cdots$:

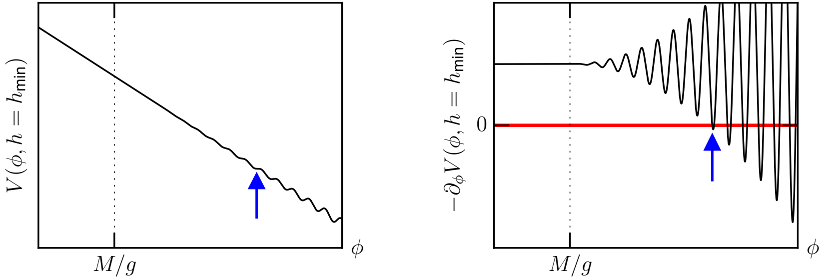
$$V(\phi, H) \sim M(M - g\phi)|H|^2 - gM^3\phi + \cdots - \Lambda^4(\langle h \rangle)\cos\left(\frac{\phi}{f}\right)$$

$$\Lambda^4(\langle h \rangle) \equiv \Lambda_{QCD}^4 \times |\langle h \rangle|/v \qquad (v \equiv 246\text{GeV})$$

- Exact initial value irrelevant, but $\phi_0 < M/g$.
- h initially has positive squared-mass parameter, of order the cutoff. EW unbroken.
- ϕ slow-rolls over large field range to larger values.
- Once $\phi \sim M/g$, h squared-mass parameter becomes negative, and EWSB triggered.
- As $\langle h \rangle$ increases, the $\Lambda_{QCD}^4 \times (|\langle h \rangle|/v)\cos(\phi/f)$ bumps in the potential grow.

[1504.07551, 1507.08649]

The relaxion scanning mechanism: Stopping



- Slow roll: $\dot{\phi} \propto -\partial_\phi V$.
- 'Slope matching' shortly after EWSB: $g \sim \Lambda_{QCD}^4 / (M^3 f)$.
- ϕ rolling stops (classically); locks in $m_{h,\,\rm phys}^2 \ll M^2$.
- Exponentially small g required. Technically natural: g explicitly breaks discrete ϕ shift-symmetry.
- Strong CP challenging... slope matching occurs at $\theta_{QCD}^{\rm eff} \sim 1$.

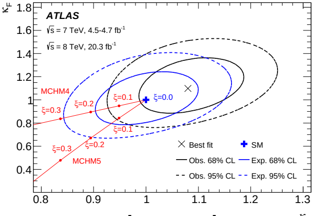
[1504.07551, 1507.08649]

Composite Higgs models: Introduction

- Also a solution to the SM Hierarchy Problem.
- Higgs is composite object built from fermions which transform under SM and new strongly-coupled group ("technicolor").
- Very close analogy to the light pseudoscalar mesons of QCD.
- Strong TC dynamics confines and spontaneously breaks global TC flavour group $G \to H$ at scale $\Lambda \sim 4\pi F_\pi/\sqrt{N}$ $[\mathcal{O}(1-10\text{TeV})]$
- The Higgs is (pseudo)-Nambu–Goldstone boson ($\in G/H$) of spontaneous $G \to H$ breaking.
- Explicit G-breaking (hence pNGB):
  - TC fermion masses
  - weakly-gauged electroweak $SU(2)_L \times U(1)_Y \subset H$
  - couplings to SM fermions to generate Yukawas (e.g., Partial Compositeness mechanism)

Composite Higgs models: EWSB and tuning

- Radiatively-generated potential (large y_t) for H triggers EWSB.
- No generic reason to expect vacuum alignment: expect $\xi \equiv v^2/F_\pi^2 \sim 1$.
- Corrections to the $W^\pm, Z$, and fermion couplings to the H of order ξ.



[1509.00672]

- Avoid EW precision (if custodial absent): $F_\pi \gtrsim 5\text{TeV}$
- Additional resonances — top partners, spin-1 resonances — around $m^* \sim 4\pi F_\pi/\sqrt{N} \gtrsim 1\text{TeV}$

The Little Hierarchy Problem: why is $\xi \equiv v^2/F_\pi^2 \ll 1$?

Relaxion + Composite Higgs: Introduction

- Idea: Use the relaxion scanning mechanism to solve the Little Hierarchy Problem.

- We need to generate
  - a Composite-Higgs–relaxion coupling
  - $\langle h \rangle$-dependent barriers for the relaxion
  - A sufficiently flat scanning potential for the relaxion

Relaxion + Composite Higgs: Basic Setup

- Suppose the relaxion is an axion of both QCD and TC, and also another strongly-coupled group TC′:

$$\mathcal{L}_{\text{relaxion}} = \frac{g_s^2}{16\pi^2}\left(\frac{\phi}{f} - \theta_{QCD}\right) G\tilde{G} + \frac{g^2}{16\pi^2}\frac{\phi}{F}\mathcal{G}\tilde{\mathcal{G}} + \frac{(g')^2}{16\pi^2}\left(\frac{\phi}{F'} - \theta'\right)\mathcal{G}'\tilde{\mathcal{G}}'.$$

- Weakly-gauge EW subgroup of TC flavour.
- Massive fermions appropriately charged under (SM+TC), TC′.
- QCD gives stopping potential (...strong CP challenging).
- TC′ present to give ϕ correct scanning potential (other options exist).
- Note the misaligned θ-angles of TC and TC′.

The cartoon version: Effective potential

- Low-energy description of the G/H pNGBs via Chiral Lagrangian.
- Including the effects of the top quark, expect an effective one-loop potential of the form:

$$V \sim -\Lambda F_\pi^2 \mathrm{Tr}\left[MUe^{i\phi/F} + \text{h.c.}\right] - \frac{c_t N_c y_t^2 \Lambda^2 F_\pi^2}{16\pi^2}\left|\mathrm{Tr}\left[U\cdot\Delta\right]\right|^2 \text{ (+ gauge)}$$
$$- \Lambda'(F'_\pi)^2 m' \cos\left(\frac{\phi}{F'} - \theta'\right) - \left[\Lambda_{QCD}(h)\right]^4 \cos\left(\frac{\phi}{f} - \theta_{QCD}\right)$$

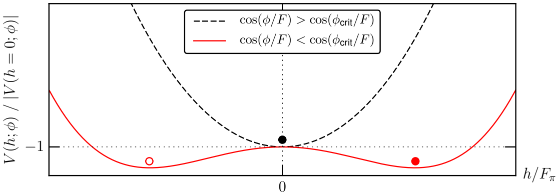
$$\sim -\Lambda F_\pi^2 m \cos\left(\frac{h}{F_\pi}\right)\cos\left(\frac{\phi}{F}\right) - \frac{c_t N_c y_t^2 \Lambda^2 F_\pi^2}{16\pi^2}\sin^2\left(\frac{h}{F_\pi}\right)$$
$$- \Lambda'(F'_\pi)^2 m' \cos\left(\frac{\phi}{F'} - \theta'\right) - \left[\Lambda_{QCD}(h)\right]^4 \cos\left(\frac{\phi}{f} - \theta_{QCD}\right).$$

Note: $\left[\Lambda^{(\prime)}, F_\pi^{(\prime)}, m^{(\prime)} \sim \mathcal{O}(1-10\,TeV)\right] \gg \left[\Lambda_{QCD} \sim 150 MeV\right]$ — $U = \exp[(2i/F_\pi)\pi^a T^a]$

The cartoon version: Higgs dynamics

$$\partial_h V \propto \sin\left(\frac{h}{F_\pi}\right)\left[\frac{\cos(\phi/F)}{\cos(\phi_{\text{crit}}/F)} - \cos\left(\frac{h}{F_\pi}\right)\right] = 0$$

$$\cos(\phi_{\text{crit}}/F) = \left(c_t N_c y_t^2 \Lambda\right) / \left(8\pi^2 m\right) \ll 1$$



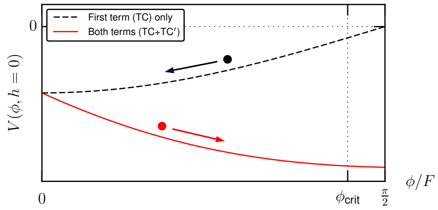
- **Assume** $\cos(\phi/F)$ decreases as the relaxion slow-rolls ($\phi/F \in [0, \pi/2]$ and increasing).
- h/F_π is initially zero. EWSB as ϕ crosses ϕ_{crit}.
- $[\Lambda_{QCD}(h)]^4 \sim \sin(\langle h\rangle/F_\pi)$, so QCD barrier heights increase.
- ϕ rapidly stops rolling, locks in $\xi \equiv \sin^2(\langle h\rangle/F_\pi) \ll 1$.

The cartoon version: Relaxion dynamics

- In the EW-symmetric phase,

$$V(\phi, h=0) = -\Lambda F_\pi^2 m \cos\left(\frac{\phi}{F}\right) - \Lambda'(F_\pi')^2 m' \cos\left(\frac{\phi}{F'} - \theta'\right)$$

$$\dot{\phi} \propto -\left.\partial_\phi V\right|_{h=0} \sim \mathcal{O}\left(V(\phi)\,/\,F^{(\prime)}\right)$$



- Need TC′ with $\theta' \neq 0$.
- Slope $\sim 1/F^{(\prime)}$ must be exponentially small for 'slope matching' and stopping.
- $F^{(\prime)}$ exponentially large ($\gg f$); super-Planckian. Clockwork mechanism [1511.01827].

$SU(3)_L \times SU(3)_R$ model: Setup **Work in progress!**

- TC $= SU(N)$
- 3 Dirac fermions with left-handed Weyl fermion components charged under $SU(N) \times SU(3)_c \times SU(2)_W \times U(1)_Y$:

$$L \sim (\boldsymbol{N}, \mathbf{1}, \mathbf{2}, +1/2) \qquad L^c \sim (\bar{\boldsymbol{N}}, \mathbf{1}, \bar{\mathbf{2}}, -1/2)$$
$$N \sim (\boldsymbol{N}, \mathbf{1}, \mathbf{1}, 0) \qquad N^c \sim (\bar{\boldsymbol{N}}, \mathbf{1}, \mathbf{1}, 0)$$

- $$\begin{aligned} & G = SU(3)_L \times SU(3)_R \times U(1)_V \\ \rightarrow\ & H = SU(3)_V \times U(1)_V \\ & \quad \supset SU(2)_W \times U(1)_Y \qquad \text{(weakly gauged)} \\ & G/H = SU(3)_A \end{aligned}$$

- Partial compositeness to generate Yukawas for SM fermions (*effectively* 4-fermion operators $\sim qq\Psi\Psi$).

$SU(3)_L \times SU(3)_R$ model **Work in progress!**

- pNGBs in G/H are $(\mathbf{3}, 0)$, $(\mathbf{2}, +1/2)$, $(\mathbf{1}, 0)$ of $SU(2)_W \times U(1)_Y$.
- Three physical neutral scalars π^0_{TC}, η_{TC}, h in unitary gauge.
- Still actively investigating if **more complicated scalar dynamics** in this particular model allows the implementation of our 'cartoon' idea.
- $SU(3)_L \times SU(3)_R$ does not allow custodial symmetry group: push F_π high ($\gtrsim$ 5TeV) to hide EWP deviations as have mechanism to explain small ξ.
- **Watch this space...**

Conclusion

- Relaxion scanning mechanism allows dynamical stabilisation of hierarchies
- Composite Higgs solves large SM Hierarchy Problem
- Suffers from Little Hierarchy Problem
- Idea: use relaxion scanning mechanism to stabilise the Little Hierarchy
- Concrete realisation of this idea still work in progress