The Relaxion in Composite Higgs Models

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August 5, 2016

ICHEP 2016
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 stabilise 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 \( \phi \): 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 $V(g\phi) \sim -gM^3\phi + \cdots$

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

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

- Exact initial value irrelevant, but $\phi_0 < M/g$.
- $h$ initially has positive squared-mass parameter, of order the cutoff. EW unbroken.
- $\phi$ 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 $\Lambda^4_{QCD} \times (|\langle h \rangle|/v) \cos(\phi/f)$ 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: $g \sim \Lambda^4_{QCD} / (M^3 f)$.
- $\phi$ rolling stops (classically); locks in $m_{h, \text{phys}}^2 \ll M^2$.
- Exponentially small $g$ required. Technically natural: $g$ explicitly breaks discrete $\phi$ shift-symmetry.
- Strong CP challenging... slope matching occurs at $\theta_{QCD}^{\text{eff}} \sim 1$. 

[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 $G \rightarrow H$ at scale $\Lambda \sim 4\pi F_\pi / \sqrt{N} \left[ O(1 - 10\text{TeV}) \right]$
- The Higgs is (pseudo)-Nambu–Goldstone boson ($\in G/H$) of spontaneous $G \rightarrow H$ 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 $\xi$.

- 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':

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

- 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 \( \phi \) correct scanning potential (other options exist).
- Note the misaligned \( \theta \)-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:

\[
V \sim -\Lambda F^2_\pi \text{Tr} \left[ M U e^{i\phi/F} + \text{h.c.} \right] - \frac{c_t N_c y_t^2 \Lambda^2 F^2_\pi}{16\pi^2} \left| \text{Tr} [U \cdot \Delta] \right|^2 \quad (+ \text{gauge})
\]

\[
- \Lambda' (F'_\pi)^2 m' \cos \left( \frac{\phi}{F'} - \theta' \right) - [\Lambda_{\text{QCD}}(h)]^4 \cos \left( \frac{\phi}{f} - \theta_{\text{QCD}} \right)
\]

\[
\sim -\Lambda F^2_\pi m \cos \left( \frac{h}{F_\pi} \right) \cos \left( \frac{\phi}{F} \right) - \frac{c_t N_c y_t^2 \Lambda^2 F^2_\pi}{16\pi^2} \sin^2 \left( \frac{h}{F_\pi} \right)
\]

\[
- \Lambda' (F'_\pi)^2 m' \cos \left( \frac{\phi}{F'} - \theta' \right) - [\Lambda_{\text{QCD}}(h)]^4 \cos \left( \frac{\phi}{f} - \theta_{\text{QCD}} \right).
\]

Note: \( \Lambda', F'_\pi, m' \sim \mathcal{O}(1-10 \text{TeV}) \gg [\Lambda_{\text{QCD}} \sim 150 \text{MeV}] \quad U = \exp[(2i/F_\pi)\pi^a T^a] \)
The cartoon version: Higgs dynamics

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

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

- **Assume** \( \cos \left( \frac{\phi}{F} \right) \) decreases as the relaxion slow-rolls \( (\phi/F \in [0, \pi/2] \) and increasing).
- \( h/F_\pi \) is initially zero. EWSB as \( \phi \) crosses \( \phi_{\text{crit}} \).
- \( [\Lambda_{QCD}(h)]^4 \sim \sin \left( \langle h \rangle / F_\pi \right) \), so QCD barrier heights increase.
- \( \phi \) rapidly stops rolling, locks in \( \xi \equiv \sin^2 \left( \langle h \rangle / F_\pi \right) \ll 1 \).
The cartoon version: Relaxion dynamics

- In the EW-symmetric phase,

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

\[ \dot{\phi} \propto -\partial_\phi V \big|_{h=0} \sim O \left( \frac{V(\phi)}{F'(\phi)} \right) \]

- Need TC' with \( \theta' \neq 0 \).
- Slope \( \sim 1/F'(\phi) \) must be exponentially small for ‘slope matching’ and stopping.
- \( F'(\phi) \) exponentially large \( (\gg f) \); super-Planckian. Clockwork mechanism [1511.01827].
SU(3)$_L \times SU(3)$_R model: Setup

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

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

$$N \sim (\mathbf{N}, 1, 1, 0) \quad N^c \sim (\bar{\mathbf{N}}, 1, 1, 0)$$

- $G = SU(3)_L \times SU(3)_R \times U(1)_V$
  $$\rightarrow H = SU(3)_V \times U(1)_V$$
  $$\supset SU(2)_W \times U(1)_Y \quad \text{(weakly gauged)}$$

$$G/H = SU(3)_A$$

- Partial compositeness to generate Yukawas for SM fermions (effectively 4-fermion operators $\sim qq\Psi\Psi$).
SU(3)$_L \times SU(3)$_R model

- pNGBs in $G/H$ are $(3, 0)$, $(2, +1/2)$, $(1, 0)$ of $SU(2)_W \times U(1)_Y$.
- Three physical neutral scalars $\pi^0_{TC}, \eta_{TC}, h$ 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 $F_\pi$ high ($\gtrsim 5\text{TeV}$) to hide EWP deviations as have mechanism to explain small $\xi$.
- 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