Technicolor at Criticality

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LHC: From Here to Where?

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Technicolor at Criticality

TC at Criticality (TCC) is a model of dynamical EW symmetry breaking with the following features:

- it is asymptotically NON-FREE, i.e the UVFP is non-trivial (strong coupling throughout the RG flow: AdS/CFT?)
- it solves the hierarchy problem (it is natural)
- the scaling dimension of the composite Higgs $\bar{Q}Q$ satisfies

$$\text{(IR)} \quad 1 \lesssim \Delta_{\bar{Q}Q} \leq 2 \quad \text{(UV)} \tag{1}$$

Outline

1. Introduction: DEWSB and its problems (solution?!)
   - Fermion Mass Generation
   - EW Precision Tests
   - Asymptotic Non-Freedom?!
2. Strong Technicolor
   - Naturalness vs Weakly Coupled Scalars
   - The Composite Higgs
   - Flavor Physics
3. Conclusions

Dynamical EWS breaking[1]

– Start with a chirally invariant strong dynamics (Technicolor = TC) and "weakly" gauge an $SU(2) \times U(1)$ subgroup of the flavor group.
– Spontaneous Chiral Symmetry Breaking, i.e. $\langle \bar{Q}Q \rangle \sim \Lambda_\chi^3$, implies EWSB.
– Choose appropriate boundary conditions so that the dynamical scale is set to $\Lambda_\chi = O(1)$ TeV.

YOU GET:

- a **natural** explanation (and stabilization) of the hierarchy $\Lambda_\chi \ll \Lambda_{UV}$
- $W^\pm, Z^0$ masses at the right scale (and $\rho = 1$)

BUT:

- what about Fermion Masses ?!
- what about Precision Tests ?!

[1] S. Weinberg '76, Susskind '79

Fermion Mass Generation (1)

We would need to couple the SM fermions ψ to the Higgs operator $\bar{Q}Q$.
This is generally accomplished with an Extended TC framework[2],
and leads to $(f, y, G = O(1))$

$$f\frac{(\bar{Q}Q)(\bar{Q}Q)}{\Lambda_{ETC}^2} \qquad y\frac{(\bar{\psi}\psi)(\bar{Q}Q)}{\Lambda_{ETC}^2} \qquad G\frac{(\bar{\psi}\psi)(\bar{\psi}\psi)}{\Lambda_{ETC}^2} \tag{2}$$

- $f \neq 0$: masses for the (pseudo) NGBs;
- $y \neq 0$: SM Fermion Masses;
- $G \neq 0$: FCNC !

[2] Dimopoulos and Susskind '79, Eichten and Lane '80

Fermion Mass Generation (2)

The typical SM fermion mass $m_f(\Lambda_{ETC})$ **strongly depends on the scaling dimension** $\Delta_{\bar{Q}Q}(\Lambda_{ETC})$ **of the Higgs**:

$$m_f = y\Lambda_\chi \left(\frac{\Lambda_\chi}{\Lambda_{ETC}}\right)^{\Delta_{\bar{Q}Q}-1} \qquad \Lambda_{ETC} > 10^3\,\text{TeV}\ \ (\text{FCNC}) \tag{3}$$

- with $\Delta_{\bar{Q}Q} \sim 3$ (QCD-like) we have $m_f \sim 1$ MeV
  we cannot explain the 2nd and 3rd generations;
- with $\Delta_{\bar{Q}Q} \sim 2$ we could explain the 2nd generation[3]
  (still, the top is too heavy...)
- with $\Delta_{\bar{Q}Q} \sim 1$ we could explain also the 3rd generation
  (hierarchy hidden in y...)

[3] Holdom '81

EW Precision Tests

The S parameter tends to be too large in models of DEWSB.

- with $\Delta_{\bar{Q}Q} \sim 3$ the Higgs $\bar{Q}Q$ is a loose bound state of N_{dof} techni-quarks and we expect

$$S \sim \frac{N_{dof}}{6\pi} \qquad (4)$$

- with $\Delta_{\bar{Q}Q} < 3$ the perturbative estimates are not reliable (2nd WSR is not satisfied, AdS/CFT) and the S parameter decreases[4]

$$S \sim ??? \qquad (5)$$

[4] Sundrum and Hsu '93, Appelquist et al. '99, ...

Asymptotic Non-Freedom ?!

The bottom line of the above discussion is that models with

$$\text{(IR)} \quad 1 \lesssim \Delta_{\bar{Q}Q} \leq 2 \quad \text{(UV)} \tag{6}$$

are phenomenologically very compelling (m_f,S,. . .)
We are driven to focus on

Asymptotically Non-Free Models

Nice. But:

- Are there explicit examples ? (main criticism to Holdom's)
- What about Naturalness ? (main feature of DEWSB)

The Conformal Window

Technicolor at Criticality (TCC) is based on the well established existence of the Conformal Window (CW) in non-abelian gauge theories:

CW: a region in flavor space in which the UV-free dynamics flows towards an interacting IRFP. In the CW

$$2 \leq \Delta_{\bar{Q}Q} < 3 \tag{7}$$

Strong TC

Suppose we were able to fine-tune the gauge coupling so that $\lambda = \lambda_{IR}$, and consider the path integral (generalized NJL)

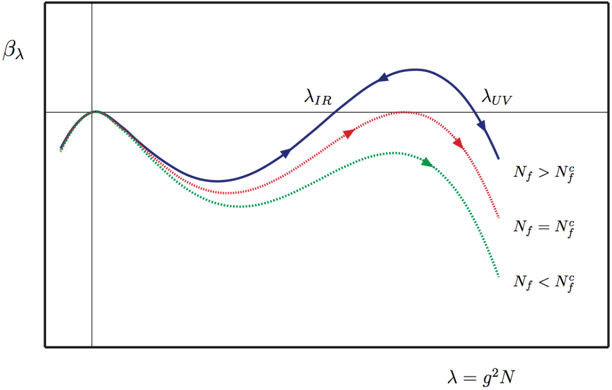
$$\langle e^{i\int f(\bar{Q}Q)^2}\rangle_{CFT} = \int \mathcal{D}[\text{CFT}]\, e^{i\int f(\bar{Q}Q)^2} \tag{8}$$

Here:

- The CFT is defined in terms of the Green's functions of the $SU(N)$ gauge theory with $\lambda = \lambda_{IR}$.
- The Higgs operator $\bar{Q}Q$ has dimension $2 \leq \Delta < 3$ for $f = 0$.

A Conjecture

Strong TC emerged in an attempt to model the conjectured[5] strong branch $\lambda \geq \lambda_{IR}$ of non-abelian gauge theories (conformal PT)



[5] D.B. Kaplan et al. '09

Calculability

Remarkably, if the CFT admits a large N expansion (N is the number of colors), the theory predicts

$$\begin{aligned} \mu\frac{df}{d\mu} &= -f^2 + (2\Delta - 4)f \\ \Delta_{\bar{Q}Q} &= \Delta - f \end{aligned} \tag{9}$$

We conclude that:

- β_f has two zeros: $f_{IR} = 0$ (i.e. λ_{IR}) and $f_{UV} = 2(\Delta - 2)$ (i.e. λ_{UV})
- Chiral symmetry breaking occurs for $f > f_{UV}$ (NJL)
- The fixed points merge when $\Delta = 2$

TC at Criticality

TCC is defined for $\Delta = 2$ (critical condition on N_f). It follows that

- the theory in the broken phase $f > 0$ naturally accounts for a hierarchical suppression of the dynamical scale:

$$\Lambda_\chi = \Lambda e^{-1/f(\Lambda)} \tag{10}$$

- the scaling dimension of the quark bilinear (in the perturbative regime of our "large N" expansion) satisfies

$$1 \lesssim \Delta_{\bar{Q}Q} \leq 2 \tag{11}$$

Naturalness vs Weakly Coupled Scalars

- The UV condition $\Delta_{\bar{Q}Q} = 2$ ensures that the 4-fermion operator is marginal ($f = 0$)

A theory is natural if the dependence of the IR scale on the UV scale (UV cutoff) is "mild". **This condition is satisfied whenever the UV formulation contains no relevant deformations**.

- The IR condition $\Delta_{\bar{Q}Q} \sim 1$ ensures agreement with experiments and implies the existence of a weakly coupled Higgs

Naturalness is a condition on the UV physics:
it does not prevent the emergence of a weakly coupled Higgs $\bar{Q}Q$ (i.e. $\Delta_{\bar{Q}Q} \sim 1$) in the IR

The Composite Higgs

A weakly coupled Higgs $\bar{Q}Q$ is anticipated by analogy with the Gross-Neveu model (the natural version of the NJL):

- no small parameter suppresses m_σ and hence $m_\sigma = O(\Lambda_\chi)$
- $\Delta_{\bar{Q}Q} \sim 1$ in the IR tells us that the Higgs/dilaton mixing is $O(1)$
- The physical Higgs emerges as a sharp (large N) resonance along with other hadrons of comparable masses

The phenomenology is analogous to that of CH models[6]:
The Higgs in TCC is a pseudo-NGB of an Approximate Dilatation Invariance of the Strong Dynamics

[6] D.B. Kaplan and Georgi '84

The Flavor Sector

The renormalization effects from the scale Λ_{ETC} at which the Yukawa operator is generated and Λ_χ at which the chiral condensate is formed gives

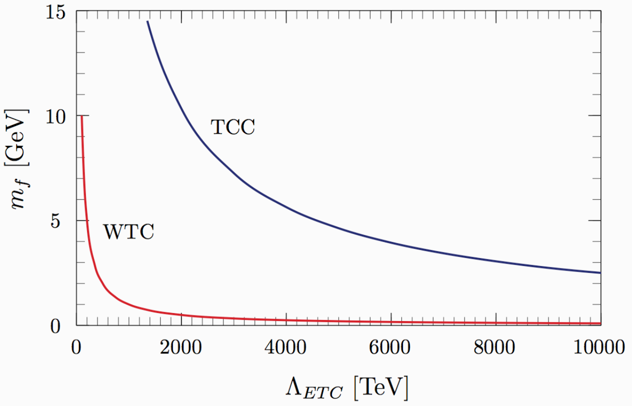
$$m_f = y\frac{\Lambda_\chi^3}{\Lambda_{ETC}^2}\exp\left(\int_{\Lambda_\chi}^{\Lambda_{ETC}}\gamma\ \mathrm{d}\log\mu\right) = y\frac{\Lambda_\chi^2}{\Lambda_{ETC}}\left[e\log\left(\frac{\Lambda_{ETC}}{\Lambda_\chi}\right)\right]. \tag{12}$$

There are two competing contributions:

- $\Lambda_\chi/\Lambda_{ETC}$ suppression typical of $\Delta_{\bar{Q}Q}\sim 2$ (WTC)
- Log enhancement coming from $f(\mu)$ ($1\sim\Delta_{\bar{Q}Q}<2$ in TCC)

The Flavor Sector: $i = 1, 2$

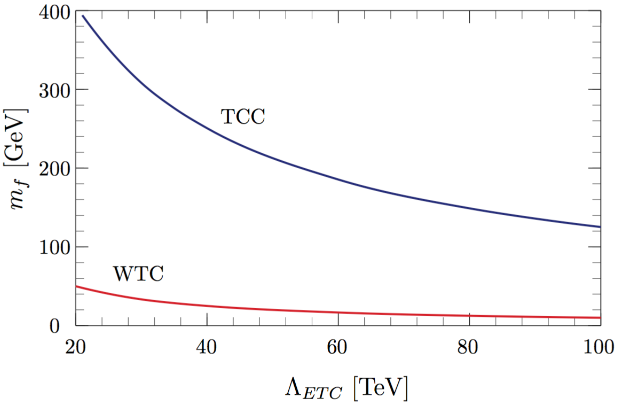
The fermion mass in TCC lies in between a WTC dynamics with $\Delta_{\bar{Q}Q} \sim 2$ and a fundamental Higgs with $\Delta_{\bar{Q}Q} \sim 1$



$\Lambda_{ETC}^{i=1,2} > O(10^4)$ **TeV for 1st and 2nd generations**

The Flavor Sector: $i = 3$

The fermion mass in TCC lies in between a WTC dynamics with $\Delta_{\bar{Q}Q} \sim 2$ and a fundamental Higgs with $\Delta_{\bar{Q}Q} \sim 1$



$\Lambda_{ETC}^{i=3} = O(10^2)$ **TeV for the top**

Conclusions

- **I presented a class of asymptotically non-free theories** (Strong TC) and proposed to interpret it as a dual description of the conjectured strongly coupled branch of non-abelian gauge theories
- **Technicolor at Criticality**
  1. solves the hierarchy problem ($\Delta_{\bar{Q}Q} = 2$ in the UV)
  2. predicts a weakly coupled Higgs, i.e. a dilaton ($\Delta_{\bar{Q}Q} \simeq 1$ in the IR) strong impact on Flavor Physics and EWPT

Thank You

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