Running top Yukawa for the naturalness

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with Raffaele D’agnolo
Higgs as pNGB

works in Naturalness

works in running Yukawa couplings
It is important to fill up the loophole in all possible explanation of the hierarchy.

Naturalness
Running Yukawa

by S Dimopoulos
Naturalness
Nnaturalness

Arkani-Hamed Cohen D’agnolo
Hook HDK Pinner, PRL (2016)
Higgs mass: random dart to 1m*1m in the disk of the solar system
\( N = 10^{32} \)
\( \Lambda_\ast = 100 \text{ GeV} \)

\( N \) copies of (MS) SM

\( m_h^2 \)

\( \text{grav} \)

\( M_{\text{pl}} \sim N \Lambda_\ast^2 \)

\( \Lambda_H = 10^{10} \text{ GeV} \)

if reheation is a pNGB

enormous reduction of dof

\( N = 10^{16} \)
\( \Lambda_\ast = \Lambda_H = 10^{10} \text{ GeV} \)

scenario I

\( N = 10^4 \)
\( \Lambda_\ast = 10^{16} \text{ GeV} \)
\( \Lambda_H = 10 \text{ TeV} \)

scenario II

Cosmology Dominantly Reheats Bottom of Spectrum

Arkani-Hamed Cohen D’agnolo
Hook HDK Pinner, PRL (2016)

Dvali Redi PRD (2009)
We present a new mechanism to stabilize the electroweak hierarchy. We introduce our copy of the Standard Model with varying values of the Higgs mass parameter. This generically yields a quadratic dependence of the potential on the Higgs field. It predicts no new particles at the LHC, but does yield a variety of experimental signatures for the next 100 TeV collider [3, 4].

\[ \nu = 0 \] seen as dark sector
\[ \nu > \nu_{us} \] dominantly reheated
\[ \nu_{us} = 246 \text{ GeV} \]

\[ \Lambda_H^2 \]
\[ m_H^2 \]

\[ (m_H^2)_i = -\frac{\Lambda_H^2}{N} (2i + r), \quad -\frac{N}{2} \leq i \leq \frac{N}{2}. \]
Scalar reheat

$A \phi H^\dagger H$

Fermion reheat

$\lambda S L H$

population of the sectors

$m_H^2 > 0$

$m_H^2 < 0$

$$\mathcal{L}_\phi^{(H) \neq 0} \supset C_1^\phi a y_q \frac{v}{m_h^2} \phi q q^c;$$

$$\mathcal{L}_\phi^{(H) = 0} \supset C_3^\phi \frac{g^2}{16 \pi^2} \frac{1}{m_H^2} \phi W_{\mu\nu} W^{\mu\nu},$$
different phase of deconstruction

\[ \Delta N_{\text{eff}}, \phi, N = 10^4 \]

phase A: extra dimension

phase B: naturalness

dark radiation \[4.4 + 3 = 7.4\]

\[ \text{Br}(i=2) \approx 0.1 \]

generic prediction \[\Delta N_{\text{eff}} \sim \mathcal{O}(1)\]

Arkani-Hamed Cohen D’agnolo
Hook HDK Pinner, PRL (2016)
Naturalness

Cosmological solution to the naturalness

It might explain no new physics at the LHC
Cosmological observables might be interesting
Why is it working?

Reheaton is pNGB (not Higgs itself)

The presence of light scalar can be explained by pNGB idea

and

extra assumption of decay via Higgs can explain why it decays predominantly to the lightest Higgs sector
Higgs as pNGB

does not work well since

\[ y_t \sim O(1) \]

For the relevant operators, it is more important (relevant) at IR

\[ g_{\text{eff}}(\mu) = c \frac{\Lambda}{\mu} \]

\[ c = \epsilon \ll 1 \]
Running Yukawa Couplings
Talk at LHCP2017, May 15-20

1709.00766

†One possible way out is to make the SM Yukawa and gauge couplings to be relevant.

$$\Delta[Qt^c] = 2$$

$$\Delta[y_t] = 1$$

$$y_t(\Lambda) = \left(\frac{\mu}{\Lambda}\right)y_t(\mu) \ll y_t(\mu)$$
origin of fine tuning
:SUSY as an example

\[- \frac{m_h^2}{2} = \mu^2 + m_H^2 + \delta m_H^2\]

\[\delta m_H^2 \propto -y_t^2 m_{\text{soft}}^2\]

\[\mu > 100 \text{ GeV} \quad \text{(bound from Higgsino mass)}\]

Let’s accept \(\mu\) and focus on the remaining parts
10% to 20% fine tuning would be acceptable

\[ \Delta = \frac{\delta m_H^2}{\left(\frac{m_H^2}{2}\right)} \sim \frac{\delta m_H^2}{(100 \text{ GeV})^2} \]

\[ \delta m_H^2 \sim (200 \text{ GeV})^2 \quad 20\% \quad \Delta \sim 5 \]

\[ \delta m_H^2 \sim (300 \text{ GeV})^2 \quad 10\% \quad \Delta \sim 10 \]
\[
\delta m_{H}^{2} \propto -\frac{3y_{t}^{2}}{16\pi^{2}} \left( m_{t_{1}}^{2} + m_{t_{2}}^{2} + |A_{t}|^{2} \right) \log \left( \frac{\Lambda}{m_{\tilde{t}}} \right)
\]

\[
\sim 10^{-2}
\]

\[
-(200 \text{ GeV})^{2}
\]

\[
m_{\tilde{t}} \sim 600 \text{ GeV} : 20\% \text{ to } 2\%
\]

\[
(M_{3}, M_{2} \sim 900 \text{ GeV})
\]
Below the sparticle mass scales, the correction is negligible

\[ \beta_{m^2_h} = \frac{d m^2_h}{d \log \mu} = \frac{3 m^2_h}{8 \pi^2} \left( 2 \lambda + y^2_t - \frac{3 g^2}{4} - \frac{g'^2}{4} \right) \]

< 10% correction

Fine tuning is determined at the sparticle mass scales,

\[ m^2_h(m_{SUSY}) = m^2_h(\Lambda) + \delta m^2_h(\Lambda \rightarrow m_{SUSY}) \]

Focus on the couplings

\[ -\frac{6 y^2_t}{8 \pi^2} m^2_{SUSY} \log(\frac{\Lambda}{m_{SUSY}}) \]

Top Yukawa: constrained at the weak scale

\[ = \mathcal{O}(m^2_{SUSY}) \]

bounds from direct search
\[ \mu = m_{\tilde{t}} \]

\[ m_H^2(m_{\tilde{t}}) = c \frac{y_t^2(m_{\tilde{t}})}{16\pi^2} m_{\tilde{t}}^2 \]

computed at high scale

All the fine tuning issues are at this scale

\[ \mu = M \]

exit from conformal window

\[ \mu = M_Z, M_h \]

electroweak symmetry breaking
\[
\delta m_h^2(m_{\text{SUSY}}) = cy_t^2 m_{\text{SUSY}}^2
\]

\[
y_{t^*} = y_t(\mu = m_{\text{SUSY}})
\]

If \( y_t \) is drastically different at \( m_{\text{SUSY}}, m_t \), EWSB can be natural with heavy stops.
\[ \delta m_h^2(m_{\text{SUSY}}) = c y_t^2 m_{\text{SUSY}}^2 \]

\[ y_{t*} = y_t(\mu = m_{\text{SUSY}}) \]

If \( y_t \) is drastically different at \( m_{\text{SUSY}}, m_t \), EWSB can be natural with heavy stops.
\[ \Delta[Q t^c] = 3 - \gamma \]

- \( \gamma < 1 \) : UV dominates
- \( \gamma > 1 \) : IR dominates
- \( \gamma = 1 \) : optimum of the slope

The idea works for \( \gamma \geq 1 \)

\[ y_t(m_{\text{SUSY}}) = \left( \frac{M}{m_{\text{SUSY}}} \right)^\gamma y_t(m_t) \]
\[ m_{\text{SUSY}} \]

\[ X \quad \text{strongly interacting} \quad t \quad H \]

\[ y_t \sim \epsilon \ll 1 \]

\[ M \]

\[ X \quad \text{weakly interacting} \quad t \quad H \]

\[ y_t \sim \mathcal{O}(1) \]
Conformal Window
Conformal window of QCD

\[ a_s = \frac{g^2 N_c}{(4\pi)^2} \quad x = \frac{N_f}{N_c} \]

\[ \beta(a_s) = -\frac{2}{3} \left[ (11 - 2x)a_s^2 + (34 - 13x)a_s^3 + \cdots \right] \]

\[ \begin{array}{c|c}
> 0 & < 0 \\
\hline
5.5 > x > 2.6 & \\
\end{array} \]

\[ a_{s*} = \frac{2}{75} (11 - 2x) : \text{fixed point for } x \text{ close to } 11/2 \]

\[ a_{s*} \sim \frac{11 - 2x}{13x - 34} \sim 0.5 \]

\[ x_c = 3.25 \]
Conformal window

\[ g_{\pm} = g_* \pm \sqrt{\alpha - \alpha_*} \]

(IR attractive)

IR fixed point
UV fixed point
(IR repulsive)

Walking for \( \alpha < \alpha_* \)

\[ \beta(g, \alpha) = \frac{\partial g}{\partial t} = (\alpha - \alpha_*) - (g - g_*)^2 \]

t = \log \mu

external parameter
coupling
Conformal window of QCD

Banks-Zaks fixed point

\[ 7.8 < N_f < 16.5 \]
(Nc=3 from large Nc)

\[ 8 < N_{f*} < 12 \]
\[ N_{f*} = 3x_c = 9.75 \]
\[ \gamma = \frac{33 - 2N_f}{N_f} = 1 \rightarrow N_{f*} = 11 \]

\[ \gamma = 2 \rightarrow N_{f*} = 8.25 \]

no chiral symmetry breaking above 12

from Peskin conjecture from SUSY
Figure 3: The infrared limit of the 2-loop coupling and the 3-loop and 4-loop $\overline{\text{MS}}$ couplings in large $N_c$ QCD as a function of $\frac{11}{2} \left( \frac{N_f}{N_c} \right)$. The dashed line corresponds to the 20th order Taylor expansion in $\epsilon$ of the 4-loop coupling. The continuous vertical line represents the bottom of the conformal window implied by superconvergence and the dashed vertical line shows the 2-loop causality boundary.

$\epsilon = \frac{11}{2} - \frac{N_f}{N_c}$

$x_c = \frac{N_f}{N_c} = 3.25$
Figure 1: The conformal window in QCD (upper plot) and SQCD (lower plot) is shown in the $N_f - N_c$ plane. In both plots the $0 = 0$ line, separating the infrared free phase from the ultraviolet asymptotically free phase is drawn as a continuous black line. This line is the upper boundary of the conformal window. The lower boundary of the conformal window as implied by superconvergence is drawn in gray. In the SQCD case, this last line is also the line below which the dual theory becomes infrared free. In both plots, the (black) dashed line shows the lower boundary of the region where the 2-loop coupling has a causal analyticity structure. Below this line and above the dot-dash line there are complex Landau singularities. Below the dot-dash line there is a space-like Landau branch point. In the lower plot, we also show in gray the dual lines which describe the analyticity structure of the dual coupling constant.
Conformality Lost

\[ x = \frac{N_f}{N_c} \]

\[ x_{\text{crit}} = 3.25 \]

\[ x_{\text{BZ}} = 11/2 \]

\[ \Delta^+ \]

\[ \Delta^- \]

\[ \Delta \bar{\psi} \psi \]

Free fermions

\[ \bar{\psi} \psi \]

\[ \text{QCD} \]

\[ \text{QCD}^* \]

From D Kaplan et al: conformality lost
Conformal window of QCD at the critical point

\[
\left[ \bar{\psi} \psi \right] = 2
\]

\[ N_{f*} \approx 10 \]

\[ g_{s*}^2 \approx 10 \]

\[ \alpha_{s*} \approx 0.8 \]

\[ \alpha_{s*} = \frac{N_c \alpha_{s*}}{4\pi} \approx 0.2 \]
Conformal window of SQCD

**gauge group** $SU(N_c)$

\[
2N_c < N_f < 3N_c \quad \implies \quad \gamma = \frac{1}{2} \quad \implies \quad g_+ \to 0
\]

\[
\frac{3N_c}{2} < N_f < 2N_c \quad \implies \quad \gamma = 1 \quad \implies \quad g_+ \to \infty \quad \text{magnetic description}
\]

\[
g_+(\text{magnetic}) \to 0
\]

- $N_f$  
- $Q, \tilde{Q}$

\[
\Delta[Q\tilde{Q}] = \frac{3}{2} R[Q\tilde{Q}] = \frac{3(N_f - N_c)}{N_f}
\]

**electric description**

- $SU(N_f - N_c)$
- $N_f$
- $q, \tilde{q}$

- $M = Q\tilde{Q}$

Seiberg
Conformal window of SQCD

Magnetic theory

\[ N_f, \tilde{N}_c = N_f - N_c \]

SUSY BZ

Free magnetic

Weakly coupled

Conformal window

\[ \frac{3}{2}N_c \]

\[ 2N_c \]

\[ 3N_c \]

Free electric

Electric theory
Running Yukawa Couplings

One concrete realization:
how to make $\Delta[Qt^c] = 2$?
$\gamma = 1$
The setup

conformal window

\[ SU(3)_1 \times SU(3)_2 \rightarrow SU(3)_C \]

\[ \langle \Sigma \rangle = \text{diag}(f, f, f) \]

(3, 3)

All the SM quarks are charged under \( SU(3)_1 \)

\[ \frac{1}{g^2_s} = \frac{1}{g^2_1} + \frac{1}{g^2_2} \]

\[ g_1^2 \approx 10 \]

\[ g_2^2 \approx 1 \]
$SU(3)_1 \times SU(3)_2$

$\langle \Sigma \rangle = f \sim M$

$SU(3)_C$

$g_s$

$y_t$

$m_t$

$M$

$m_{\text{SUSY}}$

marginal

relevant
Higgs modified by hidden sector

Two loop corrections: Higgs, top, hidden color

\[
\begin{align*}
\text{h} & \quad \text{t} \\
\hline \\
\text{g}_1 & \quad G'_{\mu} \\
\hline \\
\text{t} & \quad \text{h}
\end{align*}
\]

\[
a_{s*} = \frac{N_c \alpha_{s*}}{4\pi} \simeq 0.2
\]

M can be 1 TeV or higher
Flavor Universal Coloron

(massive color octet vector boson)

\[ f \sim 1 - 2 \, \text{TeV} \]

\[ M_{G'} = g_1 f \sim 3 f : \quad 3 - 6 \, \text{TeV} \]

\[ g_1 \bar{q} \gamma^\mu T^a G''^a_{\mu} q \]

\[ \Sigma = \phi_R + \phi_I + \Theta + \text{Goldstone} \]

\[ 18 = 1 + 1 + 8 + 8 \]

\[ \Sigma = (3, \bar{3}) \quad \text{under} \quad SU(3)_1 \times SU(3)_2 \]
Coloron physics

Figure 1: Left panel: the schematic plot for the coloron signature at the LHC as a six-jet resonance when $M_\Theta/M_G \simeq 1$, which could be much lighter than both $G$ and $G'$. We will develop a bump search strategy for this new type of signature.

Our paper is organized as follows. In Section 5, we will develop a jet-substructure-based analysis for this type of signature. We will also develop a jet-substructure-based analysis for this type of signature.

The production times branching fractions for the signatures in Section 5 are likely to form a large number of jets has a great fat-jet. Although there are non-resonance searches based on multi-jet final states, some top-partner decays, the coloron behaves as a four-prong fat jet.

In this paper, we have developed two search strategies based on the predicted signatures in the ReCoM. Both strategies could be applied to other models with similar signatures. For instance, including the decay branching fractions of all three relevant particles, the production times branching fractions for the signatures in Section 5 are likely to form a large number of jets has a great fat-jet. Although there are non-resonance searches based on multi-jet final states, some top-partner decays, the coloron behaves as a four-prong fat jet.

The comparison between the two sets of exclusion lines shows that the fat-jet based method can probe a larger region of model parameter space. For the sensitivity to increase the signal discovery and 95% CL exclusion limits in Section 6, we provide a short summary for the ReCoM strategy in the blue dot-dashed line. As a comparison, we also show the sensitivities based on the six-jet resonance search strategy in Section 9.

Using the cuts from (9/\sqrt{p_T^2} + 10/\sqrt{\sum p_T^2}) < 1, we perform a jet-substructure-based analysis for the case with a fat jet. Together with the two jets from scalar from coloron decays is not boosted, so the four partons from its decay possible di-jet. We keep the basic cuts of the production times branching fractions for the signatures in Section 5, which could be much lighter than both $G$ and $G'$.
On the other hand, a large cut-off is to have a large suppression of the Wilson coefficient in an effective field theory are not predicted, and are usually of order 1 unless some NP is introduced. Suppose now that the SM is modified at some energy \( \mu \) and \( \bar{\mu} \), where one imagines some UV-completion to determine the masses and decay modes. In particular, the mass of the Higgs boson is broken by the mass term. In general any point of the parameter space with an enhanced coupling strength \( y_h \approx 10^{-3} \) is much higher than \( \mu \).

The hierarchy problem: is Nature natural?

A simple way to reformulate the hierarchy problem is to consider the Standard Model potential (9) in the mass eigenstate basis to have the coupling strength

\[
\frac{M_1}{M_2} = \frac{\sin \beta}{\cos \beta} = \frac{\bar{\mu}}{\mu}.
\]

Introducing new terms into the potential, the value of the coefficient is

\[
\sin \chi \propto \frac{3y_t}{16\pi^2} \frac{a_s}{f} \frac{\nu}{f} \sim 10^{-2} - 10^{-3}.
\]

We get

\[
m_h = \frac{1}{2} \pm \sqrt{\frac{1}{4} - \frac{\nu^2}{f^2}}.
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\]
conformal technicolor

\[ \Delta[H^2] = 2 \rightarrow 4 \]
relevant to marginal

relevant SM

\[ \Delta[Qt^c] = 3 \rightarrow 2 \]
marginal to relevant
One concrete realization:
how to make $\gamma = 1$?

It was only half-way successful

Task: keep the anomalous dimension to be 1 while avoid large couplings:
SU(2) and U(1) extension?
Top-quark pairs

CMS Preliminary 35.9 fb$^{-1}$ (13 TeV)

Dilepton

- Data
- $t\bar{t}$ signal
- $t\bar{t}$ other
- $t\bar{t}+Z/W$
- Single $t$
- W+jets
- Z+jets
- Diboson
- Uncertainty

$m_{t\bar{t}}$ [GeV]

Data/Pred.
Summary

Light Higgs might be due to smaller couplings at high energy (off-shell)

Measuring off-shell top Yukawa coupling would be important to check this idea

It is consistent with Higgs being a pseudo-Nambu-Goldstone boson at high energy

To realize the idea in the SM, we can take several possibilities (strongly interacting QFT above M)