Higgs Mass from Compositeness at a Multi-TeV Scale

Jiayin Gu

UC Davis

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based on arXiv:1311.5928, Hsin-Chia Cheng, Bogdan A. Dobrescu, JG
and current work, Hsin-Chia Cheng, JG

Introduction

- Hierarchy problem.
- One solution: no light fundamental scalar!
- Composite Higgs that no longer exists above the compositeness scale.
- No new physics at LHC yet!
- Small hierarchy may still exist.
- New strong dynamics at the compositeness scale.
- Usually predicts a heavy Higgs due to large quartic couplings, unless the Higgs mass is protected by some symmetry (PNGB).

The Nambu-Jona-Lasinio Model

- Starting with a theory of fermions at scale Λ with four-fermion interactions, one can rewrite the theory with an auxiliary scalar field H.
- By evolving down to a lower scale with the fermion bubble approximation, one generates kinetic and quartic terms of the H field. (The H field becomes physical!)
- One can think of H as a composite particle of the fermions, while Λ is the compositeness scale at which the couplings are strong.
- The quartic coupling λ and the Yukawa coupling ξ is related by $\lambda = 2\xi^2$. If the theory is spontaneously broken, this implies $m_h = 2m_f$.

A short review of the NJL model can be found in the appendix of arXiv:hep-ph/0203079 (C. T. Hill & E .H. Simmons).

Top Condensation

- The Higgs field is a low energy condensate $\langle \bar{t}t \rangle$ triggered by some new fundamental interaction at a higher scale Λ.
- Instead of the fermion bubble approximation, the full one-loop RG equations are used. [Phys. Rev. D 41, 16471660 (1990), (Bardeen, Hill, Lindner)]
- To get the right Electroweak VEV, top quark is too heavy unless the compositeness scale is extremely large. (Need the top Yukawa coupling to be very large at Λ and be ≈ 1 at weak scale.)
  - $\Lambda = 10^5$ GeV $\Rightarrow m_{top} \approx 360$ GeV.
  - $\Lambda = 10^{19}$ GeV $\Rightarrow m_{top} \approx 220$ GeV.
- $m_h \gtrsim m_{top}$.
- It doesn't work!

Top Condensation Seesaw

- option 1: Give up.
- option 2: Modify the theory until it works!
- Minimal modification: add a new vector-like top partner.
- A number of papers at the end of last century
  - arXiv:hep-ph/9712319 (Dobrescu, Hill)
  - arXiv:hep-ph/9809470 (Chivukula, Dobrescu, Georgi, Hill)
  - arXiv:hep-ph/9908391 (Dobrescu)
  - ......
- With the top seesaw mechanism, one can have a large ($\gg 1$) Yukawa coupling while keeping the correct top mass (173 GeV).
- We found that by imposing an approximate $U(3)_L$ symmetry, the Higgs mass has a rather restricted range and we can easily obtain a 126 GeV Higgs.
- We could extend the model to embed custodial symmetry and reduce fine tuning. (Not minimal anymore...)

Introducing a new vector-like quark

- We introduce a new $SU(2)_W$-singlet vector-like quark, χ of electric charge $+2/3$.
- $\psi_L^3 = \begin{pmatrix} t_L \\ b_L \end{pmatrix}$, χ_L, t_R, χ_R form bound states due to some strong interactions at scale Λ, which approximately preserves $U(3)_L \times U(2)_R$ chiral symmetry.
- We label the composite scalars collectively as Φ, which is a 3×2 matrix

$$\Phi = \begin{pmatrix} \Phi_t & \Phi_\chi \end{pmatrix} , \tag{1}$$

$$\Phi_t \sim \bar{t}_R \begin{pmatrix} t_L \\ b_L \\ \chi_L \end{pmatrix} , \qquad \Phi_\chi \sim \overline{\chi}_R \begin{pmatrix} t_L \\ b_L \\ \chi_L \end{pmatrix} . \tag{2}$$

Yukawa couplings and scalar potential

- The Yukawa couplings of the fermions and composite scalars are

$$\mathcal{L}_{\text{Yukawa}} = -\xi \begin{pmatrix} \overline{\psi}^3_L & \overline{\chi}_L \end{pmatrix} \Phi \begin{pmatrix} t_R \\ \chi_R \end{pmatrix} + \text{H.c.} \tag{3}$$

- t and χ forms a 2×2 mass matrix. The ligher mass eigenstate is the physical top.
- Because of the seesaw mechanism, we can have $\xi \gg 1$ while keeping the top mass at 173 GeV.
- The effective potential of the scalar sector has the following form. (Mass terms explicitly break $U(2)_R$ but preserve $U(3)_L$.)

$$\begin{aligned} V_{\text{scalar}} &= \frac{\lambda_1}{2} \text{Tr}\left[(\Phi^\dagger\Phi)^2\right] + \frac{\lambda_2}{2}\left(\text{Tr}[\Phi^\dagger\Phi]\right)^2 \\ &\quad + M_{tt}^2 \Phi_t^\dagger \Phi_t + M_{\chi\chi}^2 \Phi_\chi^\dagger \Phi_\chi + (M_{\chi t}^2 \Phi_\chi^\dagger \Phi_t + \text{H.c.}) \\ &\quad - (0, 0, C_{\chi t})\Phi_t - (0, 0, C_{\chi\chi})\Phi_\chi + \text{H.c.} \end{aligned} \tag{4}$$

Chiral symmetry breaking scale

- Neutral scalars may develop VEVs

$$\langle \Phi_t \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_t \\ 0 \\ u_t \end{pmatrix} , \qquad \langle \Phi_\chi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_\chi \\ 0 \\ u_\chi \end{pmatrix} \tag{5}$$

- where

$$v^2 \equiv v_t^2 + v_\chi^2 , \qquad u^2 \equiv u_t^2 + u_\chi^2 , \qquad f \equiv \sqrt{u^2 + v^2} . \tag{6}$$

- f is the chiral symmetry breaking scale. We expect $\Lambda \sim 4\pi f$ for f to be natural. (But we have $v \ll f$ which requires tuning!)

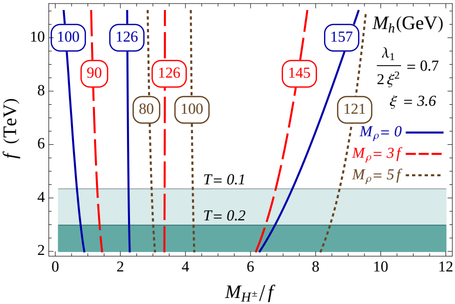
Higgs mass

- The lightest mass eigenstate of the 4 CP-even neutral scalars is a PNGB of the approximate $U(3)_L$ symmetry. It is the 126 GeV "Higgs"!
- Keeping the leading order terms in v^2/f^2 and $s_\gamma (\equiv \frac{u_t}{u})$,

$$M_h^2 \approx \frac{\lambda_1}{2\xi^2} \left(1 + \frac{\lambda_1 m_{t'}^2}{\xi^2 M_{H\pm}^2} \right)^{-1} y_t^2 \, v^2 \, . \tag{7}$$

- With $0.4 \lesssim \frac{\lambda_1}{2\xi^2} \lesssim 1$, we have $M_h \lesssim 185$ GeV . (Numerical study gives $M_h \lesssim 175$ GeV .)
- Strong connection between M_h and m_{top} in top seesaw models!
- The loop contribution of the EW gauge bosons produces additional $U(3)_L$ breaking effects and further reduces the Higgs mass. We cut off this contribution by M_ρ.

We can have a 126 GeV Higgs!



- $M_h = 126$ GeV can be obtained with reasonable parameters in our model.
- Main contraint comes from the T-parameter (from fermion loops).
  - 95% bound $\rightarrow$ $T \lesssim 0.15$ corresponds to $f \gtrsim 3.5$ TeV (for $\xi = 3.6$).
- The heavy states are too heavy to be probed at the LHC!
- This is related to the fact that $U(3)_L$ does not contain a custodial $SU(2)$ symmetry.

Extending the model to embed custodial symmetry

- If we extend the model to embed the $SU(2)_C$ custodial symmetry, the chiral symmetry breaking scale f may be reduced significantly.
- A naive extension is to introduce "Bottom Seesaw" with the addition of a bottom-partner (embedding $Sp(4)$). However, this suffers from the constraint on $Z \to b\bar{b}$ branching ratio.
  - arXiv:hep-ph/9908330 (Collins, Grant, Georgi)
  - arXiv:hep-ph/0108041 (He, Hill, Tait)
- The SM prediction for $Z \to b\bar{b}$ branching ratio is $\sim 1\sigma$ smaller than the measured value, while mixing with a heavy singlet will further reduce it.
- We surrendered to the following paper and adapted its setup, which has a custodial symmetry that also protects the $Zb\bar{b}$ coupling.
  - arXiv:hep-ph/0605341 (Agashe, Contino, Da Rold, Pomarol)
- We introduce a pair of vector-like EW doublet quarks, (X, T) .
  $\begin{pmatrix} t_L & X_L \\ b_L & T_L \end{pmatrix}$ transforms as $(2, 2)$ under $SU(2)_L \times SU(2)_R$.

Yukawa couplings and scalar potential

	$\overline{X_R}$	$\overline{T_R}$	$\overline{t_R}$	$\overline{\chi_R}$
t_L	σ^-_{tX}	σ^0_{tT}	σ^0_{tt}	$\phi^0_{t\chi}$
b_L	σ^{--}_{bX}	σ^-_{bT}	σ^-_{bt}	$\phi^-_{b\chi}$
X_L	σ^0_{XX}	σ^+_{XT}	σ^+_{Xt}	$\phi^+_{X\chi}$
T_L	σ^-_{TX}	σ^0_{TT}	σ^0_{Tt}	$\phi^0_{T\chi}$
χ_L	$\sigma^-_{\chi X}$	$\sigma^0_{\chi T}$	$\sigma^0_{\chi t}$	$\phi^0_{\chi\chi}$
collective label	Σ_X	Σ_T	Σ_t	Φ_χ

$$\mathcal{L}_{\text{Yukawa}} = -\xi \overline{\Psi_L} \Phi \Psi_R + \text{ H.c. }, \quad (8)$$

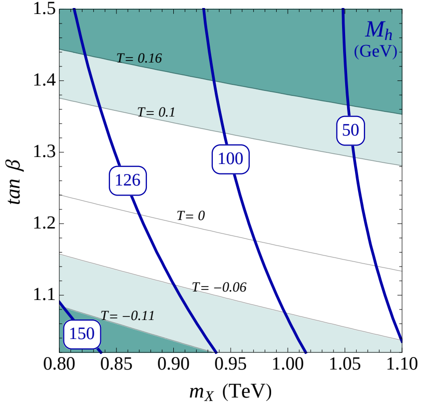
$$\begin{aligned} V &= \frac{\lambda_1}{2} \text{Tr}[(\Phi^\dagger \Phi)^2] + \frac{\lambda_2}{2} (\text{Tr}[\Phi^\dagger \Phi])^2 \\ &+ M_X^2 \Sigma_X^\dagger \Sigma_X + M_X^2 \Sigma_T^\dagger \Sigma_T + M_t^2 \Sigma_t^\dagger \Sigma_t + M_\chi^2 \Phi_\chi^\dagger \Phi_\chi \\ &- c_X \sigma^0_{XX} - c_X \sigma^0_{TT} - c_{\chi t} \sigma^0_{\chi t} - c_{\chi\chi} \phi^0_{\chi\chi} + \text{H.c.} \end{aligned} \quad (9)$$

- Too complicated!

The low energy theory

- Assuming all the degrees of freedom in $\Sigma_{X,T,t}$ are heavy, we integrate them out, keeping terms up to $\mathcal{O}(\frac{1}{M^2})$.
- Two EW doublets $\begin{pmatrix} \phi^0_{t\chi} \\ \phi^-_{b\chi} \end{pmatrix}$ $\begin{pmatrix} \phi^+_{X\chi} \\ \phi^0_{T\chi} \end{pmatrix}$, and one singlet $\phi^0_{\chi\chi}$, with VEVs v_t, v_T and u_χ.
- We add in additional mass terms to break $U(5)_L$ down to $SO(5)$.
- Including the contribution from EW gauge boson loops.
- The masses of the X, T quarks explicitly break custodial symmetry. We calculated the T-parameter and found it is acceptable in a large region of the parameter space.

We can have a 126 GeV Higgs with $f \sim 1$ TeV!



- $\xi = 3.6$, $\frac{\lambda_1}{2\xi^2} = 0.7$, $\frac{\lambda_2}{\lambda_1} = 0$, $f = 1$ TeV, $M_\rho = 3f$, $M_X = M_T = M_t = 10$ TeV.
- $\tan\beta = \frac{v_t}{v_T}$, m_X is the mass of the heavy quark X with charge $+5/3$.
- We can get a 126 GeV Higgs with a smaller f (less fine tuning)!
- Need $f \gtrsim m_X$ to get the right Higgs mass. (current LHC bound: $m_X \gtrsim 0.8$ TeV)
- Possible discovery of X and T quark at the 14 TeV LHC, other particles are probably too heavy...

Conclusion

- The Top Seesaw Model is a modification of Top Condensation by introducing a new vector like top partner.
- It addresses the origin of both electroweak symmetry breaking and top Yukawa coupling.
- The Higgs mass is related to the top mass and has a rather restricted range, $M_h \lesssim 175$ GeV , and one can easily obtain a 126 GeV Higgs.
- Constraint from T-parameter requires the chiral symmetry breaking scale to be much higher than the electroweak scale, which requires tuning.
- By introducing a pair of vector-like EW doublet quarks (X, T) and extending the scalar sector, we can embed custodial symmetry in the model and bring down the chiral symmetry breaking scale.
- Crossroads! More tuning or more complexity?
- The LHC is not enough. We need the 100 TeV collider!