Naturalness from a Composite Top?

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with Aaron Pierce

Outline:

Motivation: Gauge hierarchy problem

Model setup: Making top composite

Semi-UV completion

Screening from SU(N) hadronization

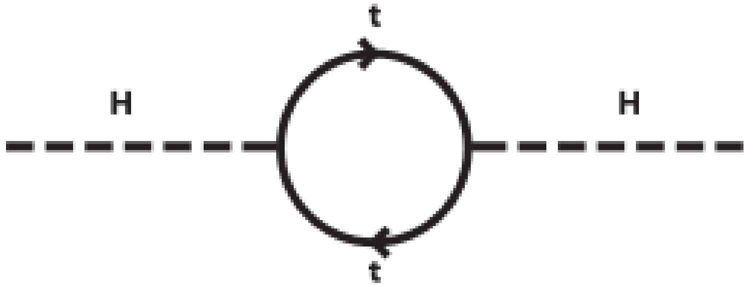
Pheno constraints

Collider signatures

Conclusion

Motivation: Gauge Hierarchy Problem

Higgs couples to SM particle, especially top Yukawa ~ 1.



$$\Delta m_h^2 \sim \frac{3y_t^2}{4\pi^2}\Lambda^2$$

No symmetry reason for SM higgs being as light as 125 GeV.

Similar problems for other particles in the loop, such as gauge couplings.

Top Yukawa, in most case, is the most serious one phenomenologically.

Motivation: Gauge Hierarchy Problem

Imposing symmetries to higgs:

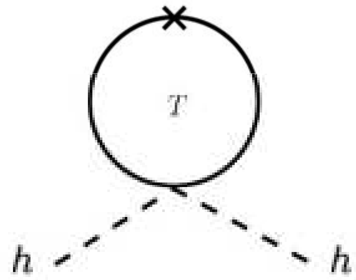
Supersymmetry:

Boson-Fermion (chiral symmetry)

Scalar top partner: stop

Composite Higgs:

PNGB (shift symmetry)



Fermionic top partner: T

Predict the existence of colored particles at EW scale.

Making top composite

Top quark is annoying and let’s do something special to it!

⇨ Make top quark a composite particle, i.e. having multiple partons

⇨ Distribute responsibilities among partons:

one parton carrying EW charge

----- coupling to higgs

another parton carrying SU(3) charge

----- giving color to composite state in IR

⇨ IR: Top quark carries SU(3) color and couples to SM Higgs

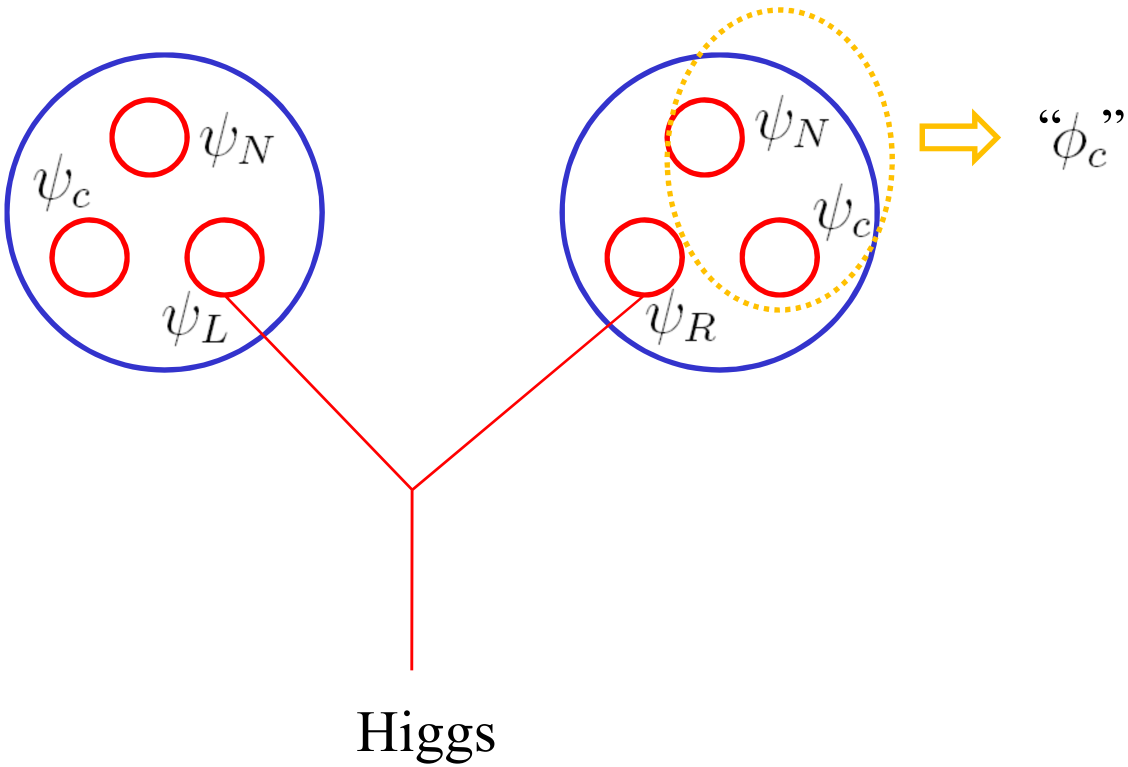
UV: Higgs directly couples to colorless particles,

but not colored partons.

Quadratic divergence will be cancelled by colorless partners.

Making top composite

Yukawa coupling between Higgs and top quark



$$\mathcal{L}_{UV} \supset y_\psi H \psi_L \psi_R \quad \Rightarrow \quad \mathcal{L}_{IR} \supset y_t H t_L t_R$$

Making top composite

Making top composite does not solve hierarchy problem!

⇨ Additional mechanism should be introduced in UV, Λ_ψ.
But they do not need to carry SU(3) charge! (safe from pheno)

$SUSY/LH/\ldots$

Λ_ψ

$t/b_L \sim (\phi_C \psi_L)$

$t/b_R \sim (\phi_C^\dagger \psi_{R,t/b})$

Elementary Higgs

Λ_c

SM

$t/b_L,\ t/b_R$

Elementary Higgs

$$\delta m_H^2 \simeq \frac{3y_t^2}{4\pi^2}\Lambda_C^2 + \frac{N y_\psi^2}{4\pi^2}\Lambda_\psi^2.$$

Making top composite

Relation between y_ψ and y_t :

NDA:

$$\mathscr{L}_{NDA} \supset f^2 \Lambda_C^2 \left(\frac{y_\psi H}{\Lambda_C} \right) \left(\frac{Q}{f\sqrt{\Lambda_C}} \right) \left(\frac{t_R}{f\sqrt{\Lambda_C}} \right) = y_\psi H Q t_R .$$

Higgs is elementary.
(different from composite higgs models)

$$\Rightarrow \quad y_\psi \sim y_t$$

Making top composite

Relation between y_ψ and y_t :

Analogy to DM DD:

$$B^{n,p}_{u,d} \equiv \frac{y_{u,d}}{y^{n,p}_{u,d}} \sim \mathcal{O}(0.1)$$

$$B^{n,p}_{s} \equiv \frac{y_{s}}{y^{n,p}_{s}} \sim \mathcal{O}(1)$$

Yukawa coupling is enhanced in IR!

⇨ Higgs couples to both valence quark and sea quark pair.
Yukawa coupling is always additive.

⇨ $y_\psi \sim 0.1$

Confinement without chiral condensation

Important assumption:

The confinement of SU(N) does not break EW symmetry.

⇨ Top quark gets all its mass from higgs condensation.

(unlike proton getting its mass from chiral condensation)

Confinement and chiral condensation is not necessarily related.

s-confinement: SQCD with $N_F = N_C + 1$

Implicit assumption in composite higgs models:

Fermionic top partner being lighter than confinement scale.

Semi-UV completion

"Semi" ← ϕ_c

Particles	$SU(N)$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
ϕ_c	$\bar{\square}$	$\square$	$\bullet$	$(\frac{1}{6} - \frac{x}{2})$
ψ_L^α	$\square$	$\bullet$	$\square$	$\frac{x}{2}$
$\psi_{R,t}^\alpha$	$\bar{\square}$	$\bullet$	$\bullet$	$-\frac{1}{2}(x+1)$
$\psi_{R,b}^\alpha$	$\bar{\square}$	$\bullet$	$\bullet$	$-\frac{1}{2}(x-1)$

Assume fermionic components in ϕ_c do not contribute to anomalies, among $\psi' s$:

Gauge anomalies are cancelled when $Nx = 1$.

Global anomalies are matched.

Abbot & Farhi : Nuclear Physics B 189(1981) 547-556
Physics Letters Vol. 101B, num 1,2

Dimopoulos & Kaplan: arXiv:hep-ph/0203001

Cutting off quadratic divergences

Making top quark composite does not stabilize higgs mass.

⇨ Additional mechanism is needed in UV.

⇨ Benefit: heavy particles do not carry SU(3) color.

$$\delta m_H^2 \simeq \frac{3y_t^2}{4\pi^2}\Lambda_C^2 + \frac{N y_\psi^2}{4\pi^2}\Lambda_\psi^2 .$$

Stabilize higgs mass through Composite Higgs or SUSY.

Cutting off quadratic divergences

Composite Higgs:

Higgs will become a PNGB at higher energy.

Colorless fermionic partner, T', is introduced at Λ_ψ .

T' shares the same quantum numbers as ψ_L or $\psi_{R,t}$.

T' can combine with ϕ_c to form a colored composite top partners!

Same as ordinary composite higgs models?

⇨ No, the production of such states will be dramatically reduced, due to SU(N) hadronization process!

Such states are effectively removed from collider point of view.

Cutting off quadratic divergences

SUSY:

Colorless superpartner of ψ_L and $\psi_{R,t}$ are introduced, ϕ_L and $\phi_{R,t}$.

Again, ϕ_L and $\phi_{R,t}$ can combine with ϕ_c to form colored stops!

The production of such states will be dramatically reduced,
due to SU(N) hadronization process!

⇨ Such states are effectively removed from collider point of view.

Additional subtleties:

Superpartners of colored parton $\tilde{\psi}_c$ needs to be around,
in order to stabilize the mass of ϕ_L and $\phi_{R,t}$.
However, they can be 2-loop away from Λ_ψ .

Screening from SU(N) hadronization

Composite colored particle seems to be unavoidable.

Their mass is controlled by the heaviest parton, around Λ_ψ .

The heaviest parton is colorless.

⇨ Only produced through SU(N) hadronization at a hadron collider.

QCD analogy:

Charm/bottom quark productions through light quark hadronization

Exponentially suppressed:

$$P_{q_i} \propto e^{-\pi m_i^2/\kappa} \quad \text{where} \quad \kappa \simeq \Lambda_{QCD}^2 \simeq 0.2 \text{ GeV}^2$$

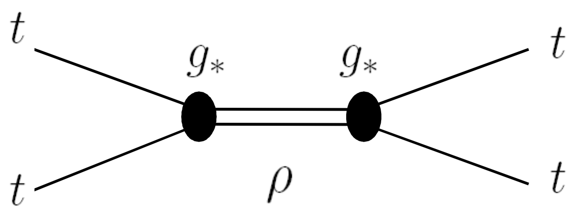
Similar suppression :

Colored composite states with heavy colorless partons

Effectively removed from collider point of view!

Pheno constraints

Higher dimension operators are introduced through SU(N):



4-Fermion interaction:

$$\frac{g_*^2}{m_\rho^2}(\bar{\Psi}\gamma_\mu\Psi)(\bar{\Psi}\gamma^\mu\Psi) \quad \text{with} \quad m_\rho \sim \Lambda_C$$

NDA: $g_* = 4\pi$

Subtleties: $g_* < 4\pi\,,\quad f \equiv \Lambda_C/g_*$ to keep track

N-dependence, model dependent (backup slides)

⇨ May show up in the denominators of coefficients.

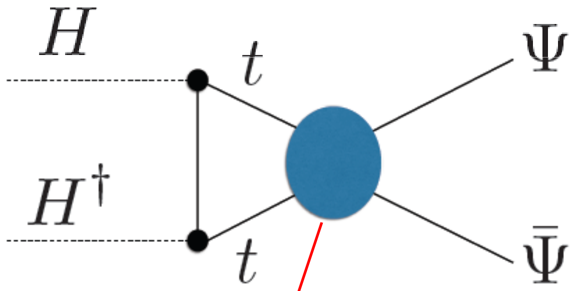
Pheno constraints

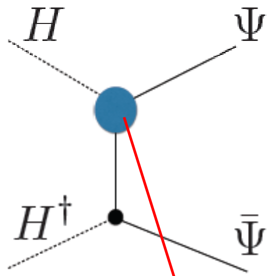
Zbb coupling:

$$\mathcal{O}_1 = ic_1(H^\dagger D^\mu H)(\bar{\Psi}\gamma_\mu \Psi) + h.c.,$$

$$\boxed{\mathcal{O}_2 = igc_2\,\bar{\Psi}W_{\mu\nu}D^\mu\gamma^\nu\Psi,}$$

does not interfere with SM





4-fermi interaction

form factor in higgs couplings

$$c_1^{loop} = \frac{\eta_b^{loop} N_c y_t^2}{16\pi^2 f^2}.$$

$$c_1^{tree} = \frac{\eta_b^{tree} y_b^2}{\Lambda_C^2}$$

$$\Rightarrow\quad f \gtrsim \sqrt{\eta_b^{loop}}\,410\ \text{GeV}$$

Pheno constraints

S&T:

$$\mathcal{O}_S = c_S(H^\dagger \tau^a H) W^a_{\mu\nu} B^{\mu\nu},$$
$$\mathcal{O}_T = c_T |H^\dagger D_\mu H|^2,$$

$$\Rightarrow \Lambda_C > \sqrt{\eta_S^\Lambda}\ 1200\ \text{GeV}$$

4-top production at the LHC (13 TeV, 3.2 fb^{-1}):

$$\mathcal{O}_{4f} = c_{4f}(\bar{\Psi}\gamma^\mu \Psi)(\bar{\Psi}\gamma_\mu \Psi).$$

$$\Rightarrow f > \sqrt{\eta_{4f}}\ 450\ \text{GeV}$$

Pheno constraints

Flavor and CP

$$
\begin{aligned}
t_{L/R,I} &\approx \theta^u_{L/R} u_{L/R,M} + \theta^c_{L/R} c_{L/R,M} + t_{L/R,M}\,, \\
b_{L/R,I} &\approx \theta^d_{L/R} d_{L/R,M} + \theta^s_{L/R} s_{L/R,M} + b_{L/R,M}\,.
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{O}_{F1} &= \frac{e^2}{\Lambda_C^2}(\bar{\Psi}_{L/R}\gamma^\mu \Psi_{L/R})(\bar{l}\gamma^\mu l), &\qquad \mathcal{O}_{F3} &= \frac{1}{f^2}(\bar{\Psi}\gamma^\mu\Psi)(\bar{\Psi}\gamma_\mu\Psi), \\
\mathcal{O}_{F2} &= e\frac{m_\Psi}{\Lambda_C^2} F_{\mu\nu}(\bar{\Psi}_{L/R}\sigma^{\mu\nu}\Psi_{R/L}), &\qquad \mathcal{O}_{F4} &= \frac{1}{16\pi^2 f^2}(H^\dagger D_\mu H)(\bar{\Psi}\gamma^\mu\Psi).
\end{aligned}
$$

$$
(\bar{t}_I\gamma^\mu t_I)(\bar{t}_I\gamma_\mu t_I) \longrightarrow (\bar{c}_M\gamma^\mu u_M)(\bar{c}_M\gamma_\mu u_M)
$$

D-meson oscillation

$$
\begin{aligned}
|\theta^{d*}_L + \theta^u_L| &\simeq |V_{ub}|, \\
|\theta^{s*}_L + \theta^c_L| &\simeq |V_{cb}|,
\end{aligned}
$$

Pheno constraints

Constraints from down-sector mixing are most serious:

⇨ Impose flavor symmetry to remove mixing from down sector.

⇨ Mixings in up-sector are totally fixed by CKM matrix.

Under such assumption, strongest constraints are from CPV in D-meson.

⇨ $$f \gtrsim \sqrt{\eta_{4f}}\, 810\ \mathrm{GeV}.$$

Constraints are imposed on f.

⇨ Subtleties from g_* and N-counting in order to link to Λ_C .

40% tuning is needed to achieve f~450 GeV as 4-top direct search.

Pheno constraints

Summary:

The strongest constraints on Λ_C directly are from S-parameter.

$$\Lambda_C \gtrsim \sqrt{\eta_S^\Lambda}\ 1200\ \mathrm{GeV}$$

The strongest constraints on f are from CPV in D-meson system.

$$f \gtrsim \sqrt{\eta_{4f}}\ 810\ \mathrm{GeV}$$

With subtleties on g_* and N-counting in mind, we claim

$$\Lambda_C \sim \text{few TeV}$$

Fine tuning is about 1%.

Collider signatures

Heavy resonances from strong dynamics:

Resonances produced through s-channel, such as ρ.

Best search channel is ttbar resonance.

CMS KK-gluon search, assuming ~15% width

⇨ 2.3 TeV at 8 TeV with 20 fb^{-1}

⇨ Constraints are weaker if wider.

Resonances only associated produced, such as excited-top.

More difficult to search than s-channel resonance.

Excited-top can have mass above Λ_C, thus naturally wide.

⇨ Different from ordinary composite higgs models
where T are lighter than Λ_C which is expected to be narrow!

Collider signatures

Multiple top/bottom productions when energy is higher than Λ_C.

Average multiplicity of any hadron species from QCD hadronization:

$$\langle n(s) \rangle \sim exp\left\{ \frac{1}{b}\sqrt{\frac{2N_c}{\pi\alpha_s(s)}} \right\}$$

Depending on beta-function of SU(N) as well as N, multiplicity may vary.

Depending on low energy spectrum from SU(N), final products from hadronization are also model dependent.

Conclusion

Consider a scenario where 3rd generation quarks are composite.

⇨ Assign different jobs to different partons.

(coupling to higgs and carrying SU(3) color charge)

⇨ Colorless particles in UV are needed to cancel quadratic divergences.

Colored composite particles are unavoidable in spectrum.

⇨ Productions are dramatically reduced by SU(N) hadronization.

⇨ Effectively removed from collider point of view.

Various pheno constraints to this scenario.

$\Lambda_C \sim \text{few TeV}$ ⇨ fine tuning at percent level

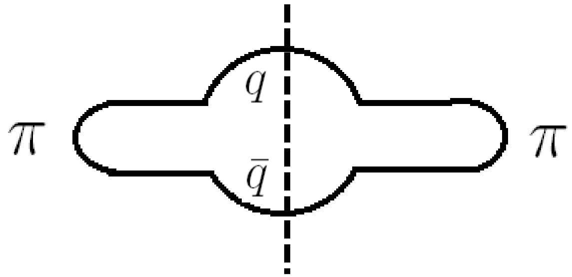
Interesting collider signatures.

⇨ No guarantee on the existence of narrow resonances.

⇨ Signatures are model dependent.

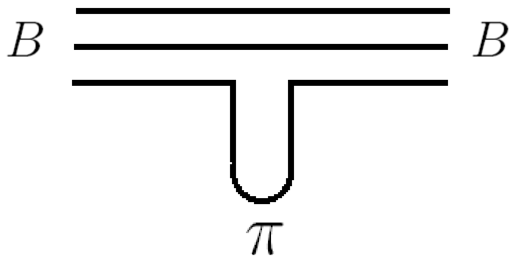
N-counting

All quarks are in fundamental rep of SU(N):



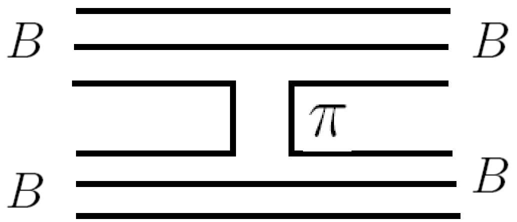
$$\Rightarrow \langle \pi(x)\pi(y) \rangle \sim N$$

$$\Rightarrow \lambda_{\pi q \bar{q}} \sim \frac{1}{\sqrt{N}}$$



$$\Rightarrow \lambda_{\pi B \bar{B}} \sim \frac{1}{\sqrt{N}} \times N \sim \sqrt{N}$$

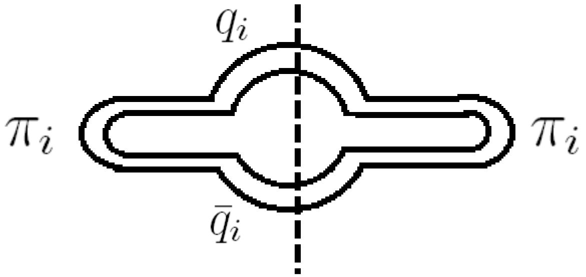
N ways of insertion



$$\Rightarrow \mathcal{M}_{BB \to BB} \sim N^0$$

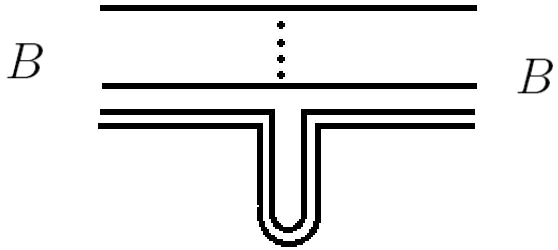
N-counting

Example: SU(6) with $\psi_{1,2,3}$ transforming as $\mathbf{6},\ \mathbf{15},\ \mathbf{20}$



$$\Rightarrow \langle \pi_i(x)\pi_i(y)\rangle \sim N^i$$

$$\Rightarrow \lambda_{\pi_i q_i \bar{q}_i} \sim \frac{1}{\sqrt{N^i}}$$



$$\Rightarrow \lambda_{\pi_i B\bar{B}} \sim \frac{1}{\sqrt{N^i}} \times 1$$

only one way of insertion

Under non-trivial reps, the interactions may have large N suppression.

Another semi-UV completion

confines

Particles	$SU(N)$	$SU(N+3)_1$	$SU(N+3)_2$	$SU(2)_L$	$U(1)_Y$
ϕ_c	$\bullet$	$\square$	$\bar{\square}$	$\bullet$	0
ψ_L^α	$\bullet$	$\square$	$\bullet$	$\square$	$\frac{1}{6}$
$\psi_{R,t}^\alpha$	$\bullet$	$\bar{\square}$	$\bullet$	$\bullet$	$-\frac{2}{3}$
$\psi_{R,b}^\alpha$	$\bullet$	$\bar{\square}$	$\bullet$	$\bullet$	$\frac{1}{3}$
$\psi_L'^\alpha$	$\bar{\square}$	$\bullet$	$\bullet$	$\square$	$-\frac{1}{6}$
$\psi_{R,t}'^\alpha$	$\square$	$\bullet$	$\bullet$	$\bullet$	$\frac{2}{3}$
$\psi_{R,b}'^\alpha$	$\square$	$\bullet$	$\bullet$	$\bullet$	$-\frac{1}{3}$
Δ	$\square$	$\bullet$	$\bar{\square}$	$\bullet$	0

Condensation of Δ :

$$SU(N)\times SU(N+3)_2 \Rightarrow SU(N)_D\times SU(3)_C$$