More Natural Composite Higgs Models

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Introduction

In Standard Model (SM) electroweak symmetry breaking is achieved by an elementary scalar Higgs field with a potential:

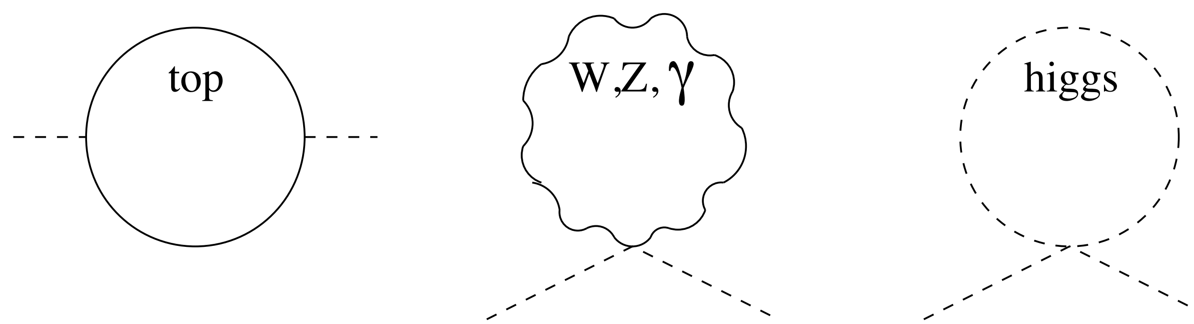
$$V(H) = -m^2 H^\dagger H + \lambda (H^\dagger H)^2$$

- From the Higgs VEV v=246 GeV and the observed Higgs boson mass 125 GeV, we can determine the parameters of the Higgs potential:

$$m^2 \simeq (88\,\mathrm{GeV})^2, \quad \lambda \simeq 0.13.$$

Introduction

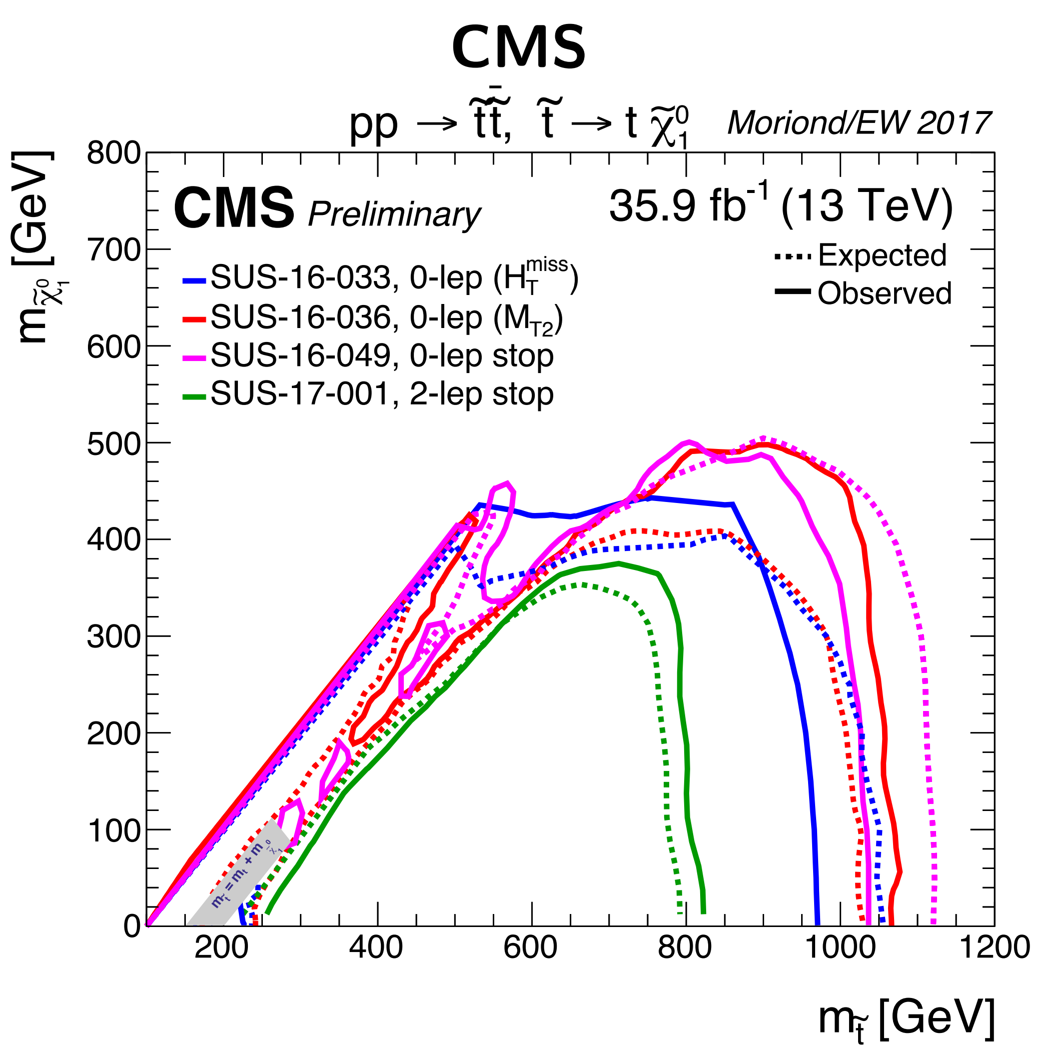
- The SM Higgs receives quadratically divergent radiative corrections from its interactions with SM fields.

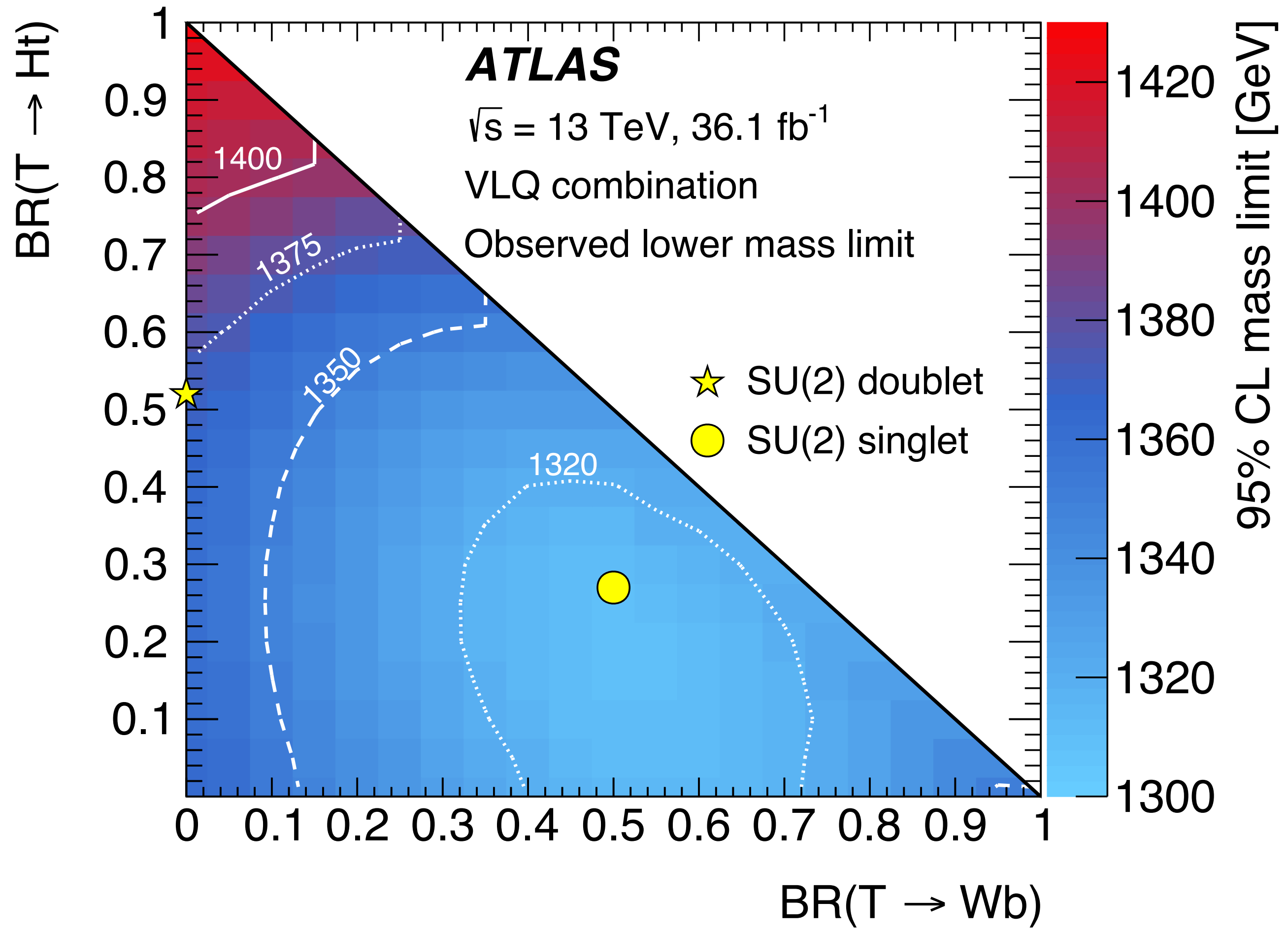


- The largest comes from the top Yukawa interaction. The solutions to the hierarchy problem based on symmetries require new particles (top partners) to cut off the top quark loop.

Introduction

- If top partners carry SM color as in traditional supersymmetric (SUSY) or composite Higgs models, they are strongly constrained by LHC searches (beyond 1 TeV except for special cases).





Introduction

- If the cutoff of the top quark loop is larger than 1 TeV, some tuning in the Higgs potential is already required.

$$\Delta m^2 \sim -(250\,\text{GeV})^2 \left(\frac{\Lambda}{1.5\,\text{TeV}} \right)^2$$

- In actual models the tuning is often more severe.
  - In SUSY models the contribution is enhanced by a log due to running from high scales.
  - In most composite Higgs models, there are even larger UV contributions to the Higgs potential, as will be discussed later.

- Tuning can be reduced if top partners do not carry SM color as in neutral naturalness models, which are not the subject of this talk.

Composite Higgs

- To naturally separate the scales of the Higgs mass and the strong composite dynamics, Higgs field should be the pseudo-Nambu-Goldstone bosons (PNGBs) of spontaneously broken (approximate) global symmetry (***G***→***H***) of the strong dynamics (analogous to pions in QCD).

  E.g., SO(5)/SO(4) (minimal composite Higgs). There are 4 PNGBs identified as the Higgs field.

  $SU(2)_W \times U(1)_Y$ is embedded in $SO(5) \times U(1)_X$, the SO(5) breaking VEV f is slightly misaligned with the direction which preserves $SU(2)_W \times U(1)_Y$, corresponding to an EW breaking VEV $v \ll f$.

Partial Compositeness

- To obtain SM Yukawa couplings, we have SM (elementary) fermions mix with composite operators of strong dynamics.

$$\lambda_L \bar{q}_L O_R, \quad \lambda_R \overline{O}_L q_R$$

q_L, q_R : elementary fermions

O_L, O_R : composite operators of some representations of ***G***

SM Yukawa couplings $y \simeq \dfrac{\lambda_L \lambda_R}{g_\psi} \simeq \epsilon_L \cdot g_\psi \cdot \epsilon_R$

g_ψ : coupling of the strong resonances (analogue of g_ρ in QCD, expected >>1). The resonances created by $O_{L,R}$ have masses ~ $g_\psi f$. $\epsilon_{L,R} = \lambda_{L,R}/g_\psi < 1$

Partial Compositeness

- The resonances created by $O_{L,R}$ are divided into representations of ***H*** (since ***G*** is broken). They play the roles of SM fermion partners which cut off the divergent contribution to the Higgs potential.
  - Adding the contribution from an individual set of resonances of a representation of ***H*** is still divergent. The finiteness is imposed by the Weinberg's sum rules, which can be shown explicitly in holographic (or deconstructed) models.
- Higgs potential is generated by λ_L, λ_R (and also SM gauge couplings) which break the global symmetry ***G*** explicitly.

Higgs Potential

- To leading order, the Higgs potential takes the form:

$$V(H) = -\alpha f^2 \sin^2 \frac{H}{f} + \beta f^2 \sin^4 \frac{H}{f}$$

where α and β are model dependent, generated by explicit breaking parameters $\lambda_L, \lambda_R, \ldots$

- To achieve realistic EWSB with $v \ll f$, we need

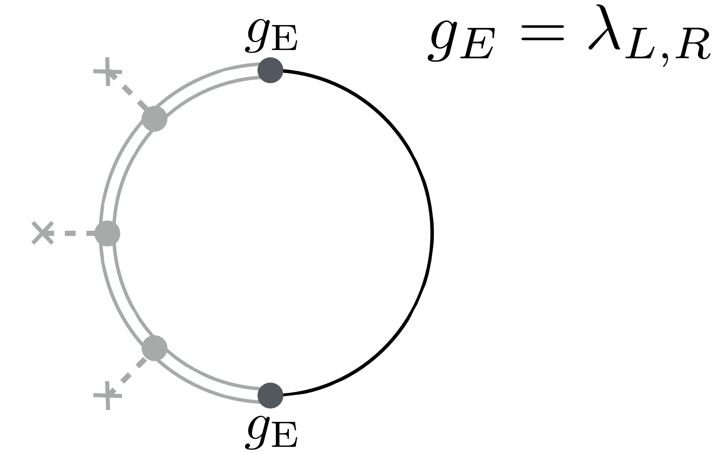
$$\frac{\alpha}{\beta} = 2\xi \equiv 2 \sin^2 \frac{\langle H \rangle}{f} \ll 1$$

also the right size of β for the 125 GeV Higgs boson.

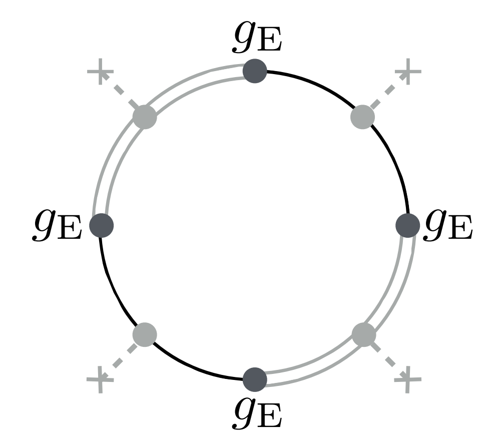
- In most composite Higgs models, one expects $\alpha \gtrsim \beta$, which is the source of fine tuning.

Higgs Potential

- Ex: SO(5)/SO(4), $O_L, O_R \in \mathbf{5}$ of SO(5)



$$\alpha \sim \frac{N_c}{16\pi^2}\lambda_{L,R}^2 m_\psi^2 \sim \epsilon_{L,R}^2 \frac{N_c g_\psi^4}{16\pi^2} f^2$$



$$\beta \sim \frac{N_c}{16\pi^2}\lambda_{L,R}^4 f^2 \sim \epsilon_{L,R}^4 \frac{N_c g_\psi^4}{16\pi^2} f^2$$

β arises at higher order in ϵ than α, also α is larger than the IR contribution from the top quark loop.

$$\Delta m_{\mathrm{IR}}^2 \sim \frac{N_c}{8\pi^2} y_t^2 m_\psi^2 \sim \epsilon_L^2 \epsilon_R^2 \frac{N_c g_\psi^4}{8\pi^2} f^2$$

Higgs Potential

- In some models, e.g., $O_L, O_R = \mathbf{14}$ of SO(5), α and β arise at the same order.

$$\alpha \sim \beta \sim \frac{N_c}{16\pi^2}\lambda_{L,R}^2 m_\psi^2 \sim \epsilon_{L,R}^2 \frac{N_c g_\psi^4}{16\pi^2} f^2$$

It's less tuned to obtain $\alpha/\beta = 2\xi$ (called "minimal tuning"), but both α, β are generically too large phenomenologically.

More Natural Higgs Potential

- To obtain a more natural Higgs potential, we would like to
  - suppress the $\mathcal{O}(\lambda_{L,R}^2)$ contributions to the quadratic term in the Higgs potential (keeping α small),
  - generate some quartic potential without inducing the quadratic term (making $\beta > \alpha$).
- The wishlist calls for the collective symmetry breaking of the little Higgs mechanism.

More Natural Higgs Potential

- The Higgs potential arise at $\mathcal{O}(\lambda_{L,R}^2)$ because the resonances created by $\boldsymbol{O_L}$, $\boldsymbol{O_R}$ are split into representations of ***H***. The partial compositeness couplings $\lambda_{L,R}$ do not preserve any symmetry to protect the Goldstone nature of the Higgs field.

- To suppress $\mathcal{O}(\lambda_{L,R}^2)$ contributions to the Higgs potential, we look for models where any single $\lambda_{L,R}$ preserves a larger symmetry which protects the Goldstone nature of the Higgs, and the Higgs potential can only arise by combining two or more such couplings.

Cosets with Collective Symmetry Breaking

- The cosets SU(5)/SO(5) and SU(6)/Sp(6) considered in little Higgs theories are promising candidates.
- If $O_{L,R} = \mathbf{5}($or $\mathbf{6})$ of SU(5) (or SU(6)), the corresponding resonances do not split under the unbroken subgroup SO(5) (Sp(6)). (They remain complex because they need to carry an additional $U(1)_X$ charge to account for the hypercharge.) As they are complete ***G*** (=SU(5) or SU(6)) multiplets. There is an enhanced symmetry for each individual partial compositeness coupling, which protects the Higgs mass.

SU(6)/Sp(6) Model

CCWZ: $SU(6) \xrightarrow{\langle\Sigma\rangle} Sp(6)$ $\quad \langle\Sigma\rangle \propto \begin{pmatrix} 0 & -I \\ I & 0 \end{pmatrix} \equiv \Sigma_0$

Goldstone matrix: $\xi^i_\alpha = e^{i\frac{\pi_A X_A}{2f}} \to V^i_j\, \xi^j_\beta\, U^{\dagger\beta}_\alpha$

$(\xi \to g\xi h^{-1})$

i: SU(6) index
α: Sp(6) index
a: SU(2)w index
A: generator index

Gauge generators: $Q^A = \begin{pmatrix} \sigma^A & & & \\ & 0 & & \\ & & -\sigma^{A*} & \\ & & & 0 \end{pmatrix}, \quad Y = \begin{pmatrix} \mathbf{0} & & & \\ & 1/2 & & \\ & & \mathbf{0} & \\ & & & -1/2 \end{pmatrix}$

$$\pi_A X_A = \begin{pmatrix} \frac{\sigma_B}{2} w_B & H_2 & \begin{pmatrix} 0 & s \\ -s & 0 \end{pmatrix} & H_1 \\ H_2^\dagger & z/2 & -H_1^T & 0 \\ \begin{pmatrix} 0 & -s^* \\ s^* & 0 \end{pmatrix} & -H_1^* & \frac{\sigma_B^*}{2} w_B & H_2^* \\ H_1^\dagger & 0 & H_2^T & z/2 \end{pmatrix}$$

14 GBs =
2 doublets, H_1, H_2
1 complex singlet s
real triplet + singlet
w_B +z

SU(6)/Sp(6) Model

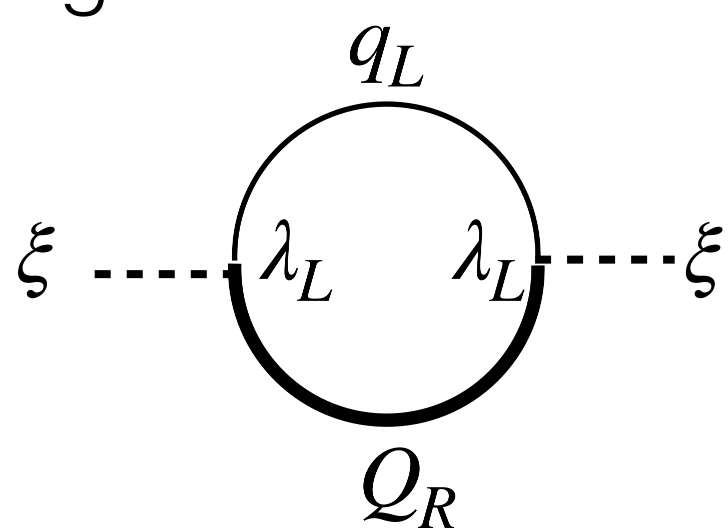
Compositeness resonances $Q_{L,R} = \mathbf{6}_{1/6}$ of Sp(6)×U(1)$_X$

$O^i_{L,R} \sim \xi^i_\alpha Q^\alpha_{L,R} \sim \mathbf{6}_{1/3}$ of SU(6) [$= \mathbf{2}_{1/6} \oplus \mathbf{1}_{2/3} \oplus \bar{\mathbf{2}}_{1/6} \oplus \mathbf{1}_{-1/3}$]

Partial compositeness couplings: $\lambda_L\, \bar{q}_{La}\, \Lambda^a_i \left(\xi^i_\alpha Q^\alpha_R\right)$

$\Lambda^a_i = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \end{pmatrix}$ is the spurion keeping track of symmetry breaking

The interaction preserves an SU(6) represented by the α index, which protects the Higgs mass. Without an insertion of Σ_0, it can't distinguish Sp(6) from SU(6).



$\propto \Lambda \xi \xi^\dagger \Lambda^\dagger = \Lambda \Lambda^\dagger$

No Higgs potential at $\mathcal{O}(\lambda_L^2)$!

SU(6)/Sp(6) Model

To obtain SM Yukawa couplings, we have the partial compositeness coupling for the right-handed fermions $\lambda_R^* \, \bar{t}_R \, \Gamma^j \, O'_{L,j}$ where

$$O'_{L,R,j} \sim \xi_j^{*\beta} \Sigma_{0\beta\alpha} Q^\alpha_{L,R} \sim \bar{\mathbf{6}}_{1/3} \text{ of SU(6)} \quad [= \bar{\mathbf{2}}_{1/6} \oplus \mathbf{1}_{-1/3} \oplus \mathbf{2}_{1/6} \oplus \mathbf{1}_{2/3}]$$

$$\Gamma^j = (0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1)$$

Combining λ_L and λ_R, we generate the SM Yukawa coupling:

$$\sim \lambda_L \, \lambda_R \, \bar{q}_{La} \, \Lambda_i^a \, \underbrace{\xi^i_\alpha \Sigma_0^{\alpha\beta} \xi^{Tj}_\beta}_{\Sigma^{ij}} \, \Gamma_j^\dagger \, t_R \supset y_t \, \bar{q}_L \, H_2 \, t_R$$

With Σ_0, SU(6) is explicitly broken and the Higgs mass term is generated at the order $\lambda_L^2 \lambda_R^2 \sim y_t^2$, which is the same as the IR contribution estimated earlier.

Collective Quartic Coupling

Little Higgs mechanism:

$$V \supset c_1 f^2 \left| s + \frac{i}{2f} H_1 H_2 \right|^2 + c_2 f^2 \left| s - \frac{i}{2f} H_1 H_2 \right|^2$$

First term invariant under

$$\begin{aligned} H_1 &\to H_1 + \epsilon_1 + \cdots, \\ H_2 &\to H_2 + \epsilon_2 + \cdots, \\ s &\to s - \frac{i}{2f}(\epsilon_1 H_2 + H_1 \epsilon_2) + \cdots, \end{aligned}$$

Second term invariant under

$$\begin{aligned} H_1 &\to H_1 + \eta_1 + \cdots, \\ H_2 &\to H_2 + \eta_2 + \cdots, \\ s &\to s + \frac{i}{2f}(\eta_1 H_2 + H_1 \eta_2) + \cdots, \end{aligned}$$

A quartic term $|H_1 H_2|^2$ is generated after integrating out s.

Collective Quartic Coupling

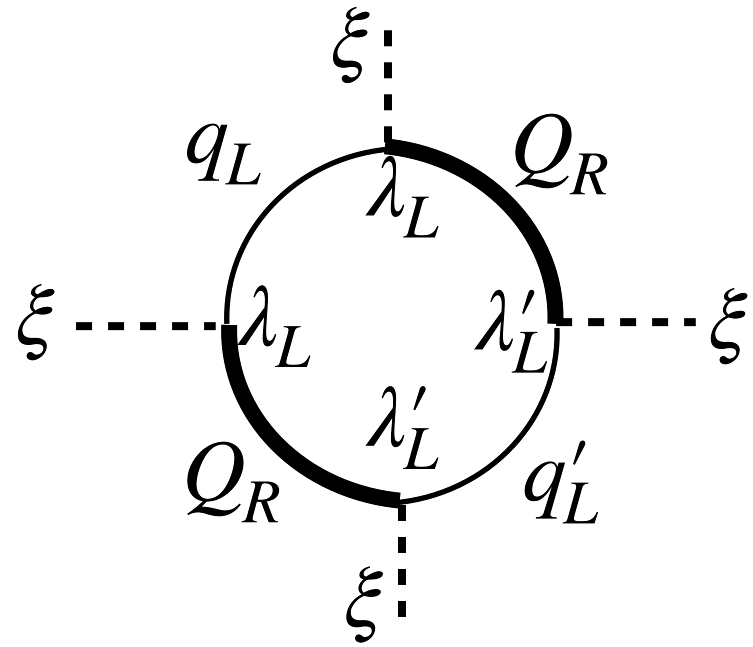
$Q_{L,R} \sim \mathbf{2}_{1/6} \oplus \mathbf{1}_{2/3} \oplus \bar{\mathbf{2}}_{1/6} \oplus \mathbf{1}_{-1/3}$ contains 2 doublets with the same quantum numbers.

In addition to $\lambda_L \, \bar{q}_{La} \, \Lambda^a_i \, \left(\xi^i_\alpha Q^\alpha_R\right)$ $\qquad \Lambda^a_i = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \end{pmatrix}$

we can have a coupling

$$\lambda'_L \, \bar{q}'_{La} \, \epsilon^{ab} \Omega^i_b \, \left(\xi^{*\alpha}_i \Sigma_{0\alpha\beta} Q^\beta_R\right) \qquad \Omega^i_a = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \end{pmatrix}$$

Λ and Ω preserve an SU(4) symmetry which protects H_1, H_2 but not the singlet s.

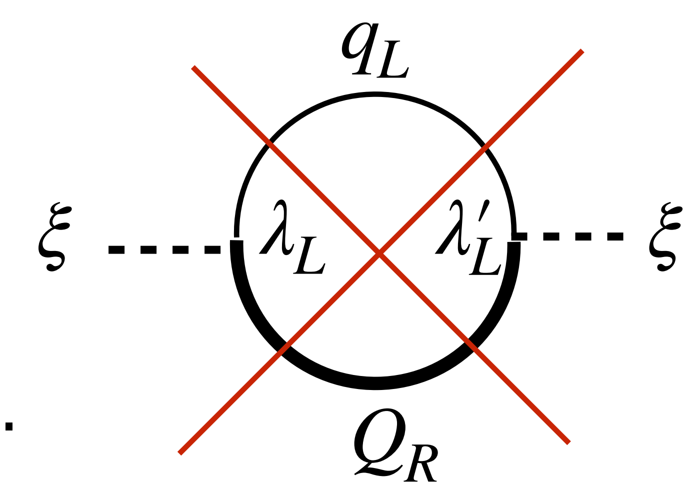


$$\sim |y_L|^2 |y'_L|^2 \mathrm{tr}\left(\Lambda^\dagger \Lambda \, \Sigma \, \Omega^\dagger \Omega \, \Sigma^\dagger\right)$$

$$\supset |y_L|^2 |y'_L|^2 \left| s + \frac{i}{2f} H_1 H_2 \right|^2$$

Collective Quartic Coupling

- q_L, q'_L should be different, to avoid generating a large s tadpole term. This term violates a U(1)$_{\text{PQ}}$ symmetry where q_L and q'_L carry different charges.



$$T_{\text{PQ}} = \text{diag}(+1, +1, 0, -1, -1, 0),$$
$$s(+2), H_1(+1), H_2(+1), q_L(+1), q'_L(-1)\,.$$

$$\sim \lambda_L^* \lambda'_L (s + \frac{i}{2f} H_1 H_2)$$

This PQ symmetry also avoids large FCNC.

- The other collective quartic term can be generated by a different set of quarks or leptons which are arranged to preserve the other SU(4) symmetry (of 1,2,3,6 entries).

- The quartic coupling is generated at the order $|\lambda_L \lambda'_L|^2$, can be larger than the quadratic term ($\beta > \alpha$) if $\lambda'_L > \lambda_R$.

Discussion and Conclusions

- The fine tuning problem in composite Higgs models can be largely relieved by choosing appropriate cosets and implementing the little Higgs mechanism to obtain the Higgs quartic coupling. There are different phenomenological implications for specific models.
- The Higgs couplings to gauge bosons and fermions are modified by $\mathcal{O}(\xi)$ as in all composite Higgs models. The current constraints require $\xi \lesssim 10\,\%$ .The SU(6)/Sp(6) model has two Higgs doublets. It should be close to the alignment or decoupling limit to be consistent with experimental data.

Discussion and Conclusions

- In SU(6)/Sp(6) model, the partial compositeness interactions induce corrections to $Z\bar{f}f$ couplings for SM fermions, which is measured to $\sim \mathcal{O}(10^{-3})$. To achieve the desired Higgs quartic coupling and to satisfy the constraints, the corresponding composite resonances should be heavy ($\gtrsim$ 5-10 TeV). This means that it's preferable to generate the collective Higgs quartic coupling using the first 2 generation quarks and leptons so that the top partner can be light ($\lesssim$ 2 TeV).

Discussion and Conclusions

- The SU(5)/SO(5) model has the custodial symmetry to suppress the $Z\bar{b}b$ vertex correction (and it contains the charge 5/3 top partner).
- The collective Higgs quartic term in SU(5)/SO(5) is obtained somewhat differently. (The two doublets in $\mathbf{5}$ have different hypercharges and are inequivalent). It can be obtained by using the neutrino couplings or adding new elementary fermions.
- However, the SU(2) triplet Higgs in this model in general will get a VEV, causing custodial SU(2) violation, and producing too large Majorana masses for neutrinos.