

# A New Mechanism for Light Composite Higgs Bosons

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## Abstract

Repeated symmetry-breaking and restoration phase transitions occur as one traverses the parameter space of interactions competing to align the vacuum. This phenomenon, augmented with a topcolor-like interaction, can make a composite Higgs boson's mass and vacuum expectation value naturally much less than its underlying structure scale, without introducing new symmetries and their associated TeV-scale particles. We illustrate it by reconstructing a simple light composite Higgs model of electroweak symmetry breaking proposed by Georgi and Kaplan.

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Precision data strongly suggest that spontaneous electroweak  $SU(2)_W \otimes U(1)_Y$  symmetry breaking (EWSB) occurs via a scalar doublet with low Higgs boson mass  $M_h \lesssim 300$  GeV [1]. On the other hand, EWSB via an elementary Higgs boson field, without new physics to stabilize its mass and VEV at such a low energy, is fraught with well-known theoretical difficulties. There are many interesting proposals for stabilizing the Higgs mass, yet none has led to a completely satisfactory “standard model of physics beyond the standard model”. Therefore, it is worthwhile to explore many approaches; one of them may even be supported by data from the LHC. We propose here a new variant of light composite Higgs (LCH) models, one in which the Higgs is an accidental Goldstone boson (AGB) [2].

An AGB is a pseudo-Goldstone bosons which is anomalously light compared to its PGB partners because its mass must vanish at second-order symmetry-phase transitions and because such transitions can occur repeatedly as one varies one or more couplings in the explicit chiral symmetry breaking interaction  $\mathcal{H}'$  that gives mass to the PGBs. The phase transitions occur on critical surfaces in  $\mathcal{H}'$ -parameter space. Varying one coupling follows a trajectory in this space and a transition occurs as it pierces a critical surface. If we happen to live in a region between two transitions, at least one PGB is likely to be very light. In Ref. [2] we studied this phenomenon, emphasizing that the generality of phase transitions and the exact vanishing of the AGB mass there. There we focused on discrete symmetry transitions but, of course, the same occurs for continuous symmetries, and that will be important for us.

In [2] we considered AGBs with a specific ultraviolet completion: They were  $\bar{\psi}_L \psi_R$  composites of  $N$  strongly interacting massless Dirac fermions  $\psi_i$  whose characteristic interaction scale is  $\Lambda_\psi \simeq 4\pi F_\pi$ , with  $F_\pi$  the PGBs’ decay constant. We suggested there that an AGB may serve as an LCH for EWSB. To qualify as an LCH, the boson must be much lighter than  $\Lambda_\psi$  and its VEV  $v$  much less than  $F_\pi$  [3, 4, 5, 6, 7]. Following common practice, we will take  $v \simeq 250$  GeV  $\ll F_\pi$  to mean  $v < (0.25\text{--}0.5)F_\pi$ , postponing the naturalness/hierarchy problem of standard elementary Higgs models to  $\Lambda_\psi = 5\text{--}10$  TeV.

Light AGB masses, due to multiple phase transitions, were easy to achieve in [2]. While we also showed that  $v \ll F_\pi$  may occur, we gave no recipe for it. The problem was that those were *discrete* symmetry transitions and the VEV did not always need to vanish when the mass did. Transitions between phases of a continuous symmetry correlate the vanishing of the mass and the VEV, and that is the basis of our approach to constructing LCH models of EWSB: A set of interactions in  $\mathcal{H}'$ , some of which come from physics well above  $\Lambda_\psi$ , compete to align the vacuum in different directions, creating a complex vacuum structure. As one follows paths in the space of  $\mathcal{H}'$  couplings, one encounters multiple spontaneous breaking and restorations of electroweak symmetry. This drives the Higgs mass and VEV repeatedly to zero, with the possibility that *both* remain small in the intervening EWSB region we live in.

This AGB mechanism is natural in that  $M_h$  and  $v$  can stay small for a sizable region,  $\Delta\kappa$ , of a basic coupling  $\kappa$  in  $\mathcal{H}'$ . We emphasize, however, that there is no symmetry in our scheme keeping  $M_h$  and  $v$  small. If the spacing  $\Delta\kappa$  between phase transitions is too large,  $v$  grows to remain close to  $F_\pi$  over most of the region. If  $\Delta\kappa/\kappa \ll 1$ ,  $M_h$  and  $v$  would be tiny,

but at the expense of fine-tuning. We find that it is easy to choose parameters so that both remain small over a region with  $\Delta\kappa/\kappa = \mathcal{O}(1)$ . We shall quantify this statement below. An advantage of not imposing additional symmetries is that we need not introduce associated TeV-scale particles that can conflict with precision measurements.

In this paper we illustrate the AGB mechanism with a toy model, albeit a fairly sophisticated one. It is based on Refs. [6, 7]. It has the nice feature of a custodial  $SU(2)_C$  symmetry preserving  $\rho \cong 1$ . The model's additional scalars are weakly coupled to ordinary matter and, so, have little impact on other precisely measured EW quantities. Given the large mass of the top quark, we will have to invoke topcolor-like gauge interactions [8] to prevent its overwhelming influence on vacuum alignment. This is a general feature of our scheme. Taking the particular model seriously, it has some interesting phenomenology that we'll discuss at the end.

Note the differences between our scheme and that of little Higgs models [9, 10, 11, 12]. There, to ensure that one is close to the EW transition without fine tuning once quantum corrections are included, approximate global symmetries, involving new heavy particles, are imposed to soften the cutoff dependence. Furthermore, the top quark plays a central role in breaking EW symmetry in little Higgs models. In topcolor, the contribution of the  $t\bar{t}$  condensate to  $v$  is small.

*The Model:* To cast our proposal in familiar terms, the model we use is based on an  $SU(5)/SO(5)$  symmetry breaking pattern, as are the models of Refs. [6, 7, 10]. In fact, we follow the pattern of the Georgi-Kaplan (GK) model exactly, relying extensively on its full description in Ref. [7].

The model has five flavors of massless Weyl fermions  $\psi = \{\psi_i, i = 1, \dots, 5\}$  transforming as the real representation of some strong ‘‘ultracolor’’ group,  $G_{UC}$ . It is assumed that  $G_{UC}$  interactions form condensates, given in the ‘‘standard vacuum’’  $|\Omega\rangle$  by

$$\langle\Omega|\psi_i\psi_j^T|\Omega\rangle \simeq -2\pi F_\pi^3\Delta_{ij}, \quad (1)$$

$$\Delta = \begin{pmatrix} \sigma_2 \otimes \tau_2 & 0 \\ 0 & 1 \end{pmatrix}. \quad (2)$$

The vacuum symmetry  $SO(5)$  contains  $SU(2)_W \otimes SU(2)'$  — the gauged electroweak  $SU(2)$  symmetry (coupling  $g$ ) and an  $SU(2)$  whose third generator is weak hypercharge  $U(1)_Y$  ( $Y = Q'_3$  with coupling  $g'$ ).

$$Q_a = \frac{1}{2} \begin{pmatrix} \sigma_a \otimes 1 & 0 \\ 0 & 0 \end{pmatrix}, \quad Q'_a = \frac{1}{2} \begin{pmatrix} 1 \otimes \tau_a & 0 \\ 0 & 0 \end{pmatrix}; \quad (a = 1, 2, 3). \quad (3)$$

When EWSB occurs,  $SU(2)_W \otimes SU(2)' \rightarrow SU(2)_C$ , the custodial  $SU(2)$ . Generators  $T_a$  of  $SO(5)$  and  $X_a$  of  $SU(5)/SO(5)$  satisfy  $\Delta T_a \Delta = -T_a^T$  and  $\Delta X_a \Delta = X_a^T$ . An important generator is  $Q_{24} = 1/\sqrt{20} \text{diag}(1, 1, 1, 1, -4)$ . We will assume it is gauged, but broken far above  $\Lambda_\psi$ .

The fluctuations of the vacuum about the standard one with condensate  $\Delta$  are described by the unitary matrix  $U$ :

$$U = e^{i\mathbf{H}/2F_\pi} e^{i\boldsymbol{\eta}/F_\pi} e^{i\boldsymbol{\pi}/F_\pi} e^{i\mathbf{H}/2F_\pi} \Delta \equiv \Sigma \Delta, \quad (4)$$

where the 14 PGB fields and their  $SU(2)_W \otimes SU(2)'$  representations are

$$\mathbf{H} = \frac{1}{\sqrt{2}} \begin{pmatrix} & \tilde{h} \\ & h \\ \tilde{h}^\dagger & h^\dagger \\ & & 0 \end{pmatrix} \in (2, 2), \quad h = \begin{pmatrix} h_1 + i h_2 \\ h_0 + i h_3 \end{pmatrix}, \quad \tilde{h} = i\sigma_2 h^*; \quad (5)$$

$$\boldsymbol{\eta} = \sqrt{2} \eta Q_{24} \in (1, 1); \quad \boldsymbol{\pi} = \frac{1}{\sqrt{2}} \pi_{ab} \begin{pmatrix} \sigma_a \otimes \tau_b & 0 \\ 0 & 0 \end{pmatrix} \in (3, 3).$$

When EWSB occurs and the three GBs in  $h$  are eaten, the Higgs field is given in unitary gauge by  $\mathbf{H} = hX/F_\pi$  where  $X_{ij} = (\delta_{i1} + \delta_{i4})\delta_{j5} + (i \leftrightarrow j)$ . So long as only the Higgs doublet gets a VEV,  $v = \langle h \rangle$ , the expectation value of  $\Sigma$  is  $\langle \Sigma \rangle = e^{i\langle \mathbf{H} \rangle} = 1 + i \sin(v/F_\pi)X + (\cos(v/F_\pi) - 1)X^2$  and the weak boson masses are, to  $\mathcal{O}(g^2\alpha)$ ,

$$M_W^2 = M_Z^2 \cos^2 \theta_W = \frac{1}{2} g^2 F_\pi^2 (1 - \cos(v/F_\pi)). \quad (6)$$

*Symmetry Breaking Interaction  $\mathcal{H}'$* : The chiral symmetries of  $\Sigma$  are explicitly broken by a Hamiltonian  $\mathcal{H}'$  which receives contributions of  $\mathcal{O}(g^2, g'^2)$  from the electroweak interactions. Additional contributions come from broken ‘‘extended ultracolor’’ (EUC) interactions of the  $\psi$ -fermions. They are mediated by heavy gauge bosons with typical mass  $M_E \gg \Lambda_\psi$  and coupling  $\alpha_E$ . We assume this  $G_{UC}$  ‘‘walks’’ [13, 14, 15, 16]. Then, the usual  $g_E^2/M_E^2$  suppression factor is enhanced by  $\approx (M_E/\chi F_\pi)^{2\gamma_\psi}$ , where  $\gamma_\psi$  is the  $\psi\psi^T$  anomalous dimension, equal to one in a strictly walking gauge theory and otherwise somewhat less, and  $\chi \simeq 1$  to  $4\pi$ , depending on where the anomalous dimension integral runs from.

In general, one expects several relevant EUC operators contributing to  $\mathcal{H}'$ , much as in the model we used to study the AGB mechanism in Ref. [2]. The resulting vacuum structure is then quite complex. To illustrate our AGB mechanism simply, we assume just one EUC operator competes with the electroweak ones, and that  $\mathcal{H}'$  is  $SU(2)_W \otimes SU(2)'$ -invariant:

$$\begin{aligned} \mathcal{H}' = & -F_\pi^4 [c_1 \text{Tr}(Y\Sigma Y\Sigma^\dagger) + c_2 \sum_{a=1}^3 \text{Tr}(Q_a \Sigma Q_a \Sigma^\dagger) \\ & + c_3 \text{Tr}(Q_{24} \Sigma Q_{24} \Sigma^\dagger) + c_4 \sum_{a=1}^2 \text{Tr}(P_a \Sigma P_a^\dagger \Sigma^\dagger + P_a^\dagger \Sigma P_a \Sigma^\dagger)]. \end{aligned} \quad (7)$$

As noted above, the top mass arises from topcolor, so that  $\Sigma$ 's coupling to top is small. The first two terms in  $\mathcal{H}'$  are in the GK model, with  $c_1 = \mathcal{O}(g^2)$ ,  $c_2 = \mathcal{O}(g^2)$  and positive. In GK, a gauge boson coupled to  $Q_{24}$  eats the  $\eta$  and produces the third term with  $c_3 < 0$ . It then

competes with the first two terms over the fate of electroweak symmetry. There is a single phase transition at a critical value of  $c_3$ . Then, the range of  $c_3$  for which  $M_h^2, v^2 \ll F_\pi^2$  is quite small, so that it must be tuned to obtain an LCH. Taken seriously, moreover, this origin for  $c_3$  makes it approximately  $4\pi^2$ . Assuming it arises from EUC interactions can make it smaller. The magnitude and sign of  $c_3$  in our scenario are discussed below. The  $c_4$  term, with  $(P_a)_{ij} = \delta_{ia}\delta_{j5}$ , is included solely to give mass to the  $\eta$ . Our mechanism is most simple if  $c_4$  is small. On the other hand, vacuum alignment is numerically difficult when massless particles are present. Therefore, we take  $c_4$  small and positive.<sup>1</sup>

With EW symmetry intact ( $v = 0$ ),  $\mathcal{H}'$  gives the following masses to the four degenerate Higgs particles  $h$ , six  $\pi$  and three  $\pi'$  from the  $(3,3)$  (split by  $U(1)_Y$ ), and the  $\eta$ :

$$\begin{aligned} M_h^2 &= \frac{1}{2}(c_1 + 3c_2 + 5c_3 + 10c_4)F_\pi^2 \\ M_\pi^2 &= 2(c_1 + 2c_2 + c_4)F_\pi^2 \\ M_{\pi'}^2 &= 2(2c_2 + c_4)F_\pi^2 \\ M_\eta^2 &= 10c_4F_\pi^2. \end{aligned} \tag{8}$$

For the  $Q_{24}$  term in  $\mathcal{H}'$ , we regard the EUC coupling  $\alpha_E$ , not  $c_3$ , as the fundamental parameter. Because ultracolor walks,  $\alpha_E \simeq \alpha_{UC}$  and it is slightly less than the critical coupling for  $\psi\psi^T$  condensation, approximately  $\pi/3C_2(R_\psi)$ . The quadratic Casimir  $C_2(R_\psi) \simeq N_{UC}$ , the number of ultracolors. The  $\mathcal{O}(\alpha_E^2)$  contribution to  $c_3$ , an ultracolor radiative correction, is about  $3\alpha_E N_{UC}/4\pi$  times the  $\mathcal{O}(\alpha_E)$  contribution and that is not negligible.<sup>2</sup> Therefore, with  $\kappa = 4\pi\alpha_E \simeq 1-10$ , we write

$$\begin{aligned} c_3 &= a_3\kappa + b_3\kappa^2; \\ |a_3| &\simeq \frac{1}{4M_E^2}\Lambda_\psi^2 \left(\frac{M_E}{\chi F_\pi}\right)^{2\gamma_\psi} = \frac{1}{4} \left(\frac{4\pi}{\chi}\right)^{2\gamma_\psi} \left(\frac{\Lambda_\psi^2}{M_E^2}\right)^{1-\gamma_\psi} \\ \left|\frac{b_3}{a_3}\right| &\simeq \frac{3N_{UC}}{16\pi^2} = \mathcal{O}(0.1) \quad \text{for } N_{UC} \simeq 4. \end{aligned} \tag{9}$$

The factor  $|a_3| = \frac{1}{4}(4\pi/\chi)^{2\gamma_\psi}(\Lambda_\psi^2/M_E^2)^{1-\gamma_\psi}$  is sensitive to its parameters and can easily lie in the range 0.1–10.

For an interaction mediated by heavy gauge boson exchange, it is entirely plausible that  $a_3 < 0$ , as GK assumed. The coefficient  $b_3$  may have either sign; we assume  $b_3 > 0$ . We choose  $c_4$  to be a small positive constant so that  $M_\eta^2 > 0$ . Let  $2.5c_3 = A\kappa + B\kappa^2$  and  $C = 0.5(c_1 + 3c_2 + 10c_4)$ . Then, if  $A^2 - 4BC > 0$  — an inequality we expect, given the origin of these terms — there are two critical values of  $\kappa$ ,  $\kappa_\mp^* = (-A \mp \sqrt{A^2 - 4BC})/2B$ , at which  $M_h^2$  vanishes and EW symmetry is broken and then restored. The relative size of the EWSB

<sup>1</sup>The consequences of a very light  $\eta$  will be discussed later.

<sup>2</sup>Appelquist, Bai and Piai [17] recently used higher-order operators to tilt the vacuum in symmetry breaking directions. We differ from them in our simplifying assertion that higher-order corrections to a single operator can induce repeated symmetry breaking.

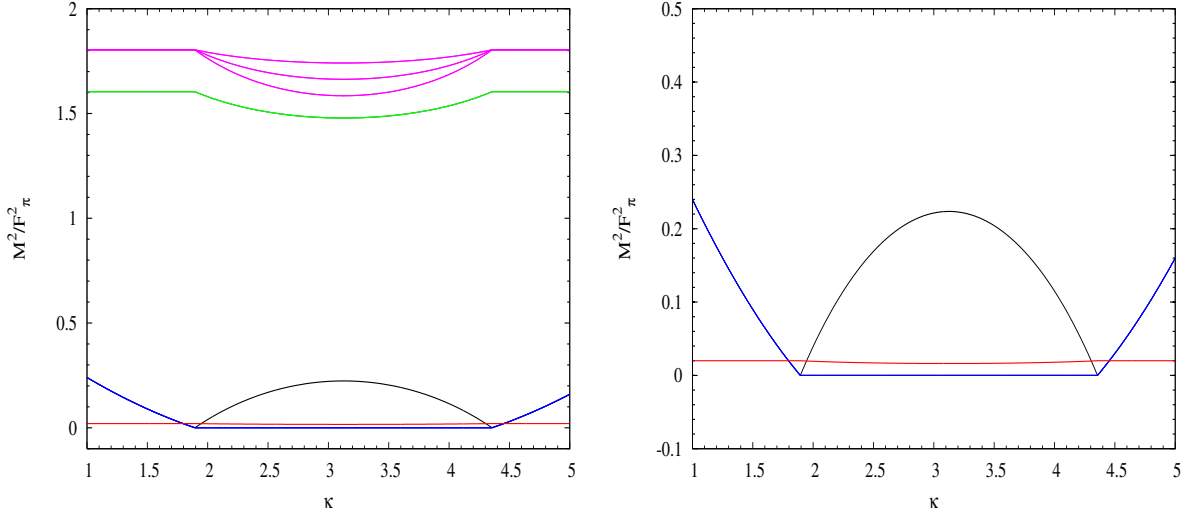


Figure 1: Squared masses relative to  $F_\pi^2$  of the six  $\pi$  (magenta), three  $\pi'$  (green),  $\eta$  (red) and four Higgs bosons (black and blue) on the left, and a closeup of the Higgs masses in the EWSB region (right) in the  $SU(5)/SO(5)$  model with parameters stated in the text.

region is

$$\frac{\Delta\kappa}{\bar{\kappa}} \equiv \frac{\kappa_+^* - \kappa_-^*}{(\kappa_+^* + \kappa_-^*)/2} = 2\sqrt{1 - 4BC/A^2}. \quad (10)$$

This provides one measure of parameter tuning in our scheme. We shall require that  $\Delta\kappa/\bar{\kappa} \simeq 0.5$ –1, i.e., no fine-tuning of the coupling  $\kappa$ .

Another measure of tuning is the amount  $A$  can be varied (for fixed  $B/A$ ) while maintaining  $\Delta\kappa/\bar{\kappa} \simeq 0.5$ –1. For nominal values of  $c_1$  and  $c_2$ ,  $C \simeq 0.5$ . Then, with  $|B/A| = \mathcal{O}(0.1)$ ,  $|A|$  should be comparable to  $C$  so that  $A\kappa + B\kappa^2 + C$  can vanish twice in the region  $\kappa \simeq 1$ –10. As just noted, this is a reasonable estimate of  $A$  (and  $B$ ). In the example described below, we find that we can vary  $A$  by  $\pm 10\%$  (i.e.,  $\Delta A/\bar{A} \simeq 0.2$ ) about a central value and still have  $\Delta\kappa/\bar{\kappa} \simeq 0.5$ –1 and  $M_h^2/F_\pi^2, v^2/F_\pi^2 \ll 1$ . For small  $v^2/F_\pi^2$ , the Higgs self-interaction in  $\mathcal{H}'$  is well-approximated by a quartic potential, so that the Higgs mass satisfies

$$M_h^2 \simeq 2\lambda_h v^2 \lesssim (M_h^2)_{\max} = 2(A^2/4B - C)F_\pi^2, \quad (11)$$

where the Higgs quartic self-coupling is  $\lambda_h = -(c_1 + 3c_2 + 20c_3 + 22c_4)/12$ .

A specific example is provided by  $c_1 = 0.1$ ,  $c_2 = 0.4$ ,  $c_3 = 0.2(-\kappa + 0.16\kappa^2)$ , and  $c_4 = 0.002$ . Vacuum alignment is carried out numerically as described in Refs. [2, 18]. The PGB masses are shown in Fig. 1. Varying  $\kappa$  from one to five, only  $h$  gets a nonzero VEV, which occurs in the region  $1.89 \lesssim \kappa \lesssim 4.36$ . In the EWSB region, note the massless (eaten) Goldstone bosons and the splitting of the charged and neutral members of the  $\pi$ -sextet. The Higgs VEV  $v^2/F_\pi^2$  is shown on the left Fig. 2. In this example,  $v \lesssim 0.5F_\pi$  or, fixing  $v = 246$  GeV,  $\Lambda_\psi \gtrsim 5$  TeV. We plot the Higgs mass, with  $v$  fixed, on the right in Fig. 2, obtaining  $M_h \simeq 215$  GeV. Then,  $M_{\pi,\pi'} \simeq 600$  GeV while the  $\eta$  is very light. Varying  $A$  by

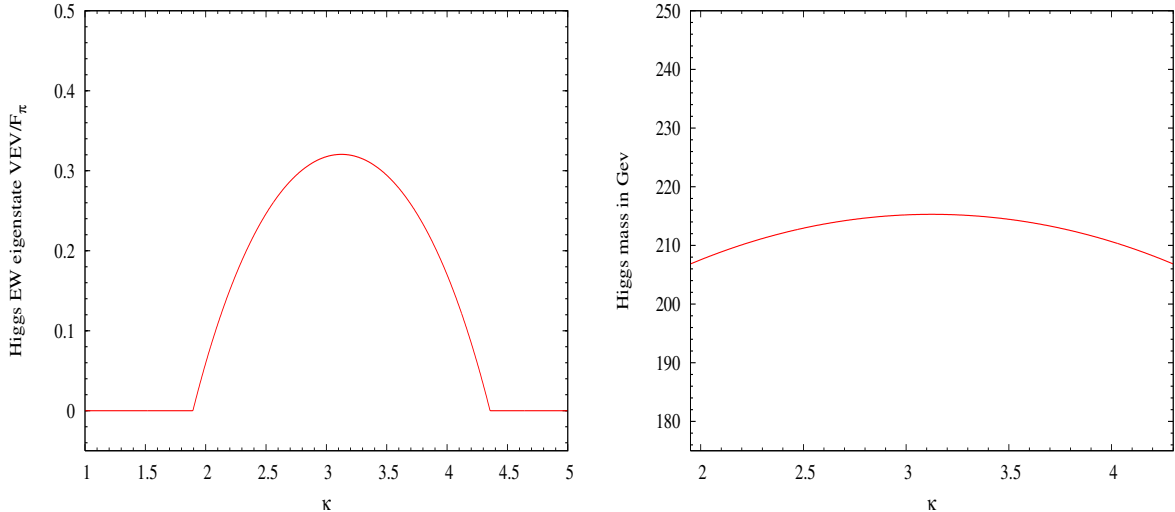


Figure 2: The Higgs boson VEV  $v^2/F_{\pi}^2$  (left) and  $M_h(\text{GeV})$  for  $v = 246 \text{ GeV}$  in the  $SU(5)/SO(5)$  model with parameters stated in the text.

$\pm 10\%$ ,  $\Delta\kappa/\bar{\kappa}$  changes from 0.9 to 0.5 and  $F_{\pi}$  from 400 to 700 GeV, but  $(M_h)_{\text{max}}$  only changes from 230 to 210 GeV — because  $\lambda_h$  varies slightly.

The new degrees of freedom below 1 TeV in our toy model are the nine  $\pi_a$  and the  $\eta$ . That there are no new  $W'$  nor heavy quarks as in little Higgs models is an attractive model-independent feature of our scheme. The new scalars are weakly-coupled to the  $W$  and  $Z$ , quarks and leptons, and to each other. The GK model has a parity-like symmetry that requires them to be emitted and/or absorbed in pairs. Thus, they have little effect on precisely-measured quantities such as the  $S$ -parameter, forward-backward asymmetries, etc.

A more model-dependent feature is the  $\eta$ -mass. We made the  $\eta$  very light to avoid complicating  $\mathcal{H}'$  with extra operators. Amusingly enough, we believe  $\eta$  could be practically massless and, with  $F_{\pi} \gtrsim 5 \text{ TeV}$ , still have evaded the searches and tests for an axion because it must be pair-produced. Furthermore, the  $h^2\eta^2$  coupling  $\lambda_{h\eta} \cong -5(c_1 + 3c_2 + 5c_3 + 10c_4)/32$  implies  $\Gamma(h \rightarrow \eta\eta) = 4.0 \text{ MeV} \simeq 0.8\Gamma(h \rightarrow \bar{b}b)$ , making the Higgs of this model somewhat harder to find than the standard-model one.

The masses of quarks and leptons — except for the top — arise technicolor-style from their EUC couplings to  $\psi$ -fermions (also see Refs. [6, 7]). To lowest order in  $g_E^2/M_E^2$ , these interactions produce

$$\mathcal{L}_Y = \Gamma_{\alpha\beta}^d F_{\pi} q_{i\alpha} \Sigma_{ij} d_{j\beta}^c + \dots, \quad (12)$$

where  $q_{i\alpha} = u_{\alpha}\delta_{i1} + d_{\alpha}\delta_{i2}$ ,  $d_{i\alpha}^c = d_{\alpha}^c\delta_{i5}$ . The Yukawa couplings  $\Gamma^{q,l}$  are enhanced by the walking  $G_{UC}$  interaction. These interactions are naturally flavor conserving [19].

We expect  $\Gamma^t \approx \Gamma^b = m_b/v$  or perhaps somewhat larger, while most of the top mass comes from  $\bar{t}t$  condensation induced by topcolor-like interactions. Because  $\langle \bar{t}t \rangle$  contributes little to EWSB [8], we ignored it in fixing  $v = 246 \text{ GeV}$  to make our mass estimates. Standard



topcolor requires a color-octet  $V_8$  and a singlet  $Z'$  to produce  $m_t \gg m_b$ . They are expected to have masses of several TeV.

To sum up, we have argued that light composite Higgs models may be constructed without excessive tuning and without the need for extra particles canceling large loop corrections to  $M_h$ . This happens when the Higgs is an accidental Goldstone boson. That is, its mass and VEV are small because we live in a region of  $\mathcal{H}'$  space that lies between successive EWSB phase transitions — at which  $M_h$  and  $v$  must vanish. A general feature of our scheme is that a topcolor-like interaction is needed to minimize the top's influence on EWSB. We illustrated our mechanism using a composite Higgs model due to Georgi and Kaplan for which we proposed a plausible dynamical origin for the operators in  $\mathcal{H}'$ . We limited the number of these operators to keep our exposition as simple as possible. But, as we have argued [2], we believe this AGB phenomenon is quite general, brought on by the competition to align the vacuum among several terms in  $\mathcal{H}'$ . And, while the model is a toy, it is consistent with precision measurements pointing to a standard electroweak model with a light Higgs boson.

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