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Top and Higgs Masses in a Composite Boson Model

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Top and Higgs Masses in a Composite Boson Model

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Recently Nambu¹ as well as Bardeen, Hill and Linden² have suggested replacing the Higgs mechanism with a dynamical symmetry breaking generated by four fermion interactions of the top quark. In fact the model for replacing the scalar sector is that of Nambu and Jona-Lasinio (NJL) and one recovers the Higgs as a $t\bar{t}$ composite. Earlier authors^{4,5,6} have also treated vector mesons as composites within the NJL framework, with perhaps the earliest suggestion being that of Bjorken⁷ for a composite photon. Here⁸ we attempt to generate the entire electroweak interaction from a specific current-current, baryon number conserving form of the four fermion interaction. The W , Z and Higgs boson appear as coherent composites of all fermions, quarks and lepton, and not just of the top quark. The four fermion interaction is assumed to be valid at some high mass scale μ , perhaps the low energy limit resulting by the elimination of non-fermionic degrees of freedom from a more basic theory. The cutoff Λ , necessary in the non-renormalizable NJL may be viewed then as the proper scale for this more basic theory.

At the intermediate mass scale μ , $\Lambda \gg \mu \gg m_W$, simple asymptotic relations are obtained for the ratios of composite boson masses to the top mass and also for the weak angle θ_W . The theory is highly restrictive specifying, under the assumption of a very massive top and three generations,

$$m_W^2(\mu) \approx 3/8 m_t^2(\mu) \quad (1)$$

and

$$\sin^2 \theta_W(\mu) \approx 3/8 \quad (2)$$

the latter reminiscent of grand unified models. The standard NJL result $m_H^2(\mu) \approx 4m_t^2(\mu)$ is also present following from a fine tuning which eliminates quadratic divergences within the scalar sector of the theory. The W to top mass ratio follows from a similar fine tuning in the vector sector which is, interestingly, equivalent to demanding a vanishing photon mass.

The scale μ at which these striking relations obtain does not represent new physics but simply a point below which the strong interactions cannot be ignored. Below the scale μ the effects of the extended $SU(3) \times SU(2) \times U(1)$ are included through the usual renormalization-group equations. The mass and angle relations provide boundary conditions for the R-G evolution downwards to m_W , and lead to predictions for m_t/m_W and m_H/m_t at present experimental energies. There is a strong phenomenological hint that μ be near the GUT scale, this we think adds to the predictability of the model relative to theories based only on the scalar sector. We then find for three generations central values $m_t \approx 155$ GeV and $m_{\text{Higgs}} \approx 140$ GeV. Using the evolution of $\sin^2 \theta_W$ to its known experimental value results in $\mu \approx 10^{13}$ GeV but a change to $\mu \approx 10^{15}$ little alters these mass predictions.

The model⁸ is defined completely by the specific choice of Lagrangian

$$\begin{aligned} \mathcal{L} = & \bar{\psi} i \gamma \partial \phi \psi - \frac{1}{2} \left[(\bar{\psi} G_S \psi)^2 - (\bar{\psi} G_S \tau \gamma_5 \psi)^2 \right] \\ & - \frac{1}{2} G_B^2 (\bar{\psi} \gamma_\mu Y \psi)^2 - \frac{1}{2} G_W^2 (\bar{\psi} \gamma_\mu \tau P_L \psi)^2 \end{aligned} \quad (3)$$

with $\psi = [\psi_L] \sim [t_L, t_R, b_L, b_R, e_L, e_R, \nu_L]$ for each included generation. G_B, G_W are universal vector couplings for the iso-scalar and iso-vector interactions respectively while P_L, Y , and τ are defined in the usual fashion. Breaking of weak isospin symmetry is introduced via the scalar coupling G_S , taken for simplicity to be diagonal. The choice in Eq. (3) is unique if the standard model for quark-boson interactions is to be recovered. The meson Lagrangian is obtained by constructing the effective potential through elimination of fermion degrees of freedom⁸.

The standard electroweak model follows, including fermion-boson couplings if two fine tunings are applied, the usual NJL scalar fine tuning³ and a look-alike for the vector sector

$$n_g \frac{G_W^2 \beta^2}{\pi^4} \sum_i Q_i^2 \int d^4 k \frac{1/2k^2 + m_i^2}{(k^2 + m_i^2)^2} \quad (4)$$

with n_g the number of generations, $\beta = \sin \theta_W$, and Q_i, m_i the charge and mass of the i th fermion. Both fine tunings provide connections between the dimensional NJL couplings and the cutoff essentially $G_{S,B,W} \sim \frac{1}{\Lambda^2}$ and after these are invoked only the usual dimensionless electroweak couplings survive.

The composite boson Lagrangian is generated directly from the effective potential, both kinetic and mass terms. Setting the photon mass term in the Lagrangian to zero produces Eq. (3) and yields the explicit relations Eq. (1) above between m_W, m_t and the symmetry breaking fermion masses. A straightforward diagonalization of the most divergent terms ($\sim \log \Lambda$) in the neutral vector meson sector in terms of the physical particles Z and the photon is responsible for the relationship $\sin^2 \theta_W(\mu) \approx 3/8$, independent of generation. Small corrections to these relations obtain because of non-vanishing lighter fermion masses and because of higher order electroweak interactions.

One might question the source of the simplicity of the mass relation and the unique value for $\sin^2 \theta_W$. One is dealing in the effective Lagrangian with the highest order terms independent of the fermion masses and, given our choice of generation and structure, the results must then reflect a symmetry consistent with the usual GUTS theories. The physics is however somewhat different, no direct baryon number breaking interactions are present and important constraints exist on the allowed boson masses.

Finally we then assume the simple parameter relations are achieved at some mass scale μ near the GUTS side and hence in a region where strong and electroweak interactions are both weak. In detailed calculation only the Higgs self-coupling $\lambda(\mu) = 2g_t^2(\mu)$ is changing at all appreciably and we tested the stability of our results by allowing for a wide variation about the $m_H^2 = 4m_t^2(\mu)$. We choose the scale μ so that $\sin^2 \theta_W$ evolves down to the experimental value 0.232. The choice of scale μ by this procedure may compensate for the vagueness in applying sharp boundary conditions. We find $\mu = 7.5 \times 10^{12}$ GeV for $\sin^2 \theta_W(m_W) = 0.232$. Evolving

$$\frac{m_t^2}{m_W^2} = \frac{2K_t}{\alpha^2} = \frac{8}{3} \quad (5)$$

leads to

$$m_t(m_W) = 2.04m_W = 163 \text{ GeV} \quad (6)$$

which is altered by some 5% for a two orders of magnitude increase in μ . Using only the single loop self-coupling to evolve the Higgs mass relation $\frac{m_H(\mu)}{m_t(\mu)} = 2$ gives $m_H(m_W) = 137(128)\text{GeV}$ for $\mu = 7.5 \times 10^{12}(7.5 \times 10^{14}) \text{ GeV}$. A drastic change in mass ratio to $(m_H/m_t)^2 = 8$ moves the Higgs mass to 153 GeV/c still a rather low value. For top masses in the region 100–150 GeV the evolution of the top mass from m_W to μ is rather flat. Thus the more rapidly evolving Higgs, essentially unimpeded by strong interactions, moves from barely bound (in terms of $t\bar{t}$) at μ to deeply bound at M_W .²

Introduction of a fourth generation is difficult. Assuming $m'_t = m'_b = m_t$ results in a top mass of 115 GeV, a barely altered Higgs and of course heavy 4th generation leptons. Such a possibility may be soon ruled out at Fermilab. The above prediction for the top is certainly consistent with higher loop correction determinations from LEP.

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