LBNL- 56564

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This work was supported in part by the Director, Office of Science, Office of High Energy Physics, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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ABSTRACT

Supersymmetric models have traditionally been assumed to be perturbative up to high scales due to the requirement of calculable unification. In this note I review the recently proposed 'Fat Higgs' model which relaxes the requirement of perturbativity. In this framework, an NMSSM-like trilinear coupling becomes strong at some intermediate scale. The NMSSM Higgses are meson composites of an asymptotically-free gauge theory. This allows us to raise the mass of the Higgs, thus alleviating the MSSM of its fine tuning problem. Despite the strong coupling at an intermediate scale, the UV completion allows us to maintain gauge coupling unification.

1. Motivation - The Little Hierarchy Problem(s)

The post-LEP era has forced models of electroweak symmetry breaking (EWSB) to confront data. For example, in models with a low cutoff one is expected to write all of the operators allowed by symmetries, suppressed by the appropriate power of the cutoff, Λ, in the spirit of EFT. Assuming these operators have coefficients of $O(1)$, one can place a lower bound on the cutoff from EW measurements $\Lambda \gtrsim 10$TeV [1]. However, since it is natural to tie the EW to the dynamical Λ, one then needs to explain the little hierarchy between them. This is the 'Little Hierarchy Problem' or 'LEP Paradox'.

In supersymmetric models, where physics is weakly coupled at a TeV, one naively does not run into this problem because there is no low cutoff at which we must introduce all of the operators allowed by symmetry. However, a little hierarchy problem emerges once the MSSM is required to fulfill the LEP bound for the mass of the Higgs, $m_h > 115$ GeV. In the MSSM the Higgs' quartic coupling is determined by SUSY and is given by the D-term potential. This places an upper-bound of m_Z on the tree level Higgs mass. One can raise this value by radiative corrections from top-stop loops, but this requires the stop to be quite heavy, $m_{\tilde{t}} > 500$ GeV. However, top-stop loops are also responsible for EWSB in the MSSM, thus the stop mass is involved in setting the EW scale. The need to address the little hierarchy between $m_{\tilde{t}}$ and the EW scale is the 'Supersymmetric Little Hierarchy problem' [a]. Within the MSSM it may only be solved by fine tuning other parameters in the Higgs potential.

The tree level bound on the Higgs mass may be raised by going beyond the MSSM. In the NMSSM an additional singlet is added along with a superpotential

$$W = \lambda N H_u H_d - \frac{k}{3} N^3, \tag{1}$$

which gives an additional quartic coupling to the Higgs, $\lambda^2 |H_u H_d|^2$. This contributes to raise the Higgs mass to $m_h^2 \sim \lambda^2 v^2 + O(m_Z^2)$ which can easily be above 115 GeV.

[a] For a more detailed discussion see e.g. [2].

However, we cannot raise the mass arbitrarily by increasing λ. The reason is that the effective $\lambda(\mu)$ grows in the UV and eventually hits a Landau pole at a scale Λ. Above this scale we lose control of the theory and even the relevant degrees of freedom are unknown. Encountering this scale below the GUT scale would be a disaster for unification. Demanding that the Landau pole be above M_{GUT} has yielded an upper-bound on $\lambda(v)$ and thus on the Higgs mass. In the NMSSM this gives $m_h < 150$ GeV.

However, in principle, nothing can prevent us from giving up unification and bringing Λ down to increase the mass of the Higgs. This model is now is an EFT below a cutoff which we imagine as some dynamical scale of compositeness. As we have seen, this model solves the supersymmetric version of the little hierarchy problem. Since we are now dealing with a low-cutoff model we may wonder if the "regular" little hierarchy problem was re-introduced i.e. explaining the little hierarchy between the cutoff and the EW scale. However this problem is trivially solved since the little hierarchy is stabilized by supersymmetry.

It is interesting to draw an analogy between the models of Little Higgs [3] and the strongly coupled version of the NMSSM peresented above. Both models are EFTs with a low cutoff suplemented by additional symmetries that protect the Higgs mass. In the former the symmetry is a global symmetry that is collectively broken and in the later it is supersymmetry. The main advantage of the supersymmetric model is that due to exact results in strongly coupled supersymmetric gauge theories, it is much easier to UV complete.

2. UV Completion – The Fat Higgs

In [2] we UV completed a cousin theory of the NMSSM given by the superpotential

$$W = \lambda N(H_u H_d - v_0^2). \tag{2}$$

This superpotential is similar to the NMSSM in that it raises the tree level Higgs mass above the LEP bound for a sufficiently large $\lambda(v)$ but then requires a UV completion above the Landau pole of λ.

In this brief note, I will only present the essential components of our model and advertise some of its features. A more complete model and its analysis is presented in [2]. The UV dynamics of our model consists of a new strongly coupled gauge group, $SU(2)_H$. The we introduce six doublets, $T^{1\ldots6}$, under $SU(2)_H$ which corresponds to $N_f = 3$. The $SU(2)_H$ is asymptotically free and thus becomes strong at some scale, Λ_H. The T's are also carry electroweak charge. The charge assignments under $SU(2)_H \times SU(2)_L \times U(1)_Y$ is

$$(T^1, T^2) \equiv T = (\mathbf{2}, \mathbf{2}, 0), \qquad (T^3, T^4) = (\mathbf{2}, \mathbf{1}, \pm\frac{1}{2}), \qquad (T^5, T^6) = (\mathbf{2}, \mathbf{1}, 0). \tag{3}$$

We also write a tree-level superpotential

$$W = -mT^5T^6 + W_{decouple} \tag{4}$$

where the meaning of $W_{decouple}$ will become clear presently. Below the scale Λ_H this theory confines and low energy degrees of freedom are described by the anti-symmetric meson matrix $M_{ij} = T_i T_j$. Let us relabel part of the meson matrix as follows

$$N = M_{56}, \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} = \begin{pmatrix} M_{13} \\ M_{23} \end{pmatrix}, \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} = \begin{pmatrix} M_{14} \\ M_{24} \end{pmatrix}, \tag{5}$$

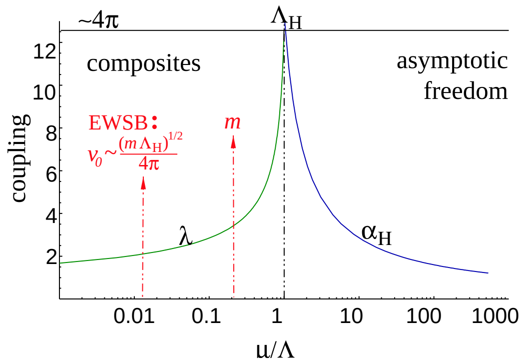

Figure 1: The renormalization of the couplings in the model presented. When $4\pi v_0 \ll \Lambda_H$ the mesons condense at weak coupling and the theory is calculable.

noting that the mesons labeled as H_u and H_d indeed transform as the Higgs fields of the MSSM, and N is a singlet, as needed in Eq. (2). The superpotential $W_{decouple}$ in Eq. (4) involves additional new fields that marry all of the other meson fields in M_{ij}. This can be done naturally by enforcing an additional Z_3 symmetry [2]. The theory below Λ_H is thus an effective theory of H_u, H_d and N alone.

This theory generates a dynamical superpotential

$$W_{dyn} = \frac{\mathrm{PfM}}{\Lambda^3} \supset \frac{1}{\Lambda^3} N H_u H_d \tag{6}$$

Once $H_{u,d}$ and N are canonically normalized to dimension one fields this will produce the renormalizable trilinear term in Eq. (2). The mass for the third flavor of Eq. (4) becomes a linear term for the singlet N. Putting these two contributions together gives a superpotential of the form of Eq. (2). This superpotential breaks EW symmetry even in the SUSY limit, which releases the stop from its role in EWSB in the MSSM. The scale v_0 at which EWSB occurs in the SUSY limit may be estimated in NDA as $v_0^2 = \frac{m\Lambda_H}{(4\pi)^2}$.

The dynamics in this model are heuristically summarized in figure 1. At high energy the theory is a weekly couple gauge theory with the T's as the relevant degrees of freedom. As we run down the theory becomes strong at Λ_H at which point we substitute the degrees of freedom to the meson fields and the coupling λ for the gauge coupling. Below Λ_H the coupling λ renormalizes quickly to weak coupling. If the scale m is somewhat below Λ_H, EWSB will occur at weak coupling. Electroweak observables in this model, such as the oblique parameters S and T or the Higgs spectrum, are thus calculable.

In [2] the Higgs spectrum was calculated for a range of SUSY breaking parameters. The lightest Higgs was indeed found to be heavier than conventional MSSM values, easily reaching 350 GeV or higher. A distinct signal for the Higgs spectrum in our models is that the pseudo-scalar Higgs is always heavier than the charged one whereas in the MSSM the converse is alway true. The S and T parameters were also calculated and were found to be within the 1σ allowed region for a wide range of parameters.

EWSB may be communicated to the matter sector by a scalar version of an ETC sector. We add heavy fundamental Higgses, $\varphi_{u,d}$ and $\bar{\varphi}_{u,d}$, that couple both to the T's and to the MSSM

$$W_f \quad = \quad M_f(\varphi_u \bar{\varphi}_u + \bar{\varphi}_d \varphi_d) + \bar{\varphi}_d (TT^4) + \bar{\varphi}_u (TT^3)$$

$$+h_u^{ij} Q_i u_j \varphi_u + h_d^{ij} Q_i d_j \varphi_d + h_e^{ij} L_i e_j \varphi_d. \tag{7}$$

At the scale M_f, the heavy Higgses can be integrated out, leaving a direct coupling between the MSSM and the right combination of T's that becomes the composite Higgs once the theory confines. The effective Yukawa to the fat Higgses is $\frac{h_{u,d}}{4\pi}\frac{\Lambda_H}{M_f}$. If $M_f \sim \Lambda_H$ this may present a problem in generating a large top mass.

In order to avoid fine tuning the SUSY breaking scale in this theory must be of order λv_0 which is set by supersymmetric scales. This problem is reminiscent of the μ problem of the MSSM. A more complete model was introduced in [2] in order to relate the SUSY breaking scale to m, Λ_H and also M_f. This was done by adding a fourth flavor of T's which results in near conformal behavior. The new walking dynamics is also beneficial to enhancing the effective MSSM Yukawa couplings by anomalous dimensions as in walking technicolor. However, in this case the anomalous dimensions are calculable due to their relation to anomaly free R-charges.

Finally, lets revisit the possibility of unification in this model. Below the scale Λ_H the matter content of our model is simply that of the NMSSM. The running of the 3-2-1 gauge couplings follow their regular trajectories. At Λ_H we must match the low energy theory to the UV completion. Due to holomorphy, the matching equation between the low and high energy theories is set by bare parameters [4]. This leads us to believe that the threshold corrections at Λ_H are small. Above Λ_H the T's must substitute the composite Higgses in the running. It is amusing that the T's contribute to the one-loop beta functions of the MSSM exactly as two Higgs doublets do, which leaves us on the MSSM trajectory. However, we have also added the fundamental Higgses $\varphi_{u,d}, \bar{\varphi}_{u,d}$, as well as new fields that take part in the $W_{decouple}$, all of which contribute as three more pairs of Higgs doublets. This deviation from the MSSM running may be corrected. For example, adding three pairs of heavy triplets with $Y = \pm 1/3$, completes the "$SU(5)$ multiplets" and brings us back on track. Though this remedy may seem somewhat contrived[b], we note that the possibility of even talking about unification *above* a compositeness scale may be viewed as significant progress.

3. Acknowledgements

I would like to thank my collaborators- Graham Kribs, Daniel Larson and Hitoshi Murayama. Many thanks to Zacharia Chacko who suggested I go to SUSY and for pointing out how many 10 minute intervals there were in February. This work was supported in part by the DOE under contracts DE-FG02-90ER40542 and DE-AC03-76SF00098 and in part by NSF grant PHY-0098840.

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[b] For a possibly more attractive solution with a slimmer Higgs see [5].