Superconformal Technicolor

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In supersymmetric theories with a strong conformal sector, soft supersymmetry breaking at the TeV scale naturally gives rise to confinement and chiral symmetry breaking at the same scale. We investigate models where such a sector dynamically breaks electroweak symmetry. We consider two scenarios, one where the strong dynamics induces vacuum expectation values for elementary Higgs fields, and another where the strong dynamics is solely responsible for electroweak symmetry breaking. In both cases there is no fine tuning required to explain the absence of a Higgs boson below the LEP bound, solving the supersymmetry naturalness problem. A good precision electroweak fit can be obtained, and quark and lepton masses are generated without flavor-changing neutral currents. Electroweak symmetry breaking may be dominated either by the elementary Higgs bosons or by the strong dynamics. In addition to standard supersymmetry collider signals, these models predict production of multiple heavy standard model particles (t, W, Z, and b) from decays of resonances in the strong sector.

PACS numbers:

Introduction—Supersymmetry (SUSY) is widely considered to be the most plausible framework for physics beyond the standard model of particle physics. It offers an elegant explanation of the fact that electroweak breaking scale $\sim 100$ GeV is much smaller than the Planck scale $\sim 10^{19}$ GeV, without fine tuning fundamental parameters. The minimal supersymmetric standard model (MSSM) also contains a viable dark matter candidate and gives a calculable framework for addressing other fundamental issues in particle physics and cosmology. However, there is a serious problem with electroweak symmetry breaking in the MSSM: the lightest Higgs has a mass that is generically $m_h < m_Z \approx 90$ GeV, while the experimental bound from LEP is $m_h > 115$ GeV [1]. The Higgs mass can be raised at the cost of re-introducing tuning at the 1% level, or by extending the model in various ways [2]. In this Letter, we propose to solve this problem by combining supersymmetry with strong dynamics at the TeV scale. A companion paper [3] gives many additional details.

The electroweak scale in the MSSM is determined by the scale of soft SUSY breaking. We assume that in addition there is a strongly-coupled sector of the theory with conformal (scale) invariance. An example of such a sector is SUSY QCD with $N_f \approx 2N_c$ [4]. Soft SUSY breaking in the strong sector also softly breaks the conformal invariance. SUSY breaking in the strong sector gives mass to all scalars (since only unbroken SUSY can forbid these masses), while fermions generally remain massless due to unbroken chiral symmetries. It is therefore very plausible that the dynamics of SUSY QCD at the SUSY breaking scale is qualitatively similar to non-SUSY QCD, with confinement and chiral symmetry breaking in particular. Since the coupling is already strong at the SUSY breaking scale, these effects occur at this scale. In such models the strong sector can dynamically break electroweak symmetry, as in technicolor models [5]. Since the scale of dynamical electroweak symmetry breaking is determined by the soft breaking of conformal symmetry, this is a SUSY version of conformal technicolor [6], so we refer to it as superconformal technicolor [7]. We assume that the SUSY breaking scale is the same order of magnitude in the MSSM and the strong sector, which is natural in many models of SUSY breaking. This class of models therefore gives a plausible framework for supersymmetry and strong dynamics at the same scale. In Ref. [8] this mechanism was employed with a SUSY breaking scale above the electroweak scale to give a realistic model for flavor in conformal technicolor (the pioneering work in this direction is Ref. [9]). In the present work, we investigate SUSY breaking and strong dynamics at the TeV scale. Early attempts in this direction posited dynamical SUSY breaking at the TeV scale [10], but this is problematic for both theoretical and phenomenological reasons. A realistic model was constructed in Ref. [11]. The present work improves on that work in giving a general and robust mechanism for the coincidence of the scales of SUSY breaking and strong dynamics.

Induced electroweak symmetry breaking—In these models there are two potential sources of electroweak symmetry breaking, the strong sector and the elementary Higgs fields of the MSSM. We first consider a scenario where electroweak symmetry breaking is induced by the
strong sector, but the $W$ and $Z$ masses are dominated by the contribution from the elementary Higgs fields. A minimal strong sector has fields transforming under $SU(2)_{SC} \times SU(2)_W \times U(1)_Y$ as

$$\tilde{\Psi} \sim (2, 2)_0, \quad \tilde{\psi}_1 \sim (2, 1), \quad \tilde{\psi}_2 \sim (2, 1)_{-\frac{1}{2}},$$

plus 2 copies of $(2, 1)_{\frac{1}{2}} \oplus (2, 1)_{-\frac{1}{2}}$ fields that play no role in breaking electroweak symmetry. (The hypercharge assignments ensure that there are no fractionally charged states in the strong sector.) The fields $\Psi$ and $\tilde{\Psi}$ have the quantum numbers of the technifermions of minimal technicolor [5]. The soft SUSY breaking terms explicitly break the global symmetry of the strong sector to $SU(2)_L \times SU(2)_R$. SUSY breaking in the strong sector is assumed to trigger confinement and chiral symmetry breaking by a fermion condensate $\langle \Psi \tilde{\Psi} \rangle \neq 0$, as in technicolor. (It is also natural to have a larger group of approximate symmetries due to special structure of the soft SUSY breaking terms, in which case there will be additional light pseudo-Nambu Goldstone bosons.) Stabilizing runaway directions in the strong sector requires additional interactions, which are discussed in Ref. 3. The strong sector is coupled to the MSSM Higgs fields via the superpotential couplings

$$W = \lambda_u H_u (\Psi \tilde{\psi}_2) + \lambda_d H_d (\Psi \tilde{\psi}_1).$$

The operators $\Psi \tilde{\Psi}$ have dimension $\frac{2}{3}$ above the SUSY breaking scale, and so the couplings $\lambda_{u,d}$ have mass dimension $\frac{2}{3}$. We require that the couplings $\lambda_{u,d}$ be large enough to be important at the SUSY breaking scale, but not non-perturbatively large. This is a coincidence large enough to be important at the SUSY breaking scale, and so the couplings $\lambda_{u,d}$ of electroweak symmetry breaking, the Yukawa couplings $\lambda_d$ are perturbative, even for the top quark. Therefore, there is no flavor problem associated with the strong dynamics.

We now turn to the phenomenology of this model. Early work on technicolor theories with Higgs scalars can be found in Refs. 14. We first discuss the precision electroweak fit. The strong sector has $N_c = 2$ and only one weak doublet, so the contributions to the $S$ and $T$ parameters from the strong sector are not dangerously large to begin with, and there are large theoretical uncertainties in their values. In fact, general theoretical arguments suggest that the $S$ parameter is suppressed in theories that are conformal above the chiral symmetry breaking scale [15]. Recent lattice simulations give some support for this behavior [16]. In the present model the IR contribution to $S$ from the strong sector is reduced compared to a conventional technicolor theory because the PNGBs are heavy, and because there is a light Higgs in the spectrum. Custodial symmetry can be broken in the strong sector by $\lambda_u v_u \neq \lambda_d v_d$. We assume that this contribution to the $T$ parameter is positive, as suggested by perturbation theory. This means that the theory has an adjustable parameter that allows a good precision electroweak fit (similar to the Higgs mass in the standard model). We can easily obtain a good precision electroweak fit, even if we assume (pessimistically) that the UV contribution to the $S$ parameter has the value obtained by extrapolation from QCD [17]. This is illustrated in Fig. 1.

Another important precision electroweak constraint is the coupling of the $Z$ to left-handed $b$ quarks. In this model the leading correction enters at $\mathcal{O}(g^2 \Lambda^2)$, with $g$ the Yukawa coupling to SM quark fields. The coupling $y_Z \bar{b}b$ agrees with the standard model at the 0.25% level, which gives a constraint $\nu < 5.6 f$. This is easily satisfied.
ory may have a prominent isotriplet vector resonance, $h$, with $A\rightarrow \bar{T}T\pi^f$, dominantly to $\bar{\pi}f$, or via weak boson fusion. The $\rho_T$ will generally have strong decays to pairs of PNGBs, but because of the large elementary Higgs VEVs, the $A^0_t$ and $H^\pm_2$ masses can be sufficiently large that decays to these states are kinematically forbidden. The effective field theory expansion breaks down in this regime, but we still expect it to be qualitatively reliable. In this case the $\rho_T$ will be a narrow resonance, similar to a $W'$ and $Z'$. Techniscalars charged under $SU(2)_L$ and $SU(2)_R$ generally have different SUSY breaking masses, so there need not be any approximate symmetry that interchanges $SU(2)_L$ and $SU(2)_R$, analogous to parity in QCD. This means that $\rho_T$ can decay to either $WW$ and $WWW$. The $\rho_T$ can also decay via mixing with the $W$ and $Z$.

Strong electroweak symmetry breaking—We now consider another scenario where there are no elementary Higgs fields below the TeV scale, and electroweak symmetry is broken entirely by the strong sector. This arises in a different parameter regime of the model described above, as follows. We assume that the couplings $\Lambda_{u,d}$ in Eq. (2) get strong at a scale $\Lambda_s > \text{TeV}$. Results on non-perturbative dynamics of SUSY gauge theories [4] indicate that below the scale $\Lambda_s$, the theory flows to a new fixed point where these couplings are strong. In this new fixed point, $H_{u,d}$ becomes operators of the strong sector with dimension $\simeq \frac{3}{2}$. This means that the Yukawa couplings of $H_{u,d}$ to quarks and leptons become irrelevant interactions below the scale $\Lambda_s$, scaling as $(E/\Lambda_s)^{1/2}$. In order to avoid too much suppression for the top quark mass, we cannot have $\Lambda_s$ arbitrarily far above the TeV scale. If $\Lambda_s \gg \text{TeV}$ the top quark Yukawa coupling gets strong at some scale above $\Lambda_s$, indicating top quark compositeness at high scales. Alternatively, models with $\Lambda_s \sim \text{TeV}$ are natural with a mechanism to explain the coincidence of scales, as described above. For $\Lambda_s \gtrsim \text{TeV}$, quark and lepton masses arise from irrelevant interactions at the TeV scale, as in technicolor. However, these interactions originate from Yukawa couplings with minimal flavor violation, and there is no flavor problem associated with the strong breaking of electroweak symmetry.

At the TeV scale, soft SUSY breaking in the strong sector is assumed to trigger confinement and electroweak symmetry breaking, as discussed above. The soft SUSY breaking terms can be chosen so that the strong sector has a minimal symmetry breaking structure $SU(2)_L \times SU(2)_R \rightarrow SU(2)$, so the only strong degrees of freedom below the TeV scale are the longitudinal components of the $W$ and $Z$. The spectrum at the TeV scale therefore includes all of the MSSM fields minus the Higgs sector, with strong resonances at the scale $4\pi v \sim 3 \text{TeV}$.

A good precision electroweak fit can be obtained with the help of a $T$ parameter induced by $\lambda_t \neq \lambda_b$. Assuming that the $S$ parameter is given by the QCD value, the precision electroweak fit is shown in Fig. 1. A good fit can be obtained if the UV contribution to the $S$ parameter is reduced compared to this estimate (as we expect, as dis-
cussed above), and the contribution to the $T$ parameter from $\lambda_u \neq \lambda_d$ is positive (as expected from perturbation theory). The correction to $g_{Z \bar{b}b}$ is of order 0.8\%, with large theoretical uncertainties. This is roughly 3 times the experimental precision so there is some tension, but given the large uncertainties this does not rule out the model. The collider phenomenology consists of SUSY signals, plus technicolor resonances at the 3 TeV scale. The $\rho_T$ can decay to both $WW$ and $WWW$ as described above, which distinguishes it from the conventional technirho.

**Conclusions**—We have described models that solve the SUSY Higgs mass problem via strong dynamics at the TeV scale. The models consist of the MSSM plus a sector with a strong conformal fixed point. In such models, it is natural for the strong sector to dynamically break electroweak symmetry at the soft SUSY breaking scale.

We considered two scenarios, one in which the strong breaking of electroweak symmetry induces the elementary Higgs VEVs, and one in which strong electroweak symmetry breaking dominates. In both scenarios the experimental bounds on light Higgs bosons are easily satisfied without tuning, and no additional flavor problem is introduced. Both scenarios have a dark matter candidate. However, gauge coupling unification is no longer a prediction of the minimal model described here, since the strong sector affects the evolution of the $SU(2)_W \times U(1)_Y$ gauge couplings but not $SU(3)_C$. Unification can be accommodated with additional matter fields, which however have no other apparent motivation in this framework. In conclusion, we believe that this is a plausible framework for electroweak symmetry breaking, and that the new signals suggested by these models deserve additional investigation.

**Acknowledgements**—We thank R. Contino, R. Kitano, T. Okui, and J. Terning for discussions. We also thank J. Serra for collaboration at early stages of this work. M.A.L. was supported by DOE grant DE-FG02-91-ER40674.

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