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Electroweak symmetry breaking[1]

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Abstract. In this note I provide a brief description of models of dynamical electroweak symmetry breaking, including walking technicolor, top-color assisted technicolor, the top-quark seesaw model, and little higgs theories.
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1. Shortcomings of the Fundamental Higgs Model

The standard electroweak theory is in spectacular agreement with precision electroweak data [1]. Unfortunately, the theory is manifestly incomplete: while we know that the electroweak gauge symmetry must be spontaneously broken down to electromagnetism, we have no direct experimental evidence for the agent responsible for this symmetry breaking. The simplest choice, the one-Higgs doublet model, has a number of shortcomings, namely:

(i) It is a theory of a fundamental scalar particle and we have, so far, observed no fundamental scalars in nature.

(ii) The model provides no explanation for why electroweak symmetry breaking occurs, or why it occurs at the weak scale.

(iii) It suffers from the hierarchy and naturalness problems – namely, if there is physics at some much higher energy (say the GUT or Planck scale), then a precise adjustment of the underlying parameters (i.e. fine-tuning) is required to keep the electroweak scale low.

(iv) The model is trivial: it does not exist as a continuum quantum field theory.

Given our absence of understanding about the nature of electroweak symmetry breaking, it is important to remember why the Higgs or so other additional dynamics is necessary. What is wrong with simply adding masses to the gauge bosons of the electroweak theory? Any scattering amplitude in a consistent quantum mechanical theory must lie within the unitarity circle. However, if we compute the scattering amplitude of longitudinal W bosons at tree-level, using the interactions of SU(2) x U(1) gauge theory, at high-energies we find contributions which grow with energy [2, 3, 4, 5, 6, 7]. The leading contributions, which grow like energy to the fourth power, cancel due to the symmetries of the underlying nonabelian gauge theory. Unfortunately, the same cannot be said of the subleading, energy-squared, divergence.

[1] Talks presented at IXth Mexican Workshop on Particles and Fields, Colima, Mexico, Nov. 17-22, 2003 and the 15th Topical Conference on Hadron Collider Physics, HCP2004, Michigan State University, June 14-18, 2004.

In the absence of additional physics contributing to the amplitude, we see that tree-level unitarity is violated at an energy of order 1 TeV – hence we conclude that some new physics is required below this energy scale. The Higgs boson, the remnant scalar degree of freedom in the one-Higgs doublet model, has couplings precisely adjusted (again, as a result of the underlying gauge symmetry) so as to precisely cancel this bad high-energy behavior. In this talk, we will focus on theories in which electroweak symmetry breaking occurs due to new strong dynamics at energy scales of order 1 TeV.[2]

2. Technicolor: Higgsless since 1976!

So, if not a Higgs boson, what might exist at energies of order 1 TeV or less and be responsible for electroweak symmetry breaking? The most elegant possibility is that electroweak symmetry breaking arises from chiral symmetry breaking due to a new, strongly-interacting, gauge theory: Technicolor [9, 10]. In the simplest such model one introduces a new strong $SU(N_{TC})$ gauge theory and, analogous to the up- and down-quarks in QCD, two new fermions transforming (which we will denote U and D) as fundamentals of this gauge symmetry. These new "techniquarks" carry an $SU(2)_L \times SU(2)_R$ global symmetry – the analog of the (approximate) chiral symmetry of the light quarks in QCD. Just as in QCD, the "low-energy" strong dynamics of this new gauge theory is expected to cause chiral symmetry breaking, that is a non-perturbative expectation value for the chiral condensates $\langle \bar{U}_L U_R \rangle = \langle \bar{U}_R U_L \rangle$ and similarly for the D fermions.

If the left-handed techniquarks form an $SU(2)_W$ doublet, while the right-handed techniquarks are weak singlets carrying hypercharge, technicolor chiral symmetry breaking will result in electroweak symmetry breaking. The Goldstone bosons arising from chiral symmetry breaking are transmuted, by the Higgs mechanism, into the longitudinal components of the electroweak gauge bosons.

Theoretically, technicolor addresses all of the shortcomings of the one-doublet Higgs model: there are no scalars, electroweak symmetry breaking arises in a natural manner due to the strong dynamics of a non-abelian gauge theory, the weak scale is related to the renormalization group flow of the strong technicolor coupling – and can be much smaller than any high energy scale and, due to asymptotic freedom, the theory (most likely) exists in a rigorous sense.

Unfortunately, the simplest versions of this theory – based, as described, on a scaled-up version of QCD – are not compatible with precision electroweak data[3] (and, as described so far, cannot accommodate the masses of the quarks and leptons). Nonetheless, this simplest version remains a paradigm for thinking about theories of dynamical electroweak symmetry breaking.

In the final analysis, the agent of electroweak symmetry breaking will be uncovered by experiment – not by theoretical investigation or prejudice. Although a scaled-up version of QCD is not a viable model of electroweak symmetry breaking, we may use our knowledge of QCD to investigate the possible collider signatures of such a sector at the Tevatron or LHC. In QCD, the most prominent resonances in pion scattering are the vector mesons. Analogously, in a theory of dynamical electroweak symmetry breaking, we expect the most prominent resonances in longitudinal W scattering will be "technivector" mesons. An illustration of the event rates in a minimal model at the LHC are shown in figure 1. This minimal model is not particularly encouraging – the number of events at the LHC at high luminosity is barely enough to see a 1 TeV resonance, much less a heavier one! Fortunately, as we will see, this minimal model is likely to severely understate the range and accessibility of signatures of a model of dynamical electroweak symmetry breaking in a realistic model which can accommodate quark and lepton masses.

[2] For a recent comprehensive review of these models, and a complete set of references, see [8].

[3] See Langacker and Erler in [11].

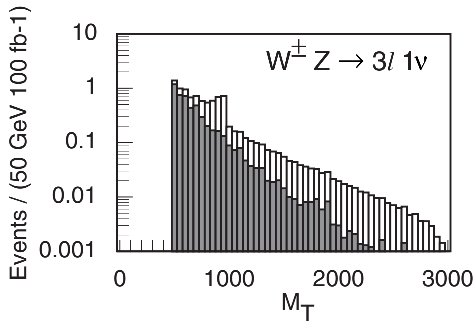

Figure 1. Event rate for $W^{\pm}Z$ scattering in "gold-plated" mode at the LHC, for a 1 TeV technirho meson [12].

3. Fermion Masses and ETC Interactions

While technicolor provides a natural paradigm for producing masses for the electroweak gauge bosons, the agent of electroweak symmetry breaking must also provide for fermion masses. In the fundamental higgs model, one introduces yukawa interactions between the fermions and the higgs with couplings proportional to the desired fermion masses. In a model of dynamical electroweak symmetry breaking, one must couple fermions to the electroweak symmetry-breaking condensate. A natural model for doing so involves enlarging the technicolor group and embedding (some or all) quark flavor into the group as shown below.

These models, known as "extended technicolor models" (ETC) [13, 14], relate the fermion masses to the masses of the extended technicolor gauge bosons responsible for coupling the fermions to the symmetry breaking condensate. In the case of a QCD-like theory, in which the techniclor theory is precociously asymptotically free, we may estimate the scale of masses of the ETC gauge bosons to be

$$\frac{M_{ETC}}{g_{ETC}} \simeq 40\,\mathrm{TeV}\left(\frac{F_{TC}}{250\,\mathrm{GeV}}\right)^{\frac{3}{2}}\left(\frac{100\,\mathrm{MeV}}{m_q}\right)^{\frac{1}{2}} \quad . \tag{1}$$

Extended technicolor is a tremendously ambitious theory: in addition to electroweak symmetry breaking, it recasts the problem of quark and lepton flavor in terms of the breaking of the extended technicolor interactions. In principle, this is progress – one could conceivably construct a dynamical explanation of flavor! In practice, however, there is a substantial obstacle [13]. In order to give rise to the various different fermion masses and mixings, the ETC interactions must distinguish amongst the various flavors of quarks (and leptons) – e.g. distinguish strange-quarks from down- or bottom-quarks. In general, such interactions will give rise to flavor-changing neutral currents. The limits on flavor-changing interactions of the strange-quark, for example, imply that the scale associated with such interactions must exceed 500-1000 TeV.[4]

Extended technicolor gauge bosons of that mass, however, can (at least in QCD-like technicolor) only accommodate a quark mass of order 1-10 MeV – much too small for the strange- or charm-quark masses, much less the third generation. ¿From this, along with constraints on precision electroweak parameters, we conclude that technicolor dynamics cannot be QCD-like.

[4] For a recent comprehensive review of flavor constraints on ETC theories, see [15].

4. Walking Technicolor and Beyond

A proposal for how technicolor could differ from QCD goes under the name of "walking" technicolor. It has been argued [16, 17, 18, 19, 20, 21] that if the β-function for the technicolor coupling, which controls how quickly the coupling constant falls as one scales to higher energy, is small, than the anomalous dimension for the technifermion mass operator (the function γ_m above) will be close to one for a large range of energies. Such a change enhances the quark or lepton masses allowed, perhaps as high as a few GeV – enough, perhaps, for the first and second generations of quarks and leptons.

In order to have a small β-function, the technicolor theory must have many fermions, perhaps in several representations of the technicolor group. Generically, this implies that there can be several different scales of technicolor chiral symmetry breaking [22, 23]. The phenomenology of these "multiscale" models could involve a large approximate chiral symmetry group, and therefore many light "pseudo-Goldstone" bosons, and potentially light technivector mesons. These considerations have driven the searches for technicolor at LEP and the Tevatron. [5] It should be emphasized that, so far, these searches are rather model dependent and are just reaching the interesting regime. Run II of the Tevatron and the LHC will substantially extend these limits.

5. The Top Quark

While walking technicolor may be sufficient to produces masses for the first two generations, it is unlikely to be able to do so for the third generation and for the top-quark in particular.[6] The difficulty with the top-quark is easy to see, top-quark mass generation in an ETC theory implies that

$$\frac{M_{ETC}}{g_{ETC}} \simeq 1\,\mathrm{TeV} \left(\frac{F_{TC}}{250\,\mathrm{GeV}}\right)^{\frac{3}{2}} \left(\frac{175\,\mathrm{GeV}}{m_t}\right)^{\frac{1}{2}} \,, \tag{2}$$

where M_{ETC} and g_{ETC} are the masses and couplings of the ETC gauge-bosons responsible for top-quark mass generation, and F_{TC} is the technicolor "F"-constant (analogous to f_π in QCD) which cannot be higher than 250 GeV. We see that, given the mass of the top-quark, the ETC gauge bosons required are very light – so light, that there is little distinction between them and the technicolor interactions, leading to potential problems with $Z \to \bar{b}b$ [25] and $\Delta\rho$ [26].

These considerations suggest that there may be a separate sector associated with generation of the top quark mass. Topcolor Assisted technicolor [27] is such a theory. In this model, technicolor is responsible for the bulk of electroweak symmetry breaking, and extended technicolor for the masses of the light quarks and leptons. An additional strong color sector, coupling only to the third generation, generates a nonzero condensate of top quarks ($\langle \bar{t}t \rangle \neq 0$), and gives rise to a large topquark mass. The simplest scheme incorporates two color groups, the stronger of which couples only to the third generation and breaks down to ordinary color at a scale of order 1 TeV, leaving a color octet of "topgluons." An additional copy of hypercharge distinguishes the top-quark from the bottom-quark, leaving a heavy Z' boson with flavor-dependent couplings. The topgluons are a particularly novel phenomenological feature of these models, and illustrate the possibility of interesting signals involving b- and t-quark jets [28].

6. Composite Higgs Bosons: Top Seesaw and Little Higgs

If topcolor with technicolor is good, perhaps we don't need technicolor! That is, perhaps the top quark plays the role of a technifermion, and a top quark condensate is responsible for all

[5] For a review, see Chivukula, Narain, and Womersley in [11].

[6] For a valiant attempt to produce all of the quark masses and mixings in a walking technicolor theory, see [24].

of electroweak symmetry breaking [29, 30]. At first sight, this would seem difficult: the top quark mass is of order 175 GeV, while the value of the electroweak scale (the expectation value of the Higgs field in the standard scalar doublet model) is 250 GeV. Our intuition from QCD, bolstered by model calculations, is that if a top-quark condensate is responsible for electroweak symmetry breaking, then the top-quark should have a mass of order 500 GeV.

Dobrescu and Hill have constructed an elegant alternative [31]. Namely, they propose that there is a new $SU(2)_W$-singlet set of quarks $\chi_{L,R}$, and the electroweak symmetry breaking condensate is of the form $\langle \bar{\chi}_R t_L \rangle$. If this were the whole story, the only non-zero mass quark would have a mass of around 500 GeV, as discussed above. However, Dobrescu and Hill propose that this state mixes via a seesaw-type mass matrix, and that the lowest mass eigenstate of the full $\chi - t$ system is to be identified with the top-quark.

Interestingly, the same dynamics that produces an electroweak symmetry breaking condensate in the top seesaw model produces a scalar bound state that couples approximately like a Higgs boson [32, 33]. Light scalar bosons without supersymmetry typically require fine-tuning, and the top seesaw model is no exception. The top condensate is, we presume, driven by strong, short-distance topcolor interactions with a natural scale of order a TeV or higher. The strength of these interactions must be adjusted carefully to produce an effective composite Higgs boson vacuum expectation value of order only a few hundred GeV – this adjustment is a dynamical manifestation of the fine-tuning that we expect in a scalar theory. Here, however, the underlying scale is only of order a TeV or so, and the fine-tuning is not nearly as severe as would be required in a scalar GUT theory.

Recently, a new class of models with a naturally light composite Higgs boson has emerged: "little higgs" theories [34, 35, 36, 37]. In these models the Higgs boson is one of many pseudo-Goldstone bosons whose mass is protected by a spontaneously broken chiral symmetry – in analogy to why the pion mass remains light in QCD. Inspired by investigations of "deconstructed" higher-dimensional gauge theories [38, 39], the chiral symmetries of the models are constrained in such a way that a Higgs-boson self-coupling can appear without the appearance of large corrections to the Higgs boson mass. In general the large contributions to the Higgs-boson mass arising from top-quark loops are cancelled by corrections from a new singlet quark (similar to the χ introduced in top seesaw models) and contributions arising from electroweak gauge bosons are cancelled by those from an extended electroweak symmetry. Unlike supersymmetry, the cancellation occurs between contributions from particles *of the same spin* – with the cancellation enforced by the underlying chiral symmetries. The properties of these models below an energy scale of 10 TeV or so depend only on the symmetries of the model and are independent of the underlying dynamics. Such a scenario suggests that the LHC would uncover only the beginning of a rich new set of dynamics, and that a very high-energy hadron collider would be required to examine the underlying theory.

7. Conclusions

- A fundamental standard model Higgs is **unnatural**, **unattractive**, and (so far) **unobserved**.
- Strong Dynamics, such as technicolor, provides an elegant dynamical explanation for EWSB, but is challenged by precision electroweak tests and FCNCs. These considerations drive the investigation of composite higgs models of various kinds.
- Current limits (from Tevatron and LEP) are just reaching the interesting regime to test models of dynamical electroweak symmetry breaking. There are important signatures of these models involving W- and Z-bosons, and t- and b-quarks.
- Strong Dynamics associated with electroweak symmetry breaking will be discovered (or ruled out) by experiments at hadron colliders in this decade

References

[1] LEP Electroweak Working Group, `http://lepewwg.web.cern.ch/LEPEWWG/` .
[2] Dicus, D. A., and Mathur, V. S., *Phys. Rev.*, **D7**, 3111–3114 (1973).
[3] Cornwall, J. M., Levin, D. N., and Tiktopoulos, G., *Phys. Rev. Lett.*, **30**, 1268–1270 (1973).
[4] Cornwall, J. M., Levin, D. N., and Tiktopoulos, G., *Phys. Rev.*, **D10**, 1145 (1974).
[5] Lee, B. W., Quigg, C., and Thacker, H. B., *Phys. Rev. Lett.*, **38**, 883 (1977).
[6] Lee, B. W., Quigg, C., and Thacker, H. B., *Phys. Rev.*, **D16**, 1519 (1977).
[7] Veltman, M. J. G., *Acta Phys. Polon.*, **B8**, 475 (1977).
[8] Hill, C. T., and Simmons, E. H., *Phys. Rept.*, **381**, 235–402 (2003).
[9] Weinberg, S., *Phys. Rev.*, **D13**, 974–996 (1976).
[10] Susskind, L., *Phys. Rev.*, **D20**, 2619–2625 (1979).
[11] Eidelman, S., et al., *Phys. Lett.*, **B592**, 1 (2004).
[12] Golden, M., Han, T., and Valencia, G. hep-ph/9511206 (1995).
[13] Eichten, E., and Lane, K. D., *Phys. Lett.*, **B90**, 125–130 (1980).
[14] Dimopoulos, S., and Susskind, L., *Nucl. Phys.*, **B155**, 237–252 (1979).
[15] Appelquist, T., Christensen, N., Piai, M., and Shrock, R. (2004).
[16] Holdom, B., *Phys. Rev.*, **D24**, 1441 (1981).
[17] Holdom, B., *Phys. Lett.*, **B150**, 301 (1985).
[18] Yamawaki, K., Bando, M., and Matumoto, K.-i., *Phys. Rev. Lett.*, **56**, 1335 (1986).
[19] Appelquist, T. W., Karabali, D., and Wijewardhana, L. C. R., *Phys. Rev. Lett.*, **57**, 957 (1986).
[20] Appelquist, T., and Wijewardhana, L. C. R., *Phys. Rev.*, **D35**, 774 (1987).
[21] Appelquist, T., and Wijewardhana, L. C. R., *Phys. Rev.*, **D36**, 568 (1987).
[22] Eichten, E., and Lane, K. D., *Phys. Lett.*, **B388**, 803–807 (1996).
[23] Eichten, E., Lane, K. D., and Womersley, J., *Phys. Lett.*, **B405**, 305–311 (1997).
[24] Appelquist, T., Piai, M., and Shrock, R., *Phys. Rev.*, **D69**, 015002 (2004).
[25] Chivukula, R. S., Selipsky, S. B., and Simmons, E. H., *Phys. Rev. Lett.*, **69**, 575–577 (1992).
[26] Chivukula, R. S., *Phys. Rev. Lett.*, **61**, 2657 (1988).
[27] Hill, C. T., *Phys. Lett.*, **B345**, 483–489 (1995).
[28] Harris, R. M., Hill, C. T., and Parke, S. J., hep-ph/9911288 (1999).
[29] V. A. Miransky, M. Tanabashi and K. Yamawaki, Mod. Phys. Lett. A **4**, 1043 (1989).
[30] Bardeen, W. A., Hill, C. T., and Lindner, M., *Phys. Rev.*, **D41**, 1647 (1990).
[31] Dobrescu, B. A., and Hill, C. T., *Phys. Rev. Lett.*, **81**, 2634–2637 (1998).
[32] Chivukula, R. S., Dobrescu, B. A., Georgi, H., and Hill, C. T., *Phys. Rev.*, **D59**, 075003 (1999).
[33] He, H.-J., Hill, C. T., and Tait, T. M. P., *Phys. Rev.*, **D65**, 055006 (2002).
[34] Arkani-Hamed, N., Cohen, A. G., and Georgi, H., *Phys. Lett.*, **B513**, 232–240 (2001).
[35] Arkani-Hamed, N., Cohen, A. G., Gregoire, T., and Wacker, J. G., *JHEP*, **08**, 020 (2002).
[36] Arkani-Hamed, N., Cohen, A. G., Katz, E., and Nelson, A. E., *JHEP*, **07**, 034 (2002).
[37] Arkani-Hamed, N., et al., *JHEP*, **08**, 021 (2002).
[38] Arkani-Hamed, N., Cohen, A. G., and Georgi, H., *Phys. Rev. Lett.*, **86**, 4757–4761 (2001).
[39] Hill, C. T., Pokorski, S., and Wang, J., *Phys. Rev.*, **D64**, 105005 (2001).