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Technicolor and Precision Tests of the Electroweak Interactions[†]

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Abstract

Precision electroweak measurements have been claimed to eliminate almost all models of technicolor. We show that the assumptions made to calculate the oblique parameters S, T, U apply to QCD-like technicolor models which were ruled out long ago on much firmer grounds. These assumptions are invalid in modern “walking” technicolor models.

1. Introduction

Technicolor—dynamical breaking of electroweak symmetry by an asymptotically free gauge interaction—was invented in 1979 [1],[2]. Extended technicolor—the gauge mechanism for introducing quark and lepton flavors and for breaking flavor symmetry—followed quickly [3],[4]. It was already pointed out in Ref. [4] that ETC theories generically have large flavor-changing neutral currents and that an ETC scale Λ_{ETC} of $O(1000 \text{ TeV}/\text{times mixing angles})$ was needed to avoid conflict with experiment in the neutral kaon system (also see Ref. [5]). This large scale implied ridiculously small quark and lepton masses, as well as light pseudo-Goldstone bosons (technipions) that were soon ruled out by experiment. Technicolor was dead.

The most promising solution to the FCNC problem was not long in coming [6]. Holdom showed that, if the technifermion bilinear condensate, $\langle \bar{\psi}\psi \rangle$, has a large anomalous dimension, γ_m , it is possible to have a very large ETC scale without unduly small fermion and technipion masses. Unfortunately, Holdom did not provide a convincing field-theoretic explanation of how this large γ_m could occur. His idea lay dormant until 1986 when several groups pointed out that a technicolor gauge theory with a very slowly running coupling,

$\alpha_{TC}(\mu) \simeq \text{constant}$ for $\Lambda_{TC} \sim 1 \text{ TeV} < \mu < \Lambda_{ETC}$, gives rise to $\gamma_m(\mu) \simeq 1$ over this large energy range [7]. This “walking technicolor” permitted the increase in Λ_{ETC} needed to eliminate FCNC. Thus, the resurrection of technicolor was brought about by abandoning the notion that its gauge dynamics were QCD-like, with *precocious* asymptotic freedom and all that implies. (For a recent review of technicolor, its problems and proposed solutions, see Ref. [8].)

In 1990, it was rediscovered that technicolor dynamics (TC, *not* ETC, in this case) could affect electroweak parameters that were just then beginning to be very precisely measured in LEP experiments [9]. Estimating the effects of technicolor on the “oblique” parameter S (or its equivalent), many authors showed that one-family TC models were inconsistent with its then-measured value. Once again, technicolor was dead.

This news received considerable attention in journals and on the conference circuit. Little attention was given to the protests of technicolor aficionados that the technicolor killed by the precision tests had been dead for a decade. Walking technicolor was *not* ruled out by these tests and it remains unclear how to confront it with the precision electroweak measurements. I am grateful to the organizers of the “Beyond the Standard Model” session at this conference for this opportunity to review the issues. I will do that as clearly as I can.

In the next section, I state the definition of the S, T, U parameters popularized by Peskin and Takeuchi,

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give their most recent values, and detail the assumptions that have been used to calculate these parameters in technicolor models. In Section 3, I show that all these assumptions are wrong or, at best, questionable in walking technicolor. This, of course, will not convince its detractors that technicolor is still viable; nor is it intended to. My intent is to persuade that the S, T, U -argument against technicolor is far from made. Finally, in Section 4, I discuss some other aspects of precision electroweak tests. These include the question of technicolor (here ETC is involved) and the rate for $Z^0 \rightarrow b\bar{b}$, as well as some other curiosities in the precision electroweak data.

2. Technicolor and Precision Electroweak Tests—The Problem

The standard $SU(2) \otimes U(1)$ model of electroweak interactions has passed all experimental tests faced so far. The parameters of this model— $\alpha(M_Z)$, M_Z , $\sin^2 \theta_W$ —are so precisely known that they may be used to limit new physics at energy scales above 100 GeV. The quantities most sensitive to new physics are defined in terms of electroweak current correlation functions:

$$\int d^4x e^{-iq \cdot x} \langle \Omega | T(j_i^\mu(x) j_j^\nu(0)) | \Omega \rangle = ig^{\mu\nu} \Pi_{ij}(q^2) + q^\mu q^\nu \text{ terms.} \quad (1)$$

Assuming that the scale Λ_{new} of this physics is *well above* $M_{W,Z}$, one may define “oblique” correction factors S , T and U that measure its effects by

$$\begin{aligned} S &= 16\pi [\Pi'_{33}(0) - \Pi'_{3Q}(0)], \\ T &= \frac{4\pi}{M_Z^2 \cos^2 \theta_W \sin^2 \theta_W} [\Pi_{11}(0) - \Pi_{33}(0)], \\ U &= 16\pi [\Pi'_{11}(0) - \Pi'_{33}(0)]. \end{aligned} \quad (2)$$

Here, the prime denotes differentiation at $q^2 = 0$, and these are the leading terms in an expansion in $M_Z^2/\Lambda_{\text{new}}^2$. The parameter S is a measure of the splitting between M_W and M_Z induced by weak-isospin conserving effects. The parameter T is defined in terms of $\rho \equiv M_W^2/M_Z^2 \cos^2 \theta_W = 1 + \alpha T$. The U -parameter measures weak-isospin breaking in the W and Z mass splitting.

Langacker recently made a global “best fit” to a set of precisely-measured electroweak quantities, using the CDF measurement of the top-quark mass, $m_t = 174 \pm 10^{+13}_{-12}$ GeV [11]. He extracted the following values of S, T, U due to potential *new physics* [12]:

$$\begin{aligned} S &= -0.15 \pm 0.25^{+0.08}_{-0.17} \\ T &= -0.08 \pm 0.32^{+0.18}_{-0.11} \\ U &= -0.56 \pm 0.61. \end{aligned} \quad (3)$$

The first error is the net experimental error, assuming a standard Higgs boson mass of 300 GeV; the second error is the effect of varying M_H from 60 to 1000 GeV.

It is clear that S, T, U can be computed precisely only if the new physics is weakly coupled. It would have been impossible to calculate the QCD analogs of S, T, U without experimental information on the hadronic weak currents—the color and flavor of quarks, the spectrum of hadrons, and so on. New standard-model data is still leading to revisions. A year ago, the quoted value of S was rather different, -0.8 ± 0.5 , from Eq. (3) (see [8]); the change is due to the fact that we now know the top-quark mass [11]. No data is available for technicolor—a strong gauge theory at a scale of several 100 GeV. Assumptions must be made to estimate its contributions to S, T, U .

The assumptions made to calculate S amount to assuming that technicolor is just QCD scaled up to a higher energy, with N_D electroweak doublets of technifermions belonging to the fundamental representation of a strong $SU(N_{TC})$ technicolor gauge group:

- 1.) Techni-isospin is a good symmetry, i.e., custodial $SU(2)$ breaking by ETC interactions is negligible.
- 2.) Asymptotic freedom sets in quickly above the technicolor scale Λ_{TC} .
- 3.) Appropriate combinations of spectral functions of current correlators may be estimated using vector-meson dominance, i.e., saturating the spectral integrals with the lowest-lying spin-one resonances. Why this works in QCD is a mystery, but it is consistent with the precocious asymptotic freedom of QCD (see the discussion in Section 3).
- 4.) The spectrum of techni-hadrons may be scaled from QCD using, e.g., large- N_{TC} arguments.
- 5.) Chiral lagrangians may be used to describe the low-energy dynamics of technipions, with coefficients of terms scaled from the QCD values [10].

As an oft-cited example of how these assumptions are employed, I present a simplified version of Peskin and Takeuchi’s calculation of S [9]. If techni-isospin is a good symmetry, then S may be written as the following spectral integral:

$$\begin{aligned} S &= -4\pi [\Pi'_{VV}(0) - \Pi'_{AA}(0)] \\ &= \frac{1}{3\pi} \int_0^\infty \frac{ds}{s} [R_V(s) - R_A(s)]. \end{aligned} \quad (4)$$

Here, $\Pi_{VV(AA)}$ is the polarization function for the product of two vector (axial-vector) weak isospin currents (e.g., $j_\mu^3 j_\nu^3$); $R_{V(A)}$ is the analog for these current of $R(s) = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$. They are the spin-one spectral functions to

which Weinberg's two sum rules apply [13]:

$$\begin{aligned} \int_0^\infty ds [R_V(s) - R_A(s)] &= F_\pi^2 \\ \int_0^\infty ds \cdot s [R_V(s) - R_A(s)] &= 0. \end{aligned} \quad (5)$$

These sum rules, written here for conserved currents, are implied by the strength of the singularity at $x \rightarrow 0$ in $\langle \Omega | T(j_{L\mu}(x)j_{R\nu}(0)) | \Omega \rangle$. The second sum rule, in particular, requires asymptotic freedom for its validity. In Eqs. (5), $F_\pi = 246$ GeV is the decay constant of the technipions that become the longitudinal components of the W and Z .

In the evaluation of S , the spectral functions R_V and R_A are approximated by saturating them with the lowest-lying vector (ρ_T) and axial-vector (a_{1T}) meson poles, using Eqs. (5) to help fix their parameters. Their masses are scaled from QCD using large- N_{TC} . In the narrow width approximation,

$$S = 4\pi \left(1 + \frac{M_{\rho_T}^2}{M_{a_{1T}}^2} \right) \frac{F_\pi^2}{M_{\rho_T}^2} \simeq 0.25 N_D \frac{N_{TC}}{3}. \quad (6)$$

It appears from Eq. (6) that all technicolor models with $N_D > 1$ and $N_{TC} > 3$ are ruled out; this includes the popular one-family model ($N_D = 4$).

The other main method of calculating S uses chiral lagrangians. Technicolor models with N_D -doublets have $4(N_D^2 - 1)$ physical technipions. Golden and Randall, Holdom and Terning, and others [9] estimated their leading chiral-logarithmic contribution, S_{π_T} , to S^\dagger . This approach is valid, independent of the nature of technicolor dynamics, so long as ETC interactions are weak enough that a chiral perturbation expansion is accurate. Assuming all technipions are degenerate and that the cutoff scale for the chiral logs is M_{ρ_T} , these authors obtained

$$S > S_{\pi_T} \simeq \frac{1}{12\pi} (N_D^2 - 1) \log \left(\frac{M_{\rho_T}^2}{M_{\pi_T}^2} \right) \simeq 0.08 (N_D^2 - 1). \quad (7)$$

Eqs. (6) and (7) agree for the popular choice of the one-family model, $N_D = N_{TC} = 4$, in which case $S \simeq 1$, almost 4σ away from the central value quoted above. This agreement is accidental; see Ref. [14]. Nevertheless, except for the simplest possible technicolor model, such estimates of S have led to the oft-repeated observation that, to paraphrase Ref. [15], "technicolor is not only really very dead, it's really most sincerely dead!"

3. Walking Technicolor and S, T, U

While chiral symmetry breaking and bound state formation in QCD are nonperturbative phenomena, requiring strong-coupling methods for their study, much interesting physics of quarks and gluons occurs above 1 GeV where it is possible to exploit asymptotic freedom. Walking technicolor, is essentially nonperturbative over the entire range, Λ_{TC} to Λ_{ETC} . Let us see how this affects the basic assumptions made in calculating S . For now, leave the question of techni-isospin aside. That has as much to do with ETC interactions as with walking TC.

The assumption that asymptotic freedom sets in quickly above Λ_{TC} is patently wrong. This assumption was used implicitly (and is essential) in approximating the spectral functions $R_V(s)$ and $R_A(s)$. It tells how these functions behave at large s and, in turn, how fast $\Pi_{VV}(q^2) - \Pi_{AA}(q^2)$ falls at large q^2 . In an asymptotically free theory, $\Pi_{VV}(q^2) - \Pi_{AA}(q^2) \sim q^{-4}$ above Λ_{TC} . In a walking gauge theory, $\Pi_{VV}(q^2) - \Pi_{AA}(q^2) \sim q^{-2}$ until the coupling becomes small, at $q^2 \lesssim \Lambda_{ETC}^2$. Consequently, the convergence of the second spectral integral to zero (Eq. (5)) is much slower in a walking gauge theory, and $R_V - R_A$ cannot be approximated by a *single, close pair* of vector and axial-vector meson poles. It follows that the masses and widths of hadrons in a walking gauge theory cannot simply be scaled up from QCD; the spectrum of a walking gauge theory is a mystery. While the integral for S is dominated by low energies, the spectral sum rules connect the low and high energy behavior of $R_V - R_A$. In a walking theory, the spectral weight of $R_V - R_A$ is shifted to higher energies. Thus, it is possible that S is smaller in such a theory than in a QCD-like one.

Another reason to be skeptical of scaling from QCD is that some or all technifermions may belong to higher-dimensional representations of the TC gauge group. Then, large- N_{TC} arguments are inapplicable.

The assumption of a reliable chiral-perturbative expansion in a walking gauge theory is also unjustified. Like the technifermion bilinear, the operators $\bar{\psi}\psi$ involved in ETC generation of technipion masses have large anomalous dimensions [7]. In the extreme walking case, these become relevant operators so that $M_{\pi_T} \sim \Lambda_{TC}$; i.e., the technipions are *not* approximate Goldstone bosons. In generic walking TC theories, then, the chiral Lagrangian estimate of a lower bound for S is also likely to be incorrect.

Now return to the question of techni-isospin conservation, and T and U as well. This assumption appeared plausible because, otherwise, T ought to be too large. However, ETC theories need to have rather large isospin breaking to account for the top-quark mass of $O(F_\pi)$! Can this be consistent with small S and T ?

† Holdom and Terning also estimated the non-chiral log part of the relevant coefficient in the chiral lagrangian by scaling from QCD. I will discuss below why such scaling is problematic.

The T -parameter is notoriously difficult to calculate (which partly explains why so few attempt it). The main problem is that T is directly determined by physics at higher scales (Λ_{TC}) even in ordinary TC theories; there is no derivative in its definition (see, e.g., Ref. [16]). This may point the way out. It is possible that there are several scales of chiral symmetry breaking in TC theories (e.g., see Ref. [17])[†]. The highest scales, mainly responsible for generating $M_{W,Z}$, may respect weak isospin. The lower scales, which contribute to S , may not. It has long been known and was emphasized in Ref. [18] that this can lead to a small and even a negative value for S . Whether multiscale theories can generate a large m_t is a model-dependent question. See Ref. [19] for an example that may produce large m_t . There is practically nothing we can say about U . It is generally presumed to be of $O(S \cdot T)$. We are unaware of attempts to compute it in a walking technicolor theory.

4. Other Electroweak Discrepancies

The deviation of the measured $Z^0 \rightarrow b\bar{b}$ rate from the standard-model expectation is [12]

$$\Delta_{b\bar{b}} \equiv \Gamma(Z \rightarrow b\bar{b})/\Gamma(Z \rightarrow b\bar{b})_{SM} - 1 = 0.031 \pm 0.014, \quad (8)$$

i.e., 2.2σ away from zero. This rate may turn out to be the most incisive test of TC/ETC theories. The reason for this is that the top-quark is so heavy that the ETC boson which generates m_t is probably very light, of order a few TeV (an exception to this will be mentioned below). Consequently, the Fierz'd ETC interaction

$$\xi^2 \frac{1}{\Lambda_{ETC}^2(t)} \left(\bar{T}_L \gamma^\mu \frac{\vec{\tau}}{2} T_L \right) \cdot \left(\bar{\psi}_L \gamma_\mu \frac{\vec{\tau}}{2} \psi_L \right) \quad (9)$$

modifies the coupling of left-handed b -quarks to the Z^0 [20]. Here, $\Lambda_{ETC}(t)$ is the ETC scale involved in generating m_t ; T_L is a left-handed technifermion doublet and $\psi_L = (t, b)_L$; and ξ is a model-dependent factor expected to be $O(1)$.

In a QCD-like technicolor theory,

$$\Delta_{b\bar{b}} = -0.065 \xi^2 \left(\frac{m_t}{175 \text{ GeV}} \right), \quad (10)$$

in clear conflict with the value quoted in Eq. (8). The situation is little improved if α_{TC} walks because a low $\Lambda_{ETC}(t)$ is still needed to produce such a large m_t [21].

Clearly this is a problem of the ETC, not just the TC, interaction. Two modifications to ETC can eliminate the conflict with $\Delta_{b\bar{b}}$. The first, which appears to be necessary anyway to explain the large m_t , is

[†] If the lower scales in these multiscale TC models are close to M_Z , the assumption that oblique corrections are characterized by just the lowest derivatives S, T, U is also incorrect.

known as strong extended technicolor (SETC). An ETC scale of $O(1 \text{ TeV})$ makes no sense dynamically. There is not enough splitting between the scale at which ETC breaks to TC and the TC scale itself. To maintain a substantial hierarchy between $\Lambda_{ETC}(t)$ and Λ_{TC} , it seems necessary that some ETC interactions be strong enough to participate with TC in the breakdown of electroweak symmetry [22]. This requires some fine tuning of the ETC coupling and leads to a composite scalar state light compared to $\Lambda_{ETC}(t)$ [23]. The increased $\Lambda_{ETC}(t)$ leads to a $\Delta_{b\bar{b}}$ too small to detect [24].

The second modification of ETC which can eliminate conflict with $\Delta_{b\bar{b}}$ is to give up the time-honored, but apparently inessential, assumption that the ETC gauge group commutes with electroweak $SU(2)$ [‡]. Chivukula, Simmons and Terning have recently considered the magnitude of $\Delta_{b\bar{b}}$ in such noncommuting ETC theories *without* the assumption of SETC [25]. They found that it is possible to obtain $\Delta_{b\bar{b}}$ of order the value in Eq. (10), but with *either* sign. This will be especially interesting if the deviation in Eq. (8) survives.

Finally, I draw attention to two other curiosities in the precision measurements. The first involves $\sin^2 \theta_W$. The SLD measurement reported at this conference is [26]

$$\sin^2 \theta_W(\text{SLD}) = 0.2292 \pm 0.0009 \pm 0.0004. \quad (11)$$

The LEP average value reported here is [27]

$$\sin^2 \theta_W(\text{LEP}) = 0.2321 \pm 0.0003 \pm 0.0004. \quad (12)$$

These differ by 2.9σ . An equivalent (and perhaps more direct) expression of this intercontinental disagreement is provided by the left-right asymmetry. The SLD measurement is (from Ref. [12], whose notation we follow)

$$A_e^0(\text{SLD}) = 0.164 \pm 0.008 \quad (13)$$

The asymmetry inferred from LEP measurements of the forward-backward asymmetry in $e^+e^- \rightarrow Z^0 \rightarrow e^+e^-$ and the angular distribution of τ -polarization is

$$A_e^0(\text{LEP}) = 0.129 \pm 0.010 \quad (14)$$

The disagreement here is 2.7σ .

The second discrepancy is smaller and wouldn't be worth mentioning if it weren't in a quantity of such great theoretical interest. It is the QCD coupling renormalized at M_Z , $\alpha_S(M_Z)$. The LEP average value, extracted from the Z^0 lineshape, is [12]

$$\alpha_S(M_Z|\text{LEP}) = 0.124 \pm 0.005 \pm 0.002. \quad (15)$$

Most low-energy measurements of $\alpha_S(M_Z)$ give a lower value. The one with the smallest quoted error is

[‡] See [4] for a discussion of this assumption.

extracted from the charmonium spectrum using lattice-QCD methods to separate out the confining potential's contribution [28]:

$$\alpha_S(M_Z|\text{Lattice}) = 0.115 \pm 0.002. \quad (16)$$

These values differ by 1.5σ . Langacker stresses that the value of $\alpha_S(M_Z)$ extracted from the Z^0 lineshape is sensitive to certain types of new physics. His global fit, allowing a nonzero $\Delta_{b\bar{b}}$, gave the result in Eq. (8) and $\alpha_S(M_Z) = 0.103 \pm 0.11$, 2σ away from the LEP measurement.

What are we to make of these discrepancies? The deviation $\Delta_{b\bar{b}}$ is 2σ from zero. Shall we say that the standard model is ruled out? Surely, almost everyone believes that will happen someday. The LEP and SLD measurements of $\sin^2\theta_W$ differ by almost 3σ . Is this just experimental error? If so, who's wrong? Low and high-energy determinations of the QCD coupling are on the verge of being inconsistent. Is this just (!) the effect of new physics at high energies? Given these discrepancies, might it not be premature to say that essentially nonperturbative theories such as walking technicolor are ruled out by the values of S and T . At the very least, we ought to bear in mind Vernon Hughes' admonition [29]:

Half of all three sigma measurements are wrong.

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