

Revenge of the One-Family Technicolor Models

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Abstract

We describe how isospin splitting and techniquark-technilepton splitting in one-family technicolor models can reduce the predicted value of the electroweak radiative correction parameter S , without making a large contribution to the T parameter.

1 Introduction

Recent work [1, 2, 3] has shown that the electroweak radiative correction parameter S typically receives positive contributions in theories where QCD-like technicolor (TC) interactions spontaneously break the electroweak gauge symmetry. These contributions grow with the number of technicolors N_{TC} and the number of technicolored weak doublets. Experiments, however, seem to be finding S to be very small or even negative [2, 4]. In TC theories with non-QCD-like dynamics, the value of S could be smaller [5]. However, it is difficult [3] to reliably estimate S in such theories, because we cannot use QCD as an “analog computer”. There also exist mechanisms for producing negative values for S in certain TC models [6]. Thus, while it is an open question whether there are realistic TC models that predict

an acceptably small value for S , previous work suggests that this can be difficult, especially in models with more than one doublet. In particular, one-family models, which are attractive in their economical use of ETC gauge bosons, appear to be disfavored by the preceding discussion.

However, previous work on estimating S in models with one family of technifermions has assumed that all the technifermions are approximately degenerate in mass, and hence that isospin is a good symmetry. In this letter we point out that technifermion degeneracy is not very likely in realistic one-family models, and furthermore that such non-degenerate technifermions can significantly reduce S , without making the weak-isospin-violating-parameter T too large.

In the next section we discuss the spectrum of technifermions in realistic one-family models. In section 3, we estimate the effect that this has on S and T . In section 4 we present our conclusions and some speculations on possible experimental signatures for the class of TC models considered here.

2 The Spectrum of Technifermions

In order for a model of electroweak symmetry breaking to be realistic, one must explain not only how the W 's and Z get their masses (which TC does well) but also why ordinary fermions have such a bizarre mass spectrum. In the TC context this means that one must have not only a model of TC, but also a model of extended technicolor (ETC) interactions which feed masses down to ordinary fermions from technifermion masses. Getting the correct masses for ordinary fermions is particularly a problem in models with one family of technifermions if one assumes that

there is only one ETC mass scale for each ordinary family. Fermion masses are naively expected to be roughly $g_{ETC}^2 4\pi f^3/M^2$, where f is the Nambu-Goldstone boson (NGB) decay constant, M is the mass of the ETC gauge boson, and g_{ETC} the ETC gauge coupling. It is then difficult to see how one can arrange for the t quark to have a mass around 150 GeV, while the τ lepton has a mass of 1.8 GeV, when both masses arise through the exchange of the same ETC gauge boson.

A possibility is that QCD interactions in concert with a near-critical ETC interaction can greatly enhance the masses of quarks over leptons [7, 8]. One calculation [8] found that quark masses could be up to two orders of magnitude larger than lepton masses, without excessive fine-tuning of the ETC interaction. The same would then be true for techniquark and technilepton masses renormalized at the ETC scale. At TeV energies and below, this QCD enhancement also makes the techniquarks (U, D) heavier than the technileptons (N, E), but by a much smaller factor, say of order 3-5. We note that the bulk of the W and Z masses in such a model would come from the techniquarks, since, for example, the mass of the Z is given to lowest order by

$$M_Z^2 = \frac{g^2 + g'^2}{4} \left(\frac{1}{2} f_N^2 + \frac{1}{2} f_E^2 + 3f_Q^2 \right), \quad (1)$$

where f_N , f_E , and f_Q are the NGB decay constants associated with NGB's composed of technineutrinos, technielectrons, and techniquarks respectively. Here g and g' are the $SU(2)_L$ and $U(1)_Y$ gauge couplings. We expect the NGB decay constants to have ratios similar to corresponding ratios of TeV-scale technifermion masses.

Since T is small, one must require in such a model (with the techniquarks dominating the weak-scale physics) that weak isospin symmetry is not broken too

badly for the techniquarks at TeV scales and below. This can be difficult with the very different t and b quark masses which must be arranged for in the theory, since the U and D masses at the ETC scale are typically on the order of the t and b masses. One way to arrange the t - b hierarchy, and yet to keep the U and D masses close to each other at TeV scales and above, is to have different ETC scales for the t and b [9]. Another way is through extra mixing for the b (e.g. a generalization of the scenario in reference [10]). In this paper, it will be assumed that some mechanism of this sort leads to a relatively small splitting between the TeV-scale U and D masses.

Since the lighter technileptons make only a small contribution to the gauge boson masses, however, the technielectrons and technineutrinos are allowed to have substantially different TeV-scale masses. That they should be different is natural in an ETC theory, which must explain the large splitting between neutrinos and charged leptons. However one arranges for this, it must involve different ETC couplings for the technielectron and technineutrino. If the ETC interactions are near-critical (in order to get a large t - τ splitting) then they can have a potentially large effect, and we expect that the technielectron and the technineutrino will have significantly different masses. In what follows we will assume that, as in the ordinary lepton pattern, the technineutrino will be lighter than the technielectron.

Thus we expect that in a realistic one-family model (without a plethora of ETC scales), there will be a hierarchy of technifermion masses. At TeV scales and below, we expect to have heavy techniquarks which are approximately degenerate, a much lighter technielectron, and an even lighter technineutrino. If the bulk of the W and Z masses is to come from the techniquarks through equation 1, then using a

naive scaling from QCD, the TeV-scale masses of the U and D can be estimated to be approximately $860/\sqrt{N_{TC}}$ GeV. For purposes of our numerical estimates, we will use $N_{TC} = 2$ (which minimizes S). The main constraint on the technilepton masses is that they must be larger than roughly $M_Z/2$. For our estimates we will take the mass of the technielectron E to be 150 GeV and the mass of the technineutrino N to lie in the range 50 to 150 GeV.

It should be pointed out that this pattern of mass scales is different from that envisaged in conventional one-family models. The intrinsic scale of TC (which we take to be around 100 GeV) is smaller than is usually considered, since techniquarks receive a large part of their masses from near-critical ETC (together with QCD) interactions. We are thus assuming that ETC interactions have a major effect on the dynamical, TeV-scale technifermion masses, rather than being a small perturbation. In the next section we will estimate the effect that this unusual spectrum of technifermions has on the S and T parameters.

3 Precision Electroweak Measurements

We first estimate the value of S in realistic one-family technicolor models, as described above. The S parameter corresponds to a certain term in the chiral Lagrangian description of the electroweak interactions [2, 11]. It is generated by integrating out everything except the standard model corrections themselves. This will include contributions from the pseudo-Nambu-Goldstone bosons (PNGB's), referred to here as the “low-energy” contributions, as well as “high-energy” contributions from the techniquarks and technileptons.

In order to calculate the PNGB contribution, we must first estimate the spectrum of PNGB's. When discussing one-family TC models, it is often assumed that the approximate global chiral symmetry is $SU(8)_L \otimes SU(8)_R \otimes U(1)_V$ (corresponding to 3 techniquark doublets, and one technilepton doublet)¹. The large splitting in technifermion masses discussed in the last section indicates that in the type of models we are discussing, the approximate global chiral symmetry of one-family of technifermions is rather² $SU(6)_L \otimes SU(6)_R \otimes SU(2)_L \otimes U(1)_{2R} \otimes U(1)_{8L} \otimes U(1)_{8R} \otimes U(1)_V$. The $U(1)_{8L}$ and $U(1)_{8R}$ correspond to the generators of $SU(8)_L$ and $SU(8)_R$ which are proportional to $\text{diag}(1, 1, 1, 1, 1, 1, -3, -3)$, and $U(1)_{2R}$ corresponds to the diagonal generator of $SU(2)_R$. TC interactions spontaneously break this global chiral symmetry to $SU(6)_V \otimes U(1)_{2V} \otimes U(1)_{8V} \otimes U(1)_V$. Thus instead of having 60 PNGB's as is usually assumed, we have only 36. The explicit breaking of $SU(8)_L \otimes SU(8)_R$ is so large here that the color triplet PNGB's usually present in one-family models are not expected to exist.

The PNGB's and NGB's can thus be enumerated as follows (we display their quantum numbers in terms of technifermion fields):

$$\begin{aligned}
\Theta_a^\alpha &\sim \bar{Q} \gamma_5 \lambda_a \tau^\alpha Q , \\
\Theta_a &\sim \bar{Q} \gamma_5 \lambda_a Q , \\
P_Q^\pm &\sim \bar{Q} \gamma_5 \tau^\pm Q , \\
P_Q^3 &\sim \bar{Q} \gamma_5 \tau^3 Q , \\
P_L^\pm &\sim \bar{L} \frac{1}{2} (1 - \gamma_5) \tau^\pm L ,
\end{aligned} \tag{2}$$

¹It is assumed here that TC and/or the near-critical ETC dynamics distinguishes between technifermions and anti-technifermions [12]. For the $SU(2)$ TC group to be employed in our numerical estimates, it is the ETC interaction that must provide this distinction [13].

²The 6 corresponds to the techniquarks, and the 2 to the technileptons.

$$\begin{aligned}
P_L^3 &\sim \bar{L}\gamma_5\tau^3L, \\
P^0 &\sim \bar{Q}\gamma_5Q - 3\bar{L}\gamma_5L,
\end{aligned}$$

where Q represents the techniquarks, L the technileptons, the λ_a 's are $SU(3)_C$ generators, and the τ^α 's are Pauli matrices. The NGB's which are eaten by the W 's and Z are linear combinations of the P 's. The PNGB mass eigenstates are formed from the orthogonal combinations (i.e. the coupling to an electroweak gauge boson vanishes). In general there is mixing between the P^3 's and the P^0 , which is model dependent. In the limit of large isospin splitting we expect that the mass eigenstates will be approximately $P_N \approx \bar{N}\gamma_5N$ and $P_E \approx \bar{E}\gamma_5E$, with a small admixture of techniquarks.

The PNGB contribution to S comes from loops of the Θ_a^α 's and the P^\pm 's. It is given by [2, 15]:

$$S_{PNGB} = \frac{1}{6\pi} \left[\ln \left(\frac{\Lambda_\chi}{M_{P^\pm}} \right) + 8 \ln \left(\frac{\Lambda_\chi}{M_{\Theta_a^\alpha}} \right) \right], \quad (3)$$

where Λ_χ is the ultraviolet cutoff scale in the loop integration. We take Λ_χ to be the scale where $SU(6)_L \otimes SU(6)_R$ chiral perturbation theory breaks down, which is roughly $4\pi f_Q/\sqrt{6} \approx 720$ GeV. Using this cutoff probably overestimates the contribution from the P^\pm loop, since these PNGB's are mainly composed of the (lighter) technileptons, and thus should be associated with a smaller decay constant, and hence a lower cutoff. The mass of the P^\pm is very model dependent since it arises mainly through ETC interactions. This means that the squared mass is proportional to technifermion condensates, and is thus sensitive to details of the TC dynamics, e.g. whether the TC coupling is running or walking. Experimentally we know that

the P^\pm must be at least as heavy as $\approx M_Z/2$. We will take the range to be

$$50\text{GeV} < M_{P^\pm} < 150\text{GeV} . \quad (4)$$

Fortunately, since the P^\pm makes only a small contribution to S , our final results are not that sensitive to this uncertainty. The mass of the Θ_a^α 's has been estimated in QCD-like TC theories [12] to be 245-315 GeV. This estimate relies on scaling up a QCD dispersion relation. If the TC dynamics are not QCD-like, then this mass estimate will be modified. We will consider the range

$$250\text{GeV} < M_{\Theta_a^\alpha} < 500\text{GeV} . \quad (5)$$

With this range of PNGB masses, we find $0.2 < S_{PNGB} < 0.6$.

The calculation of the ‘‘high-energy’’ contribution to S is more difficult, since it directly involves non-perturbative physics. The two methods used in the past [2, 5] (scaled-up QCD data from dispersion relations or chiral Lagrangians, or non-local chiral quark models) have relied on the assumption that isospin is not broken. Here we are assuming that isospin is badly broken for technileptons. The non-local chiral quark model could be generalized to overcome this difficulty, but not without considerable effort. Even a modified dispersion relation approach would not be straightforward, since the spectrum is unlike that of QCD.

A naive approach, neglecting strong technicolor interactions, will be adopted here. We note that in the case of one-doublet³, QCD-like TC theories, both methods mentioned above arrive at a value for the ‘‘high-energy’’ contribution to S that is about twice as large as the perturbative, one-technifermion loop estimate (using constant technifermion masses). We also note that studies of walking [5] TC arrive

³Where there is no PNGB contribution to S .

at values of S that are as small as half the scaled-up QCD result, i.e. approximately equal to the perturbative result (using constant masses). On the other hand, in the case of one-family QCD-like theories (with $N_{TC} = 3$) the dispersion-relation result for the “high-energy” piece (i.e. $S - S_{PNGB}$) is about half as big as the perturbative result. Here we will simply calculate the perturbative (one-technifermion loop) contribution, using twice and one half of this value to estimate the range of possible values for the “high-energy” contribution.

With this assumption, the calculation of the “high-energy” techniquark contribution to S is straightforward. We use the definition [2]

$$S_{TQ} \equiv -8\pi \Pi_{3Y}^{TQ'}(q^2 = 0) , \quad (6)$$

where

$$\Pi_{3Y}^{TQ} = (q_U - q_D) \Pi_{LR}^{TQ} , \quad (7)$$

q_U and q_D are the electromagnetic charges of the U and D , and the prime indicates a derivative with respect to q^2 . It has been assumed here that isospin is a good approximate symmetry for techniquarks. The Π 's refer to the coefficients of $ig_{\mu\nu}$ in vacuum polarizations (with gauge couplings factored out, as usual), and L and R refer to left- and right-handed currents. Using constant masses for the perturbative calculation leads to the standard result [2]:

$$S_{TQ} = \frac{N_{TC} N_C}{6\pi} . \quad (8)$$

With $N_{TC} = 2$, our estimated range is therefore $0.2 < S_{TQ} < 0.6$.

We turn next to the calculation of the contribution to S from technileptons. We will, of course, *not* assume that isospin is a good approximate symmetry for the

technileptons. We note that the technilepton masses being employed here are too small for the original⁴ definition of S to be justified. The contribution to S from the technileptons is therefore defined as (cf. ref. [14])

$$S_{TL} \equiv -8\pi \frac{\Pi_{3Y}^{TL}(q^2 = M_Z^2) - \Pi_{3Y}^{TL}(q^2 = 0)}{M_Z^2}. \quad (9)$$

We note that equation (9) reduces to the same form as equation (6) when the masses of the technileptons become much larger than M_Z . Now,

$$\Pi_{3Y}^{TL} = \frac{Y}{2} \left(\Pi_{LL}^N - \Pi_{LL}^E \right) + q_N \Pi_{LR}^N - q_E \Pi_{LR}^E. \quad (10)$$

As we will see, it is the first term in equation (10) that can give a negative contribution to S .

The required one-loop results (with constant masses) are well known [16]:

$$\begin{aligned} \Pi_{LL}(m_1, m_2, q^2) &= \frac{-1}{4\pi^2} \int_0^1 dx \ln \left(\frac{\Lambda^2}{m^2 - x(1-x)q^2} \right) \left(x(1-x)q^2 - \frac{1}{2}m^2 \right), \\ \Pi_{LR}(m_1, m_2, q^2) &= \frac{-m_1 m_2}{8\pi^2} \int_0^1 dx \ln \left(\frac{\Lambda^2}{m^2 - x(1-x)q^2} \right), \end{aligned} \quad (11)$$

where Λ is an ultraviolet cutoff, m_1 and m_2 are the masses of the fermions in the loop, and $m^2 = xm_1^2 + (1-x)m_2^2$. This leads to:

$$\begin{aligned} S_{TL} &= \frac{-N_{TC}}{\pi} \int_0^1 dx \ln \left(\frac{M_E^2 - x(1-x)M_Z^2}{M_N^2 - x(1-x)M_Z^2} \right) x(1-x) \\ &\quad + \frac{N_{TC}}{2\pi} \frac{M_N^2}{M_Z^2} \int_0^1 dx \ln \left(\frac{M_N^2}{M_N^2 - x(1-x)M_Z^2} \right) \\ &\quad + \frac{N_{TC}}{2\pi} \frac{M_E^2}{M_Z^2} \int_0^1 dx \ln \left(\frac{M_E^2}{M_E^2 - x(1-x)M_Z^2} \right) \end{aligned} \quad (12)$$

Thus we find that the technileptons can give a negative contribution to S . For example with $N_{TC} = 2$, $M_E = 150$ GeV, and $M_N = 50$ GeV, we obtain $S_{TL} = -0.2$, and thus an estimated range of -0.1 to -0.4 .

⁴i.e. keeping only the leading term in a Taylor series expansion of the vacuum polarization

Putting all three contributions (equations (3), (8), (12)) together, we arrive at the estimates given in Table 1, for the smallest TC group: $SU(2)_{TC}$. Recent fits to experimental data [4] (with a t quark mass of 140 GeV, and translating⁵ to $M_{\text{Higgs}} = \Lambda_\chi$) lead to upper limits on S (at the 90% confidence level) that are typically no more than a few tenths. The reduction in the theoretical prediction discussed here could therefore be important in attaining agreement with experiment.

M_N	S_{TQ}	S_{TL}	S
50 GeV	0.2 - 0.6	-0.1 - -0.4	-0.02 - 1.1
100 GeV	0.2 - 0.6	0.01 - 0.03	0.4 - 1.3
150 GeV	0.2 - 0.6	0.06 - 0.2	0.5 - 1.5

Table 1: Estimates of $S = S_{PNGB} + S_{TQ} + S_{TL}$, for different values of the technineutrino mass (M_N), with $M_E = 150$ GeV, and $N_{TC} = 2$. We have used $0.2 < S_{PNGB} < 0.6$.

It can be seen from equation (10) that if we were doing a more realistic calculation, taking into account the strong interaction dynamics of the technifermions, it is the techni- ρ composed of technineutrinos (which would be lighter than the techni- ρ composed of technielectrons) that gives a negative contribution to S . If techni- ρ 's are lighter than standard estimates suggest [3], then the negative contribution to S will be enhanced.

We next discuss the computation of T in realistic one-family TC models, arising from isospin splitting in PNGB's and technileptons. The point of the estimate is to show that, although there is a large isospin breaking for technileptons, this does

⁵Since TC is an alternative to the standard model Higgs sector, one must subtract off from S the Higgs contribution to vacuum polarizations which is already included in standard model fits to data, so the value of S depends on the Higgs mass used in a given fit.

not lead to a large contribution to T . Since the bulk of the W and Z masses come from the heavier techniquarks, the large isospin breaking in the (relatively light) technileptons gives a much smaller contribution than if the technileptons were the sole contributors to the gauge boson masses.

We again use one-technifermion-loop graphs (with constant masses) to estimate the “high-energy” contribution, and chiral perturbation theory to estimate the “low-energy” contribution. First recall that [2]

$$\alpha T \equiv \Delta\rho_* \equiv \frac{g^2 + g'^2}{M_Z^2} [\Pi_{11}(0) - \Pi_{33}(0)] . \quad (13)$$

We first consider the “high-energy” technilepton contribution to T . The perturbative result for one fermion loop is [17]:

$$\alpha T_{TL} = \frac{(g^2 + g'^2) N_{TC}}{64\pi^2 M_Z^2} \left[M_N^2 + M_E^2 - \frac{4M_N^2 M_E^2}{M_N^2 - M_E^2} \ln \left(\frac{M_N}{M_E} \right) \right] . \quad (14)$$

Thus for $N_{TC} = 2$, $M_E = 150$ GeV, and $M_N = 50$ GeV, we find $\Delta\rho_{TL} = \alpha T_{TL} = 0.26\%$. We take our estimated range to be from one half of to twice this value: $0.1\% < \Delta\rho_{TL} < 0.5\%$. If the isospin splitting is smaller, then these numbers become even smaller. For $M_N = 100$, for example, we find $0.03\% < \Delta\rho_{TL} < 0.1\%$.

The contribution to T from PNGB’s is zero [15], unless there is mass splitting within isospin multiplets. Since there is a large isospin splitting for technileptons, we should expect some contribution from the PNGB’s composed of technileptons. We assume that the PNGB isospin eigenstate ($I = 1$, $I_3 = 0$) is given by the linear combination of mass eigenstates $c_\theta P_N - s_\theta P_E$. For maximal isospin breaking, $c_\theta = s_\theta = 1/\sqrt{2}$. Using the results in ref. [15], we find

$$\alpha T_{PNGB} = \frac{g^2 + g'^2}{32\pi^2 M_Z^2} \left[\begin{aligned} & c_\theta^2 \int_0^1 dy \Delta_N \ln \left(\frac{\Lambda_\chi^2}{\Delta_N} \right) + s_\theta^2 \int_0^1 dy \Delta_E \ln \left(\frac{\Lambda_\chi^2}{\Delta_E} \right) \\ & - M_{P^\pm}^2 \ln \left(\frac{\Lambda_\chi^2}{M_{P^\pm}^2} \right) \end{aligned} \right], \quad (15)$$

where

$$\begin{aligned} \Delta_N &= M_{P_N}^2 + (1-y)(M_{P^\pm}^2 - M_{P_N}^2), \\ \Delta_E &= M_{P_E}^2 + (1-y)(M_{P^\pm}^2 - M_{P_E}^2). \end{aligned} \quad (16)$$

We will examine the plausible and broad range of masses given by equation (4), and by

$$M_{P^\pm}^2 < M_{P_E}^2 < 2M_{P^\pm}^2, \quad (17)$$

$$10\text{GeV} < M_{P_N} < M_{P^\pm}. \quad (18)$$

Taking $c_\theta = s_\theta = 1/\sqrt{2}$, we find that the PNCB contribution to $\Delta\rho_*$ is $-0.3\% < \Delta\rho_{PNGB} < 0.2\%$. Thus the contribution to $\Delta\rho_* \equiv \alpha T$ from technileptons and PNCB's (for the parameters we have considered above) is in the following range:

$$-0.3\% < \Delta\rho_{TL} + \Delta\rho_{PNGB} < 0.7\%. \quad (19)$$

Recent global fits to the data [4], show that most of the above range is experimentally allowed.

4 Conclusions

We have argued that in realistic one-family TC models the techniquarks will be much heavier than technielectrons, which in turn will be much heavier than technineutrinos. We have estimated the possible effects on precision electroweak measurements

that arise in TC models of this type, and noted that S can be substantially smaller than traditional estimates suggest.

We note that if technineutrinos are really as light as we have been considering in this letter, then the techni- ρ composed of technineutrinos (ρ_N) will also be light, presumably in the range 100-300 GeV. Such a particle could provide a spectacular signal at LEP II or, if it is somewhat heavier, at the next e^+e^- collider or the SSC. This would be the first experimental signature of the type of model being considered here. We expect the following ρ_N decay modes (in order of predominance, if kinematically allowed): P_N pairs (which in turn decay into third generation fermions), $P_N Z$, $P^\pm W^\mp$, $W^\pm W^\mp$, and ZZ (cf. ref [18]). If the ρ_N is too light for the possibilities listed above, then it will be extremely narrow, and decay predominantly into quarks and leptons through the Z , and also (with a small branching fraction) into third-generation fermions through an ETC gauge boson.

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