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A global fit to extended oblique parameters

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Abstract

The *STU* formalism of Peskin and Takeuchi is an elegant method for encoding the measurable effects of new physics which couples to light fermions dominantly through its effects on electroweak boson propagation. However, this formalism cannot handle the case where the scale of new physics is not much larger than the weak scale. In this case three new parameters (V, W and X) are required. A global fit to precision electroweak data for these six parameters is performed. Our results differ from what is found for just *STU*. In particular we find that the preference for $S < 0$ is no longer statistically significant.

1. Introduction

As we impatiently await our first glimpse of physics beyond the standard model, an important task is to develop methods for parametrizing measurable effects of new physics. This activity constitutes the vital link between experiment and the actual calculation of the effects of specific underlying models. One such parametrization is the *STU* treatment of Peskin and Takeuchi [1], the end product of which is a set of expressions for electroweak observables, consisting of a standard model prediction corrected by some linear combination of the parameters S, T and U. The power of this formulation is that it permits the encapsulation of the experimental implications of a very broad class of new physics in terms of a very small number of parameters. It has broad applications because it relies only on the validity of two requirements. (i) The new physics must contribute to light-fermion scattering dominantly through changes to the propagation of the usual electroweak gauge bosons. (Such self-energy contributions have come to be called 'oblique' corrections, and were first baptised as such in Ref. [2].) (ii) The scale, M, of new physics must also be large enough to justify approximating the new-physics contributions to gauge-boson self-energies at linear order in q^2/M^2 [3]. Typically this requires $M \gtrsim 1$ TeV. The technique has been applied to a wide variety of models [4] which satisfy these two requirements, including technicolor models, multi-Higgs models, models with extra generations, and the like.

The requirement that the scale of new physics be large is something of a handicap, since the possibility of having previously-undetected new physics that is comparatively light is especially interesting. At first sight any useful relaxation of this assumption appears to be doomed, even if the dominant corrections are still

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of the oblique form. This is because in this case the full q^2-dependence of the vacuum polarizations cannot be summarized in terms of the values of a few constants. But the use of the entire vacuum polarization precludes obtaining reasonably model-independent constraints, since they contain too much information to be usefully fitted to the data.

A way around this difficulty has recently been pointed out in Ref. [5]. To the extent that precision electroweak measurements are limited to momentum transfers $q^2 \approx 0$ and $q^2 = M_Z^2$ or M_W^2 – presently a practical limitation – only three new parameters, V, W and X, are required to parametrize current experiments. This opens the possibility of using present data to constrain the large class of models with $M < 1$ TeV.

In this Letter we briefly summarize the conclusions of Ref. [5], and report on the result of a global fit to the current range of precision electroweak measurements using this extended set of parameters. Adopting the conventional normalization, in which an explicit factor of the electromagnetic fine-structure constant, α, is included in their definitions, we find the parameters S through X to be bounded to be O(1). For comparison, the contribution of a typical light particle to these parameters is expected to be of order $1/4\pi s_w^2 \simeq 0.3$. We see that the data is sufficiently strong to constrain models for which the electroweak scale is well populated with new particles.

A second motivation is to see how the inclusion of V, W and X alters the bounds that have previously been obtained for S, T and U [1]. Global fits to S, T and U alone tended to favour central values for the parameter S that were negative, with $S = +1$ being excluded at the 2σ level. This conclusion was particularly interesting considering that many models of the underlying physics at scale M, such as technicolour models, predict positive values for S and T [6]. Our more general fit finds that the preference for negative S is no longer statistically significant. In a joint fit for all six parameters we find that the 2σ allowed range for S becomes $-4.3 < S < 2.5$. Technicolour models might be able to use this result to evade the bounds from electroweak data, but *only* if they predict the existence of sufficiently light particles to allow significant contributions to the new variables V, W and X.

2. Expressions for observables in terms of S through X

Insofar as it is sufficient to encode new physics effects in gauge-boson self-energies only, one can express electroweak observables as the usual SM prediction plus a contribution involving four types of possible new-physics-generated self-energies, $\delta\Pi_{ab}(q^2)$, where $\{ab\} = \{WW\}, \{ZZ\}, \{Z\gamma\}$ and $\{\gamma\gamma\}$. Oblique corrections as general functions of q^2 have been treated in [7] and [2]. To the extent that precision observables only probe $q^2 \approx 0$ and $q^2 = M_Z^2$ and M_W^2, a simple counting argument then shows that all corrections to electroweak observables can be expressed in terms of six independent combinations of the various $\delta\Pi$'s. The counting proceeds as follows.

(1) *A priori* one would expect ten parameters to arise in observables, to linear order in $\delta\Pi_{ab}$. These would consist of: $\delta\Pi_{\gamma\gamma}(q^2)/q^2$ $(q^2 = 0, M_Z^2)$, $\delta\Pi_{Z\gamma}(q^2)/q^2$ $(q^2 = 0, M_Z^2)$, $\delta\Pi_{WW}(q^2)$ $(q^2 = 0, M_W^2)$, $\delta\Pi_{ZZ}(q^2)$ $(q^2 = 0, M_Z^2)$, $\delta\Pi'_{WW}(M_W^2)$, and $\delta\Pi'_{ZZ}(M_Z^2)$, where the prime denotes differentiation with respect to q^2. (Note that $\delta\Pi_{\gamma\gamma}(q^2)/q^2$ and $\delta\Pi_{Z\gamma}(q^2)/q^2$ are well-defined at $q^2 = 0$ since $\delta\Pi_{\gamma\gamma}(0)$ and $\delta\Pi_{Z\gamma}(0)$ are zero by gauge invariance.)

(2) Three combinations of these parameters can never lead to observable deviations from the Standard Model, since they can be absorbed into renormalizations of Standard-Model quantities. These can be taken to be the renormalizations for the electroweak gauge potentials, W_μ^a, B_μ, and of the Higgs *vev*, $\langle\phi\rangle$, for example. This brings the total number of precisely measurable combinations down from ten to seven.

(3) Finally, new-physics contributions to $\delta\Pi_{\gamma\gamma}(M_Z^2)$ are not expected to be measurable. This is because, at the Z resonance, the effect of $\delta\Pi_{\gamma\gamma}(M_Z^2)$ is already suppressed by $\Gamma_Z/M_Z \sim 0.03$ relative to the effects of $\delta\Pi_{Z\gamma}(M_Z^2)$ and $\delta\Pi_{ZZ}(M_Z^2)$. Thus, new-physics contributions to $\delta\Pi_{\gamma\gamma}(M_Z^2)$ are corrections to corrections, and can be neglected. This reduces the number of measurable oblique correction parameters to six.

We therefore expect, to within the accuracy demanded by current data, that all oblique corrections to observables should depend only on six combinations of the vacuum polarizations. We have verified that this is true by explicit calculation. The resulting expressions suggest the following six definitions [5]:

$$\frac{\alpha S}{4s_w^2c_w^2} = \left[\frac{\delta\Pi_{zz}(M_z^2) - \delta\Pi_{zz}(0)}{M_z^2}\right] - \frac{(c_w^2 - s_w^2)}{s_w c_w}\,\delta\widehat{\Pi}_{z\gamma}(0) - \delta\widehat{\Pi}_{\gamma\gamma}(0), \tag{1}$$

$$\alpha T = \frac{\delta\Pi_{ww}(0)}{M_w^2} - \frac{\delta\Pi_{zz}(0)}{M_z^2}, \tag{2}$$

$$\frac{\alpha U}{4s_w^2} = \left[\frac{\delta\Pi_{ww}(M_w^2) - \delta\Pi_{ww}(0)}{M_w^2}\right] - c_w^2\left[\frac{\delta\Pi_{zz}(M_z^2) - \delta\Pi_{zz}(0)}{M_z^2}\right] - s_w^2\delta\widehat{\Pi}_{\gamma\gamma}(0) - 2s_wc_w\delta\widehat{\Pi}_{z\gamma}(0) \tag{3}$$

$$\alpha V = \delta\Pi'_{zz}(M_z^2) - \left[\frac{\delta\Pi_{zz}(M_z^2) - \delta\Pi_{zz}(0)}{M_z^2}\right], \tag{4}$$

$$\alpha W = \delta\Pi'_{ww}(M_w^2) - \left[\frac{\delta\Pi_{ww}(M_w^2) - \delta\Pi_{ww}(0)}{M_w^2}\right], \tag{5}$$

$$\alpha X = -s_wc_w\left[\delta\widehat{\Pi}_{z\gamma}(M_z^2) - \delta\widehat{\Pi}_{z\gamma}(0)\right], \tag{6}$$

where $\delta\widehat{\Pi}_{ab}(q^2) \equiv \delta\Pi_{ab}(q^2)/q^2$. The first three of these agree with the standard definitions of S, T and U that appear in the literature. Manifestly, the expressions for the remaining three quantities, V, W and X, would vanish if $\delta\Pi_{ab}(q^2)$ were simply a linear function of q^2. This ensures that existing expressions for observables in the *STU* formalism are easily modified, when necessary, with the appropriate additional corrections encoded by V, W and X.

General expressions for the oblique corrections to electroweak observables may be found in Refs. [7] and [2], which reduce in the present case [5] to a dependence of these observables on the variables S through X. In this analysis, as is commonly done, we take as numerical inputs the following three observables: α as measured in low-energy scattering experiments, G_F as measured in muon decay, and M_Z. These observables are chosen because they are the most precisely measured. With this choice, the parameter U appears only in the observables M_w and Γ_w, and W appears only in Γ_w.[2] We next outline these results, whose numerical values are summarized in Table 1.

[2] By contrast, a different choice of inputs – such as M_Z, M_W and α for instance – would lead to U-dependence throughout all the neutral current observables.

Table 1
Summary of the dependence of electroweak observables on S, T, U, V, W and X

$$\Gamma_Z = (\Gamma_Z)_{\rm SM} - 0.00961S + 0.0263T + 0.0194V - 0.0207X \ (\text{GeV})$$
$$\Gamma_{b\bar{b}} = (\Gamma_{b\bar{b}})_{\rm SM} - 0.00171S + 0.00416T + 0.00295V - 0.00369X \ (\text{GeV})$$
$$\Gamma_{l^+l^-} = (\Gamma_{l^+l^-})_{SM} - 0.000192S + 0.000790T + 0.000653V - 0.000416X \ (\text{GeV})$$
$$\Gamma_{\rm had} = (\Gamma_{\rm had})_{SM} - 0.00901S + 0.0200T + 0.0136V - 0.0195X \ (\text{GeV})$$
$$A_{\rm FB}(\mu) = (A_{\rm FB}(\mu))_{\rm SM} - 0.00677S + 0.00479T - 0.0146X$$
$$A_{\rm pol}(\tau) = (A_{\rm pol}(\tau))_{\rm SM} - 0.0284S + 0.0201T - 0.0613X$$
$$A_e(P_\tau) = (A_e(P_\tau))_{\rm SM} - 0.0284S + 0.0201T - 0.0613X$$
$$A_{\rm FB}(b) = (A_{\rm FB}(b))_{\rm SM} - 0.0188S + 0.0131T - 0.0406X$$
$$A_{\rm FB}(c) = (A_{\rm FB}(c))_{\rm SM} - 0.0147S + 0.0104T - 0.03175X$$
$$A_{\rm LR} = (A_{\rm LR})_{\rm SM} - 0.0284S + 0.0201T - 0.0613X$$
$$M_W^2 = (M_W^2)_{\rm SM}(1 - 0.00723S + 0.0111T + 0.00849U)$$
$$\Gamma_W = (\Gamma_W)_{\rm SM}(1 - 0.00723S - 0.00333T + 0.00849U + 0.00781W)$$
$$g_L^2 = (g_L^2)_{\rm SM} - 0.00269S + 0.00663T$$
$$g_R^2 = (g_R^2)_{\rm SM} + 0.000937S - 0.000192T$$
$$g_V^e(\nu e \to \nu e) = (g_V^e)_{\rm SM} + 0.00723S - 0.00541T$$
$$g_A^e(\nu e \to \nu e) = (g_A^e)_{\rm SM} - 0.00395T$$
$$Q_W({}^{133}_{55}\text{Cs}) = Q_W(\text{Cs})_{\rm SM} - 0.795S - 0.0116T$$

In preparing this table we used the numerical values $\alpha(M_Z^2) = 1/128$ and $s_w^2 = 0.23$

In observables defined at $q^2 \approx 0$, only the usual parameters S and T contribute. For example, the effective value of the weak mixing angle, $(s_w^2)_{\rm eff}$, as measured in various low-energy asymmetries (such as atomic parity violation, the low-energy neutral current scattering ratio $R = \sigma(\nu_\mu e)/\sigma(\bar{\nu}_\mu e)$, etc.) is given by

$$(s_w^2)_{\rm eff}(q^2{=}0) = (s_w^2)_{\rm eff}^{\rm SM}(q^2{=}0) + \frac{\alpha S}{4(c_w^2 - s_w^2)} - \frac{s_w^2c_w^2\,\alpha T}{c_w^2 - s_w^2}, \tag{7}$$

and the relative strength of the low-energy neutral- and charged-current interactions is given by

$$\rho = \rho_{\rm SM}(e, G_F, M_Z)\ (1 + \alpha T). \tag{8}$$

As for measurements at the Z resonance, the effective weak mixing angle is given by

$$(s_w^2)_{\rm eff}(q^2{=}M_Z^2) = (s_w^2)_{\rm eff}^{\rm SM}(q^2{=}M_Z^2) + \frac{\alpha S}{4(c_w^2 - s_w^2)} - \frac{c_w^2s_w^2\alpha T}{(c_w^2 - s_w^2)} + \alpha X, \tag{9}$$

and an example of a correction to Z-decay is

$$\Gamma(Z \to \bar{\nu}\nu) = \Gamma_{\rm SM}(Z \to \bar{\nu}\nu)\,(1 + \alpha T + \alpha V). \tag{10}$$

We thus see that V describes a contribution to the overall normalization of the strength of the neutral-current interaction, while X acts to shift the effective value of $(s_w^2)_{\rm eff}$ measured at the Z pole.

The W boson mass and width are

$$M_w^2 = (M_w^2)_{\rm SM}(e, s_w, m_Z) \times \left[1 - \frac{\alpha S}{2(c_w^2 - s_w^2)} + \frac{c_w^2 \alpha T}{(c_w^2 - s_w^2)} + \frac{\alpha U}{4 s_w^2}\right], \tag{11}$$

$$\Gamma(W \to {\rm all}) = \Gamma_{\rm SM}(W \to {\rm all}) \times \left[1 - \frac{\alpha S}{2(c_w^2 - s_w^2)} - \frac{s_w^2 \alpha T}{(c_w^2 - s_w^2)} + \frac{\alpha U}{4 s_w^2} + \alpha W\right]. \tag{12}$$

As advertised, the parameter W turns out to appear only in the expression for Γ_w.

A comprehensive list of expressions for the electroweak observables that we include in our analysis is given in Table 2. These expressions consist of a radiatively corrected standard model prediction plus a linear combination of the six parameters S, T, U, V, W and X. Γ_Z and $\Gamma_{b\bar{b}}$ are the total width and partial width into $b\bar{b}$; $A_{\rm FB}(f)$ is the forward–backward asymmetry for $e^+e^- \to f\bar{f}$; $A_{\rm pol}(\tau)$, or P_τ, is the polarization asymmetry defined by $A_{\rm pol}(\tau) = (\sigma_{\rm R} - \sigma_{\rm L})/(\sigma_{\rm R} + \sigma_{\rm L})$, where $\sigma_{L,R}$ is the cross section for a correspondingly polarized τ lepton; $A_e(P_\tau)$ is the joint forward-backward/left-right asymmetry as normalized in Ref. [8]; and $A_{L,R}$ is the polarization asymmetry which has been measured by the SLD collaboration at SLC [9]. The low-energy observables $g_{\rm L}^2$ and $g_{\rm R}^2$ are measured in deep inelastic νN scattering, g_V^e and g_A^e are measured in $\nu e \to \nu e$ scattering, and $Q_W(\rm Cs)$ is the weak charge measured in atomic parity violation in cesium.

There are several features in Table 1 worth pointing out. First, as has already been mentioned, due to the choice of numerical inputs (α, G_F, M_Z), only the two parameters S and T contribute to the observables for which $q^2 \sim 0$; the parameter U appears only in M_w and Γ_w. The limit on U comes principally from the M_w measurement, since Γ_w is at present comparatively poorly measured. For the same reason, the parameter W is weakly bounded, since it contributes only to Γ_w. In addition to S and T, observables on the Z^0 resonance are also sensitive to V and X, which are expressly defined at $q^2 = M_Z^2$. Observables that are not explicitly given in Table 1 can be obtained using the given expressions. In particular the parameter R is defined as $R = \Gamma_{\rm had}/\Gamma_{l\bar{l}}$, and $\sigma_p^h = 12\pi\Gamma_{e\bar{e}}\Gamma_{\rm had}/M_Z^2\Gamma_Z^2$ is the hadronic cross section at the Z-pole.

Table 2
Experimental values for electroweak observables included in global fit

Quantity	Experimental value	Standard model prediction
M_Z (GeV)	91.187 ± 0.007 [10]	input
Γ_Z (GeV)	2.488 ± 0.007 [10]	2.490 [±0.006]
$R = \Gamma_{\rm had}/\Gamma_{l\bar{l}}$	20.830 ± 0.056 [10]	20.78[±0.07]
σ_p^h (nb)	41.45 ± 0.17 [10]	41.42 [±0.06]
$\Gamma_{b\bar{b}}$ (MeV)	383 ± 6 [10]	375.9 [±1.3]
$A_{\rm FB}(\mu)$	0.0165 ± 0.0021 [10]	0.0141
$A_{\rm pol}(\tau)$	0.142 ± 0.017 [10]	0.137
$A_e(P_\tau)$	0.130 ± 0.025 [10]	0.137
$A_{\rm FB}(b)$	0.0984 ± 0.0086 [10]	0.096
$A_{\rm FB}(c)$	0.090 ± 0.019 [10]	0.068
$A_{\rm LR}$	0.100 ± 0.044 [9]	0.137
M_W (GeV)	79.91 ± 0.39[11]	80.18
M_W/M_Z	0.8798 ± 0.0028[12]	0.8793
Γ_W (GeV)	2.12 ± 0.11[13]	2.082
$g_{\rm L}^2$	0.3003 ± 0.0039 [8]	0.3021
$g_{\rm R}^2$	0.0323 ± 0.0033 [8]	0.0302
g_A^e	-0.508 ± 0.015 [8]	−0.506
g_V^e	-0.035 ± 0.017 [8]	−0.037
$Q_W(\rm Cs)$	$-71.04 \pm 1.58 \pm$ [0.88][14]	−73.20

The Z-pole measurements are the preliminary 1992 LEP results taken from Ref. [10]. The couplings extracted from neutrino scattering data are the current world averages taken from Ref. [8]. The values for standard model predictions are taken from Ref. [15] and have been calculated using m_t = 150 GeV and M_H = 300 GeV. We have not shown the errors in the standard model predictions associated with theoretical uncertainties in radiative corrections or with the uncertainty regarding the measurement of M_Z, since these errors are in general overwhelmed by experimental errors. The exception is the error due to uncertainty in α_s, shown in square brackets. We include this error in quadrature in our fits. The error in square brackets for $Q_W(\rm Cs)$ reflects the theoretical uncertainty regarding atomic wavefunctions [16] and is also included in quadrature with the experimental error.

3. Numerical fit of *STUVWX*

We now determine the phenomenological constraints on *STUVWX* by performing a global fit to the

Table 3
Global fits of *STUVWX* to precision electroweak data. The second column contains the results of inidividual fits, obtained by setting all but one parameter to zero. The third column is a fit of *STU* setting *VWX* equal to zero, and the final column allows all parameters to vary simultaneously. We have shown the 1σ errors.

Parameter	Individual fit	STU fit	STUVWX fit
S	-0.19 ± 0.20	-0.48 ± 0.40	-0.93 ± 1.7
T	0.06 ± 0.19	-0.32 ± 0.40	-0.67 ± 0.92
U	-0.12 ± 0.62	-0.12 ± 0.69	-0.6 ± 1.1
V	-0.09 ± 0.45	—	0.47 ± 1.0
W	2.3 ± 6.8	—	1.2 ± 7.0
X	-0.10 ± 0.10	—	0.10 ± 0.58

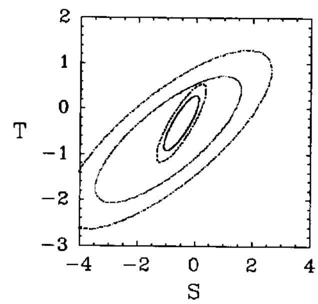

Fig. 1. Constraints on S and T from a global fit of precison electroweak measurements. The solid line represents the 68% C.L. setting *VWX* to zero, the dashed line represents the 90% C.L. setting *VWX* to zero, the dotted line represents the 68% C.L. allowing *VWX* to vary, and the dot-dashed line represents the 90% C.L. allowing *VWX* to vary.

precision data. The experimental values and standard model predictions of the observables used in our fit are given in Table 2. The standard model predictions are taken from Ref. [15] and have been calculated using the values m_t = 150 GeV and M_H = 300 GeV. The LEP observables in Table 2 were chosen because they are closest to what is actually measured, and are relatively weakly correlated. In our analysis we include the combined LEP values for the correlations [17].

In Table 3 are displayed the results of the fit. In the second column are shown the results of individual fits, obtained by setting all but one parameter to zero. The third column is a fit of *STU*, with *VWX* set to zero. Finally, in column four, we give the results for the fit in which all six parameters were allowed to vary simultaneously.

The most important observation concerning these results is that all of the parameters are consistent with zero. In other words there is no evidence for physics outside the standard model. The second observation is that the inclusion of *VWX* in our fits weakens the constraints on *STU*. This can be seen graphically in Fig. 1 where we have plotted the 68% and 90% C.L. contours for S and T. We show the results for the case in which the parameters *VWX* have been set to zero as well as that in which they have been allowed to vary. Notice in particular that although the entire 1σ allowed range for S satisfies $S < 0$ in the fit to *STU* alone (which corresponds to heavy new physics), this is not true for the fit with all six parameters, the light-physics scenario.

4. Conclusions

We have performed a global fit for the complete set of six oblique correction parameters, S through X. This fit extends the results of previous fits for S, T and U to a much wider class of models for the underlying physics, including in particular new light particles which need not be much heavier than the weak scale. We find that these parameters are bounded by the data to be $\lesssim 1$, corresponding to an O(1%) correction to the weak-boson vacuum polarizations, $\delta\Pi(q^2)$. Such bounds are sensitive enough to constrain many models for new physics near the weak scale, much as did the original *STU* analysis for technicolour models at the TeV scale.

We have also compared our joint fit of the six parameters S through X to a three-parameter fit involving only S, T, and U (with $V=W=X=0$). Not surprisingly, we find in the general case that the allowed ranges for S, T, and U are relaxed. In particular, the preference found in earlier fits for negative values for S – which had been uncomfortable for many underlying models – is no longer statistically significant for the six-parameter fit. Models for new physics can use this result to evade the stronger bounds coming from the S, T, U fit to the electroweak data, but *only* if they predict the existence of sufficiently light particles to allow significant contributions to the new variables V, W and X.

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