Constraints on extensions of the Standard Model from precise electroweak data

John Ellis

CERN, CH-1211 Geneva 23, Switzerland

G.L. Fogli and E. Lisi

*Dipartimento di Fisica di Bari, Bari, Italy
Sezione INFN di Bari, Bari, Italy*

Abstract

We present an analysis of the constraints on one-loop “oblique” (vacuum polarization) electroweak radiative corrections imposed by precise data from LEP and other experiments. We present these constraints in full 3-dimensional S , T , U space, using a complete set of low-energy data, and LEP data on heavy flavour production as well as leptons and hadrons. We take into account the uncertain top quark and Higgs boson contributions to non-oblique radiative corrections and discuss quantitatively variations associated with higher-order effects. We compare our bounds with recent estimates in a number of different technicolour scenarios.

The advent of copious LEP data [1] has increased greatly the precision with which the electroweak sector of the Standard Model can be tested. Within the theoretical context of the Standard Model, it is now possible to predict the mass of the undiscovered top quark to be about 125 GeV with an estimated error of $\pm 20\%$, and now also to get some preliminary indications on the mass of the Higgs boson, which seems more likely to weigh less than 300 GeV rather than more [2]. However, it is generally agreed that the Standard Model cannot be the whole story, and that some extension of it is likely to appear at an energy scale less or $\simeq 1$ TeV, either to replace or to complement the single elementary Higgs boson of the Standard Model. Among the leading candidates for this new physics are technicolour [3] – in which the elementary Higgs boson is replaced by a composite state which is just part of a whole new strongly-interacting sector – and supersymmetry [4] – in which there are at least 5 physical Higgs bosons and supersymmetric partners for all the known particles. Since this hypothesized new physics is expected to appear below 1 TeV, one could hope that it would already show up indirectly in precision experiments at accessible lower energies, at LEP in particular.

When looking for such indirect effects of new physics, which could take any of a number of possible forms, a powerful approach is to adopt a parametrization of them that is as model-independent as possible. Various authors have proposed related parametrizations of one-loop electroweak radiative corrections that treat “oblique” [5] (vacuum polarization) effects model-independently. The basic idea is to expand the relevant vacuum polarizations in powers of the momentum [6], [7], [8]: $\Pi_{ij}(q) = \Pi_{ij}(0) + q^2 \Pi'_{ij}(0) + \dots$, implicitly assuming that any interesting new physics has a threshold above 100 GeV, and then retain just the first two coefficients in the series expansion, $\Pi_{ij}(0)$ and $\Pi'_{ij}(0)$. There are 6 such quantities of relevance to electroweak experiments, of which 3 are reabsorbed by the standard renormalization procedure [9] in specifying the measured values of α , G_F and M_Z , leaving 3 quantities to be determined or constrained by precision experiments, by assuming a suitable parametrization of this 3-dimensional space, as we review later in this paper.

This type of parametrization is not wholly satisfactory, one reason being that it only

includes oblique corrections and omits vertex and box corrections. This is a potential drawback if one is interested in some theories, such as supersymmetry, in which vertex corrections are present and may not be small compared with oblique corrections. However, such a 3-dimensional parametrization is applicable to conventional technicolour theories [3], to the extent that their oblique corrections are calculable and they do not also have important vertex or box corrections. A further drawback is that whereas these parametrizations are formulated at the one-loop level and at first order in the momentum, the LEP data are so precise that higher-order effects are not unimportant, and their leading contributions are now routinely resummed [10] and incorporated in analyses [2], [11] within the framework of the Standard Model.

Several papers have been published [6], [7], [12], [13], [14], [15], [16], [17], [18], analyzing precise electroweak data in terms of parameters in the 3-dimensional one-loop space, often with quite negative conclusions for technicolour theories. However, not all these analyses have been truly 3-dimensional, with one of the variables called conventionally U (or ϵ_2) often being fixed to zero, as suggested by some theories. Also, some 3-dimensional analyses have not used purely oblique parameters, but quantities with an admixture of vertex corrections. Moreover, none of these analyses with which we are familiar confronts the full power of the low-energy data with those available from LEP, nor discusses explicitly the higher-order ambiguities. We therefore thought it useful to present yet another analysis with a somewhat complementary point of view.

We analyze the data in a 3-dimensional wholly-oblique parameter space, using for reference the Standard Model with $m_t = 130$ GeV and $M_H = M_Z$ to estimate non-oblique and higher-order corrections. We also discuss how our constraints on the oblique parameters are altered if m_t is varied between 90 and 250 GeV, or M_H between 50 and 1000 GeV. We use the full set of electroweak data available at the LP-HEP 91 Conference [1], with just a minor update of the LEP data on A'_{FB} . We confront our resulting phenomenological constraints not only with the predictions of traditional “running” technicolour models [3], but also with recent more general calculations that include “walking” technicolour models [14], [15].

To specify the 3-parameter wholly-oblique parameter space in which we work, we start from the standard one-loop quantities $\Delta\varrho$, Δr_e (which is the more familiar Δr

with the $\Delta\alpha$ contribution removed), and $\Delta\kappa$, whose relations to the fundamental renormalized one-loop vacuum polarizations are given by

$$\Delta\rho = \hat{\Pi}_{11}(0) - \hat{\Pi}_Z(0) \quad (1a)$$

$$\Delta r_w = -\hat{\Pi}_{11}(0) + \hat{\Pi}_\gamma(M_Z^2) \quad (1b)$$

$$\Delta\kappa = -\frac{c_W}{s_W} \hat{\Pi}_{\gamma Z}(M_Z^2) \quad (1c)$$

in the notation of, for example, ref. [19]. In the following we use two alternative proposed sets of variables, (S, T, U) [6] and $(\epsilon_1, \epsilon_2, \epsilon_3)$ [8], that are proportional to each other and linearly related to the previous standard quantities:

$$\alpha S = 4s_W^2\epsilon_3 = 4s_W^2c_W^2(\Delta\rho + \Delta r_w) + 4s_W^2(c_W^2 - s_W^2)\Delta\kappa \quad (2a)$$

$$\alpha T = \epsilon_1 = \Delta\rho \quad (2b)$$

$$\alpha U = -4s_W^2\epsilon_2 = -4s_W^2c_W^2\Delta\rho + 8s_W^4\Delta\kappa - 4s_W^4\Delta r_w \quad (2c)$$

but it is simple to transform our constraints into other choices of variables. We note that in the absence of other considerations, there is an $O(10\%)$ ambiguity in the relationship between different sets of variables induced by varying s_W^2 in the range 0.21 to 0.23.

Within the Standard Model, the most important contributions to $(\epsilon_1, \epsilon_2, \epsilon_3)$ are those from the undiscovered top quark t and Higgs boson H . Since these two particles are necessary for the Standard Model to be renormalizable, their contributions to $(\epsilon_1, \epsilon_2, \epsilon_3)$ and other radiative corrections are in general divergent as $m_t, M_H \rightarrow \infty$, and reference values of m_t, M_H must be assumed in order to specify finite Standard

Model contributions to $(\epsilon_1, \epsilon_2, \epsilon_3)$ and other one-loop quantities. The allowed values of additional contributions $(\delta\epsilon_1, \delta\epsilon_2, \delta\epsilon_3)$ depend on the choice of these reference values of (m_t, M_H) . In a recent global analysis [2] of essentially the same set of electroweak data as used here (the only modification being a shift of about a half standard deviation in the estimate of the LEP forward-backward leptonic asymmetry A_{FB}^L), we found that within the Standard Model the preferred values of (m_t, M_H) were (122, 10) GeV, and the preferred value of m_t is 130 GeV if $M_H = M_Z$ is assumed. Here we take (130 GeV, M_Z) as our primary reference values of (m_t, M_H) , but will also consider the effect of choosing other reference values.

These reference values should also be used when calculating non-oblique radiative corrections, of which the most important are the m_t -dependent contributions to $\Gamma(Z \rightarrow b\bar{b})$. However, these non-oblique corrections are either largely independent of (m_t, M_H) , or the experimental errors are large compared with the theoretical range. Therefore, our bounds on non-Standard Model contributions to $(\epsilon_1, \epsilon_2, \epsilon_3)$ would not differ greatly if other “plausible” values of (m_t, M_H) were used for reference in the calculation of non-oblique one-loop radiative corrections. The range of m_t that we consider “plausible” is (90 to 250) GeV, where the lower bound is essentially that quoted by the CDF Collaboration [20], and the upper bound is suggested by analyses of flavour-changing neutral currents and rare K decays [21]. The range of M_H that we consider “plausible” is (50 to 1000) GeV, where the lower bound is essentially that established by the LEP Collaborations [22], and the upper bound is motivated by unitarity arguments (see for example refs. [23]).

Larger effects on our bounds on $(\delta\epsilon_1, \delta\epsilon_2, \delta\epsilon_3)$ are induced by the fact that the type of “model-independent” analysis that we pursue here is formulated only at the one-loop level, whereas the data begin to feel two-loop effects. It is only within the context of the Standard Model that a recursion procedure connecting s_W^2 to m_t and M_H at fixed M_Z has been proposed [19], and that a complete procedure for resumming the dominant higher-order effects has been developed [10], which is known to have a discernible effect on the preferred range of (m_t, M_H) [2], [11]. At present, the best that one can do in the “model-independent” approach is to expand each of the measured experimental quantities C_α to linear order in the ϵ_i :

$$C_\alpha = C_\alpha^{\text{ref}} + \left(\frac{\partial C_\alpha}{\partial \epsilon_i} \right)_{\text{ref}} \delta \epsilon_i \quad (3)$$

evaluating the coefficients C_α^{ref} , $\left(\frac{\partial C_\alpha}{\partial \epsilon_i} \right)_{\text{ref}}$ in the Standard Model at the one-loop level, and at the reference values of (m_t, M_H) . In the expansion (2), the development is expressed in terms of the $\delta \epsilon_i$, defined to be the additional contributions to the ϵ_i relative to the reference Standard Model values. If one were able to take into account all orders in the perturbation expansion and avoid any linearization such as in (2), the resulting bounds on the $\epsilon_i = \epsilon_i|_{\text{SM}} + \delta \epsilon_i$ could become independent of the reference values of (m_t, M_H) . However, since we are reduced to making a linearized one-loop approximation, the bounds on the ϵ_i do depend on (m_t, M_H) , and this dependence is considerably stronger than that induced by the (m_t, M_H) -dependence of the non-oblique corrections. In particular, the coefficients $\left(\frac{\partial C_\alpha}{\partial \epsilon_i} \right)_{\text{ref}}$ depend on s_{W}^2 , without any prescription for the choice of this parameter. It seems reasonable to assume the same $\hat{s}_{\text{W}}^2$ as that characterizing the reference point (m_t, M_H) through the recursion procedure of ref. [19], but this introduces different values of $\hat{s}_{\text{W}}^2$ for different reference points, without any indication about the value of s_{W}^2 to be used when we go far from the SM region in the $(\delta \epsilon_1, \delta \epsilon_2, \delta \epsilon_3)$ space. We will return later to a quantification of this effect.

The 19 electroweak measurements that we include in our analysis are the four squared chiral couplings describing the $\nu - q$ interaction $u_L^2, d_L^2, u_R^2, d_R^2$, the $\nu - e$ couplings g_L and g_R , $\sin^2 \theta_{\text{W}}$, as measured by CHARM, the $e - q$ couplings C_{1u}, C_{1d} and $C_{2ud} = C_{2u} - \frac{1}{2} C_{2d}$, all these couplings extracted from low-energy experiments, and the quantities $M_{\text{W}}/M_Z, \Gamma_Z, \sigma_h^0, R = \Gamma_h/\Gamma_t, \Gamma_{\text{e}\bar{\text{e}}}, \Gamma_{\text{b}\bar{\text{b}}}, A_{\text{FB}}^e, A_{\text{FB}}^b$ and A_{pol}^{τ} from high-energy experiments (our notation is as in ref. [2]), where definitions of these variables may be tracked down). We treat the errors in each of these measurements as Gaussian, and include all the correlation effects of the low-energy and LEP measurements as in ref. [2]. Because of the linearization (3), the resulting $\Delta \chi^2 = 1$ bound on the $\delta \epsilon_i$ takes the form of an ellipsoid in the 3-parameter space, which is exhibited in Fig. 1, with the reference choice $(m_t, M_H) = (130 \text{ GeV}, M_Z)$ taken as the origin.

Also shown in Fig. 1 is a curved surface which shows the values of $(\delta \epsilon_1, \delta \epsilon_2, \delta \epsilon_3)|_{\text{SM}}$

for the “plausible” ranges $m_t \in (90, 250) \text{ GeV}$, $M_H \in (50, 1000) \text{ GeV}$, relative to the point marking our reference values $m_t = 130 \text{ GeV}$, $M_H = M_Z$. We see that this curved surface intersects the $\Delta \chi^2 = 1$ ellipsoid, reflecting the fact that a restricted zone of the Standard Model is compatible with the electroweak data at better than the $1-\sigma$ level. A precise Standard Model fit involves going beyond the linearized one-loop approximation used here, and favours $90 < m_t < 150 \text{ GeV}$ and $m_H < 150 \text{ GeV}$ as concluded in our recent Standard Model analysis [2].

Fig. 2a is the projection of this full 3-dimensional information onto the $(\delta S, \delta T)$ [or $(\delta \epsilon_3, \delta \epsilon_1)$] plane. The “ellipse” gives the favoured range of δS and δT if δU is allowed to vary freely. In fact, as can be seen from the $(\delta S, \delta U)$ projection in Fig. 2b and the $(\delta T, \delta U)$ projection in Fig. 2c, the favoured ranges of δS and δT are almost unaltered if we assume $\delta U = 0$ as in many models. Naturally, each of the 3 projections in Figs. 2 also shows a clear overlap between the “plausible” Standard Model ranges and the ellipses favoured by the data. (Note, however, that it was logically possible that there could have been overlaps in each of these projections, but not in the full 3-dimensional space, which is one of the reasons why we chose to present Fig. 1 first.) We read off from Figs. 2 the preferred ranges of the $\delta \epsilon_i$ due to the Beyond the Standard Model(BSM) contribution

$$\delta \epsilon_1|_{\text{BSM}} = -(0.23 \pm 0.32) \times 10^{-2} \quad (4a)$$

$$\delta \epsilon_2|_{\text{BSM}} = +(0.06 \pm 0.74) \times 10^{-2} \quad (4b)$$

$$\delta \epsilon_3|_{\text{BSM}} = -(0.50 \pm 0.47) \times 10^{-2} \quad (4c)$$

for the reference choice $(m_t, M_H) = (130 \text{ GeV}, M_Z)$.

This analysis should be redone independently for each choice of the reference values of (m_t, M_H) . As already mentioned, because of the (m_t, M_H) -dependence of the non-oblique corrections and the linearized one-loop approximation used, the bounds

on the total $\epsilon_i = \epsilon_i|_{SM} + \delta\epsilon_i$ depend on the reference choice of (m_t, M_H) , and hence the magnitude and orientation of the favoured ellipsoid relative to the Standard Model surface depends on the reference values of (m_t, M_H) chosen. This means that the favoured region of the $\delta\epsilon_i|_{BSM}$ for a different reference choice of (m_t, M_H) cannot be obtained by simply adding the corresponding changes in the $\epsilon_i|_{SM}$ to the $\Delta\chi^2$ contours in Figs. 1, 2, as could have been done by shifting the origin of $(\epsilon_1, \epsilon_2, \epsilon_3)$ to the chosen value of (m_t, M_H) on the curved Standard Model surface shown there. Some impression of the relative shift of the favoured ellipsoid and the Standard Model surface can be obtained from Fig. 3, which shows the $(\delta\epsilon_1, \delta\epsilon_3)$ projections analogous to Fig. 2a for different choices of the reference values of (m_t, M_H) . This relative shift in the $\Delta\chi^2 = 1$ contour is not negligible, but can correspond to a standard deviation or more. This observation reflects the previously-mentioned fact that the LEP and other electroweak data are already sensitive to higher-order effects, indicating a limitation of this type of “model-independent” analysis, at least in its present formulation. It is possible to calculate reliably the leading higher orders in a specific perturbative framework such as the Standard Model or its minimal supersymmetric extension, but not yet with the same reliability in a non-perturbative framework such as technicolour. This means that the confrontation with technicolour predictions must necessarily be cruder than that with the Standard Model.

The numerical values of our bounds on the $\delta\epsilon_i|_{BSM}$ for different reference values of (m_t, M_H) at the corners of the “plausible” domain of these Standard Model parameters can be read off Fig. 3 by comparing the appropriate Standard Model points A, B, C, D with the corresponding ellipses. Also shown in Fig. 3 is a star marking the reference point chosen in ref. [12] to present their bounds on the $\delta\epsilon_i$. It corresponds to assuming the tree level relations between the different observables and incorporating the running of the QED fine structure constant between zero momentum and $q^2 = M_Z^2$. As can be seen, their reference point lies close to the centre of the ellipses, but rather far from any Standard Model point. Therefore the recursion procedure of ref. [19] is not applicable, and a different prescription is used in ref. [12] to choose a value for s_W^2 . Their procedure is appropriate for the three major leptonic observables emphasized in ref. [12], but requires modifications if other observables are to be included.

Several estimates of technicolour contributions to S and T have been presented in the literature, the two most recent being those in refs. [14] and [15]. Ref. [14] uses a dispersion-theoretic approach and strong interaction data to estimate

$$\delta S_{TC} \simeq 0.05 N_{TF} N_{TC} + 0.127, \quad (5)$$

taking into account both resonant and non-resonant contributions to the relevant spectral functions, and making a correction to accommodate our different choice of $M_H|_{ref} = M_Z$. In eq. (5), N_{TF} is the number of technifermions, which must be at least 2 and would be 8 if there were a complete generation of technifermions, and N_{TC} is the number of technicolours, which must also be at least 2. Clearly, even the minimal possibility $N_{TF} = N_{TC} = 2$ ($\delta S_{TC} \simeq 0.3$) is disfavoured by our result (4a), whilst the more conventional possibility $N_{TF} = 2N_{TC} = 8$ ($\delta S_{TC} \simeq 1.7$) is strongly disfavoured. Ref. [15] considers the possibility that technicolour dynamics differs significantly from QCD, with a possibly different momentum dependence of the dynamical fermion mass just above the confinement scale. Its Table 2 gives 20 representative estimates of contributions to S_{TC} in the case $N_{TC} = 4$ based on different theoretical assumptions. The lowest estimate is $\delta S_{TC} = 0.38$, to which should be added a positive semidefinite contribution from pseudo-Goldstone bosons. Hence these models are also disfavoured.

Ref. [14] also presents two estimates of T_{TC} , one assuming that enhanced hypercharge interactions create a larger condensate for the charge $-\frac{2}{3}$ member of a doublet of techniquarks. In this case, in addition to the Standard Model contribution to T , there is an extra contribution

$$\delta T_{TC} \simeq N_C N_{TC} \frac{1}{12\pi s_W^2 c_W^2} \left(\frac{m_t^2}{M_Z^2} \right) \simeq 0.150 N_C N_{TC} \left(\frac{m_t^2}{M_Z^2} \right) \quad (6)$$

where $N_C = 3(1)$ if the technifermion doublet carries (does not carry) colour as well. The estimate (6) is to be confronted with the bound (4b) and those shown in the Table. We see that for $m_t \geq M_Z$ as indicated by direct searches the data prefer $N_C N_{TC} \leq 5$. This means that the conventional choice $N_{TC} = 4$ is favoured only if $N_C = 1$, in which

case the technifermions do not constitute a conventional generation. Alternatively, the technigeneration choice $N_C = 3$ is disfavoured if $N_{TC} > 2$. The other estimate of δT_{TC} in ref. [14] is based on the alternative hypothesis of isospin asymmetry in the spectrum of extended technicolour gauge bosons, a possibility also studied in ref. [15]. In this case, acceptably small values of δT_{TC} are found for sufficiently small masses of the ETC boson that gives a mass to the t quark and/or the amount of isospin asymmetry in the technifermion masses.

Fig. 4 compares graphically the predictions of various technicolour models [14], for $(\delta S, \delta T)_{TC}$ with the $\Delta\chi^2 = 1$ ellipse indicated by the data for the reference value $(m_t, M_H) = (130 \text{ GeV}, M_Z)$. We see that the technicolour models all agree with the data less well than does the Standard Model.

We conclude that although technicolour theories cannot be ruled out, nevertheless the data do not point in their direction. For the reasons discussed above, it is difficult to make this comparison more precise without a direct experimental determination of m_t and/or a prescription for extending technicolour calculations to larger numbers of loops. Some consideration should also be given to the possibility that some technicolour models might also contain larger non-oblique corrections to electroweak observables, as well as to more precise estimates of the one-loop oblique corrections. However, we doubt that more detailed calculations could rescue the technicolour models known to us.

Acknowledgement

One of us (J. E.) thanks the Università degli Studi di Bari for hospitality while this work was completed.

References

- [1] ALEPH, DELPHI, L3 and OPAL Collaborations, as presented by J. Carter, Proceedings of the *International Lepton-Photon Symposium and Europhysics Conference on High Energy Physics*, S. Hegerty, K. Potter and E. Quercigh eds. (Geneva, 1991), to appear.
- [2] J. Ellis, G.L. Fogli and E. Lisi, preprint CERN-TH 6273/91 (1991).
- [3] For reviews, see:
E. Farhi and L. Susskind, Phys. Rep. **74C** (1981) 277;
K. Lane, in Proceedings of the *International Lepton-Photon Symposium and Europhysics Conference on High Energy Physics*, S. Hegerty, K. Potter and E. Quercigh eds. (Geneva, 1991), to appear.
- [4] For a review, see:
H.E. Haber and G.L. Kane, Phys. Rep. **117C** (1985) 75.
- [5] D. Kennedy and B.W. Lynn, Nucl. Phys. **322** (1989) 1;
B.W. Lynn, M.E. Peskin and R.G. Stuart, in “*Physics at LEP*” J. Ellis and R. Peccei eds. (CERN, Geneva, 1986).
- [6] M.E. Peskin and T. Takeuchi, Phys. Rev. Lett. **65** (1990) 964.
- [7] W.J. Marciano and J.L. Rosner, Phys. Rev. Lett. **65** (1990) 2963.
- [8] G. Altarelli and R. Barbieri, Phys. Lett. **B253** (1990) 161.
- [9] A. Sirlin, Phys. Rev. **D22** (1980) 971.
- [10] M. Consoli, W.F.L. Hollik and F. Jegerlehner, Phys. Lett. **B227** (1989) 167;
B.A. Kniehl and J.H. Kühn, Nucl. Phys. **B329** (1990) 547;
B.A. Kniehl, Nucl. Phys. **B347** (1990) 86;
F. Halzen and B.A. Kniehl, Nucl. Phys. **B353** (1991) 567.
- [11] F. Halzen, B.A. Kniehl and M.L. Strong, Wisconsin preprint MAD-PH-658 (1991).
- [12] G. Altarelli, R. Barbieri and S. Jadach, Nucl. Phys. **B369** (1992) 3;
an updated version of this analysis has been presented by G. Altarelli in Proceedings of the *International Lepton-Photon Symposium and Europhysics Conference on*

High Energy Physics, S. Hegerty, K. Potter and E. Quercigh eds. (Geneva, 1991), to appear, preprint CERN-TH. 6245/91 (1991).

- [13] A. Ali and G. Degrossi, preprint DESY 91-035 (1991).
- [14] M. E. Peskin and T. Takeuchi, SLAC preprint SLAC-PUB-5618 (1991).
- [15] T. Appelquist and G. Triantaphyllou, Yale University preprint YCTP-P49-91 (1991).
- [16] G. Bhattacharyya, S. Banerjee and P. Roy, Tata Institute preprint TIFR/TH/91-38 (1991).
- [17] ALEPH Collaboration, D. Decamp et al., CERN preprint PPE-91-105 (1991).
- [18] P. Renton, Oxford University preprint OUNP-91-30 (1991).
- [19] W.F.L. Hollik, Fortsch. Phys. **C38** (1990) 165.
- [20] CDF Collaboration, preprint FERMILAB-Pub-91/280-E (1991).
- [21] M. Schmiedler and K. Schubert, Karlsruhe preprint IEKP-KA-91-4 (1991);
Y.L. Wu, Mainz preprint MZ-TH/91-14 (1991);
J. Maalampi and M. Roos, Helsinki preprint HU-TFF-91-31 (1991);
A. Pich, CERN preprint TH.6122/91 (1991);
J.R. Cudell and H. Steger, private communication.
- [22] ALEPH, DELPHI, L3 and OPAL Collaborations, as presented by M. Davier, Proceedings of the *International Lepton-Photon Symposium and Europhysics Conference on High Energy Physics*, S. Hegerty, K. Potter and E. Quercigh eds. (Geneva, 1991), to appear.
- [23] M. Sher, Phys. Rep. **179** (1989) 275;
L. Maiani, Proceedings of the Cargèse Summer School (1990), Roma Univ. preprint N. 775 (1991).

Fig. 1 — The ellipsoid in the 3-parameter $(\delta\epsilon_1, \delta\epsilon_2, \delta\epsilon_3)$ space favoured by electroweak data at the $\Delta\chi^2 = 1$ level, together with the two-dimensional manifold calculated in the Standard Model. Also indicated are projections onto the $(\delta\epsilon_i, \delta\epsilon_j)$ planes shown in Fig. 2. The reference values $(m_t, M_H) = (130 \text{ GeV}, M_Z)$ have been used.

Fig. 2a

Fig. 2b

Fig. 2c

Fig. 2 — Projections of Fig. 1 onto (a) the $(\delta\epsilon_1, \delta\epsilon_3)$ or $(\delta S, \delta T)$ plane, (b) the $(\delta\epsilon_1, \delta\epsilon_2)$ or $(\delta T, \delta U)$ plane, and (c) the $(\delta\epsilon_2, \delta\epsilon_3)$ or $(\delta S, \delta U)$ plane. Again, the reference choices $(m_t, M_H) = (130 \text{ GeV}, M_Z)$ have been made. The Standard Model surface of Fig. 1 is bounded by the extreme points A, B, C, D, whose reference values in terms of (m_t, M_H) are (masses in GeV): A $\equiv (90, 1000)$, B $\equiv (250, 1000)$, C $\equiv (250, 50)$, D $\equiv (90, 50)$. The intermediate points correspond to $m_t = 110, 130, \dots, 210, 230 \text{ GeV}$ and $M_H = M_Z, 150, 300, 500 \text{ GeV}$.

Fig. 3 — As for Fig. 2a, but for the different choices of the reference values of (m_t, M_H) corresponding to the points A, B, C, D of fig. 2. In each case the origin has been shifted to the Standard Model $(m_t, M_H) = (130 \text{ GeV}, M_Z)$ point. The bounds on the $\delta\epsilon_i|_{\text{BSM}}$ for each of the cases A, B, C, D are given by the differences between the corresponding ellipses and Standard Model points. The star (*) marks the reference point used in ref. [12] to define $(\delta\epsilon_1, \delta\epsilon_3)$.

Fig. 4 — The predictions of various technicolour models [14], [15], compared with the $\Delta\chi^2 = 1, 2, 7$ ellipses and the Standard Model values taken from Fig. 2a, for the reference choices $(m_t, M_H) = (130 \text{ GeV}, M_Z)$.